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Abstract

Research Focus: Trajan's Column constructed in ancient Rome is probably the best-known “sculpted tower” of the ancient world. It consisted of twenty Carrera marble drums, each weighting thirty-two tons. Today, the largest sculpted tower, in the world was built in Kuwait City and rises over 1200 feet higher than Trajan's Column. The façade of this tower named Al-Hamra consists of 258,000 square feet of limestone tiles. A still higher tower to the south is the tallest building in the world, Burj Khalifa.

The Middle East is starting to attract many tourists from all around the world, and the reason is the amount of tall of skyscrapers that have been or are being built. “Burj Khalifa” in Dubai, UAE is the tallest building in the world, Skidmore, Owings & Merrils provided the engineers and architects, while Turner Construction was the main contractor. I intend to compare those two towers with the “One World Trade Center”. There's a difference of a massive 941 feet between the two buildings. Both buildings are covered completely by glass. Burj Khalifa used around 1,528,000 square feet of glass to clad the exterior. While the One World Trade Center used around 600,000 square feet. The buildings are in the complete opposite sides of the world.

Research Method: As a native of Kuwait and with relatives in Dubai, I intend to draw on some personal experience with the area. It's fascinating to see the difference between two different cultures and environments and compare and contrast between the three buildings. In addition, all three of the modern towers have a common architectural/engineering firm—Skidmore Owings and Merrill, and two of the three have a common Construction Manager Turner. I intend to seek information from the firms and the many articles and statistics already available.

Results and Findings: At present it is not certain what findings will be made.

The main objective is to see the different methods to use glass between the three. Burj Khalifa and Al-Hamra are both in a desert while One World Trade Center is in a city. Burj Khalifa used aluminum and glass, and One World Trade Center used stainless steel panels and glass. The conclusion is to see which method was best used to compensate for the weather in the city. And if there were other elements that required design changes.

Keywords: Dubai, Al-Hamra, Trajan’s Column, Burj Khalifa, One World Trade Center, Freedom Tower

1 Introduction

Countries all around the world have been constructing buildings that are bigger and more unique. Trajan’s Column constructed in ancient Rome is probably the best-known “sculpted tower” of the ancient world. It consisted of twenty Carrera marble drums, each weighing thirty-two tons. Today, the largest sculpted tower, in the world was built in Kuwait City and rises over 1200 feet higher than Trajan's Column. The façade of this tower named Al-Hamra consists of 258,000 square feet of limestone tiles. A still higher tower to the south is the tallest building in the world, Burj Khalifa. A hemisphere away is the One World Trade Center, currently the tallest building in the United States at a symbolic 1776 feet. An interesting point that is underrated is the amount of ego that comes with building these remarkably huge and stunning buildings. A person cannot have an exceptional reputation without his/her ego. Dubai wanted to have the tallest building in the world so they built the tallest sculpted tower in the world. The Trajan’s column was built in honor of the Roman Emperor for being victorious of the Dacian Wars. One World Trade Center was rebuilt after the devastating events of September 11th 2001, and proving that the people of New York are united and strong. Glass now fits in perfectly with a developer’s ego, because over time construction has gone a long way. It all started with marble being the main material and in time glass became the main material to use while designing buildings.

2 Al-Hamra
Al-Hamra Tower is located in Kuwait City, Kuwait. Kuwait is one of the wealthiest countries in the world. However it does not attract as much tourism as Dubai, because the government does not want the exposure and tourists from all over the world, especially since nightlife and alcohol is illegal in the country. Al-Hamra was built as an icon to symbolize national pride. The form of the building is cut from a prism, a void taken from the center and from each floor plate rotating counter-clockwise around the core. It shifts from west to east, which exposes the core of the building, which is wrapped around with transparent walls around the building. The transition between these two conditions is the solid flared walls, covering the complex geometry of the rotating floor plates. It stands around 1500 feet tall. Skidmore Owings & Merrill designed it and Turner Construction was the project manager. Since Al-Hamra tower has a unique design, fabricating the glass was challenging. The coating of the building was very important to make sure that it would be compatible with the heating and bending process required to fabricate the glass that wraps around the corners of buildings. The exterior glass makes up 30 percent of the building’s glazing. Fiberglass was used to build the lamellae. Using drawings from SOM’s 3-D model first generated the process of the lamellae and took around 100 days to complete constructing it. The glass supplier was Guardian Industries for all the glass that was used. The glass is made to withstand strong sandstorms and the blazing heat of Kuwait.

3 Trajan’s Column

While Al-Hamra Tower is currently the tallest sculpted building in the world, Trajan's column is one of the most famous towers in the whole world. It was built as a trophy in Rome, Italy, for the Roman Emperor and was completed in the year 113 after being victorious in the Dacian Wars. Its only 98 feet, but what makes it so unique is that it was made from a series of colossal Carrara marble drums which weighed around 32 tons each. Carrara marble is a type of marble that was popular for sculpting décor with drawings on them. The ones that were used on Trajan column had drawings of soldiers. The tower has a hollow interior and a small doorway with 185 steps that give access to the top platform. What separates the Trajan’s column from the rest is that it is the only building out of the four mentioned that does not have one piece of glass in it. That is what makes it so fascinating and to see how much construction has come over time. Back in the day having marble as the main material in a tower was making a statement of how powerful the Emperor was. Now more people want buildings that have all glass on the outside, because it looks modern and expensive. The more modern the building looks, the better reputation that developer will get, and with reputation comes ego. Ego is a person’s sense of self-importance. The Roman Emperor wanted to make his mark and show how powerful he was and that he could do whatever he wanted because he was the ruler. Its remarkable how much time has changed and how designs of buildings have been affected, going from all marble to all glass buildings.
4 Burj Khalifah

Sculpted buildings are unique and intriguing however having the tallest building in the world in your own city is a remarkable and unique situation all by itself. Burj Khalifah stands tall at 2,722 feet with 163 floors. Skidmore Oweings and Merrill (SOM) were the designers and Turner Construction were also one of several main contractors working on the project. The building set several world records along the way, including the amount of installation of an aluminum and glass façade. The exterior cladding consists of around 1,528,000 square feet of reflective glass, and aluminum. With Dubai being located in a desert, the exterior was designed specifically to be able to endure the extreme hot weather and sandstorms. It consists of 24,348 total windows. Guardian Industries was also selected to provide the glass. The glass was produced and coated in Germany and Luxemburg. Insulated Glass was used with a clear outboard float glass. According to Bill Baker of SOM, who worked on Burj Khalifah states, “The building cladding must be mainly “see-through.” It is made from different materials with different thermal properties. Glass moves differently
than aluminum, which moves differently from steel. The exterior wall sees thermal swings, which the inside does not see. So with the weather constantly changing the exterior wall is hung on the structure in a way that it is able to breathe and grow and shrink as it needs to go through the weather fluctuation, while still keeping the hot weather out. The building is built with low-emissivity glass with enhanced thermal insulation for the hot weather. With the heat in mind heat strengthened glass was used, compared to tempered glass, which is often used around the world, especially Europe. The strengthened glass is better quality because it will hold on longer than tempered glass. It has low risk of breakage. The glass is able to withstand wind speeds of 155 mph. According to Guardian Industries the architects demanded to have “matt, silver reflective color on the outside without disturbing the inside. No body tinted glass or ceramic frit was accepted,” ClimaGuard, which is a low emissivity glass, is requested in Middle East to keep the heat out of the building during the nighttime. Low emissivity glass is very common in the Middle East because it helps reduce condensation on the exterior glass throughout the hot weather. The final compositions of the glass that was used were: for the outerpane 10 mm heat strengthened SunGuard Solar Silver 20, and for the innerpane there was 4mm to 10mm heat strengthened ClimaGuard. There was about 12mm to 18mm of air in between the outerpane and innerpane. The supply of the glass needed to be very tough to ensure that the glass would not break. With the blazing heat climate of Dubai the glass of the building is very important and needs to be very strong so it does not collapse and cause injuries and deaths to people. Even with buildings being built everyday in the world, nobody can build a taller building than Burj Khalifah, because the designers have made it possible to have space to build more on top so it stays the tallest building. Being one of the most modern buildings and the tallest building, glass is the main material to use for the exterior. Glass exterior brings class and modern feelings to people who are looking at the tall buildings. Dubai’s leaders wanted to reflect their personalities in this building, by having it all glass because of their high class wealth and reputation.
5 One World Trade Center (Freedom Tower)

With September 11th 2001 still on many Americans’ minds, the rebuilding of the One World Trade Center (WTC) should boost American pride and unity. It is the tallest building in the western hemisphere. It stands tall at 1776 feet. SOM were also the designers, however Tishman Construction was the main contractor. WTC had initial plans of having a signature prismatic glass façade for the first 20 stories. It was a decorative glass, however it failed testing and to change the designs. David Childs, the main architect, i suggested using around 2,000 prismatic glass panels that would reflect light. The glass came from PPG Industries a company in Pittsburgh, Pennsylvania, but was manufactured in China. The 185-foot podium is the concrete base of the building, which is covered with sapphire glass and with an innovative glass curtain wall that will give the building a unique look. Most of the materials used were previously recycled. Surprisingly SOM designed a building that is less structural stable for better visibility. Usually iron is designed in glass walls to make the glass stable, however the amount of iron was reduced due to the building being more visible and having more daylight. Even with that said, for safety issues the glass is made to become blast-resistant. Building WTC again is very important to the American community, not because it has glass exterior, shiny and looks beautiful.. The building represents all American’s ego’s not only the developers and the people who worked on them. It brings the building to a whole new perspective and hope of being strong and united as one country. It is a very tall glass building, which visually looks stunning and it is proving that Americans are remembering all the 9/11 victims and honoring them with the tragic events that happened that day.
6 Conclusion

In conclusion, different hemispheres with different climates result in different designs and structures. Even with Skidmore Owings & Merrill being the designers for the three modern buildings they all had something unique, with varying designs. Different type of glass was used, whether it was for bombproof or just resisting Mother Nature’s blazing heat. Heat Strengthened glass with low emissivity is used in the Middle East for Burj Khalifah and Al-Hamra tower to be able to withstand the heat. While prismatic glass panels were used to make the One World Trade Center to make it look more visible. Ego comes in as a main factor here also. The Trajan’s Column was built as a trophy and to honor the emperor of Rome for being victorious of the Dacians Wars. Kuwait has everything they ever wanted yet something was missing. The thing that was missing was a new landmark in the country, and Al-Hamra Tower fills that part perfectly as the tallest sculpted tower in the world and one of the most unique looking buildings in the world. Dubai is an up and coming city for tourism, and what better way to make their mark other than having the tallest building in the whole world. One World Trade Center brings back horrible memories to many Americans, however it also symbolizes the pride of the American people. Buildings and sculptures started by having marbles all around to prove their egos. The beautifully sculpted Trajan’s column is the shortest out of the four mentioned buildings, and is the only one without glass. In time glass has become one of the most used materials to use for exteriors, because visually they look very nice and are strong enough to withstand any climate whether it is hot or cold. There are different types of glass but no matter where you are in the world, and no matter which building is being built, glass is always going to bring the ego of a person come out because of its features.

References

Glazed System Cost Comparison Using Dynamic and Static Equivalent Design Methodologies for UFC Blast Applications

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Abstract
For glazed window and curtain wall systems, Standard 10 of Unified Facilities Criteria (UFC) 4-010-01 (including change 1 dated 1 October, 2013) provides options to perform a dynamic analysis or a static equivalent analysis. The dynamic analysis requires application of the appropriate pressure and impulse from the applicable explosive weight at the actual standoff distances at which the windows are sited using a single degree of freedom or more high-fidelity dynamic model (e.g. Finite Element Model). The static analysis approach is a simplified approach that utilizes ASTM F2248 in combination with ASTM E1300 to determine a static equivalent loading and glazing resistance, respectively. While both options can be used to meet the UFC requirements when setback is greater than 43 feet for Explosive Weight I and 23 feet for Explosive Weight II, the UFC notes that the static methodology will result in a more conservative design. This paper evaluates multiple window types (e.g. multi-paned punched opening, storefront, and curtain wall) using both design methods to compare the resulting system requirements, with costs as the basis of comparison. The analysis completed as part of the research presented in this paper is based on a Primary Gathering Building requiring a Low Level of Protection with parking and roadways within a controlled perimeter. The available standoff distances used in the analysis are 100 feet to the controlled perimeter for Explosive Weight I and 50 feet to the nearest parking or roadways for Explosive Weight II. The analysis results and conclusions are of particular interest to design professionals specializing in DoD facilities.

Keywords: Unified Facilities Criteria (UFC), Blast, Dynamic, Static, Charge Weight, Standoff, Cost

1 Introduction
1.1 Background
According to the Heritage Foundation, which has tracked terrorist plots against the United States since the events of September 11, 2001, there have been sixty (60) terrorist plots reported in that time period. Figure 1 shows the number of terrorist plots per year and indicates a substantial rise in the number of events in recent years [8].
Although many of these plots have been foiled by law enforcement or luck, it is imperative that infrastructure and construction design projects consider occupant safety and hazard mitigation in their designs as the last line of defense against terrorist attack. Historical data indicates that for explosive events, the majority of non-lethal injuries are caused by window glazing failing in a hazardous manner, resulting in large shards entering occupied spaces at high velocities. As such, the Department of Defense (DoD) and other government agencies (including the Interagency Security Committee (ISC), Veterans Administration (VA), Department of State (DoS), and others) provide design requirements intended to reduce the risk of significant injury to building occupants from glass failure due to a terrorist attack.

The DoD provides explicit guidance for the design of blast-mitigating window and curtain wall systems in Unified Facilities Criteria (UFC) 4-010-01. As stated in the document, UFC 4-010-01 “represents a significant commitment by DoD to seek effective ways to minimize the likelihood of mass casualties from terrorist attacks against DoD personnel in the buildings in which they work and live.” Because of this mission to protect DoD personnel, it is a necessity to provide the required level(s) of protection, but it is the responsibility of the architects and engineers designing the facilities to ensure the desired level of protection is provided in a cost-effective design.

1.2 Discussion of UFC Requirements
UFC 4-010-01 has continued to evolve with analysis methodologies and building technologies. The original 2003 version of UFC 4-010-01 began with a goal of
providing setback requirements that would allow for the use of conventional construction. As such, this version prescribed only a simplified static design approach for the design of blast-mitigating window systems. The prescribed design loads were based on conventional construction standoff distances being achieved and provided prescriptive minimum requirements for laminated glass layups.

As UFC 4-010-01 has evolved from the 2003 version, subsequent versions of the UFC have revised the static equivalent design approaches and also allowed for the use of an alternate dynamic analysis for “any or all of the glazing, framing members, connections, and supporting structural elements may be designed using dynamic analysis to prove the window system will provide performance equivalent to or better than the hazard rating associated with the applicable level of protection as indicated in Table 2-1 [of UFC 4-010-01]. The design loading for a dynamic analysis will be the appropriate pressure and impulse from the applicable explosive weight at the actual standoff distance at which the window is sited, but not greater than the conventional construction standoff distance.”

Starting with UFC 4-010-01 dated 9 February 2012 and again in Change 1 dated 1 October 2013, the UFC requirements started to shift from promoting the static design approach as the preferred design methodology, towards the use of dynamic analyses based on the explosive weights located at their actual available standoff distances as the preferred design method. In the 2013 UFC, setback requirements have become specific to the actual construction used, and there is no longer a conventional construction limit for window design. As such, window openings are designed based on the applicable explosive weights located at the actual available standoff distance to the nearest appropriate site feature (i.e. site perimeter, parking, roadways, etc.), which may now be a lot closer than allowed in previous versions of the UFC. The 2013 criteria still allows for the use of a static equivalent design approach, however, the approach has become significantly more conservative. Per the static analysis approach defined in the 2013 UFC:

- Glazing to use laminated glass with a minimum interlayer thickness of 0.030-inch (0.75-mm) and a load resistance determined from ASTM E1300 to be greater than or equal to the 3-second duration equivalent design load determined from ASTM F2248.
- Window frame members are designed to restrict deflections of edges of blast resistant glazing they support to L/60 under two times the load resistance of the glazing determined using ASTM E1300.
- Connections are designed using allowable stress levels at two times the glazing resistance determined per ASTM E1300.
- For the design of building structure, “building elements that have only glazing framed into them, such as curtain walls and storefronts, shall be designed as frame members.

The 2013 UFC explicitly states “the application of ASTM F2248 and ASTM E1300 results in a medium level of protection as reflected in Table 2-1 [of the UFC] which is a higher level of protection than that required in these standards.”

As such, it is recommended to use a dynamic analysis approach to reduce the amount of conservativeness present in a given design. Per the 2013 UFC, the dynamic analysis approach states “any of the glazing, framing members, connections, and supporting structural elements may be designed using dynamic..."
analysis to prove the window or skylight systems will provide performance equivalent to or better than the hazard rating associated with the applicable level of protection as indicated in Table 2-1. Dynamic analysis guidance is presented in PDC TR 10-02. The design loading for dynamic analyses will be the appropriate pressures and impulses from the applicable explosive weights at the actual standoff distances at which the windows are sited.” The mullion rotation for a Low Level of Protection (LLOP) per PDC TR 10-02 is limited to 6 degrees and a ductility of 7 for glazed aluminium systems.

2 Approach
In response to the most current DoD design requirements, this paper evaluates multiple window types using both static and dynamic design methods specified in the 2013 version of UFC 4-010-01. Additionally, this paper provides additional dynamic analysis results using more high-fidelity finite element models to more accurately predict the system response. The intent of the work provided in this paper is to compare the resulting material requirements for each option and find the least expensive design approach. Reducing the material requirements means a substantial reduction in costs for the materials themselves and can also mean a reduction in the amount of labor for installation as well. The analysis presented in this paper is based on the requirements of UFC 4-010-01 Change 1 dated 1 October 2013 for a Primary Gathering Building requiring a Low Level of Protection with parking and roadways within a controlled perimeter. The available standoff distances used in the analysis are 100 feet to the controlled perimeter for Explosive Weight I and 50 feet to the nearest parking or roadways for Explosive Weight II. The standoff distances used in the analysis are based on setback distances that occur regularly on blast projects requiring the UFC design standards. The analysis consisted of a multi-paned punched opening, a single span storefront, and a two-span curtain wall using both the static and dynamic design methods. Figure 2 through Figure 4 provide elevation layouts and dimensions of each of the three sample elevations used in the analysis presented in this paper.

![Figure 2. Elevation view of multi-paned punched window used in analysis.](image)
2.1 Static Analysis Procedures
The static design approach prescribed is a simplified approach that can be more easily completed by typical structural or façade engineers without requiring a
significant amount of structural dynamic design experience. Though, developing a true static equivalent design load would require the use of UFC 3-340-02 (Army TM-1300) in conjunction with the calculated natural period of the individual framing members being designed to determine dynamic load factors. This is because the dynamic response of any structural system is a function of the load applied, the natural period(s) of the structural component or system, and the ultimate capacity of the component or system. The dynamic load factor would then be multiplied by the peak dynamic pressure to develop actual static design pressure for a given member or system. However, in accordance with the static design approach outlined in UFC 4-010-01 Change 1 dated 1 October 2013, the window systems provided in this paper were designed as described in Section 1.2:

- Glazing uses laminated glass with a minimum interlayer thickness of 0.030-inch (0.75-mm) and a load resistance determined from ASTM E1300 greater or equal to the 3-second duration equivalent design load determined from ASTM F2248.
- Window frame members are designed to restrict deflections of edges of blast resistant glazing they support to L/60 under two times the load resistance of the glazing determined using ASTM E1300.
- Connections are designed using allowable stress levels at two times the glazing resistance determined per ASTM E1300.

The 3-second equivalent design loads were determined using the chart from ASTM F2248. For security purposes, the actual calculated 3-second duration equivalent design loads are not explicitly provided in this paper. In accordance with ASTM E1300, the glazing was analysed to show the laminated layup had a load resistance greater than the 3-second equivalent design loads per ASTM F2248. The actual glazing layups and load resistance values per ASTM E1300 are provided in the glazing results in Section 3.1.

2.2 Simplified Dynamic Analysis Procedures

The UFC defines a dynamic analysis approach based on the peak dynamic response of the system to demonstrate the systems achieve the required level of protection. The dynamic response provided in this paper is based on the loads from the peak pressure and impulse associated with each Explosive Weight at the actual standoff distance to the appropriate site feature. Figure 5 shows the shapes of the linear equivalent pressure-time histories associated with Explosive Weights I and II at 100 feet and 50 feet, respectively, as used in the analysis provided herein. Note only the positive phase blast load is shown, as the negative phase blast loading is typically not included for design purposes. The peak dynamic pressure for Explosive Weight I at 100 feet of standoff is in the high single digit psi range and for Explosive Weight II at 50 feet of standoff is in the low double digit psi range. For security purposes, the actual calculated pressures and impulses are not explicitly provided in this paper.

Dynamic analyses approaches are inherently more accurate than equivalent static loads because dynamic analyses considers the short duration of blast loads, the actual material response and the stiffness of the system, and the post-elastic response of the framing members. The post-elastic response is critical in a blast analysis, because the systems are generally allowed to achieve deflections up to several times the yield deflection. As an example,
UFC 4-010-01 allows deflections up to 7 times the yield deflection for mullions. This is defined as the ductility limit.

**Dynamic Blast Loads**

**Pressure vs. Duration**

![Graph showing linear equivalent pressure-time load curve shapes for Explosive Weights I & II.]

**Figure 5.** Linear equivalent pressure-time load curve shapes for Explosive Weights I & II.

The dynamic analysis methods provided in this report use two methods for analysis. The first method specified in this section of the report is the simplified Single-Degree-of-Freedom (SDOF) analysis in which the loads specified in Figure 5 are applied over the tributary area of each member to determine the member response and end reactions. The anchor loads were then determined by summing up the end reactions for each member that frames into that anchor. This simplified SDOF dynamic approach assumes the tributary area is an infinitely stiff plate and does not account for the energy absorbed by response of the glass in the member response. Because the simplified SDOF response does not consider the glazing response in the mullion design when only the tributary width of the load is considered, the glazing must be analyzed separately to demonstrate its performance. Alternatively, the actual glazing edge shears from the glazing analysis could be applied to the mullion in a decoupled SDOF solution for simplified systems, such as punched openings.

The simplified dynamic analysis was completed using Applied Research Associates’ (ARA) programs SDOF version 3.0 for analyzing the framing members and WINGARD PE version 6.0 for analyzing the glazing response. In accordance with PDC TR 10-02, the framing response for a LLOP was limited to 6 degrees of rotation and ductility of 7. The glazing response was limited to a Performance Condition 3B, which permits the glass to fail in a non hazardous manner. The glazing performance conditions are summarized in Table 1 and Figure 6.
Table 1. Glazing protection levels based on fragment impact locations.

<table>
<thead>
<tr>
<th>Performance Condition</th>
<th>Protection Level</th>
<th>Hazard Level</th>
<th>Description of Window Glazing Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Safe</td>
<td>None</td>
<td>Glazing does not break. No visible damage to glazing or frame.</td>
</tr>
<tr>
<td>2</td>
<td>Very High</td>
<td>None</td>
<td>Glazing cracks but is retained by the frame. Dusting or very small fragments near sill or on floor acceptable.</td>
</tr>
<tr>
<td>3a</td>
<td>High</td>
<td>Very Low</td>
<td>Glazing cracks. Fragments enter space and land on floor no further than 3.3 ft from the window.</td>
</tr>
<tr>
<td>3b</td>
<td>High</td>
<td>Low</td>
<td>Glazing cracks. Fragments enter space and land on floor no further than 10 ft from the window.</td>
</tr>
<tr>
<td>4</td>
<td>Medium</td>
<td>Medium</td>
<td>Glazing cracks. Fragments enter space and land on floor and impact a vertical witness panel at a distance of no more than 10 ft from the window at a height no greater than 2 ft above the floor.</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>High</td>
<td>Glazing cracks and window system fails catastrophically. Fragments enter space impacting a vertical witness panel at a distance of no more than 10 ft from the window at a height greater than 2 ft above the floor.</td>
</tr>
</tbody>
</table>

* In conditions 2, 3a, 3b, 4 and 5, glazing fragments may be thrown to the outside of the protected space toward the detonation location.

Figure 6. Glazing protection levels based on fragment impact locations.
2.3 Finite Element Based Dynamic Analysis Procedures
In addition to the simplified dynamic analysis using SDOF calculations, a second dynamic analysis approach was considered using more complex finite element models to more accurately predict the system response. The finite element models were constructed using ARA’s WINGARD MP software, which couples the advanced glazing analysis models contained in WINGARD PE with a non-linear, elastic Finite Element Analysis (FEA) code to predict the response of a multi-paned window system when subjected to blast loads. This coupled solution considers the glazing response in conjunction with the mullion to determine a coupled solution. An example of the curtain wall system as modelled in WINGARD MP is provided in Figure 7.

Figure 7. WINGARD MP model of representative curtain wall system.
The *WINGARD MP* model considered the flexural response of the glazing as well as that of the framing members. Additionally, the model considers the load distribution on the glass itself; this minimizes the amount of “load overlap” that occurs when a typical tributary width SDOF model in which the tributary loads applied to the vertical and horizontal mullions overlap. As such, the anchor loads calculated using *WINGARD MP* are generally less conservative than those determined using the simplified SDOF approach which results in much smaller anchor requirements for supporting the system.

Dynamic analysis methods require specialized training and tools, and should only be attempted by blast engineers experienced in performing dynamic analyses.

### 3 Calculation Results

#### 3.1 Glazing Requirements

The glazing requirements determined using each design approach are provided in Table 2. Table 2 includes the glazing resistance per ASTM E1300 for the equivalent static design approach and the glazing Performance Conditions for the dynamic design approaches for the layups shown. Note the use of laminated glass for each glazing layup specified. Per the requirements of UFC 4-010-01, “laminated glass is preferred as the protective layer (the inner lite in an insulating glass window) in glass windows required to meet these standards because when laminated glass fails the laminate interlayer tends to retain the glass fragments, significantly reducing the hazardous fragments entering inhabited areas. Monolithic glass and acrylic is not allowed by these standards because those glazing’s break into hazardous fragments.”

**Table 2.** Glazing requirements for each design approach.

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Glazing Layup</th>
<th>Resistance per ASTM E1300 (psi)</th>
<th>Performance Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punched Window</td>
<td>1/8” Heat strengthened glass 0.060” (1.5 mm) Polyvinyl-butyral interlayer</td>
<td>0.873</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1/8” Heat strengthened glass 1/2” Air space</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/4” Annealed glass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Storefront</td>
<td>3/16” Heat strengthened glass 0.060” (1.5 mm) Polyvinyl-butyral interlayer</td>
<td>1.211</td>
<td>3B</td>
</tr>
<tr>
<td></td>
<td>3/16” Heat strengthened glass 1/2” Air space</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/4” Annealed glass</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Curtain Wall</td>
<td>3/16” Heat strengthened glass 0.060” (1.5 mm) Polyvinyl-butyral interlayer</td>
<td>1.063</td>
<td>3B</td>
</tr>
<tr>
<td></td>
<td>3/16” Heat strengthened glass 1/2” Air space</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1/4” Annealed glass</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
3.2 Framing Requirements

The framing requirements were determined using each design approach and are provided in Table 3. The part numbers/sections specified in Table 3 are based on Kawneer Company’s (Kawneer) 1600 System 1 “stick-built” curtain wall system. Other members may be used to provide an equivalent level of protection; however, they must meet the minimum equivalent section properties provided in Table 4. The equivalent section properties are based on 6063-T6 aluminum having a minimum yield strength of 25 ksi and a typical yield strength of 31 ksi.

Table 3. Kawneer specific framing requirements for each design approach.

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Design Approach</th>
<th>Vertical Frame</th>
<th>Vertical Mullion</th>
<th>Horizontal Frame</th>
<th>Horizontal Intermediate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punched Window</td>
<td>Static</td>
<td>162-001</td>
<td>162-001 w/ 162-362 steel</td>
<td>162-094</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>162-001</td>
<td>162-001</td>
<td>162-094</td>
<td>N/A</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>162-001</td>
<td>162-001</td>
<td>162-094</td>
<td>N/A</td>
</tr>
<tr>
<td>Storefront</td>
<td>Static</td>
<td>162-064 w/ 162-365 steel</td>
<td>162-064 w/ 162-363 steel</td>
<td>162-095</td>
<td>808-292 w/ 162-303 steel</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>162-004</td>
<td>162-003 w/ 162-301 steel</td>
<td>162-095</td>
<td>808-292</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>162-003</td>
<td>162-003 w/ 162-301 steel</td>
<td>162-095</td>
<td>808-292</td>
</tr>
<tr>
<td>Curtain Wall</td>
<td>Static</td>
<td>162-064 w/ 162-365 steel</td>
<td>162-064 w/ 162-363 steel</td>
<td>162-095</td>
<td>808-292 w/ 162-302 steel</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>162-004</td>
<td>162-003 w/ 162-301 steel</td>
<td>162-095</td>
<td>808-292</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>162-004</td>
<td>162-003 w/ 162-301 steel</td>
<td>162-095</td>
<td>808-292</td>
</tr>
</tbody>
</table>
The equivalent properties based on 6063-T6 aluminum are provided in Table 4. **Table 4.** Equivalent shape framing requirements for each design approach.

<table>
<thead>
<tr>
<th>Kawneer Part Number</th>
<th>Equivalent Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Area (in²)</td>
</tr>
<tr>
<td>162-001</td>
<td>1.79</td>
</tr>
<tr>
<td>162-001 w/ 162-362</td>
<td>3.21</td>
</tr>
<tr>
<td>162-094</td>
<td>1.45</td>
</tr>
<tr>
<td>162-003</td>
<td>2.05</td>
</tr>
<tr>
<td>162-003 w/ 162-301</td>
<td>3.75</td>
</tr>
<tr>
<td>164-004</td>
<td>2.39</td>
</tr>
<tr>
<td>165-095</td>
<td>1.71</td>
</tr>
<tr>
<td>808-292</td>
<td>2.2</td>
</tr>
<tr>
<td>808-292 w/ 162-302</td>
<td>3.23</td>
</tr>
<tr>
<td>808-292 w/ 162-303</td>
<td>3.07</td>
</tr>
<tr>
<td>162-064 w/ 162-363</td>
<td>6.4</td>
</tr>
<tr>
<td>162-064 w/ 162-365</td>
<td>5.53</td>
</tr>
</tbody>
</table>

### 3.3 Anchorage Requirements

The anchorage requirements were determined using each design approach and are provided in Table 5. All anchors are based on 1/4 inch thick, A36 steel custom “F” and “T” anchors with vertical legs welded to a baseplate and engaging the vertical framing members. The anchor dimensions provided in Table 5 were included in the calculation to determine the overall unit cost per square foot for each elevation shown in Table 6 in Section 4 of this paper. As noted in Section 2.3, the finite element analysis approach provides less conservative anchor loads than those determined using the simplified SDOF approach, which results in much smaller anchor requirements.
Table 5. Steel anchorage requirements for each design approach.

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Design Approach</th>
<th>Anchor Depth (in)</th>
<th>Anchor Length (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punched Window</td>
<td>Static</td>
<td>3.375</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>3.375</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>3.375</td>
<td>16</td>
</tr>
<tr>
<td>Storefront</td>
<td>Static</td>
<td>7.625</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>4.625</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>4.625</td>
<td>16</td>
</tr>
<tr>
<td>Curtain Wall</td>
<td>Static</td>
<td>7.625</td>
<td>32</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>4.625</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>4.625</td>
<td>16</td>
</tr>
</tbody>
</table>

4 Summary of Costs
A summary of the framing system costs by window type and design approach are provided in Table 6. The table provides the estimated cost per square foot for each elevation in terms of 2014 dollars. Because of inflation, material availability, and other market factors, the cost per square foot is subject to change. Therefore, a cost ratio was included which is the ratio of costs of materials for the static and simplified dynamic design approaches to that of the finite element model based dynamic design approach. The costs provided in the table were based on information provided by Kawneer.
Table 6. Summary of costs categorized by the design approach.

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Design Approach</th>
<th>Cost per ft² (in 2014 Dollars)</th>
<th>Cost Ratio (% of Cost for Static Design)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Punched Window</td>
<td>Static</td>
<td>$28.92</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>$28.29</td>
<td>1.09</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>$26.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Storefront</td>
<td>Static</td>
<td>$26.04</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>$17.07</td>
<td>1.08</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>$15.82</td>
<td>1.00</td>
</tr>
<tr>
<td>Curtain Wall</td>
<td>Static</td>
<td>$18.09</td>
<td>1.65</td>
</tr>
<tr>
<td></td>
<td>Dynamic (SDOF)</td>
<td>$11.27</td>
<td>1.03</td>
</tr>
<tr>
<td></td>
<td>Dynamic (FEA-MP)</td>
<td>$11.02</td>
<td>1.00</td>
</tr>
</tbody>
</table>

Costs provided herein only consider the material costs. Additional costs associated with shipping, fabrication, and installation were not evaluated. However, it would be reasonable to assume that shipping and installation costs would be increase proportionally for the more robust and more expensive systems.

5 Conclusions

While the primary stated goal of implementing the UFC document 4-010-01 is to protect the personnel occupying DoD owned facilities, a secondary goal should include providing those protective measures in the most cost effective manner. The design criteria offers a dynamic design approach for designers trained in structural dynamics and a static equivalent approach that can be implemented by engineers more comfortable designing in the static realm. This study concludes that for small, punched openings, using the static design approach will result in an increase in material costs of approximately 10% over the least conservative dynamic analysis. For larger storefront and curtain wall systems, using the more conservative static equivalent design approach will result in a potential increase in material costs of approximately 50-60%. The increase in costs will also carry over into shipping, fabrication, and installation of the heavier, more conservative systems, as well as the elements supporting the window systems that would have to be designed to carry the larger, more conservative design reactions into the building diaphragm. This could result in a substantial cost impact for the building owner (DoD).
References


Modern photoelastic technology for residual stress measurement in architectural glass panels

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GlasStress Ltd., Estonia

Abstract
Rapidly evolving glass industry creates a demand for new and efficient methods for the control of residual stress in architectural glass panels. The paper describes the application of the photoelastic scattered light method for the measurement of stress through the thickness of glass panels. A small portable scattered light polariscope has been designed for this purpose. This device measures stress both in thermally tempered panels and float glass. Chemical tempering can be detected. Due to the portability it can be applied for stress measurement in existing buildings. With this device it has been shown that due to discrete location of cooling jets in tempering ovens the residual stress field at the surface of tempered glass panels is inhomogeneous and at a distance of 10 mm stress may vary for tens of MPa. The new measurement technology is suitable for the measurement of total stress in load bearing glass panels. It is also shown that edge stress in tempered glass panels is practically equal to the surface stress. Thus the traditional edge stress measurement gives complete information about the stress field in glass panels.

Keywords: glass, residual stress, quality control, photoelasticity, tempering stress, edge stress.

1 Introduction

Standards for architectural glass panels prescribe application of the four-point bending test and/or the fragmentation test. Both of these tests are destructive and time-consuming.
At the same time, during recent years photoelastic residual stress measurement methods have been considerably developed and applied. In [1] data is described about testing of 360 glass panels by first measuring the residual surface stress with the GASP polariscope [2]. Paper [1] shows that a good correlation exists between surface compressive stress data and mechanical strength and measurement of the surface residual stress roughly determines the bending strength of the glass.

By assessing the degree of temper in glass panels via non-destructive residual stress measurement, one should bear in mind the following. Residual
compressive stress at the surface of glass panels in the middle part of the panel is usually isotropic. It means that the compressive stress has the same value in all the directions in the surface of the panel. However, near the borders and corners of the panel this is usually no longer the case and measurement results depend on the direction of the stress measurement. Since European standards demand stress measurement both in the centre as well as at the corners of the glass panels, that should be taken into account.

Another factor to be considered is possible local variation of the residual stress. Since in tempering furnaces the cooling of the panels is carried out by jets, the cooling of the surface of the panel is inhomogeneous. Due to this, the residual stress may vary at a distance comparable with the distance between cooling jets. Let us mention that vibration of the jet grids leads to more uniform distribution of the tempering stress (see, e.g. [3], p. 135).

In the first part of this paper we describe the scattered light method for residual stress measurement in glass panels and show that the residual stress field is inhomogeneous. In the second part of the paper we describe a new approach to the edge stress measurement.

2 The scattered light method

Scattered light polariscopes for residual stress measurement in glass have been developed by several authors [4,5]. However, these polariscopes are complicated devices, which can be used only in laboratory conditions and cannot be used in factory conditions near the production line.

For industrial applications a portable scattered light polariscope, referred to as the SCALP, has been developed at GlasStress Ltd [6]. A schematic of the optical measurement arrangement and a photograph of the SCALP are shown in Fig. 1. A laser beam is passed through the panel at an angle of about 45°. Stress birefringence changes the polarisation of the laser beam. These changes are recorded by measuring the variation of the intensity of the scattered light along the laser beam with a CCD camera. From this measurement data stress profile through the panel thickness is determined. Spatial resolution of the SCALP in the plane of the panel to be measured is about 0.5 mm; in the direction of the thickness of the panel it is about 20 μm.

Figure 1. Optical measurement arrangement schema (a) and photograph (b) of the portable scattered light polariscope SCALP.
The SCALP is calibrated using a four point bending test. Since it has no moving parts, no additional calibration is needed. The polariscope is automatic, and stress profile measurement time is about 3 s. However, to calculate the stresses, the value of the photoelastic constant is to be known.

If the residual stress state is isotropic \((\sigma_1 = \sigma_2)\) then measurement in one direction using the device is sufficient. If \(\sigma_1 \neq \sigma_2\), measurements in two perpendicular directions using the device, parallel to the principal stress directions, are needed. Figure 2 shows an example of principal stress profiles through the thickness of a tempered glass panel of thickness 6 mm. In the general case, measurements in three directions \((0^\circ, 45^\circ, -45^\circ)\) permit measurement of the principal stress directions and their profiles through the panel thickness.

![Graph](image)

**Figure 2.** Principal stress profiles through the panel thickness at a point on the symmetry axis of a tempered glass panel of thickness 6 mm: \((\ldots) \sigma_1, (\ldots\ldots) \sigma_2\).

### 3 Local variation of tempering stresses

Stress field in a tempered glass panel No. 1 of dimension 300 × 300 mm with thickness 5.5 mm was calculated and partly measured experimentally with the SCALP [7]. Calculations were made on the basis of a mathematical model, described in [8]. Figure 3 shows photoelastic fringe pattern in a circular polariscope. Inhomogeneity of the stress field is clearly visible.
Figure 3. Photoelastic fringe pattern of the panel No. 1.

Distribution of the calculated and measured stress $\sigma_x$ in the mid-surface and upper surface of the plate are compared in Fig. 4. It should be mentioned that the very high stress gradient in the plane of the plate may have influenced the precision of the photoelastic measurements.

Figure 4. Distribution near the edge of $\sigma_x$ on the $x$ axis in panel No. 1 (—— calculated, —— measured).

Figure 5 shows the fringe pattern of a part of a tempered glass panel No. 2 and variation of the stresses $\sigma_x$ and $\sigma_y$ along the scanned line.
It can be seen that in the middle part of the panel (at a distance from the edge more than 50 mm) the stresses are more or less isotropic, i.e., $\sigma_x \approx \sigma_y$ while near the edge the stress components $\sigma_x$ and $\sigma_y$ differ considerably. Local variation of the stresses between $x = 7$ mm and $x = 31$ mm is also distinct – being about 10 MPa at a distance of 10 mm.

Let us mention that if surface stress measurement is carried out with the SCALP, which measures stress variation along a laser beam, the local variation of the surface stress can be measured and the stress value is determined at the point where the laser beam enters the surface of the panel. In contrast, the GASP device gives an average value of the stresses for a small distance along the measurement direction.

Figure 6 shows the fringe pattern in a transmission polariscope of the middle part of a sidelite. Figure 7 depicts the surface stress ellipses for the points 1 and 2, the distance between which is 12 mm. It is seen that although the distance between the points 1 and 2 is very small, the surface stresses differ considerably.
4 Global variation of the tempering stresses

Besides the local variation of the tempering stresses in the scale of several centimetres, on glass panels the value and character of the residual stresses depends also on the location on the panel. In the middle part of the panels the residual stresses have mostly isotropic or close to the isotropic character. I.e., in all the directions the stresses have about the same value. Near the edges and corners the formation of the tempering stresses is influenced by inhomogeneous cooling conditions and therefore stresses in different directions may differ considerably. This is valid in general. However, local variation of stresses may considerably influence the situation.

Figure 8 shows geometry of a tempered glass panel of thickness 6 mm. According to European standards the surface residual stress should be measured
at the centre and at the points A, B, C and E. Figure 9 depicts the surface stress ellipses at the central point and at the corner point A and E. It can be seen that, as expected, residual stress at the central point is rather homogeneous, with stresses in all directions being approximately equal.

Figure 8. Geometry of a tempered glass panel. According to European standards the stresses are to be measured at the centre and at the four corners.

Figure 9. Directional variation of the surface residual stress at the centre and at the points A and E.

At the corner points the stress ellipses have considerable eccentricity. It means that at these points stress measurement in an arbitrary direction is not sufficient. To obtain real values of the residual stresses, if measurements are carried out with the SCALP, the measurements should be carried out in three directions, at 0°, 45° and 90° to the coordinate axes. On the basis of these measurements the directions of the principal stresses and their values are automatically calculated. We have shown that residual stresses in tempered glass panels can be highly inhomogeneous. Both the local and global inhomogeneity has been investigated and demonstrated on several examples. General information about the inhomogeneity of the stresses can be obtained by observing the panel normal to its surface in a plane circular polariscope. Using the device SCALP, both local and global inhomogeneity of the tempering stresses have been recorded in several cases. From the given examples it follows that while in the middle of the glass panels the tempering stress is usually isotropic and stress measurement in
one direction may be sufficient, near the edges and corners that may not be the case and direction-dependent measurements should be carried out. Due to possible local inhomogeneity of tempering stresses, to talk about the precise value of the residual stress at the panel surface has no sense. One may speak about a certain interval of the values of tempering stresses. This interval depends on the technology of tempering. Since the local variation of the surface tempering stress may reach about 10 MPa or even more, the precision of the SCALP (several MPa's) is sufficient for non-destructive assessment of the strength of the panels.

5 A new approach to edge stress measurement

A traditional method for assessing the degree of temper of glass panels is the edge stress measurement. By edge stress measurement a simple transmission polariscope is used for photoelastic measurement of the stress at the edge and in the region near the edge [9–12]. Figure 10a shows photoelastic fringe pattern in a light-field circular polariscope near the edge of a tempered glass panel of 6 mm thickness. The dark stripe on the left is the image of the chamfered edge of the panel. Figure 10b shows the edge stress distribution. The most important is the area A, where the average stress through the thickness of the panel is tensile. According to Gulati [13], in this area a delayed crack growth may take place. However, since the thickness stresses are not known, traditional edge stress measurement gives no information about the real surface stresses in the area A and no information is obtained about the thickness of the compressive layer near the surfaces of the panel.

![Figure 10(a) and 10(b)](image)

Figure 10. Photoelastic fringe pattern in a light-field circular polariscope near the edge of a 6 mm thick glass panel (a) and membrane stress distribution (b).

Let us mention that since at the edge of the panel the stress component, perpendicular to the edge, is zero, the stresses at the edge can be correctly determined from the photoelastic image using extrapolation. Inside the panel the stress component, perpendicular to the edge, is different from zero and the photoelastic image does not allow determining separately the stress component
parallel to the edge. Both stress components can be determined using e. g. the oblique incidence method [3]. We applied the oblique incidence method for the panel shown in Fig 10. It was established that up to the distance of 15 mm from the edge the influence of the stress component, perpendicular to the edge, was negligible.

It is evident that the edge stress $\sigma_e$ and the surface stress $\sigma_s$ must be in correlation, and knowing one of them it should be possible to obtain certain information about the other. Our aim is to establish the correlation between the edge stress and the surface stress in tempered glass panels. It has been shown that a simple linear relationship exists between the edge and surface stresses. Therefore measurement of the edge stress gives also the value of the surface stress and real stress distribution in the zone of the average tensile stress. Thus the edge stress measurement is considered much more informative than until now.

6 Experiments

We ordered from a glass tempering factory a number of glass panels of the size $100 \text{ mm} \times 300 \text{ mm}$, of 6 and 10 mm thickness with different degree of tempering, with surface stress $\sigma_s$ varying from zero (annealed glass) up to 120 MPa. We measured in all the specimens the edge stress $\sigma_e$ with the polariscope AP-07 (Glasstress Ltd.), shown in Fig. 11a. Since the edges of the specimens were chamfered, extrapolation of stresses near the edge was carried out with a polynomial of 4th degree. Figure 10b shows typical results of the edge stress measurement (in a 6 mm panel).

![Figure 11. Edge stress measurement with the automatic transmission polariscope.](image)

The surface stress $\sigma_s$ in all the specimens was measured with the scattered light polariscope SCALP. Figure 12a shows the relationship between the edge stress and surface stress in panels of 6 mm thickness, and Fig. 12b in panels of 10 mm thickness. Considering the inhomogeneity of the residual stress in tempered glass panels the surface stress values in Fig. 12 are the average of 5 measurements. The correlation equation for the panels of 6 mm thickness is the following ($R^2 = 0.9405$):

$$\sigma_s = 1.0493\sigma_e + 1.7663,$$

(1)
and for the panels of 10 mm thickness

\[ \sigma_s = 1.0177 \sigma_c. \]  (2)

Figure 12. Relationship between the edge stress and surface stress in panels of 6 mm (a) and 10 mm (b) thickness.

7 Mathematical modelling of the tempering process

To check the somewhat unexpected results of the experiments, edge stresses were calculated also by using a mathematical model of the glass tempering process [14-16]. It has been assumed that the heat transfer coefficients perpendicular to the panel surface and in the panel surface are the same. The modelling results for the case of 6 mm panels are shown in Fig. 13. It can be observed that the surface stress is equal to the edge stress. Thus mathematical modelling confirms the experimental results.

Figure 13. Results of the mathematical modelling of stresses near the edge in a 6 mm panel.

8 Complete stress analysis in the panel
In tempered glass panels most critical is the area A (Fig. 10b), where the average through the thickness stress is tensile. This stress is determined during the edge stress measurement. Since according to our investigation surface stress is equal to edge stress, after the edge stress measurement we know the surface stress and that permits to reconstruct the parabolic thickness stress $\sigma_t$ distribution through the thickness of the panel (Fig. 14a). In the area of average tensile stress a superposition of these stresses takes place. Figure 14b shows the average membrane stress distribution in the “tension zone”. Total stress in this area is the sum of these two stress fields (Fig 14c). Thus in new interpretation the edge stress measurement gives information about the real stresses in the “tension zone”. That permits to estimate whether near the surface the compression zone is deep enough or even whether tensile stresses have reached the surface. Thus the edge stress measurement actually gives complete information about the stress field in the panel.

9 Conclusions

It has been shown that the scattered light method permits measurement of the stress through the thickness of architectural glass panels. A simple portable scattered light polariscope SCALP has been described. This polariscope can be used to measure stress also in glass panels of existing buildings. A new way to interprete the edge stress measurement data has been proposed. That permits determination of the whole stress field near the edge.

References


Structural stability of compressed monolithic and laminated glass elements under blast loads

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Abstract
Current applications in buildings of structural glass elements frequently require design rules and formulations able to provide acceptable predictions for phenomena complex to describe, which depend on combination of several geometrical/mechanical aspects. The estimation of the buckling resistance of glass elements, for example, represents a topic of large interest for researchers, due to typical high slenderness ratios, limited tensile strength and brittle behavior. In the paper, the buckling response of glass columns under impulsive orthogonal pressures (e.g. blast) and combined static compressive vertical loads (e.g. gravity loads or further service loads) is investigated. Advanced numerical nonlinear dynamic simulations are performed on various laminated columns, by means of 3D numerical Finite Element (FE)-models able to take into account the interaction of simultaneous loads and possible glass cracking. Analytical calculations are then carried-out by means of single-degree-of-freedom (SDOF) formulations, to correctly estimate blast and second-order effects on maximum deflections and corresponding tensile stresses. Finally, based on the good correlation generally found between numerical/analytical calculations, a design approach is proposed for practical estimation of buckling strength in the analyzed loading and boundary conditions.

Keywords: laminated glass, dynamic buckling, SDOF system, numerical dynamic simulations, design approach

1 Introduction
Current use of glass in structural applications frequently requires the development of analytical approaches and practical formulations able to provide acceptable predictions for structural phenomena – often rather complex to describe – which depends on combination of multiple geometrical and mechanical aspects. Glass, for example, is a typical brittle material, characterized by high compressive strength but limited tensile resistance. Although used in conjunction with thermoplastic polymers able to provide ductility and enhanced post-breakage behavior, since glass elements are commonly associated to high slenderness ratios, they are strongly susceptible to buckling failure mechanisms. Extended experimental, numerical and analytical studies have been performed in the last years, in order to provide useful information and possible design
approaches for the prediction of the effective buckling strength of monolithic and laminated glass columns, beams or panels under various boundary and loading conditions. In the case of laminated glass (LG), specifically, the effective interaction between multiple layers, as well as possible stiffness degradation of the bonding interlayers – typically time-loading and temperature dependent - have been deeply analyzed (e.g. [1]-[6]). Nevertheless, further knowledge is still required, especially for a rational investigation of specific structural conditions that could be encountered in practice.

1.1 Investigation of dynamic buckling
In this work, the attention is focused on the dynamic buckling behavior of compressed glass elements under impulsive pressures (e.g. blast). It is well-known that dynamic loads commonly involve typical responses in structural systems that strongly differ from their same response under static loads. Because of this reason, the investigation of major effects due to explosive loads on various structural typologies recently encountered the interest of researchers [7]-[13]. Assessment of equivalent single-degree-of-freedom (SDOF) models derived from classical theory of dynamics [14]-[16] was proposed in these earlier contributions. Pure dynamic stability phenomena in members, finally, have been investigated over the past years for various structural typologies [17]-[21].
In this paper, a simple analytical model for the static buckling analysis of monolithic and laminated glass (LG) columns under axial compressive $N$ and bending loads (e.g. uniformly distributed, static loads $q$) is briefly recalled from literature [4]. Geometrical nonlinear, FE-numerical dynamic analyses are then performed on glass columns subjected to orthogonal blast waves and static vertical compressive loads (ABAQUS/Explicit [22]). Careful consideration is given to LG columns. The typical 3D FE-model, as shown, provides accurate simulation of dynamic effects due to interacting loads, second order effects, possible brittle failure and progressive damage of glass sheets. Nevertheless, sophisticated numerical studies often require large computational cost. Further assessment of FE-simulations is consequently performed by means of simple analytical formulations (SDOF approach [13]). Good correlation is generally found between analytical and numerical maximum displacements and tensile stresses in glass, for a wide series of columns. As a result, a simple design approach is proposed for the dynamic buckling resistance of the examined structural elements under combined $N$-$q$ loads.

2 Static buckling analysis of glass columns under compression and bending

2.1 Monolithic glass
Let us consider the pinned monolithic glass column depicted in Figure 1, subjected to a compressive load $N$ and an equivalent sine-shaped distributed orthogonal load of maximum amplitude $q_0 = q \frac{r^2}{8}$. The first one ($N$) could describe the gravity loads acting on the column. At the same time, the sine-shaped load $q_0$ - well representative of the bending effects due to an uniformly distributed load of constant amplitude $q$, could be rationally able to describe possible quasi-static equivalent loads (e.g. wind). The column, having monolithic $b \times h$ cross section, is composed of glass (Young’s modulus $E$), and affected by an
initial sine-shaped, geometrical imperfection of maximum sag $u_0$ [23]. In these hypotheses, the structural effects of the applied $N-q$ loads on its typical load-carrying behavior can be estimated in the form of maximum mid-span deflection $u_{\text{max}}$ and corresponding tensile stress $\sigma_{\text{max}}$ relationships [4]:

$$u_{\text{max}} = \left( \frac{L_0^2}{8} \left( \frac{L_0 q + 8 N u_0}{E J_y \pi^2 - N L_0^2} \right) + u_0 \right) \leq u_{\text{lim}} = \frac{L_0}{\gamma_{M1}}, \quad (1)$$

$$\sigma_{\text{max}} = \left( -\frac{N}{A} + \frac{N u_{\text{max}}}{W_y} + \frac{q L_0^2}{8 W_y} \right) \leq \sigma_{\text{Rd}} = \frac{\sigma_{Rk}}{\gamma_{M2}}, \quad (2)$$

with $J_y = bh^3/12; A = bh; W_y = bh^2/6; \gamma_{M1}, \gamma_{M2}$ appropriate safety coefficients, $\sigma_{\text{Rd}}$ and $\sigma_{Rk}$ the design and characteristic tensile strength of glass respectively.

Figure 1. Static buckling of a column under $N-q$ loads

Based on eqns (1) and (2), due to the application of $N-q$ static loads, the buckling failure of the column could be prevented by opportune limiting the maximum deflection $u_{\text{max}}$ (eqn (1)) to an appropriate safety ratio ($L_0/\gamma_{M1}$), as well as by avoiding the attainment of maximum tensile stresses $\sigma_{\text{max}}$ on glass (eqn (2)) exceeding a well-calibrated ratio of the corresponding characteristic tensile strength ($\sigma_{Rk}/\gamma_{M2}$). Equivalently, the applied compressive vertical load $N$ could be properly limited, compared in this case to the Euler's critical buckling load $N_{cr,0}^{(E)}$ of the same column, being:

$$N \leq N_{\text{lim}} = N_{cr,0}^{(E)} \left( \frac{1}{\gamma_{M3}} \right) = \left( \frac{\pi^2 E J_y}{L_0^2} \right) \frac{1}{\gamma_{M3}} \quad (3)$$

and $\gamma_{M3}$ a partial safety coefficient.
2.2 Laminated glass
The same analytical approach discussed in Section 2.1 could be reasonably extended to laminated glass (LG) columns composed of two glass sheets and a middle interlayer (Figure 2).

![Figure 2. Laminated glass element (cross-section)](image)

In it, the structural interaction between the external glass sheets directly depends on the mechanical properties of the adopted bonding interlayer. A simple approach for a rational estimation of the effective interaction provided by the used thermoplastic foil (e.g. PVB, SG, etc.) can be derived from simplified equivalent thickness formulations of literature, already successfully applied to structural glass elements over the past years. With reference to Figures 1 and 2, specifically, the layered cross-section can be in fact studied in the form of an “equivalent monolithic” section composed of glass and having total thickness [24],[25]:

\[
h_{eq,w} = \sqrt[3]{h_1^3 + h_2^3 + 12G_{int}J_s},
\]

(4)

where

\[
0 \leq \Gamma_b = \frac{1}{1 + \pi^2 \frac{Eh_1h_2G_{int}}{(h_1 + h_2)G_{int}L_0^2}} \leq 1
\]

(5)

\[
J_s = h_1(0.5h_1 + 0.5h_{int})^2 + h_2(0.5h_2 + 0.5h_{int})^2.
\]

(6)

In eqn (5), \(G_{int}\) represents the shear stiffness of the adopted interlayer. Based on master curves available in literature, its quasi-static equivalent value should be properly calibrated for the specific time-loading and temperature condition taken into account [26],[27]. The resulting so called “shear transfer coefficient” \(\Gamma_b\), based on this assumption, would be consequently able to rationally reproduce the
structural bending behavior of the physical laminated cross-section, leading to a specific level coupling between the glass sheets typically comprised between the well-known layered limit ($I_b = 0$, absence of connection) and monolithic limit ($I_b = 1$, full rigid connection).

In these hypotheses, based on eqns (4)-(5)-(6), it is clear that maximum deflections, tensile stresses and compressive loads $N$ attained in a generic LG column affected by initial geometrical imperfections ($u_0$) and subjected to combined $N$-$q$ static loads could be calculated and checked by means of eqns (1)-(2)-(3), thus properly limited as for a monolithic cross-section of total thickness $h_{eq,w} = h$.

### 3 Dynamic buckling analysis of glass columns under impact loads

Although the nonlinear buckling response of monolithic or LG pinned columns under static $N$-$q$ loads can be performed by means of the analytical approaches discussed in Section 2, this is not the case of the same columns under impact loads (e.g. air blast waves) and quasi-static compressive loads (e.g. gravity loads and further service loads).

Let us consider, for this purpose, the column depicted in Figure 3a - having total buckling length $L_0$ and width $b$ - where a static compressive load $N$ cost and an impulsive blast load $q(t)$ act simultaneously. For blast, based on recommendations of standards, a time-varying load function should be generally used for appropriate investigations (Figure 3b). Its initial intensity $q_{max}$, in fact, rapidly decays to zero (usually in a period $t_{blast}$ of few milliseconds), whereas the time instants ($t_{blast} < t < t_{max}$) define the so-called “negative phase” [28]. Although for simple structural systems the maximum effects of a given explosive event can be rationally estimated by assuming for the positive phase (“Phase I”) a triangular decaying path (Figure 3b) and neglecting its negative phase (“Phase II”), careful attention should be generally paid for the analysis of structural systems under impulsive loads.

![Figure 3.](image)

**Figure 3.** a) glass column under impulsive load $q$ and vertical compression $N$. b) time-varying pressure function for blast
3.1 Finite-element (FE) numerical approach (MDOF)

In order to investigate through advanced numerical simulations the typical response of compressed glass members under static vertical loads \(N\) and impulsive blast loads \(q\), wide series of geometrical nonlinear, dynamic FE-simulations were performed with the computer software ABAQUS/Explicit [22]. Attention was paid especially for LG columns, in order to properly analyze the dynamic buckling behavior of these multi-layered elements. For this purpose, LG columns having several \(L_0 \times b\) aspect ratios and different glass/PVB thicknesses \(h= h_1= h_2\), \(h_{\text{int}}\) were investigated.

3.1.1 FE-numerical models

3.1.1.1 Solid-shell (SS) FE-model

The typical “SS” FE-model consisted of 8-node stress/displacement linear solid elements (C3D8R) with reduced integration, and 4-node quadrilateral (S4R), stress/displacement shell elements with reduced integration and large-strain formulation. 3D solid elements were used for the description of the PVB-interlayer, whereas shell elements were considered for glass (Figure 4).

![Figure 4. Geometry detail of the typical SS FE-model](image)

Restraints were introduced at the top and bottom sections of each model, in the form of nodal boundaries applied to the end-sections of the solid layer (Figure 4, yellow dots). “Rigid” end sections - fully composed of glass - were defined at the ends of the columns, in order to prevent local distortional effects. The total thickness of these rigid-ends was properly calibrated (\(\approx 10\) mm), so that their presence could not affect the global behavior of the studied systems. Possible displacements at the bottom section of each column were then restrained along the three directions \((d_x= d_y= d_z= 0)\), whereas a vertical roller was introduced at their top end \((d_x= d_y= 0)\). An idealized flexural deformed shape was also guaranteed during the dynamic simulations (especially for glass columns with large \(b/h_{\text{tot}}\) ratios, with \(h_{\text{tot}}\) the total cross-sectional thickness), by introducing additional restraints along each transversal cross-section (null rotations \(r_z\) around the vertical \(z\)-axis). Finally, all the examined columns were subjected to initial
geometrical sine-shaped imperfections of maximum amplitude $u_0 = L_0/400$ [23] described in the form of appropriate out-of-plane nodal displacements ($x$-direction). As a result, dynamic simulations were performed on geometrically pre-deformed models.

Careful consideration was dedicated to the mechanical characterization of materials. Glass was described as a typically brittle, linear elastic, isotropic material. Nominal values were assigned to Young modulus ($E = 70$GPa), Poisson ratio ($\nu = 0.23$) and density ($\rho = 2500$ Kg/m$^3$) [28, 29]. The possible brittle failure in tension was also properly taken into account in the dynamic simulations, by means of the ABAQUS “brittle cracking” smeared model. Input parameters of this damage model are the fracture energy of glass ($G_f = 3$J/m$^2$ [30]) and its characteristic tensile strength $\sigma_{R_k}$. In this context, due to the impulsive nature of the applied explosive loads, strain rate effects were taken into account in the form of magnified nominal characteristic tensile strengths $\sigma_{R_k}$. As a result, static strengths $\sigma_{R_k}$ of annealed (AN), heat-strengthened (HS) and fully tempered (FT) glass - 45MPa, 70MPa and 120MPa respectively - were replaced with the corresponding "dynamic" tensile strengths of 85MPa, 120MPa and 160MPa [31]. Concerning the PVB foils, based on test results of literature, an idealized elasto-plastic relationship was taken into account, with $E_{int} = 500$MPa the “glassy” Young modulus, $\sigma_{y, int} = 11$MPa the yielding strength and $\varepsilon_{u, int} = 300\%$ the ultimate strain. Hardening effects were neglected [29]. Material density and Poisson’s ratio were also set equal to $\rho_{int} = 1100$kg/m$^3$ and $\nu_{int} = 0.49$.

### 3.1.1.2 Multi-layer shell (SM) FE-model

A second geometrically simplified and extremely computational efficient FE-model (SM) was also developed for the same columns. In this case, the nominal cross-sectional geometry (Figure 2) was described in the form of a multi-layered shell element (S4R-composite type), able to take into account the effective thicknesses and mechanical properties of all the bonded layers. Material properties and boundaries were described as for the corresponding SS FE-models (Section 3.1.1.1).

### 3.1.2 General numerical approach

Each dynamic simulation consisted of three steps. First ($I^o$, Figure 5), only compressive loads $N$ were gradually applied to each column. For convenience, the resulting compression $N$ was expressed as a dimensionless loading ratio:

$$R_N = \frac{N}{N_{cr,0}^{(E)}}$$

(7)

with $N_{cr,0}^{(E)}$ the Euler’s critical load already defined in eqn (3).
In the second step (II°, Figure 5), blast loads were applied to the same columns, in the form of uniformly distributed pressures acting on the $L_0 \times b$ surface of each LG element. A linear time-varying function was used to describe the blast wave between the first instant of application ($t=3s$, with $q=q_{max}$) and $3s+t_{blast}$ ($q=0$). In the third step (III°, Figure 5), finally, the dynamic response of the columns was monitored.

3.1.3 Parametric numerical dynamic investigations

Preliminary dynamic numerical studies were performed in order to assess the accuracy of SS and SM FE-models. A general optimal correspondence was found between them, both in terms of time evolution of deflections and tensile stresses in glass. Examples are given in Figure 6 for a (10/10 AN + 4.52mm PVB) column ($L_0=2m$, $b=1m$). This agreement suggested the use, for extended parametric numerical dynamic simulations, of the latter.

In general, parametric simulations performed on various SM FE-models (e.g. different $h/h_{int}$ ratios, glass types, $L_0 \times b$ shapes, $R_N$ loading ratios compared to blast loads, maximum amplitude $u_0$ of initial sine-shaped imperfections) confirmed that the progressive increase of $R_N$ - for a given impulsive load $q$ - typically results in the increase of maximum deflections, thus in largest maximum tensile stresses in glass and possible failure mechanisms (Figure 7). A further effect of the applied $N$ loads is represented by the modification of the fundamental period of vibration $T$ of the studied columns.

For a pinned LG column under blast only, $T$ could be rationally estimated as [16]:

$$T = T_{N=0} = \frac{2\pi h_{eq,w}^2}{9.869} \sqrt{\frac{\rho_{eq} b h_{eq,w}}{E J_{y,eff}}}$$

(8)
Figure 6. Comparison between SS and SM FE-models. a) maximum deflections; b) maximum envelope of tensile stresses in glass (ABAQUS/Explicit)

with $h_{eq,w}$ the corresponding monolithic thickness (eqn (4)), $J_{y,eff} = J_y$ given in eqn (3) and

$$\rho_{eq} = \frac{2h\rho + h_{int}\rho_{int}}{h_{eq,w}}$$

(9)

the equivalent density. In contrary, careful consideration should be given to the analysis of the same column under blast and pre-established loading ratios $R_N$. A simple way - although approximate - to consider this effect is given by [16]:

$$T = T_N = \frac{T_{N=0}}{\sqrt{1 - R_N}} = \frac{T_{N=0}}{\sqrt{1 - \frac{N}{N_{cr,0}^{(E)}}}}$$

(10)
with $R_N$ defined in eqn (7). Numerical studies generally highlighted that eqn (8) provide accurate estimation for the period $T$ ($R_N = 0$). Otherwise, especially for columns with $R_N \neq 0$, the sensitivity of numerical fundamental periods $T$ to the $R_N$ ratios resulted overestimated by eqn (10), also in presence of moderate levels of vertical pre-compression (e.g. $R_N < 0.4$). Consequently, it is clear that further assessment of simplified formulations for the dynamic buckling analysis of glass columns is required.

![Figure 7](image-url)

**Figure 7.** Parametric numerical studies on a LG column. a) maximum deflections; b) maximum tensile stresses (ABAQUS/Explicit, SM model).

### 3.2 SDOF approach

In this work, further assessment of FE-numerical predictions has been performed by means of analytical formulations partly derived from literature [14]-[16].

Based on classical dynamical theory [14] and Ritz's method, as known, the simplest analytical approach for the estimation of the dynamic response of a given structural system is the approximation of the real column by means of an equivalent single-degree-of-freedom (SDOF) system.
In the hypothesis of linear-elastic behavior for the composite resisting section - well representative of the mechanical behavior of glass up failure in tension - the deflection of the column depicted in Figure 8 can be rationally described by means of the static deformed shape \( \phi(z) \) of a simply supported beam-column under uniform load \( q \):

\[
\phi(z) = \frac{16}{25L_0^4} \left( L_0^3 z - 2L_0^3 z^3 + z^4 \right),
\]

with \( 0 \leq z \leq L_0 \) the Cartesian coordinate. Based on the choice of this reference deformed shape \( \phi(z) \), the application of Ritz’s method to the real system typically manifests in the estimation of its equivalent dynamic parameters (e.g. mass and resistance function). In doing so, with reference to Figure 8, the presence of additional compressive vertical loads \( N \) acting contemporarily to blast waves \( q \) can be rationally described in the form of additional equivalent lateral loads (ELL) well representative of second-order effects, and defined as [16]:

\[
\eta(t) = \frac{8N}{L_0} u(t),
\]

with \( u(t) \) the displacement of the system at a generic time instant \( t \). In these hypotheses, the equation of motion able to describe the dynamic response of the structural system depicted in Figure 8 is [14]:

\[
K_M M \ddot{u}(t) + K_L R u(t) = K_L \left( Q(t) + \eta(t) \right).
\]

In it, \( M \) and \( R(u(t)) \) respectively represent the total mass and the resistance function of the real column subjected to a time-varying total load \( Q(t) = q(t) \times L_0 \).
At the same time, the transformation coefficients $K_M$ and $K_L$ - being directly dependent on the shape function defined by eqn (11) - are given by:

$$K_M = \frac{M^*}{M} = \frac{\int_0^L \rho_{eq} h_{eq,w} \phi^2 \, dz}{\rho_{eq} h_{eq,w} L_0} = \frac{3968}{7875} \approx 0.5,$$

(14)

$$K_L = \frac{Q^*(t)}{Q(t)} = \frac{\int_0^L \phi \, q(t) \, b \, dz}{q(t) \, b \, L_0} = \frac{16}{25} \approx 0.64.$$

(15)

It is consequently clear, based on eqns (13)-(14)-(15), that the simultaneous dynamic action of $N$-q loads should be carefully taken into account in the structural analysis of a given system, since typically associated to behaviors (e.g. displacements $u(t)$ and corresponding tensile stresses $\sigma_{\text{max}}(t)$ variable in time and depending on a combination of multiple factors).

From a practical point of view, simplified analytical procedures derived from theory of dynamics are proposed for a rational estimation of maximum effects associated to a given impulsive load $q$. The maximum dynamic displacement $(u_{max})_N$ of a given SDOF system subjected to combined $N$-q loads, can be in fact directly estimated as:

$$(u_{\text{max}})_N = DLF \left( \frac{1}{1 - R_N} \right) \frac{q_{\text{max}}}{K_{N=0}^*},$$

(16)

The main advantage of eqn (16) is that – although approximately – the dynamic interaction of the applied $N$-q loads can be properly taken into account.

In it, the dimensionless coefficient $DLF = f(t_{\text{blast}}/T^*)$ represents the so-called “Dynamic Load Factor” and represents a useful practical tool for calculations. Physically, the DLF coefficient represents the magnifying effects that dynamic loads can have on the structural response of a system subjected to the same static loads. Based on the total duration of the positive phase of blast ($t_{\text{blast}}$), specifically, as well as on the period of vibration of the studied SDOF system (with $T^* \equiv T$ given by eqn (10)), the corresponding DLF coefficient does not depend on the intensity of applied loads and can be graphically estimated from non-dimensionless charts (“shock spectra”) of literature (Figure 9).

In eqn (16), moreover, $q_{\text{max}}$ represents the maximum amplitude of the assigned blast wave (e.g. peak pressure at $t=0$), whereas $R_N$ is the loading ratio given by eqn (7). Finally, $K_{N=0}^*$ is the equivalent stiffness of the SDOF system, calculated in absence of compressive loads ($N=0$):

$$K_{N=0}^* = K_L K = K_L \frac{384 \, EJ}{5L_0^3}.$$

(17)
Based on the equivalent thickness approach discussed in Section 2 and the numerical investigations partly shown in Section 3.1, the same SDOF approach can be applied to monolithic glass columns under combined $N$-$q$ loads, as well as to LG columns, by simply replacing the total thickness ($h = h_{eq,w}$) and the related inertial properties (e.g. $J_y = J_{y,eff}$).

In any case, since the calculation of the maximum deflection ($u_{\text{max}}$) alone does not provide suggestion on the possible cracking of glass panes, a further appropriately estimated static equivalent distributed load should be defined, in order to estimate the effective dynamic buckling resistance of the studied systems. In this work, an equivalent load $q_{eq}^{st}$ is defined as the distributed, equivalent load able to reproduce statically on the given columns the same bending effects of the applied dynamic $N$-$q$ loads (e.g. maximum deformed shape). Specifically, the deflection ($u_{\text{max}}^{\text{dyn}}$) given by eqn (16) is set equal to the maximum static displacement $u_{\text{max}}$ provided by eqn (1), hence resulting in a distributed load (with $N=0$ and $u_0= 0$ in eqn (1)) equal to:

$$q_{eq}^{st} = \frac{8EJ_y \pi^2}{L_0^4} \left( u_{\text{max}}^{\text{dyn}} \right)_N.$$

Once $q_{eq}^{st}$ is known, the corresponding maximum tensile stress $\sigma_{\text{max}}$ on glass can be directly estimated as:

$$\sigma_{\text{max}} = -\frac{N}{A} + \frac{q_{eq}^{st} L_0^2}{8 W_y}.$$

**Figure 9.** “Shock spectra” for the estimation of the DLF coefficient for SDOF systems under triangular, rectangular or half sine wave impulsive loads respectively [14].
3.3 Comparative MDOF and SDOF calculations
Large series of parametric calculations were performed on glass columns having various geometrical and mechanical properties, in order to assess the accuracy of eqns (16) and (19). In each numerical simulation, the attainment of a maximum tensile stress \(\sigma_{\text{max}}\) equaling the characteristic magnified tensile strength of glass was identified as the condition of buckling failure for the examined columns. The same comparative calculations were performed both for monolithic and LG members. Various combinations of \(N-q\) loads were taken into account (e.g. \(t_{\text{blast}}\) ratios, \(R_N\) ratios, etc.).

Comparative dynamic numerical and simplified analytical calculations, partly proposed in Figure 10, resulted in general good agreement between numerical and predicted maximum dynamic deflections (eqn (16)). Discrepancies typically resulted in an overestimation of about 2-3% for a range of compressive loads \(0 \leq R_N \leq 0.4\). For highest \(R_N\) loading ratios \((0.4 \leq R_N \leq 0.8)\), divergences up to 7-8% were found. Concerning the prediction of maximum tensile stresses in glass, calculations given by eqn (19) provided rather good level of accuracy, compared to numerical predictions. In this case, the discrepancy between them was approximately equal to 7-8%, for low compressive loading ratios \((0 \leq R_N < 0.4)\) as well as for high loading ratios \((0.4 \leq R_N \leq 0.8)\).

![Figure 10. Numerical (ABAQUS/Explicit) and analytical (SDOF approach) results. a) maximum deflections; b) maximum tensile stresses.](image)

4 Verification approach for dynamic buckling of glass columns
Based on assessment and validation partly discussed in Section 3.3, it is clear that a rational dynamic buckling verification of glass columns under \(N-q\) loads could be performed by means of simplified analytical approaches derived from literature. Two different analytical procedures are presented in Sections 4.1 and 4.2.

4.1 General analytical procedure
Generally, the collapse condition for a glass column - identified as the attainment of first glass cracking \((\sigma_{\text{max}} \equiv \sigma_{\text{rd}}\), being \(\sigma_{\text{rd}}\) the design tensile strength of glass
defined in eqn (2)) – can be estimated by means of eqns (16), (18) and (19).
From a practical point of view, the maximum effects of design $N-q$ loads can be in
fact calculated by taking into account the following steps:

a) Estimation of the fundamental period $T = T_N$ for the column subjected to
compressive loads ($N = N_{Ed} \neq 0$), by means of eqn (10);

b) Calculation of the corresponding magnifying coefficient $DLF$. For a given
impulsive triangular load (maximum amplitude $q_{max} \equiv q_{Ed}$, total duration
$t_{blast}$) $DLF$ can be graphically estimated by means of Figure 9, as a
function of the ratio ($t_{blast}/T^*$), with $T^* = T$ given at point (a);

c) Calculation of the maximum dynamic deflection $u_{max}^{dyn}/N$ (eqn (16));

d) Estimation, based on eqns (18) and (19), of the corresponding maximum
tensile stress $\sigma_{max}$ on glass and comparison of $\sigma_{max}$ with the
corresponding design tensile strength $\sigma_{Rd}$.

As a result, it is clear that the buckling failure condition for a given glass column
under $N-q$ dynamic loads could be rationally checked from points (a)-(d).

4.2 Simplified approach
For stability verification purposes, however, a generalized, dimensionless design
curve (e.g. buckling curve or normalized resisting domain) could be extremely
useful for practical calculations. Based on the Eurocode design approach and
recent contributions of literature [4], the design buckling resistance $N_{b,Rd}$ of the
studied glass columns could be rationally calculated as:

$$N_{b,Rd} = \chi A \sigma_{Rd},$$

where

$$\chi = \frac{1}{\Phi + \sqrt{\Phi^2 - \overline{\lambda}^2}},$$

$$\Phi = 0.5 \cdot \left(1 + \alpha_{imp} \left(\overline{\lambda} - \alpha_0 \right) + \overline{\lambda}^2 \right),$$

$$\overline{\lambda} = \sqrt{\frac{A \sigma_{Rk}}{N_{cr,0}^{(E)}}},$$

and $\alpha_{imp}$, $\alpha_0$ appropriate imperfection factors [4].

In this specific work, due to the impulsive nature of blast loads, possible
imperfection effects were neglected ($\alpha_{imp} = \alpha_0 = 0$). At the same time, further
dimensionless coefficients were introduced:
\begin{equation}
\overline{R}_N = \frac{N_{Ed}}{N_{b,Rd}},
\end{equation}
\begin{equation}
\overline{R}_q = \frac{q_{Ed}}{\left(q_{\text{max}}\right)_{N_{Ed}=0}}.
\end{equation}

Eqn (23), specifically, represents the ratio between the design compressive load \(N_{Ed}\) and the design buckling strength \(N_{b,Rd}\) of the studied column (eqn (20)). At the same time, eqn (25) defines the ratio between the applied design blast pressure \((q_{Ed} = q_{\text{max}})\) and the maximum amplitude \((q_{\text{max}})_{N_{Ed}=0}\) of the impulsive “ultimate” blast pressure of total duration \(t_{\text{blast}}\) associated to the collapse of the same column, with \(N_{Ed} = 0\).

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{normalized_domain.png}
\caption{Normalized domain for glass columns under impulsive loads \(q\) and vertical compressive loads \(N\) (eqn (28)).}
\end{figure}

This latter term, specifically, should be properly calculated, since physically related to a maximum dynamic deflection \(\left(u_{\text{max}}^{\text{dyn}}\right)_{N=0}\) leading to \(\left(\sigma_{\text{max}} = \sigma_{Rd}\right)\). Due to impulsive distributed loads \(\left(q_{\text{max}}\right)_{N_{Ed}=0}\), only, the SDOF system results in fact subjected to a maximum dynamic deflection:

\begin{equation}
\left(u_{\text{max}}^{\text{dyn}}\right)_{N=0} = \frac{\left(q_{\text{max}}\right)_{N_{Ed}=0}}{K_{N=0}} DLF,
\end{equation}
with $K_{N=0}^*$ given by eqn (17), $DLF= f(t_{blast}/T^*)$ taken from Figure 9 (with $T^* \equiv T_{N=0}$ of eqn (8)). The corresponding maximum tensile stress $\sigma_{max}$, based on eqns (18), (19) and (26), can then be estimated as:

$$\sigma_{max} = \frac{\pi^2 E_y}{L^2 W_y} \left( \frac{u_{max}}{N=0} \right).$$  \hspace{1cm} (27)

In these hypotheses, the dynamic buckling verification of a column under $N$-$q$ loads requires the satisfaction of a simple linearized condition (Figure 11):

$$\bar{R}_N + \bar{R}_q \leq 1,$$

thus manifests in a linear normalized resisting domain of practical use.

5 Conclusions

The dynamic buckling behavior of glass columns subjected to impulsive orthogonal loads (e.g. blast waves) and simultaneous compressive vertical static loads has been investigated numerically and analytically.

Deep studies have been preliminary performed in ABAQUS/Explicit, in the form of geometrical nonlinear, dynamic analyses carried-out on well-calibrated FE-models. The main advantage of the discussed FE-models is given by correct estimations of dynamic effects due to interacting applied loads (e.g. second order effects), as well as by realistic simulation of possible glass cracking. Several geometrical and mechanical parameters (e.g. glass and interlayer thicknesses, column aspect ratios, type of glass, loading ratio $R_N$ and blast wave impulse) were taken into account.

Assessment of numerical predictions has been successively performed by means of simplified analytical formulations derived from classical theory of dynamics. The main advantage of proposed simplified SDOF approach is a suitable estimation of maximum dynamic effects (e.g. maximum deflection) for a given system under certain loading conditions. As shown, acceptable agreement was found for glass columns under impulsive blast loads and various levels of compressive vertical loads. Based on the estimated maximum deflection, a static equivalent load was then introduced, to be used for a practical estimation of the maximum tensile stress in glass due to interacting $N$-$q$ loads. Comparative results generally provided interesting correlation between analytical and numerical predictions.

A practical design approach, based on the use of a simple linear interaction curve, has been finally proposed for dynamic buckling check of monolithic and laminated glass columns.

References


Recent initiatives to enhance cooperation in structural glass research and education in Europe

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Ghent University, Belgium

Jens Schneider  
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Christian Louter  
Ecole Polytechnique Fédérale de Lausanne, Switzerland

Jürgen Neugebauer  
Fachhochschule Joanneum, Austria

Abstract
Glass is used as a structural material in buildings for about two decades now. Ever since, structural glass is gaining importance in building practice at fast pace. So far, Europe has fulfilled a pioneering role in the development of structural glass towards the autonomous scientific and technical domain it is today. However, in particular in research, several initiatives have been taken in Europe recently to strengthen its strong position and to overcome a number of existing shortcomings, such as a lack of research coordination and cooperation, a lack of (at least) European-wide structural glass design guidelines and standards, and a lack of Structural Glass educational programs for academic engineers and architects. A key aspect in this process was the creation of a strong, open-minded multidisciplinary scientific and technical network on Structural Glass. Through the strong support of the EU COST program, COST Action TU0905 “Structural glass: Novel design methods and next generation products” succeeded in establishing a strong scientific network on a European level and in addressing current needs in this field. In this contribution, a short overview is given of the main activities of the Action, illustrating its great impact on the enhancement of cooperation in structural glass research and education in Europe. This paper is providing a summary and update of earlier releases about COST Action TU0905 by the authors.

Keywords: structural glass, COST, COST Action TU0905, cooperation in science and technology, European research

1 INTRODUCTION

1.1 Background

Glass is used as a structural material in buildings for about two decades now. Ever since, structural glass is gaining importance in building practice at fast pace. So far, Europe has fulfilled a pioneering role in the development of structural glass towards the autonomous scientific and technical domain it is today. However, in particular in research, several initiatives have been taken in Europe
recently to strengthen its strong position and to overcome a number of existing shortcomings, such as a lack of research coordination and cooperation, a lack of (at least) European-wide structural glass design guidelines and standards, and a lack of Structural Glass educational programs for academic engineers and architects. A key aspect in this process was the creation of a strong, open-minded multidisciplinary scientific and technical network on Structural Glass.

1.2 The COoperation in Science and Technology program of the EU

In this section the COoperation in Science and Technology (COST) program of the EU, which over the last four years enabled a significant improvement of the scientific Structural Glass community network in Europe, is briefly introduced. COST is a bottom-up EU funding program to help reducing the fragmentation in European research investments and to increase research networking in specific research domains. COST provides a platform for European scientists to cooperate on particular projects, called "Actions". Each COST Action is a network centered around nationally-funded research projects and typically runs for a duration of four years. COST Action TU0905 “Structural glass: Novel design methods and next generation products” was successfully launched in April, 2010. More information on the COST program in general is available on the official COST website [1], while additional information on COST Action TU0905 can also be found in [2].

1.3 Structural Glass: COST Action TU0905

1.3.1 Structure and members

The COST Action has about 115 members from 25 different member states, as listed in Table 1. Each member is part of at least one specific Task Group (TG), working on a specific sub-topic related to Structural Glass. Clusters of three to four TGs forms one Working Group (WG). In total four WGs were installed, each of which had been identified already in the general work plan (Memorandum of Understanding (MoU)) before the start of the Action. An updated overview of WGs and TGs is listed in Table 2.
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<td>25</td>
<td>United Kingdom</td>
<td>WG3 Leader (University of Cambridge)</td>
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Table 2. Overview of Working Groups (WG) and Task Groups (TG) of COST Action TU0905. * TG14 is a “vertical” TG, meaning that it does not belong to a specific WG but contains members from all other TGs.

<table>
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<td>Eurocodes</td>
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1.3.2 Aims
COST Action TU0905 has four principal objectives, stated in its Memorandum of Understanding. Firstly, it wants to identify and share the outcomes of existing fragmented activities within the European Structural Glass research community. Secondly, it targets to establish a diverse multi-disciplinary network that will encourage new research and collaborations. Next, the Action intends to contribute strongly to the ongoing development of innovative high-performance structural glass products mainly in architectural applications and to European standards in this field, preferably in dialogue with colleagues from other parts of the world. Finally, the last key objective is to strengthen the current and future generations of European glass designers by developing an academic structural glass education pack for its members all over Europe. Additional information on the COST Action on Structural Glass can be found on the Action’s website [2]. A detailed overview of the history of the Action has been reported on previously [3,4].

2 ACTIVITIES
2.1 Meetings
A key objective of the Action is to create a scientific network. Obviously, the best way to do so is to bring people physically together to discuss research topics of common interest. Consequently, numerous meetings have been organized at different levels of the Action. In detail, these levels are related to the Core Group...
(CG), Management Committee (MC), Working Groups (WG), and Task Groups (TG). A detailed overview of 17 meetings organized during the Action is available in previous publications [4].

2.2 Training Schools

The education pack, created earlier by an impressive joint effort of many COST Action WG/TG members according to the MoU objectives, was successfully customised and opened to a broader public for the first time during the COST Training School organised in April 2012 in Ghent, Belgium (Prof. Jan Belis). During this one-week event, 116 students from 20 different countries were educated in Structural Glass Engineering by 15 international COST experts. In addition, the Training School offered excellent networking opportunities – in particular for Early Stage Researchers – as well as valuable technical activities. A more detailed report on the Training School is available in [5].

Following the excellent feedback received after the first Training School, a second Training School was organised by the Action in Darmstadt in March 2013 (Prof. Jens Schneider). Again, students were very enthusiastic about the concept, and also an increasing educational interest was observed from industry as well as from American and Canadian engineers.

In total, both Training Schools together reached an audience of 137 participants, 94% of which was ESR.

2.3 Workshops

Throughout the Action, also several workshops have been organised by Action Members to disseminate results of the Action and to increase the involvement of Early Stage Researchers. In order of appearance, they include an “ESR Think Tank Session” held in Poreč, 2013, focusing at young researchers in Structural Glass; a “Structural Glass Crash Course” held prior to GPD2013 in Tampere, targeting a wider audience; and finally a three-days “ESR Workshop and Networking Event” in Lausanne, 2014, focusing at young researchers and including e.g. specific glass-related numerical modelling lectures, exercises, visits to realized projects, and company visits. An impression of the atmosphere during the workshop is given by Fig. 1.
2.4 Conferences

Although in the original MoU only a Final Conference event was foreseen, the Action Management decided to organize an additional Mid-Term Conference to disseminate the knowledge gained in the network and to create a platform open to the public to discuss the state of the art in Structural Glass research. The COST Action TU0905 Mid-Term Conference on Structural glass took place in Poreč, HR, on April 18+19, 2013 (organized by Dr Mocibob, Dr Louter and Prof. Belis). The conference attracted about 100 participants, of which about 50 % were external to the Action. Furthermore, the Mid-Term Conference was a success especially in terms of great Early Stage Researcher (ESR) involvement, valuable scientific contributions, and very good participant feedback [5].

The Final Conference took place on February 6 and 7, 2014, at the Ecole Polytechnique Fédérale de Lausanne in Lausanne, Switzerland, obviously an attractive location in winter season. To create synergy and to avoid at the same time an overload of international conferences in the same period, forces were joined with Challenging Glass, a conference of which already three very successful editions had set very high standards and an excellent reputation in the field. The organization of the Challenging Glass 4 & COST Action TU0905 Final Conference was in the hands of Dr Louter, Dr Bos, Prof. Belis and Prof. Lebet. Approximately 230 participants attended the event, which was considered a great success.
It is noteworthy that for both conferences all submissions were peer-reviewed and a well-reputed scientific publisher was in charge of publishing the hardcover proceedings, ensuring their availability also after the end of the Action.

Finally, the Action was actively promoted and results disseminated through COST Action TU0905 papers, sessions and mini-symposia at international conferences organised by other parties. Noteworthy are the Challenging Glass 3 Conference in Delft (organised by Dr F. Bos, Dr C. Louter, Dr F. Veer and Prof. R. Nijsse in June 2012); the second International Conference on Structures and Architecture (ICSA) in Guimarães, (organised by Prof. P. Cruz in July 2013); Glass Performance Days 2013 in Tampere (organised by J. Vitkala in June 2013), Places and Technologies in Belgrade (organised by Prof. E. Vaništa Lazarević, Prof. A. Krstić-Furundžić, Prof. A. Dukić and Dr M. Vukmirović in April 2014) and GlassConGlobal conference in Philadelphia, USA (organised in June 2014 – this issue).

2.5 Short Term Scientific Missions

To encourage in first place Early Stage Researchers (ESR) to cooperate with each other as well as with more established experts in the network, the Action actively promotes its Short Term Scientific Missions (STSM). The Action provides significant financial support for STSMs, which allows researchers to visit another institute in one of the participating Member States. Usually STSMs are triggered by a common research interest, by complementary expertise, or by specific equipment available at the host institute. At the beginning of the Action there was a surprisingly low interest in STSMs, but happily this changed rather drastically throughout the Action’s lifetime due to active promotion by the Action’s Management and due to very valuable output obtained. Indeed, in many cases STSMs resulted in joint peer-reviewed articles or common research proposals. Finally, by the end of the Action a rather impressive number of 42 STSMs was successfully accomplished. An overview of guest’s institutes and host’s institutes is listed in Table 3.
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<tr>
<th>Nr.</th>
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<td>41</td>
<td>Ghent University</td>
<td>TU Graz</td>
</tr>
<tr>
<td>42</td>
<td>University of Belgrade</td>
<td>FH Joanneum, TU Graz</td>
</tr>
</tbody>
</table>
2.6 TUD Conference Grants

As part of the COST strategy for Early Stage Researchers (ESR) the COST Committee of Senior Officials (CSO) has introduced a Conference Grant for Early Stage Researchers. Typically, the Domain for Transport and Urban Development (TUD) offers three supporting grants per year for ESRs to participate in an international conference held anywhere in world and outside of COST Action activities.

In total, three members of COST Action TU0905 have been selected by the TUD Domain Committee to be awarded a TUD Conference Grant: one in 2011, one in 2012 and one in 2013.

3 EVALUATION OF THE ACTION

3.1 Meeting the MoU objectives (and beyond)

The key objectives of the Action have without exception been fulfilled. By organizing expert meetings and by triggering discussions about well-defined research topics related to Structural Glass, thanks to COST Action TU0905 the European scientific community in this domain made a giant leap forward in getting to know each other, each others work, as well as existing strengths and weaknesses. Gaps in the research activities could more easily be detected, and complementary research groups found each other in a very natural way. Testimonies of the scientific success are the numerous joint papers published and research projects initiated between members since the start of the Action.

Forces were really joined by the large COST-network of international experts the first time during the creation of the Education Pack, a huge collection of well-structured customizable Powerpoint presentations prepared to boost the development of academic educational courses in Structural Glass at European Universities.

Finally, thanks to a very fortunate timing, the Action actively and significantly contributed to the initial works of CEN TC250 WG3, responsible for the creation of a new Eurocode on Structural Glass. Obviously, works in this WG are currently ongoing (and most probably will continue to do so for the next coming years), but to date a comprehensive background document was prepared which was recently released by the EU Joint Research Council (JRC) [8]. More information on the Eurocode 10 ongoing work is available in [9].

3.2 Annual progress monitoring by TUD Domain Committee

To monitor the progress and overall quality of all running COST Actions within the Transport and Urban Development (TUD) Domain, COST Office and the TUD Domain Committee (DC) every year organize an Annual Progress Monitoring Conference (APC). In preparation of the APC, Action Chairs have to prepare an Annual Progress Report (APR), and defend their Action’s activities in front of the TUD DC during an oral presentation at the APC. Chairs’ presentations and APRs are publically available at COST’s homepage at the following url:
Throughout the successive APCs held in Vienna, Reykjavik and Rijeka, respectively, the corresponding DC Evaluation of COST Action TU0905 increasingly evolved from “under development” the first year to “in line” the second year and finally to “outstanding”, the best possible score, during the third year. The Action was considered a “Success Story”.

4 TOWARDS THE FUTURE

During the Action, several seeds have been planted to enable the network to continue its work at least partly also after the official ending of the Action in April 2014.

First of all, the ongoing works related to Eurocode 10 on Structural Glass will be continued the next coming years, with continuous input from many COST Action members who are also national representatives in CEN TC250 WG3 (see also section 3.1).

Secondly, the European Federation of Structural Glass Laboratories (EU GlassLabs) was founded by several COST Action Members as an international non-profit association of Structural Glass Laboratories from across Europe, sharing a common vision and having similar or complementary equipment. More information is available at http://eu-glass-labs.org/.

Thirdly, joint activities are forecasted with Working Group 1 “Structural Glass” of the International Association of Bridge and Structural Engineering (IABSE).

Next, initiatives have recently been taken to correspond to the increasing need of the international scientific Structural Glass community for a high-level peer-reviewed journal on Structural Glass. More details will be released in due time.

Finally, the recently launched Horizon 2020 program will definitely create great funding opportunities to solidify COST Action TU0905’s efforts and achievements, and to continue the creation of a solid scientific base for designing great and safe glass structures in future.

5 CONCLUSIONS

Looking back, we are proud to see that COST Action TU0905 succeeded “cum laude” to create a very active, open, European specialist network on Structural Glass. In contrast to the situation four years ago, many Action Members are actively searching cooperation and joining forces, which is a major general achievement.

Without exception, all targets stated in the Memorandum of Understanding have been achieved, and along the way the already ambitious work plan was pushed beyond its original limits, creating even more positive spin-off than expected.

Particular successes have been achieved for our ESRs, the next generation of researchers which will have to push forward the limits in Structural Glass
research in future. Many of them have been trained during our Training Schools and/or workshops, have participated in Think Tank Sessions or Student Colloquia, have traveled abroad for a Short Term Scientific Mission in the context of ongoing PhD research, and above all, have built a strong network including established experts as well as youngsters of their own generation. By actively participating in the intensive networking activities our COST Action was able to offer, many of our ESRs (and other members, of course) have started or deepened friendships. This we consider to be the best guarantee for future successes for COoperation in Science and Technology in the domain of Structural Glass.

ACKNOWLEDGEMENTS

The authors gratefully want to acknowledge the support and excellent networking opportunities provided by COST Action TU0905 “Structural Glass – Novel Design Methods and Next Generation Products”. In particular, they want to thank all Action TG and WG Members, WG Chairs and TG Leaders, but also COST Science Officer Dr Thierry Goger, Administrative Officer Ms Carmencita Malimban, and TUD DC Rapporteur Prof. Kiril Gramatikov for their professional guidance and continuous help to make this Action a great success.

REFERENCES


Enhancing Security with Laminated Glass

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*DuPont Glass Laminating Solutions, USA*

David M. Rinehart  
*DuPont Glass Laminating Solutions, USA*

**Abstract**

Severe weather from hurricanes and tornadoes, along with a growing number of terrorist attacks on buildings, has created a demand for impact resistant glazing. This has led to a growing demand for laminated glass because of its glass retention capabilities after breakage, which helps to minimize glass-related injuries and damage to buildings. Laminated glass is constructed with two or more plies of glass and interlayers. There are several types of interlayers on the market today—PVB, ionoplast, polyurethane and cast-in-place resins. Ionoplast interlayers offer improved impact and tear resistance due to their stiff physical properties when compared to other softer interlayers.

Laminated glass has been a part of glazing systems installed in both residential and commercial construction. Recently, systems have been specified for essential facilities, such as 911 centers, hospitals, shelters and schools. These buildings are expected to remain in operation during a hurricane. Additionally, laminated glass made with ionoplast interlayers has been tested to even higher tornado impact requirements and is now being specified for projects like the University of Iowa Children’s Hospital in Iowa City, Iowa.

In many cases, security from intrusion or bombs will lead to glass and interlayer constructions that are similar to those found in wind-borne debris areas. Blast testing of existing hurricane glazing systems demonstrates the overlap in benefits from one application to another.

1. **Introduction**

Over the years, security glazing was associated with bullet resistant glazing. It was thick and heavy to install, but provided penetration and spall (fragmentation) protection. Commonly associated with banks, data processing centers, and other high security areas, bullet resistant glass was a niche product with a small share of the laminated glass market. Today, security laminates are used in a range of applications that include homes and buildings in parts of the country that are prone to severe weather to buildings in our city centers that could be targeted for terrorist attacks. Unlike monolithic glass that falls out of its frame upon breakage, laminated glass provides retention of glass fragments after breakage, thus providing intrusion resistance and life safety performance to building occupants. This is an important feature of laminated glass designed for wind-borne debris resistance. It is also an important benefit after an explosion, because the interlayer holds the laminate together, minimizing the possibility of glass-related injuries from flying glass.

The construction of laminated glass is based on the application. For example, intrusion and bomb blast glazing may only require two plies of glass and interlayer. In the case of bullet resistant laminates that are designed to stop bullet penetration and fragmentation, often more than two plies of glass and interlayer are required. In some cases, the same construction can provide multiple benefits, such as wind-borne debris, blast, and intrusion resistance.

Physical testing of security glazing based on industry or government standards is required for most projects and/or applications. There are many different standards that have been developed for security glazing and the manufacturers can be expected to demonstrate compliance with test reports. In some jurisdictions, certification of products and/or systems may be required. This is true in the State of Florida for glazing systems required to provide impact protection. Software programs may be used to predict performance of the glazing intended for use in buildings that have blast resistance requirements.

2. **Interlayer types**

PVB or plasticized polyvinyl butyral sheet is made from polyvinyl butyral resin, plasticizer and proprietary chemical additives. This interlayer was invented in the 1930s for automotive windshields, but has since been used for a variety of architectural applications, including safety, security, and acoustics. Ionoplast interlayers are defined as partially neutralized co-polymers of ethylene/methacrylic acid containing small amounts of metal salts. Originally developed for the hurricane market, this interlayer is 100 times stiffer than PVB and five times more tear resistant. Polyurethane
interlayers are based on isocyanates and mostly polyester or acrylic polyols, or both. Polyurethane interlayers have been used to bond glass-clad polycarbonate laminates since adhesion is good to both polycarbonate and glass layers. Liquid resin interlayers are liquid formulations, generally polyester-, urethane-, or acrylic-based that react to form solid interlayers.

3. Severe weather

3.1 Hurricanes

Despite evidence that hurricanes can cause widespread damage, impact protection of buildings did not exist until the 1994 South Florida Building Code. Hurricane Andrew was the impetus for the building code changes. This 1992 hurricane claimed 65 lives, destroyed or severely damaged 600,000 homes and businesses and caused more than $25 billion in property damage. The primary cause of the property damage was windborne debris that penetrated windows and doors breaching the building’s exterior envelope, leading in many cases, to an increase in internal pressures and ultimately, collapse of the structure.

The classification of a hurricane is based on the Saffir-Simpson Hurricane Scale. This scale is broken into five categories, which categorizes hurricanes by the intensities of their sustained winds. The scale (using 3-sec gusts) goes from Category 1 at 116 mph to Category 5 with winds exceeding 189 mph. Typically Category 1 hurricanes do not cause significant structural damage. A Category 5 hurricane, on the other hand, like Hurricane Andrew, can cause extensive damage to buildings.

### Saffir-Simpson Hurricane Scale

<table>
<thead>
<tr>
<th>Classification</th>
<th>Wind Speed MPH (KPH)</th>
<th>Storm Surge Feet (meter)</th>
<th>Damage Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tropical Depression</td>
<td>&lt; 39</td>
<td>N/A</td>
<td>None or Minimal</td>
</tr>
<tr>
<td>Tropical storm</td>
<td>39 – 73</td>
<td>N/A</td>
<td>Minimal</td>
</tr>
<tr>
<td>Category 1</td>
<td>74 – 95</td>
<td>4 – 5</td>
<td>Minimal</td>
</tr>
<tr>
<td>Category 2</td>
<td>96 – 110</td>
<td>6 – 8</td>
<td>Moderate</td>
</tr>
<tr>
<td>Category 3</td>
<td>111 – 130</td>
<td>9 – 12</td>
<td>Extensive</td>
</tr>
<tr>
<td>Category 4</td>
<td>131 – 155</td>
<td>13 – 18</td>
<td>Extreme</td>
</tr>
<tr>
<td>Category 5</td>
<td>&gt; 155</td>
<td>&gt; 18</td>
<td>Catastrophic</td>
</tr>
</tbody>
</table>

The Saffir-Simpson Hurricane Scale is used worldwide to characterize the severity of a hurricane.

3.2 Tornadoes

While tornadoes are found in hurricane-prone areas, these potentially devastating weather events can occur in many other parts of the country as well, bringing severe weather with very little notice. In November, 2013, a tornado, with wind-speeds of 170-190 miles per hour damaged as many as 400 homes in Washington, Illinois. The tornado damage was estimated at an EF-4 level. Characterized as the deadliest tornado to hit the state of Illinois since 1950, what followed the Washington event was a series of tornadoes across Illinois, Missouri, Michigan, Indiana, Kentucky, Ohio, and Tennessee with at least seven fatalities. Several months before, an EF-5 tornado struck Moore, Oklahoma.
with peak winds estimated at 210 miles per hour. Twenty-four people were killed and more than 377 people were injured. Two of the hardest hit areas in Moore were Briarwood Elementary School and Plaza Towers Elementary School, where seven children died.

Tornadoes were first classified according to the Fujita School (F-Scale), named after Dr. Tetsuya Theodore Fujita of the University of Chicago. The scale was divided into six categories from F0 (Gale) to F5 (Incredible). Since 1975, the F-Scale has been replaced by the Enhanced Fujita scale (EF-Scale), a set of wind estimates based on damage. The 3-sec gust wind speeds are estimated, based on degrees of damage, from the beginning of visible damage to total destruction.

<table>
<thead>
<tr>
<th>FUJITA SCALE</th>
<th>OPERATIONAL EF SCALE</th>
</tr>
</thead>
<tbody>
<tr>
<td>F Numb er</td>
<td>3 Second Gust (mph)</td>
</tr>
<tr>
<td>0</td>
<td>40-72</td>
</tr>
<tr>
<td>1</td>
<td>73-112</td>
</tr>
<tr>
<td>2</td>
<td>113-157</td>
</tr>
<tr>
<td>3</td>
<td>158-207</td>
</tr>
<tr>
<td>4</td>
<td>208-260</td>
</tr>
<tr>
<td>5</td>
<td>261-318</td>
</tr>
</tbody>
</table>

### 3.3 Standards for testing

Impact resistant systems intended for use in coastal areas are tested according to the large and small missile requirements cited in industry defined performance standards. ASTM E1886 Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors and Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials defines impact and pressure cycling test requirements. For performance qualification in most areas, the glazed panel is required to be impacted with a specified wooden “missile”. In addition, three individual and identical test specimens must be tested at impact locations at either the center or corner of the glass lite. Failure is defined as an opening through which air can pass that is larger than 125mm in length and 1mm in width or an opening through which a 75mm sphere can freely pass at the conclusion of the cyclical portion of the testing.

The most common large missile testing for building elevations below 30 feet is conducted with missile level “D” (a 9-pound wood 2 x 4 traveling at 50 ft./sec), according to ASTM E1996, Standard Specification for the Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Windborne Debris in Hurricanes. Enhanced protection for emergency facilities requires the use of a missile level “E” which is a 9-pound wood 2 x 4 traveling at 80 ft./sec. Additionally, ASTM E1996 creates other hurricane protection levels and additional missile types for other coastal areas that may not have the severe weather exposure that is found in the High Velocity Hurricane Zone found in southeast Florida.

Missile criteria for tornado mitigation is based on a percentage of the maximum design wind speeds for a given tornado rating. For instance a shelter designed for an EF-3 tornado with a maximum wind speed between 130 to 165 mph (3-sec gust) would require a 15-pound wood 2 x 4 traveling at 80 mph. A shelter designed around a the
maximum rated tornado of EF-5 would result in a maximum design wind speed of 250 mph would require a 2 x 4 traveling at 100 mph.

ASTM E1996 Missile Levels

<table>
<thead>
<tr>
<th>Wind-zone</th>
<th>Enhanced &lt;30 ft</th>
<th>Enhanced &gt; 30 ft</th>
<th>Basic &lt; 30 ft</th>
<th>Basic &gt; 30 ft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wind-zone 1</td>
<td>D</td>
<td>D</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>Wind-zone 2</td>
<td>D</td>
<td>D</td>
<td>C</td>
<td>A</td>
</tr>
<tr>
<td>Wind-zone 3</td>
<td>E</td>
<td>D</td>
<td>D</td>
<td>A</td>
</tr>
</tbody>
</table>

ICC 500-08/FEMA 361 08 Missile Levels

<table>
<thead>
<tr>
<th>Hurricane</th>
<th>H</th>
<th>H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tornado</td>
<td>T</td>
<td>T</td>
</tr>
</tbody>
</table>

Missiles

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>2 gm steel balls@130 fps (89 mph)</td>
</tr>
<tr>
<td>C</td>
<td>4.5 lb 2 x 4@40 fps (27 mph)</td>
</tr>
<tr>
<td>D</td>
<td>9 lb 2 x 4@ 50 fps (34 mph)</td>
</tr>
<tr>
<td>E</td>
<td>9 lb 2 x 4 @ 80 fps (55 mph)</td>
</tr>
<tr>
<td>H</td>
<td>9 lb 2x4 @max 132 fps (90 mph), ie 40% wind-speed</td>
</tr>
<tr>
<td>T</td>
<td>15 lb 2 x 4@max 147 fps (100 mph), varies by wind-speed</td>
</tr>
</tbody>
</table>

3.4 Test results

3.4.1 Broward County Public Safety Building

A 911 Emergency Call Center and the Sheriff’s office are housed in Broward County, Florida’s, Public Safety Building. The building was designed as an Essential Facility, because it is required to remain in operation at all times.

Testing of the glazing system was done in accordance with ASTM E1996 requirements for Level E impact protection. The impactor was a 9 lb. wood 2 x 4 traveling at 54 mph (80 fps). After impact, the glass was subjected to 9,000 pressure cycles.

Laminate construction: Insulating glass unit with an outboard ¼” fully tempered outboard lite, ⅛” air space, inboard lite of 2 plies of ¼” (¼”) heat strengthened glass with a 180-mil ionoplast interlayer

4. Intrusion resistance

Retail stores, pharmacies, schools, and other public buildings are often the targets of vandals attempting to damage or gain entry into buildings. Laminated glass in windows and doors can deter a criminal, especially when combined with an alarm system, perimeter lighting, and surveillance cameras. Time is the key element in smash and grabs crime—if an intruder cannot gain entry quickly, he/she is likely to move on.

4.1 Standards for testing

The UL 972 Test is a multiple impact series of tests using a 5 lb steel ball to generate specified impact energies. These impact levels include a multiple impact test that generates 50 ft-lbs and a high energy impact test that generates 200 ft-lbs.

### 4.2 Test Results

Two plies of 1/8", 3/16", and 1/4" glass with 60-mil PVB or ionoplast interlayer have successfully passed the UL 972 test requirements.

### 5. Blast resistance

Over the last decade, countries around the world have experienced terrorist bombings. From Iraq, Indonesia, India, and Pakistan, to the embassy bombings in East Africa, to the Boston Marathon in 2013, thousands of people have been injured or lost their lives as a result of terrorist attacks. Much of the destruction worldwide can be linked to car and truck bombs, which serve as their own delivery mechanisms and carry a relatively large amount of explosive without causing suspicion. Car bombs produce flying debris, including glass, which can cause secondary damage to people and property.

#### 5.1 Standards for Testing

ASTM F1642 *Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings* was first published in 1996. The most current edition of the standard is 2010. ASTM F1642 enables the user to determine a hazard rating for the glazing or system utilizing either a shock tube or arena test. ASTM F2912 *Standard Specification for Glazing and Glazing Systems Subjected to Airblast Loadings* addresses exterior windows, glazed curtain walls, glazing panels in doors and other glazed protective systems.

ISO 16933 *Explosion Resistant Security Glazing—Test and Classification for Arena Air-Blast Loading* was published in 2007, along with ISO 16934 *Explosion Resistant Security Glazing—Test and Classification by Shock-Tube Loading*. ISO 16933 contains seven mean peak airblast pressure and mean positive phase impulse levels simulating vehicle bombs, ranging from 30 kPa (180 kPa-msec duration) to 800 kPa (1600 kPa-msec duration). Hand-carried satchel bombs are simulated according to seven mean peak airblast pressure and mean positive phase impulse levels, 70 kPa (150 kPa-msec duration) to 2800 kPa (2800 kPa-msec duration). ISO 16934 contains six peak airblast pressure and mean positive phase impulse levels from 30 kPa (170 kPa-msec duration) to 200 kPa (2200 kPa-msec duration).

#### 5.2 Test Results

In 2010, DuPont sponsored a laminated glass testing program using the shock tube at ATI Laboratories in York, Pennsylvania to compare performance of various PVB laminated glass constructions to ionoplast laminated glass make-ups. Following the shock tube testing, DuPont then sponsored several rounds of arena testing of current hurricane resistant fenestration systems outside of Lubbock, Texas, run by HTL Laboratories. The purpose was to further examine the use of these interlayers in window, storefront, and curtain wall systems. In both cases, the targeted peak pressure and impulse were set at 6 psi (41 psi-msec duration), representative of levels found in the Unified Design Criteria (UFC) of the U.S. Department of Defense.

The PVB/ionoplast comparison test specimens were 49.75” x 67.75” in wet glazed onto an aluminum framing assembly that was anchored into a wood frame. The results are presented in Table 1. ASTM Hazard Ratings are expressed differently than those of the U.S. General Services Administration (GSA). GSA Condition 3a equates to the Very Low Hazard level defined in ASTM F1642 where the glass cracks, and fragments land on the floor no further than 1 meter. GSA Condition 2 equates to ASTM F1642 No Hazard, where glass cracks but is retained in the frame.
<table>
<thead>
<tr>
<th>Glass</th>
<th>Interlayer Thickness (mm)</th>
<th>Interlayer Type</th>
<th>Hazard Rating</th>
<th>GSA Performance Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>3mm-3mm</td>
<td>0.76</td>
<td>PVB</td>
<td>Very low hazard</td>
<td>3a</td>
</tr>
<tr>
<td>3mm-3mm</td>
<td>1.52</td>
<td>PVB</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td>3mm-3mm</td>
<td>0.96</td>
<td>Ionoplast</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td>6mm-6mm</td>
<td>0.76</td>
<td>PVB</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td>6mm-6mm</td>
<td>1.52</td>
<td>PVB</td>
<td>None</td>
<td>2</td>
</tr>
<tr>
<td>6mm-6mm</td>
<td>0.96</td>
<td>Ionoplast</td>
<td>None</td>
<td>2</td>
</tr>
</tbody>
</table>

6. Conclusions

Impact resistant laminated glass assemblies improve security and potential minimize injury and damage from hurricanes, tornadoes, intrusion and explosions. While there are a variety of laminated glass interlayers, the ionoplast interlayer has been tested in systems designed for essential facilities and, even, buildings in tornado-prone areas. The stiffness of the ionoplast interlayer is 100 times that of PVB and the tear resistance is 5x greater than PVB. The University of Iowa Children’s Hospital is a good example of a system designed for a higher level of impact protection with a relatively passive appearance when considering the protection level provided. There are other emerging opportunities, including emergency call centers, hospitals, schools, and public safety buildings. In many cases, security from intrusion or bombs will lead to glass and interlayer constructions that are similar to those found in wind-borne debris areas. Blast testing of existing hurricane glazing systems demonstrates the overlap in benefits from one application to another.

6.1 References

Thermal and structural performance of architectural insulation modules for curtain wall construction

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Stanley Yee  
*Dow Corning Corporation, U.S.A.*

Nick Bagatelos  
*BISEM-USA, U.S.A.*

Abstract

Increasing pressure to enhance curtain wall thermal performance is occurring globally. High vision areas of typical commercial aluminum curtain walls are at a thermal disadvantage compared to other construction types, giving rise to the potential of highly insulating spandrel sections of the curtain wall to improve the overall U-value of the façade while maximizing the architectural desire for large glazing areas.

Architectural Insulation Modules are designed to be highly insulating spandrel sections that replace double- or triple-glazed assemblies within the curtain wall. Thermal performance of the modules is modeled in both two-dimensional and three-dimensional models. A comparison is made with typical existing spandrel curtain wall configurations in North America, showing reductions in heat flow of up to 68% are possible using the Architectural Insulation Modules without extreme changes in design, materials or engineering.

The Architectural Insulation Modules were installed as part of a full-size curtain wall mock-up and subject to laboratory performance testing in accordance with AAMA 501, which included seismic racking in both design and proof-load conditions.

The study concludes that higher-performing curtain walls can be achieved without sacrificing the existing structural, seismic, air infiltration, water infiltration and aesthetic performance while achieving increased thermal performance.

**Keywords:** curtain wall, vacuum insulation panel, architectural insulation module, AAMA 501

1 Introduction

While the preference for use of high-vision-area glazing façades continues in popularity, there is a competing global push to enhance curtain wall thermal performance. Because vision areas are at a thermal disadvantage compared to
other construction materials, designers depend on highly insulating spandrel sections to achieve the necessary thermal performance balance.

Today, the curtain wall industry may provide 60% or even 70% vision glazing area in response to the ongoing architectural drive for transparency. Typically, glazing assemblies widely used today can meet the thermal performance requirements at the prescriptive window-to-wall ratio (WWR) levels. However, curtain wall assemblies are increasingly challenged to keep pace with the changing prescriptive thermal performance requirements in northern climates (such as Climate Zone 5 and above). Also, any curtain wall/façade solution must meet the structural requirements for local windloads and seismic aspects.

Use of Architectural Insulation Modules has been demonstrated to meet both the thermal and structural performance needs.

2 Innovative technologies for a better-performing wall

Recent innovations based on vacuum insulation technology are allowing architects a higher degree of freedom using curtain wall spandrel that not only meets thermal performance needs, but also provides the necessary durability and physical performance characteristics of traditionally constructed curtain walls using insulating glazing technology.

Architectural Insulation Modules (AIM) are façade modules that integrate a Vacuum Insulation Panel (VIP) within a protective architectural finish (Figures 1 and 2). The modules contain fumed-silica-based Vacuum Insulation Panels within the air space between two rigid structural panels, such as glass or metal. The separation between the rigid plates is maintained with warm-edge insulating glass technology that utilizes a primary seal of polyisobutylene and a secondary seal technology of structural silicone and moisture-absorbing desiccant. Modules are available in a variety of architectural options, commonly including opaque, metal, glass with ceramic frit or ceramic frit patterns, silicone water-based coatings, or similar options.

The AIM units are used as highly insulating spandrel sections that replace double- or triple-glazed assemblies within the curtain wall. Installed using the same tools and techniques as traditional insulating glass, the modules can be seamlessly integrated into modern curtain wall designs, providing architects with opportunities to build a better thermally performing wall.
Figure 1. Vacuum Insulation Panels offer step-change thermal performance improvements compared to traditional building insulation materials.

Figure 2. Architectural Insulation Modules are assembled in ISO-compliant state-of-the-art manufacturing facilities.

3 Collaborating for proof of performance

Regardless of the potential for thermal performance improvement, adoption of new technology on high-profile, high-budget construction projects can often meet with hesitation and resistance. Establishing this new technology as “proven” was made possible due to collaboration from industry leaders. With the latest technologies from Dow Corning Corporation and a leading curtain wall design, fabricating, and installation company – BISEM-USA – a curtain wall was
developed applying a systems approach, not only providing thermal performance but also meeting industry-established performance criteria for air and water resistance as well as structural and seismic performance.

Recognizing the need for real-world testing to provide proof of performance, the Architectural Insulation Modules were both mathematically modeled and physically tested per industry standards in a mock-up representing a typical final installed assembly.

As a component of a curtain wall assembly, Architectural Insulation Modules are very similar in nature (from a materials, application and logistics perspective) to standard insulating glass units. To reinforce the importance and value of predictive modeling, emphasis was placed on validation of these modeled results through testing. Testing of the individual components and how the individual components behave and withstand full assembly testing provides the validation to demonstrate that the Architectural Insulation Module – and its incorporation into curtain wall assemblies – can be considered a proven solution.

4 Thermal modeling

Thermal performance of 1,500 mm x 1,500 mm modules was modeled via both two- and three-dimensional finite element analysis. In addition, the modeling was validated with guarded hot-box testing of the modules according to ASTM C1363. Architectural Insulation Modules of 1,500 mm x 1,500 mm x 50 mm were shown to achieve total U-values of 0.30 (W/m²K) in hot-box testing (see Table 1).

<table>
<thead>
<tr>
<th>Assembly</th>
<th>U-Value, W/m²K</th>
<th>R-Value, m²K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 mm Double IG</td>
<td>1.87</td>
<td>0.53</td>
</tr>
<tr>
<td>44 mm Triple IG</td>
<td>1.02</td>
<td>0.98</td>
</tr>
<tr>
<td>50 mm Triple-Glazed AIM</td>
<td>0.48</td>
<td>2.07</td>
</tr>
<tr>
<td>50 mm Double-Glazed AIM</td>
<td>0.30</td>
<td>3.36</td>
</tr>
</tbody>
</table>

This was further modeled to be placed into curtain wall spandrel areas to achieve a total spandrel U-value of 0.39 (W/m²K), including framing. A comparison of these results is made with the three-dimensional models of typical existing spandrel curtain wall construction in North America, showing reductions in heat flow up to 68% are possible using the Architectural Insulation Modules without extreme changes in design, materials or engineering.

Three-dimensional modeling of the unitized wall utilizing the double-glazed AIM (VIP thickness 38 mm) showed the spandrel section U-value of 0.39 W/m²K and the model with the triple-glazed AIM (VIP thickness 15 mm) had a U-value of 0.53 W/m²K. The AIM units used in this scenario represent a nominal tripling and doubling of the thermal resistance, respectively.
Figure 3 shows a benchmark high-performance unitized curtain wall system with triple-glazed insulating glass (IG) units that have a center-of-glass U-value of 0.10 W/m²K and the standard 100 mm of mineral wool. This benchmark curtain wall has a modeled U-value of the spandrel of 1.2 W/m²K.

Results of modeling are shown in Table 2.

**Table 2.** Three-dimensional modeled results of 1,520 mm x 1,520 mm spandrel sections.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>U-Value, W/m²K</th>
<th>R-Value, m²K/W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical conventional stick curtain wall</td>
<td>1.16</td>
<td>0.86</td>
</tr>
<tr>
<td>Conventional stick curtain wall with double-glazed AIM (VIP thickness 38 mm)</td>
<td>0.54</td>
<td>1.85</td>
</tr>
<tr>
<td>Typical high performance stick curtain wall</td>
<td>0.89</td>
<td>1.12</td>
</tr>
<tr>
<td>High-performance stick curtain wall with double-glazed AIM (VIP thickness 38 mm)</td>
<td>0.41</td>
<td>2.45</td>
</tr>
<tr>
<td>High-performance stick curtain wall with triple-glazed AIM (VIP thickness 15 mm)</td>
<td>0.51</td>
<td>1.95</td>
</tr>
<tr>
<td>Benchmark unitized curtain wall</td>
<td>1.21</td>
<td>0.83</td>
</tr>
<tr>
<td>Unitized curtain wall with double-glazed AIM (VIP thickness 38 mm)</td>
<td>0.39</td>
<td>2.59</td>
</tr>
<tr>
<td>Unitized curtain wall with triple-glazed AIM (VIP thickness 15 mm)</td>
<td>0.54</td>
<td>1.87</td>
</tr>
</tbody>
</table>

The modeled results presented show that Vacuum Insulation Panels placed and hermetically sealed within two pieces of glass curtain wall become more thermally efficient than what is in use today in non-vision areas of curtain walls, primarily due to the concept of placing the insulation layer on the exterior of the structural mullions and transoms in a curtain wall.
The guarded hot-box test results on full-size vision and spandrel glass assemblies (without any framing) show that upgraded thermal performance is achievable using technology that is readily available. The test results provide the design community with the assurance that high performance can be obtained in architecturally pleasing glass-based technology that has proven its durability performance using edge assemblies available and used today with insulating glass technology.

5 Performance mock-up testing

In collaboration with BISEM-USA – a specialist curtain wall design, fabrication and installation contractor – a performance mock-up test configuration, test curtain wall system and test procedure were designed and developed. The system was tested in accordance with AAMA 501 [1], as published by the American Architectural Manufacturers Association (AAMA), an industry-recognized and accepted independent performance test standard for air and water resistance and structural, seismic and thermal performance.

BISEM contracted with an independent testing facility, Architectural Testing, Inc., to conduct and document performance testing on the BISEM Vacuum Wall system mock-up. Actual structural tests confirmed that the curtain wall system can be expected to continue to perform on the building after experiencing both specifically prescribed and overload conditions, without over-deflecting, while also being a component that provides a complete envelope that defends against air and water infiltration.

6 Performance mock-up test – configuration and procedure

The performance mock-up configuration guidelines, test procedures and the associated referenced standards for individual tests are documented in AAMA 501, Method of Tests for Exterior Walls. AAMA 501 is an amalgamation of individual tests that validate and/or confirm physical performance attributes of the exterior wall assembly. Some tests were developed through ASTM International (formerly known as the American Society for Testing and Materials), while others were established and developed by AAMA. AAMA 501 is viewed as a widely accepted industry standard in North American curtain wall and exterior wall construction performance testing. Figure 4 shows the designed configuration of the performance mock-up test, identifying size and location of each of the components of the assembly. Figure 5 shows the completed installation of the performance mock-up prior to being tested.
A summary of the test procedure and sequence of the tests conducted includes:

1. Pretesting
2. Air infiltration test – static pressure
3. Water infiltration test – static pressure
4. Water infiltration test – dynamic pressure
5. Structural test uniform load – design load
6. Repeat: water infiltration test – static pressure
7. Repeat: water infiltration test – dynamic pressure
8. Interstory vertical displacement
9. Repeat: water infiltration test – static pressure
10. Repeat: water infiltration test – dynamic pressure
11. Interstory horizontal displacement
12. Repeat: water infiltration test – static pressure
13. Repeat: water infiltration test – dynamic pressure
14. Structural test uniform load – proof load (overload)
15. Interstory horizontal displacement (seismic) – proof load

The repeated static and dynamic water infiltration tests after structural and movement capacity test are meant to confirm the performance characteristic of the curtain wall assembly after each of these events. If a non-confirming performance occurs at any of these stages, a reason for the failure can be attributed to a specific event in the test process.

The AAMA 501 test process is comprehensive in nature; only a brief description of the individual tests conducted and their technical significance is provided here.

- Air infiltration resistance of the overall curtain wall assembly is tested in accordance with ASTM E283, *Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors* [2]. Uncontrolled air infiltration is a contributing factor to several performance characteristics in a curtain wall assembly; specifically, the capacity to manage water infiltration and the overall energy performance of the curtain wall. There is a correlation between uncontrolled air infiltration and energy consumption in commercial buildings. This test measures the amount of uncontrolled air leakage that occurs over the net area of the test mock-up at a prescribed interior/exterior pressure differential (for commercial applications) of 300 Pa. With the Architectural Insulation Modules as part of the performance mock-up test, the test provides possible confirmation of their capacity to function as an air barrier within the context of the larger system equivalent to a standard piece of nonvision insulating glass.

- Water penetration resistance under a constant static pressure is tested to ASTM E331, *Standard Test Method for Metal Curtain Walls and Doors by Uniform Static Air Pressure* [3]. The test measures the amount of uncontrolled water leakage that occurs over the net area of the test mock-up at a prescribed interior/exterior static pressure...
differential of positive 720 Pa (for commercial applications) for a 15-minute duration. Water, in a prescribed and uniform spray pattern, is applied to the mock-up at a minimum rate of 3.4 L/m²-min. With the Architectural Insulation Modules as part of the performance mock-up test, the test provides possible confirmation of their capacity to function as a water barrier within the context of the larger system equivalent to a standard piece of nonvision insulating glass. Water penetration resistance under dynamic pressure is tested to AAMA 501.1, *Standard Test Method for Metal Curtain Walls for Water Penetration Using Dynamic Pressure* [4]. The test measures the amount of uncontrolled water leakage that occurs over the net area of the test mock-up at a prescribed wind speed of 34.3 m/s that is generated by an airplane engine or equivalent. The wind speed corresponds to an interior/exterior static air pressure differential of 720 Pa (for commercial applications). Water, in a prescribed and uniform spray pattern, is simultaneously applied to the mock-up for 15 minutes. The generated wind and water spray simulate a high-wind and -rain event that may cause water infiltration across the system and its joints and interfaces. With the Architectural Insulation Modules as part of the performance mock-up test, the test provides possible confirmation of their capacity to function as a water barrier within the context of the larger system equivalent to a standard piece of nonvision insulating glass, particularly in a simulated combined wind and rain event.

- The structural performance of the curtain wall and the Architectural Insulation Modules is tested to ASTM E330, *Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Test Method* [5]. The specific uniform loading for this test sequence is selected to be a design pressure of positive and negative 2.4 kPa, and at a 150% proof-loading positive and negative 3.6 kPa. At this design pressure, a large majority of medium to large commercial projects would be included. With the test representing a design wind event, we can study how the Architectural Insulation Module, its atypical edge seal spacer configuration and the Vacuum Insulation Panels behave and confirm that the test produces no deleterious effects on the components. The deflection of the framing members cannot exceed L/175, or 19 mm, where L is the clear span of the framing member. Typically, the allowable maximum deflection of infill material components is 25 mm. In the instance of proof-load conditions, there can be no permanent deformation of framing members in excess of 0.02 times the clear span of members. This structural test with the Architectural Insulation Modules as a part of the performance mock-up confirms the modules' capacity to transfer loads to the curtain wall framing member without over-deflecting or negatively impacting the edge seal configuration or the Vacuum Insulation Panels.

- Interstory vertical differential movement is tested to AAMA 501.7, *Recommended Static Test Method For Evaluating Windows, Window Wall, Curtain Wall and Storefront Systems Subjected To Vertical Interstory Movements* [6]. This test simulates the day-to-day live load...
deflection of a floor slab. Three complete cycles are performed in the vertical direction at the simulated floor slab at a movement magnitude of 19 mm. While the test is more of a movement capacity confirmation of the curtain wall system itself, some in-plane loading does occur in the glass (and hence the Architectural Insulation Modules), and verification is sought to ensure the movement does not negatively impact the edge seal configuration or the Vacuum Insulation Panels.

- Interstory lateral differential movement is a test that confirms a curtain wall system’s capacity to manage movement caused by high wind or seismic events (whichever governs). The test is conducted in accordance with AAMA 501.4, *Recommended Static Test Method for Evaluating Curtain Wall and Storefront Systems Subjected to Seismic and Wind-Induced Interstory Drifts* [7]. Three complete cycles are performed in the horizontal direction at the simulated floor line. Testing was conducted at lateral movements up to 47 mm (\(\Delta s\)), and at a maximum of 89 mm (\(\Delta M\)) of interstory drift. While the test is more of a movement capacity confirmation of the curtain wall system itself, some in-plane loading does occur in the glass (and hence the Architectural Insulation Modules) and verification is sought to ensure the movement does not negatively impact the edge seal configuration or the Vacuum Insulation Panels.
Figure 6. Elevation showing transducer locations for mock-up.

Figure 7. Location of transducer on the architectural insulation module.
7 Performance mock-up test – results

Table 3 shows a summary of the results of the performance mock-up test, demonstrating that the criteria established in the test procedures were met, and qualitative observation of the Architectural Insulation Modules after testing showed no deleterious effects to the edge seals or the Vacuum Insulation Panels.

**Table 3. Results of full-scale mock-up test.**

<table>
<thead>
<tr>
<th>Test</th>
<th>Measured</th>
<th>Allowed</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preload @ + 1.2 kPa</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Air Infiltration Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static Pressure @ 300 Pa</td>
<td>0.05 L/s m2</td>
<td>0.3 L/s m2</td>
<td>PASS</td>
</tr>
<tr>
<td>Water Infiltration Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static Pressure @ 720 Pa</td>
<td>No uncontrolled leakage</td>
<td>No uncontrolled leakage</td>
<td>PASS</td>
</tr>
<tr>
<td>Water Infiltration Test Dynamic @ 720 Pa</td>
<td>No uncontrolled leakage</td>
<td>No uncontrolled leakage</td>
<td>PASS</td>
</tr>
<tr>
<td>Structural Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Uniform Load Design Load @ +/-1.2 kPa; +/- 2.4 kPa</td>
<td>See Figure 7</td>
<td>See Table 4</td>
<td>PASS</td>
</tr>
<tr>
<td>Repeat - Water Infiltration Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static @ 720 Pa</td>
<td>No uncontrolled leakage</td>
<td>No uncontrolled leakage</td>
<td>PASS</td>
</tr>
<tr>
<td>Repeat - Water Infiltration Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic @ 720 Pa</td>
<td>No uncontrolled leakage</td>
<td>No uncontrolled leakage</td>
<td>PASS</td>
</tr>
<tr>
<td>Interstory Vertical Displacement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Cycles @ 19 mm</td>
<td>No visible damage</td>
<td>No visible damage</td>
<td>PASS</td>
</tr>
<tr>
<td>Repeat - Water Infiltration Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static @ 720 Pa</td>
<td>No uncontrolled leakage</td>
<td>No uncontrolled leakage</td>
<td>PASS</td>
</tr>
<tr>
<td>Repeat - Water Infiltration Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic @ 720 Pa</td>
<td>No uncontrolled leakage</td>
<td>No uncontrolled leakage</td>
<td>PASS</td>
</tr>
<tr>
<td>Interstory Horizontal Displacement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Cycles @ 47 mm</td>
<td>No visible damage</td>
<td>No visible damage</td>
<td>PASS</td>
</tr>
<tr>
<td>Repeat - Water Infiltration Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Static @ 720 Pa</td>
<td>No uncontrolled leakage</td>
<td>No uncontrolled leakage</td>
<td>PASS</td>
</tr>
<tr>
<td>Repeat - Water Infiltration Test</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic @ 720 Pa</td>
<td>No uncontrolled leakage</td>
<td>No uncontrolled leakage</td>
<td>PASS</td>
</tr>
<tr>
<td>Structural Test Uniform Load Proof Load @ +/- 1.8 kPa; +/- 3.6 kPa</td>
<td>See Figure 7</td>
<td>See Table 5</td>
<td>PASS</td>
</tr>
<tr>
<td>Interstory Horizontal Displacement</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Proof Load @ 89 mm</td>
<td>No visible damage</td>
<td>No visible damage</td>
<td>PASS</td>
</tr>
</tbody>
</table>
Figure 6 shows the placement of the linear transducers on the performance mock-up to measure the relative deflection of key components during the structural capacity test. Figures 6 and 7 represent the location of the transducers on the Architectural Insulation Modules.

Table 4 shows the relative deflection of the Architectural Insulation Modules under design pressure of 2.4 kPa. Transducer #11 is placed at the mid-point of the Architectural Insulation Module. Transducer #12 is placed at an adjacent mullion. The difference between the two values is the relative deflection of the Architectural Insulation Module.

**Table 4.** Uniform load deflection of Architectural Insulation Module at design pressure.

<table>
<thead>
<tr>
<th>Indicator Location</th>
<th>Positive 2.4 kPa</th>
<th>Net Deflection</th>
<th>Negative 2.4 kPa</th>
<th>Net Deflection</th>
<th>Allowed</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>32 mm</td>
<td>16 mm</td>
<td>50 mm</td>
<td>21</td>
<td>25</td>
<td>PASS</td>
</tr>
<tr>
<td>12</td>
<td>16 mm</td>
<td>--</td>
<td>29 mm</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 5 shows the permanent set (or permanent deformation) values of the Architectural Insulation Modules under proof-load pressure of 3.6 kPa. Transducer #11 is placed at the mid-point of the Architectural Insulation Module. Transducer #12 is placed at an adjacent mullion. The difference between the two values is the relative permanent set of the Architectural Insulation Module.

**Table 5.** Permanent set of the Architectural Insulation Module at proof-load pressure.

<table>
<thead>
<tr>
<th>Indicator Location</th>
<th>Positive 3.6 kPa</th>
<th>Net Deflection</th>
<th>Negative 3.6 kPa</th>
<th>Net Deflection</th>
<th>Allowed*</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>0.8 mm</td>
<td>0.3 mm</td>
<td>0.3 mm</td>
<td>0 mm</td>
<td>--</td>
<td>PASS</td>
</tr>
<tr>
<td>12</td>
<td>0.5 mm</td>
<td>--</td>
<td>0.3 mm</td>
<td>--</td>
<td>--</td>
<td>--</td>
</tr>
</tbody>
</table>

*General note: Allowable amounts are based on 0.02 of their clear span for framing members.

**8 Conclusion**

The study concludes that higher-performing curtain walls can be achieved without sacrificing the existing structural, seismic, air infiltration, water infiltration, and aesthetic performance while meeting increased thermal performance. The Architectural Insulation Modules not exhibit deleterious effects when subjected to air, water, structural and seismic loading. The edge seals were observed to maintain their integrity, and the Vacuum Insulation Panels did not appear affected by the repeated loading conditions of the AAMA 501 test regimen.

To meet current and future codes, some curtain wall systems will need to be modified in some way to provide the necessary performance and still meet the architectural demand for higher share of vision area. The Architectural Insulation Modules described here provide the architectural community another avenue to
maximize the transparency of the wall while still meeting code- and regulatory-mandated performance characteristics. Using conventional construction techniques, modeled results of aluminum-framed unitized curtain wall with a double-glazed AIM in a specific climate zone approached the ASHRAE 2010 thermal performance requirement for opaque assemblies. With astute curtain wall engineers, curtain wall systems will be able to maximize the performance of this type of assembly to meet more stringent prescriptive – and, more importantly, performance – requirements of individual projects.

References


Means and Methods of CHOP Water Intrusion Task Force

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& Drexel University, USA

Abstract
The Children’s Hospital of Philadelphia (CHOP) is a 5.27 million sf. (2012-CHOP) quaternary care stand alone pediatric hospital and research institute located in Philadelphia, Pennsylvania, USA, with 535 licensed beds and ranked by several national publications in 2013 as the best pediatric hospital in the United States. From 2005 through 2013 CHOP has spent approximately $1.9 billion USD on new facilities and is projected to do the same between 2013 and 2020. In 2011 Hurricane Irene traversed the Eastern coastline of the US and resulted in strong winds and heavy rainfalls in Philadelphia. CHOP experienced significant water infiltration in numerous buildings of different designs and ages, resulting in disruption to patient care and business operations and creating a potential for undesirable consequences from the water intrusions. As a result CHOP created a multi-disciplinary Water Intrusion Task Force (WITF) charged with using a comprehensive approach to diagnose and eliminate all water intrusions within two calendar years across the enterprise. The WITF developed a systemic identification and reporting system to dimension the problems leveraging the existing computerized facilities management systems and extensive in-house expertise. Significant external resources were also used to supplement the resident teams. For each discrete incident or water intrusion typology a researched-based analytical approach was taken to determine all relevant problem data and to develop a hypothesis regarding the leak mechanisms and viable remediation alternatives. Hypothesizes were then tested, and if testing bore out the corrective theory, optimal repair methods were used to for each condition and subsequently a validation period was entered. Only once validation was completed without reoccurrence was the specific incident considered closed. The body of knowledge developed through these incidents was compiled and specifications for in-flight and future construction project designs, materials, means and methods were changed to reflect the water intrusion avoidance strategies uncovered in the process. After two years CHOP has achieved the goal of complete elimination of exterior envelope leaks through the validation process and several significant natural storms.

Keywords: water infiltration, leaks, cladding, envelope, natural storms, means and methods, Children’s Hospital of Philadelphia, CHOP

1 Introduction
CHOP is the local acronym for The Children’s Hospital of Philadelphia. CHOP is currently ranked as the #1 pediatric hospital in the United States (US News & World Report, 2013-14 rankings) and one of the world leaders in quaternary pediatric care. The hospital was founded in Philadelphia in 1855 and has grown into the premier pediatric academic medical center in the United States in partnership with the University of Pennsylvania School of Medicine. The enterprise is comprised of eight (8) buildings on the main campus which cover 4.25 million sf. (395,000 sm) and buildings in 46 other locations which total 1.02 million sf. and comprise an integrated care system which includes primary care through the most complex levels of pediatric clinical care and all types of scientific research. The FY 14 Facilities Management operating budget totals about $31 million USD which includes about $14.8 million USD of energy costs. The annual capital costs have consistently ranged between $200 to $300 million USD per year. Significant investment in new buildings has taken place from 1988 through 2014 and are expected to continue at least through 2022. The hospital currently has 535 licensed pediatric beds and has occupancy rates that range from 85% to 100% and at times reach 105% thus the hospital often runs at or near full capacity making very high utilization rates of all spaces and beds both the norm and essential for the successful execution on the CHOP mission and safe care.

2 The Current State Circa 2011
In August 2011 Hurricane Irene traveled through the Caribbean and up the east coast of the United States before weakening over the Canadian Maritime Provinces. Irene arrived in the Philadelphia region on August 28th 2011 with substantial rainfall and high winds. The CHOP enterprise was prepared to provide safe continuous care for patients throughout the storm with very robust redundant building systems for water, power, natural gas, fuel oil and sanitary systems. Being relatively new to CHOP operations, the interim Senior Vice President was seeking to learn as much as possible about the levels of redundancy and reliability of the building systems for the CHOP hospital and network buildings and decided to stay overnight at the hospital during the storm. It did not occur to Carney that the potentially least reliable systems would be the exterior building envelopes and in particular the cladding systems. Ironically CHOP had a history of challenging cladding systems. In 2003 a major project was undertaken to essentially overbuild the remaining existing portions of the original 1974 main building’s east façade cladding due to chronic leaks over 25 years since the original construction (glass magazine, May 2006, vol 56, num. 5). This, along with the numerous current leaks, had the effect of conditioning CHOP staff and clinicians that cladding leaks were somehow normal. The consequence of this normality was to accept an array of buckets and a bucket brigade throughout the buildings and also to appreciate the extraordinary reactive efforts of staff to control the water intrusions after they occurred, rather than demand there be no leaks. More importantly, several leak locations resulted in damage to interior spaces, albeit minor, but still wetting that required extensive removal and replacement of materials to ensure there was no trapped water with the potential to cause organic growth. As a result, important critical care spaces were
sometimes taken out of service due to leaking, and again in order to make the associated repairs thus ensuring a completely dry interior.

3 Why change, what is the burning platform?
While it may be obvious that buildings should not leak, sometimes they do. It is truly more difficult to correct a leaking building than ensure one does not leak in the first place, but both efforts require technical expertise, appropriate funding, a systematic approach, and perseverance to see them through to resolution. In the case of CHOP, there were several reasons to correct the range of building leaks that were often occurring. The most compelling reason for preventing building leaks is patient safety. CHOP has a strong reliability culture and concerted process improvement efforts to eliminate preventable harm throughout the enterprise. Building leaks of all kinds are inconsistent with this culture and the institutional goal to eliminate preventable harm in all areas. The simple introduction of water into the clinical environment creates potential risk of supporting organic growth which has the potential to harm immunosuppressed or dermis-compromised patients thus the extensive corrective actions undertaken post-water intrusion by CHOP. The corrective responses can only be described as comprehensive and intensive, often closing clinical areas for what are in healthcare terms, long periods so that Infection Control and Risk Assessment (ICRA) barriers can be installed, all direct wetted material is removed and portable testing devises and dryers are used to ensure no moisture remains before repairing all removed materials to like new conditions. Prior to all restorations, in-house industrial hygienists use thermal imaging to ensure no water remains hidden in the building’s construction. Needless to say the entire restoration process is time consuming, disruptive to the clinical operations, and very costly to the organization. Interestingly the costs are not limited to just the repair costs. Since CHOP is a quaternary care facility, many of the clinical programs are available only at CHOP or conceivably just one or two other places worldwide. As a result, the opportunity costs of reducing the bed availability in the hospital for corrective actions associated with water intrusions potentially delays care and reduces revenues. By any lean process definition, this is system waste that should be eliminated, but how to do this when the problem seemed so widespread?

4 A concept for a change plan
Clearly what had been the practice would not work in the future. Change was needed. The first key step was dimensioning the problem so an effective change management plan could be designed. To this end CHOP created what it called the “Water Intrusion Task Force” (WITF) and charged it with finding a solution to the water leak problems throughout the enterprise. The WITF was comprised of a cross-functional team of in house staff and external consultants (Figure 6). The WITF was led by a bright young Engineer named Joshua Fischer, a Drexel University graduate and CHOP employee. Internally CHOP members included directors, managers, maintenance staff, project managers, and support by senior leadership. Many of the CHOP team are also licensed architects and engineers. In addition consulting architects, engineers and experienced staff from Architectural Testing Inc. (ATI/Intertek) in York PA were employed by CHOP on
an itinerate basis to supplement the team’s expertise and provide diagnostic, testing, and consulting services.

The first business matter for the WITF was to establish a framework for its efforts. Two key goals were developed by the team: 1) all buildings in the enterprise should be leak free and the “new normal” expectation should be that the Facilities team should operate the buildings in alignment with the CHOP goal of eliminating preventable errors, which in this case meant NO water intrusions, and 2) the process should take no more than two (2) years to become “leak free.” Thus the team set these goals in 2011 with the expectation they would be accomplished by fall of 2013 and set about their work. Consistent with the Kotter change model (www.kotterinternational.com), the next step the team took was to announce the goals in a public way to the whole CHOP leadership team and ask for their help. This was a key step in two ways. First it ensured a public accountability for the team and their goals, and second, it enlisted the enterprise broadly in reporting all leaks to help with identifying the work. Finally, the process of changing the enterprise mindset to one that would not tolerate cladding water intrusions began to take shape.

In order to dimension the magnitude of the problem it was essential that every instance of a leak, even one previously logged, was reported so it could be tracked in the computerized facilities management system (CMS/Archibus). This was especially important with the more vexing cladding leaks as the familiar reader will recognize; temperature, precipitation type, wind speed and direction can all change the pattern of a specific cladding leak making causation very difficult to diagnose. To address these challenges, in addition to systematic leak reporting, CHOP installed a real-time weather station on its highest building so the most difficult cladding leaks could be correlated to specific weather conditions as they occurred. The data collection efforts resulted in 112 major water intrusion incidents of all types. Each incident may represent more than one actual leak location or even numerous locations. As an example, when a given facade leaked in a similar way, this was tracked as a single incident but might have had dozens of locations. A great deal of learning about the types and frequency of the leaks we were experiencing resulted from this data collection and the effort to correlate the cofactors in time with each leak. As it evolved there were four (4) main categories of mechanisms of water intrusions experienced at CHOP:

- Roof leaks
- Cladding leaks
-Leaks from mechanical rooms
-Leaks from piping systems

For the purposes of this paper, we focus on leaks associated with the building cladding systems.

5 Water Intrusion Task Force (WITF) approaches
While the data collection effort was underway, the team recognized there was a need to develop taxonomy so the water intrusions could be classified by complexity and typology. To this end a matrix was developed to rank and prioritize each WITF-logged incident based on a simple algorithm represented by (Priority index) x (Difficulty index) to arrive on an importance score. While the goal was zero defects, or the complete elimination of all water intrusions in the two-year period, this matrix organized the work and set realistic expectations regarding timelines for addressing each condition. Both the priority and difficulty of a given incident was rated by the WITF on a scale (1 to 3 points) thus the lowest importance score (most urgent) could be 1 while the highest (least urgent) could be 9.

**Figure 1. Rating System**

<table>
<thead>
<tr>
<th>Priority Scoring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Priority Level 1</strong></td>
</tr>
<tr>
<td>Impacts Patient Care directly, Immediate Safety Concern, Long Term Research Impact, Grey/Black Water</td>
</tr>
<tr>
<td><strong>Priority Level 2</strong></td>
</tr>
<tr>
<td>Impacts Staff Work Flow, Business Continuity, Asset Damage (Building/Equipment), Secondary Impacts (Environmental), Potable/Clear Water, Public Relations Impact, Potential Safety Concern</td>
</tr>
<tr>
<td><strong>Priority Level 3</strong></td>
</tr>
<tr>
<td>Very Low Volume, Nuisance</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Difficulty Scoring</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Difficulty Level 1</strong></td>
</tr>
<tr>
<td>Unknown Source, Intermittent Occurrence, Intermittent Access, High Technical Complexity, Multiple Unsuccessful Attempts, Long Duration Shutdown Required</td>
</tr>
<tr>
<td><strong>Difficulty Level 2</strong></td>
</tr>
<tr>
<td>Age, Inconvenient Access, Location, Previous Attempts, Secondary Impacts to Repair, Size/Area, Seasonal Factors, Shutdown Required, Unsuccessful Attempts</td>
</tr>
<tr>
<td><strong>Difficulty Level 3</strong></td>
</tr>
<tr>
<td>Source (Known), Cost, Easy Access, No Shutdown Required, No Unsuccessful Attempts</td>
</tr>
</tbody>
</table>

Using these criteria applied to the algorithm, each incident was then ranked in an importance level and grouped into three tiers so the most urgent incidents could be addressed. Then the WITF could work through the entire program based on the importance/urgent score of each incident. The results revealed 24 tier 1 incidents, 66 tier 2 incidents, and 22 tier 3 incidents.
Using detailed scored incident logs, the WITF then applied a disciplined researched based decision method (Figure 7) to solve each incident. The same rigorous method was used to analyze and then solve the technical challenges associated with each water intrusion incident. The following steps were taken with each problem to be solved:

5.1 **Data Collection**
In every case when an incident was reported a period of data collection was established which varied based on the rating system. Simple matters had shorter data collection periods than more complex ones. Data was gathered over time regarding the incident. Data sources were mined and correlated to create an incident specific picture of all available relevant information. A WITF member was assigned as a project manager (PM) to manage each specific incident through closure. Each incident was tracked against and inspected during relevant weekly weather conditions by the assigned PM.

5.2 **Analysis of the available data**
In the WITF regular meetings, each PM reported on all assigned incidents and their status. In the data analysis phase, the WITF team brainstormed the causation of each leak. If the available data was insufficient, specific
investigations would be developed and executed either by in-house staff or contractors to further inform the analysis.

5.3 Hypothesis
Upon the WITF’s determination that the data was sufficient and the analysis complete to the extent a hypothesis could be made as to the causation of an event and the likely successful corrective measures, the team would formulate and document a solution hypothesis.

5.4 Test of hypothesis
Depending on the cost and difficulty of a postulated solution, the WITF would implement a test of hypothesis mock-up of an anticipated solution for a leak. If appropriate, field testing of the correction mock-ups was performed. Every relevant weekly weather event was tracked and communicated to the WITF team so members could evaluate hypothetical solutions as the weather events occurred. As conditions that were thought to be corrected or had been mocked up were subjected to weekly weather events, they were inspected to determine if the proposed corrective measures appeared to be working, or not. In many cases these corrections did work. In several they did not and we returned to brainstorming and developed new hypotheses.

5.5 Cost projection
Upon completion of a successful test of a corrective measure, the required funds to implement the full scale modifications to make final systematic corrections and close a given incident were estimated and funding secured. Funding sources came from a variety of sources including operating budgets, an annual allocation to the WITF for analysis, design and corrective measures, and the normal capital funding request process of the hospital. Based on costs as of 2014 the total costs of this program are expected to be slightly over $5 million USD.

5.6 Corrective measures
With funding in place, corrective measures were implemented. Examples of two (2) representative corrective measures are discussed in the appendix.

5.7 Validation
Simply completing the corrective measures was not sufficient for the WITF to declare a victory for an incident. To ensure a corrective measure was successful, a validation period was established for each incident depending on the complexity and unique weather conditions associated with the leak mechanism through the data collection and analysis process. Validation periods typically ranged from three (3) to six (6) months and some could be as long as one year.

5.8 Incident Closeout
Once the validation period was finished without any leaking, it was either extended for further validation depending on the confidence the WITF had in the solution or the incident was then closed.

This process was repeated for every incident on the log until all incidents had been addressed. As of May 2014 several remain in validation but there are
currently no actively leaking buildings at CHOP. Since January of 2014 Philadelphia has experienced 22” (55.9cm) of precipitation, close to the 1983 record. On May 1st, 2014, Philadelphia experienced a 5” (12.7cm) rain storm (4.91” NOAA/Philadelphia airport) in a 12-hour period which was the 7th worst recorded rainfall in history at Philadelphia with no water intrusion through the cladding systems at CHOP.

Figure 3. Partial Storm log, Philadelphia at CHOP

<table>
<thead>
<tr>
<th>Storm (cladding only)</th>
<th>Rainfall</th>
<th>Date</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hurricane Irene</td>
<td>10” (25.4 cm)</td>
<td>8/28/2011</td>
<td>extensive leaks</td>
</tr>
<tr>
<td>Tropical Storm Lee</td>
<td>6-10” (15.2 - 25.4 cm)</td>
<td>9/5/2011</td>
<td>extensive leaks</td>
</tr>
<tr>
<td>Hurricane Sandy</td>
<td>7” (17.8 cm)</td>
<td>10/29/2012</td>
<td>several leaks</td>
</tr>
<tr>
<td>Tropical Storm Andrea</td>
<td>3” (7.6 cm)</td>
<td>6/7/2013</td>
<td>no leaks</td>
</tr>
<tr>
<td>unnamed</td>
<td>8” (20.3 cm)</td>
<td>7/29/2013</td>
<td>no leaks</td>
</tr>
<tr>
<td>unnamed</td>
<td>5” (12.7 cm)</td>
<td>5/1/2014</td>
<td>no leaks</td>
</tr>
</tbody>
</table>

source: www.noaa.gov

6 Exportation of the obtained body of knowledge regarding leak mechanisms

Given the aggressive capital program of the Children’s Hospital of Philadelphia, it would not simply be sufficient to correct 100% of the existing cladding defects. It was essential that the body of knowledge accumulated in the water intrusion task force process be included in the standards, design, testing, and specification process for all new CHOP construction. To this end, the WITF working with other project team members made or created new requirements for the CHOP model specifications to be implemented appropriately on all future design and construction projects. These model changes for all leak modalities have been summarized for all leak modalities and include cladding specific changes such as the following:

- Set the appropriate cladding design loadings and water/air infiltration standards before design begins
- New buildings should have cladding systems designs reviewed or created by a cladding consultant in design and should be followed through construction
- Full size design and functional cladding mock ups should be performed
- Full sized laboratory testing should be performed for all critical cladding systems
- Field water and air testing should be performed on production installations in situ at the first convenient and agreed upon cladding installation and work NOT advanced until the in situ mockup has passed 100% of the appropriate testing
7 Conclusion
Clearly water intrusions through cladding systems are a disruption to building owners and their business operations are adversely impacted by these events. In the case of the hospital operations at CHOP this meant closing patient rooms, potentially delaying care, at times relocating patients from leaking rooms, extensive leak responses including expensive water damage restoration in an operating hospital. Water infiltration into any building creates risk of water induced organic growth and the associated possible adverse outcomes which can result. These concerns are especially significant to a healthcare organization. Finally the cost of interruptions to business continuity is significant as well.

As a result of a systematic, well led, disciplined approach to eliminating water intrusions, building cladding leaks can be corrected and more importantly prevented in the first place. The best corrective measure for a building leak is to design the cladding correctly, validate the design through appropriate testing, fabricate and install the systems correctly, and validate the installations with additional appropriate field testing. If these thoughtful steps are followed, the disruption, risk and expense of water intrusions can be avoided in new buildings thus obviating the need for a task force as was required by CHOP.

8 Figures

Figure 4. Incidents Vs. Status

![Incidents Vs. Status Chart]

- Reported
- Evaluation
- Implementation
- Validation
- Closed
**Figure 5.** Incident Vs. Status

![Incident Vs. Status Graph]

**Figure 6.** Water Intrusion Task Force Members (WITF) & consultants

<table>
<thead>
<tr>
<th>Task Force Member</th>
<th>Title</th>
<th>Firm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mark Bricker</td>
<td>Director - Facilities Services</td>
<td>CHOP</td>
</tr>
<tr>
<td>Kevin McCarthy, PE</td>
<td>Director - Building Systems Operations</td>
<td>CHOP</td>
</tr>
<tr>
<td>Joe Kiernan, AIA</td>
<td>Director - Design &amp; Construction</td>
<td>CHOP</td>
</tr>
<tr>
<td>Greg Conicello</td>
<td>Project Manager - Facilities Services</td>
<td>CHOP</td>
</tr>
<tr>
<td>Mike Dougherty</td>
<td>Manager - Building Systems Operations</td>
<td>CHOP</td>
</tr>
<tr>
<td>Nike Majeski</td>
<td>Manager - Facilities Services</td>
<td>CHOP</td>
</tr>
<tr>
<td>Micheal Goldberg</td>
<td>Industrial Hygiene Manager</td>
<td>CHOP</td>
</tr>
<tr>
<td>Seth Hatt</td>
<td>Fire Life Safety Manager</td>
<td>CHOP</td>
</tr>
<tr>
<td>Brian Kovacs</td>
<td>Safety Inspector</td>
<td>CHOP</td>
</tr>
<tr>
<td>Amanda Scott</td>
<td>Director Environmental Health &amp; Safety</td>
<td>CHOP</td>
</tr>
<tr>
<td>Beth Lorenz, PE</td>
<td>Project Manager/Engineer</td>
<td>CHOP</td>
</tr>
<tr>
<td>Gordon Woollam</td>
<td>Project Manager/Construction</td>
<td>CHOP</td>
</tr>
<tr>
<td>George Zafiropoulos, PE</td>
<td>Team Leader/Project Management</td>
<td>CHOP</td>
</tr>
<tr>
<td>Douglas Carney, AIA</td>
<td>SVP - Facilities, Planning, Design, Construction &amp; Real Estate</td>
<td>CHOP</td>
</tr>
<tr>
<td>Robert Flagg</td>
<td>Consultant &amp; Testing</td>
<td>Architectural Testing Inc.</td>
</tr>
<tr>
<td></td>
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<td>[<a href="http://www.architecturaltesting.com">www.architecturaltesting.com</a>]</td>
</tr>
<tr>
<td>Mark Magrino</td>
<td>Consultant</td>
<td>TBS Services</td>
</tr>
<tr>
<td></td>
<td></td>
<td>[<a href="http://www.tbsservices.com">www.tbsservices.com</a>]</td>
</tr>
</tbody>
</table>
Figure 7. Water Intrusion Task Force Incident decision process map

Figure 8. WITF Scoring Matrix

<table>
<thead>
<tr>
<th>Priority Level (High)</th>
<th>Difficulty Level (High)</th>
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</thead>
<tbody>
<tr>
<td>Patient Care, Immediate Safety Concern, Long Term Research Impact</td>
<td>Unknown Source, Intermittent Occurrence, High Technical Complexity</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Priority Level (Moderate)</th>
<th>Difficulty Level (Moderate)</th>
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</thead>
<tbody>
<tr>
<td>Staff Work Flow, Business Continuity, Asset Damage</td>
<td>Inconvenient Access, Age/Previous Attempts, Secondary Impacts to Repair</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Priority Level (Low)</th>
<th>Difficulty Level (Low)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Very Low Volume, Nuisance</td>
<td>Known Source, Easy Access, No Shutdown Required</td>
</tr>
</tbody>
</table>
Strength and Testing of In-Service Fully Tempered Glass

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Keywords
1=Window 2=Testing 3=In-service 4=Tempered 5=ASTM E 1300

Abstract

ASTM E 1300-12a [1] provides a procedure for calculating the load resistance (LR) for specific glass types and compositions under uniform loads. Values in the standard are calculated using the glass failure prediction model developed at Texas Tech University that incorporates a two parameter Weibull distribution to account for the surface flaw characteristics of weathered, in-service, glass. The strength of heat-treated glass is found by applying a glass type factor (GTF) to the calculated non-factored load (NFL) for annealed glass. The GTF for heat-strengthened (HS) glass is 2, and the GTF for fully-tempered glass is 4, indicating strengths of 2 and 4 times than the strength of ordinary annealed glass. The GTFs for heat-treated glass are based on assumptions of increased strength caused by the magnitude of residual compressive surface stress (RCSS) in the heat-treated glass. Although much attention has been paid to correlating actual test results with theoretical models to determine the LR of annealed glass, limited test data is available to verify the GTF used for HS and FT glass.

This paper presents the results of laboratory testing of FT glass samples that were removed from an existing building in the southwestern United States. The residual compressive surface stresses were documented in accordance with ASTM C 1048-12a [2] prior to testing, and the glass was tested to failure. The resulting design strength of the glass was determined from the test data and compared to the design strength specified by ASTM E 1300-12a [1] as well as a method to determine LR of HS and FT glass proposed by Norville and Morse [3].

Introduction

Early methods for determining LR of glass utilized empirical test data from thousands of various sized annealed lites tested to failure that produced a single, straight line design chart for the determination of glass thickness. This chart was used until 1979 when PPG Industries, Inc. introduced its “Glass Thickness Recommendations to meet Architects’ Specified 1-minute Wind Load” [4]. This procedure utilized a maximum principal stress method, combined with finite element analysis, to determine the glass thickness for a given load. It introduced the use of the aspect ratio of the glass and 1-minute load duration to calculate the recommended glass thickness from a set of corresponding charts for annealed, heat-strengthened, tempered, and laminated glass and insulating glass (IG) units. However, the PPG method created confusion over the early single chart as it typically lead to larger glass thicknesses for the same loading conditions [5].

The uncertainty created within the industry by these two methods gave rise to the development of the Glass Failure Prediction Model (GFPM) [6]. This method predicts the LR of annealed glass by incorporating a two parameter Weibull distribution to account for the surface flaw characteristics of weathered, or in-service, glass. The GFPM became the basis for ASTM E1300 standard. However, the GFPM and the first version of the standard, ASTM E1300-89, did not address the LR of HS or FT glass.
Starting with the second version of the ASTM E1300 in 1994, a glass type factor (GTF) was introduced to determine the LR for heat-treated glass. The non-factored load for annealed glass is multiplied by the GTF to account for the greater strength of both HS and FT glass. The GTF for a single lite of monolithic glass is 2 for HS glass and 4 for FT glass. While this method provides a way of calculating the LR of heat-treated glass, the basis of these GTFs is not well-documented and may be conservative for HS and FT glass.

Using the GFPM as a basis, Norville and Morse [3] developed a model to address the role that RCSS plays in the LR of heat-treated glass. The theory assumes that since glass always fails in tension, it is necessary to overcome any existing pre-compression in the glass in order for crack growth to continue. The Norville and Morse model [3] incorporates the RCSS of the glass as well the other physical characteristics of the glass (thickness, aspect ratio, etc.) to develop a type factor and load charts to calculate the LR.

**In-Service Glass**

Existing insulating glass (IG) units, were removed from a 22-story building located in the southwestern United States. Select units were removed and replaced in the context of an investigation regarding alleged storm damage to existing outboard lites of the unit. The existing glass had been in-service for approximately 20 years prior to the replacement. As part of the investigation, approximately 35 of the existing units were stored for further investigation and testing. At the conclusion of the investigation, the units were no longer needed and were released for testing.

**Glass Testing Protocol**

Glass specimens were received as 838 mm x 2362 mm insulating glass units consisting of a 6 mm annealed glass outboard lite, a 12 mm spacer, and a 6 mm FT inboard glass lite. The existing insulating glass units (IGUs) were labeled and disassembled in the laboratory for testing. A total of sixteen, monolithic FT glass specimens were tested.

The thickness of the glass was measured using a portable scattered light polariscope (SCALP). RCSS values were measured using a Grazing Angle Surface Polarimeter (GASP) in accordance with ASTM C 1048 [2]. Readings were taken at five locations (as shown in Figure 1) with two measurements taken at each location oriented 90 degrees to each other. The ten readings were then averaged to determine the RCSS for each specimen. Measured RCSS values ranged from 79.3 MPa to 90.3 MPa. The glass was set into a vacuum-loaded test frame (Figure 2) conforming to the test frame described in ASTM E 997-12 [7]. Glass specimens were loaded to failure at an average stress rate of 50 Pa/s using a manually controlled chamber valve. The intent of the chosen load rate was to achieve glass failure within approximately 60 seconds. Time duration, chamber pressure, and center of glass deflection were recorded digitally for each test.

![Figure 1 - Location of RCSS readings](image)
Failure Loads

The 3-second duration equivalent failure stress was calculated by integrating the time load history of each test using the procedures summarized in papers by Abiassi [8] and Beason [9]. Calculations used a static fatigue coefficient of 16 for FT glass. The 3-second equivalent failure load corresponding with each 3-second equivalent failure stress was determined by iteration using a finite difference scheme to analyze the glass lites under load [10].

Analysis

Equivalent failure loads were compared to LRs calculated using ASTM E 1300-12a \( \varepsilon_1 \) [1] and the model for determining LR of heat-treated glass developed by Norville and Morse [3]. The design load for an 838 mm x 2362 mm x 6 mm piece of FT glass calculated in accordance with ASTM E 1300-12a \( \varepsilon_1 \) [1] was 7.59 kPa. Failure loads are summarized in Figure 3 and compared to the allowable design load calculated in accordance with ASTM E 1300-12a \( \varepsilon_1 \) [1]. As seen in the chart, the actual failure loads are typically more than double the anticipated LR of 7.59 kPa.
The failure loads for the specimens were also compared to the LRs calculated using the Norville and Morse [3] model. This model employs simplified heat strengthened load (HSL) or fully tempered load (FTL) charts to produce a value that varies with the thickness, surface area, aspect ratio, and minimum RCSS. The HSL or FTL value is then multiplied by the heat strengthened type factor (HSTF) or fully tempered type factor (FTTF) to provide the LR. The HSTF and FTTF are derived from an equation using the actual RCSS of the glass.

Using the Norville and Morse [3] model, the calculated LR and actual failure load for the tested specimens are shown in Figure 4. The average calculated LR of the specimens was 13.8 kPa which is 1.8 times greater than the LR calculated using ASTM E 1300-12a[^1]. The average failure load was 22.0 kPa which is approximately 1.6 times greater than the calculated LR of 13.8 kPa.
In many cases, the actual RCSS of the lite may be unknown. However, this does not prevent the model from being used to calculate the LR. Based on the results shown in Figure 4, the calculated LR does not change significantly with the change in actual RCSS. Using the Norville and Morse model with the same size and thickness specimens, the minimum RCSS for tempered glass, 68.9 MPa can be substituted for the actual RCSS value in the FTTF equation. This results in an LR value of 11.8 kPa which significantly exceeds the anticipated LR when calculated using ASTM E 1300-12a[1] as shown in Figure 5.
Conclusions

Testing of 20 year old, in-service FT glass showed that the service conditions did not reduce the tested equivalent 3-second LR of the glass below the expected design LR calculated according to ASTM E 1300-12a [1]. In all samples, the tested LR exceeded the design LR of 7.59 kPa calculated according to ASTM E 1300-12a [1]. In 15 of the 16 specimens the tested LR was more than twice the predicted E1300 [1] value. The tested LR also surpassed the LR value calculated according to the Norville and Morse model. The average LR value of 13.8 kPa, predicted by the model, is 1.8 times greater than the E1300 [1] and in most cases significantly less than the actual tested LR.

The significance of the findings is twofold:
1. The tested LR of the FT glass was typically much greater than the calculated value using ASTM E 1300-12a [1]. The magnitude of this difference suggests that the GTF used in E 1300 [1] may be overly conservative. The Norville and Morse model [3] produces design values that are greater than E 1300 [1] but still less than the failure strength of the glass, which may be more realistic and accurate prediction of the LR for heat-treated glass.
2. The LR of the in-service glass exceeded the values calculated using E 1300 [1] and the Norville and Morse model [3]. In this case, the service conditions did not reduce the LR below current design values. The authors note that LRs predicted by the Norville and Morse [3] methodology as well as by ASTM E 1300-12 [1] are associated with a probability of breakage of 8 lites per 1000 at the first occurrence of the design load. The values reported in this treatise must undergo further statistical analysis to verify the Norville and Morse [3] model.

Geometrical Rationalization of Complex Building Enclosure Systems

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Abstract
Formally complex buildings are an evident progression in contemporary architecture, driven by structural, environmental, regional, aesthetic, programmatic, and economic considerations. Building enclosures express the geometric complexities of designs, often translating into the need for curved panels, mass customization, and a comprehensive understanding of material properties, tolerances, and limitations. Our paper is structured around four key steps in the design of complex enclosures: Form, Analyze, Optimize, and Document. We will show how the use of digital design tools aids in formulating a solution for a combination of design drivers, analyzing and optimizing for specific materials and fabrication constraints, and documenting clearly and precisely.

Keywords: building enclosure, complex geometry, geometrical rationalization

1 Introduction
Advances in computational design tools and fabrication techniques make the construction of large-scale architectural surfaces with complex geometry increasingly feasible [4]. While in mathematics, *complex geometry* is clearly defined, it is only loosely defined in an architectural context. Typically, it refers to polygonal geometry, spline-curve geometry, double-curved/free-form surfaces, or forms constructed with many unique parts and unique connection types. The architectural computational community also employs the term *rationalization*. A general definition for its root *rational* is based “on or in accordance with reason or logic,” and specifically in mathematics, “a number, quantity, or expression that is expressible” [8]. Architecturally, it describes the process of transforming a tacit design idea into an explicit, fully documented building design document. We consider a geometric solution architecturally rational when it is understood to the point where it can be documented explicitly, and when the geometric solution does not entail prohibitive construction costs.

This paper is structured around the four key steps in realizing complex building enclosures:

- **Form**: The rationale behind complex building enclosures
- **Analyze**: Understand implications of complex enclosures
- **Optimize**: Improve constructability, reduce cost, maintain design intent
- **Document**: Communicate decisions in a clear, cogent manner
Although these steps are described in a linear fashion, the process is an iterative feedback loop that is often repeated many times during the design phase. Refer to a diagram freely modeled after the four-stage design process [3] by Nigel Cross (see Fig. 1).

![Diagram of Design Process](image)

**Figure 1.** A Process Diagram for Documenting Complex Enclosures

### 2 Form: The Rationale behind Complex Building Enclosures

Structural efficiencies, planning regulations, sustainability, programmatic, and aesthetic considerations are some of the most common drivers behind complex building enclosures. The combination and prioritization of these criteria ultimately lead to the final form.

#### 2.1.1 Structural Efficiency

Elementary physics teaches us that objects with wide bases and narrower tops are inherently stable. This is as true for a building as for any object. In the case of supertall towers, wind has as much of an impact on the structure of the tower as gravity. In addition to lowering the building's overall centroid, the tapering form also mitigates the effect of increased wind loads at higher elevations. This combination of intrinsic stability of a form, and its ability to resist external loads, illustrates the need for form and structure to work synergistically.

Although we might not consider the John Hancock Center [9] “geometrically complex,” the tapering form does add some complexity. The building sheds water differently due to the sloped facades, and the corner panels are not rectangular (see Fig. 2). The structural system also features cross-braced columns, which also truncate otherwise rectangular panels. Another example of a tapering building is the design of the Lotte Super Tower, a proposal for a 555-meter tower in Seoul, South Korea. In addition to tapering, the building’s floor plates transform from a square at the base to a circle at the top (see Fig. 2).

![Image of Hancock Center and Lotte Super Tower](image)

**Figure 2.** 1970: Hancock Center, Chicago, IL (left) Proposal: Lotte Super Tower, Seoul, Korea rendering (middle) and two structural variations (right)
Structural efficiencies are not only key for high-rise buildings but also for long-span structures such as railway stations, stadia, and airports. Optimized dome structures distribute the loads evenly, however, often resulting in double curved surfaces which are considered “complex geometry.” An example is the Kuwait University Tennis Center (see Fig. 3). The stress and deflection of the spherical dome was structurally optimized to a catenary shape, adding additional complexity to the enclosure [1].

2.1.2 Response to Planning Regulations
Zoning regulations are another driver for building form. In midtown Manhattan, for example, zoning typically requires buildings to fill the site and set back the massing as the tower rises. The tower at 9 W 57th Street, and the W.R. Grace Building on 42nd Street, closely follow the setback requirements to comply with

zoning regulations that maximize usable floor area, resulting in curved building envelopes. Another example is the Muqarnas Tower in Riyadh (see Fig. 4). The master plan requires faceted buildings along the development’s main circulation spine. Both examples demonstrate how planning regulations can trigger the need for complex enclosures.

2.1.3 Sustainability
A key variable in a building’s performative metric is its shape, inviting or avoiding solar exposure depending on the local climate. The Al Hamra tower is a simple glazed form with a complex stone clad opening that is shaped by the sun’s path (see Fig. 5). The opening reveals the building’s core, and removes the glazed program space that would have been rendered uninhabitable due to extremely high solar heat gain.

Figure 5. Figure 5. 2011: Al Hamra Tower, Kuwait City, Kuwait

The integration of wind turbines into buildings for renewable energy generation is another example. The Pearl River Tower’s shape is derived from the concept of funneling the wind to maximize the efficiency of its wind turbines (see Fig. 6).

Figure 6. 2013: Pearl River Tower, Guangzhou, China

2.1.4 Programmatic
The building’s functional program helps define its geometric shape. Different programmatic functions have different lease span requirements (floor plate depth), potentially varying floor plate size from level to level. For office buildings,
lease spans of about 12 to 15 meters are typical. If the lease span is too great, natural light cannot penetrate deep enough into the office space; if the lease span is too shallow, the floor plan is uneconomical [7]. In the mixed-use Tianjin CTF Finance Centre (see Fig. 7), the enclosure mitigated the difference between the deep lease spans of the lower levels’ office program and the shallower hotel and service apartment functions at the upper levels. Other common spaces that require a transition in lease spans are performance spaces, observatory decks, and ballrooms.

Figure 7. Proposal: Tianjin CTF Finance Centre, Tianjin, China

Directing views from apartments to desirable vistas or landmarks can require the use of complex geometry. The site of the Cayan Tower, for instance, did not allow maximized views of the nearby marina and gulf using a straight vertical extrusion (see Fig. 8). The skyscraper’s 73 floor plates are all identical, but each is slightly rotated against the story below it, resulting in a full 90-degree twist over the course of the tower’s 307-meter rise. This provided maximal views toward the gulf and marina at the top floor, in high-revenue apartments.

Figure 8. Cayan Tower, Dubai, United Arab Emirates

2.1.5 Aesthetics

Another criteria of importance for form-finding is aesthetics, as the Cathedral of Christ the Light exemplifies (See Fig. 9). The form responds directly to the vision
of the design concept—a spiritually uplifting space—and the functional requirements of the specific use for which this building was designed.

Figure 9. 2008: Cathedral of Christ the Light, Oakland, CA

The Deerfield Academy Koch Center for Science, Math and Technology includes a skylight formed by an astronomical phenomenon called an analemma (see Fig. 10). The skylight’s complex geometry was determined entirely by its required behavior—to project a direct spot of light into the space below between the hours of 11:00 am and 1:00 pm. The analemma skylight was created in collaboration with artist James Turrell and astronomer Dick Walker.

Figure 10. 2007: Deerfield Academy – Koch Center for Science, Math and Technology, Deerfield, Massachusetts
2.2 The Dilemma of Conflicting Criteria
Architecture itself can be thought of as the aesthetic reconciliation of potentially conflicting solutions to a project’s design drivers. We need to consider a number of objectives and satisfy multiple constraints in our work. Solving for individual criteria can often lead to contrary formal outcomes, so we need to develop a hierarchy of the criteria and compromise among them.

We may want a building form to maximize best views—but in hot climates we want to minimize the amount of solar heat gain by limiting the amount of glass. We may want to maximize usable area in the lowest number of floors, and minimize core area by selecting deep floorplates. But we also want a sustainable environment that provides consistent daylight and promotes air circulation, which is better suited to a shallow footprint.

2.3 Algorithmic Optimization of Form Parameter
Genetic algorithms can be used as a form-finding tool to search for “optimal solutions.” The genetic algorithm is based on an iterative process that utilizes evolutionary selection. Successive generations produce better results than the previous iteration. The new models are consequently used as a starting point in the next iteration. This process was used in the following example to create a building form optimized both for wind stability and constrained by overall floor area (see Fig. 11).

![Figure 11. Structural Optimization through Algorithmic Search](image1)

The goal of the optimization below was to maximize solar exposure, given a fixed site and the surrounding context of buildings [2]. The image on the left shows various steps in the optimization process, and the image on the right shows the resulting form with the context buildings which helped shape it (see Fig. 12).

![Figure 12. Minimizing Solar Exposure through Algorithmic Search](image2)
2.4 Challenges
In order to realize the benefits of geometrically complex enclosures, challenges will arise:

- Understanding of complex 3-dimensional conditions
  - Single or double curved glass panels
  - Non-rectangular panels
  - Unique panel conditions
  - Torqued, irregular, non-repetitive mullions
  - Unique or complex joint conditions
- Overhead and potential errors in documenting the unique conditions

3 Analyze: Understanding implications of complex enclosures

In practice we observe two common analysis processes:

**Computational Execution: Analyzing the problem based on experience**

We already have an implicit understanding of the problem we wish to analyze. Often, we also have a general idea of the solution, and utilize computation as an auxiliary agent to extend our capabilities and efficiently validate or refine our assumptions. We can either intuit by logic, manually calculate, or compute the solution in question. Methods of Computational Execution include drawing geometry models in 3D CAD tools such as AutoCAD®, Revit®, Rhinoceros®, or Catia™. Refer to 3.1 for a series of examples.

**Computational Investigation: Defining the problem based on analysis**

With complex geometries, we lack an implicit understanding of the problem and rely on computation to assist in its definition and in our analysis. In a previously mentioned example, the Tianjin CTF Finance Centre, the floor plates change shape and size due to programmatic requirements. We cannot logically identify or intuit every atypical condition that spans the building’s 96 levels. Computation helps us identify and understand the enclosure’s panel complexities arising from those transitions. Methods of Computational Investigation involve analysis performed through standard functionality in 3D CAD tools (mentioned above), but often the creation of custom scripts is required. Refer to 3.2 for examples.

3.1 Computational Execution

The following three building geometries are studies that demonstrate how the overall form relates to panelization. The given panelization strategies are derived by means of reasoning—visualized and verified through 3-dimensional computer models. We consider these examples to fall into the category of Computational Execution.

3.1.1 Vertical Extrusions

Vertical extruded buildings are relatively simple to panelize. All panels can be vertical, rectangular, planar, and similar. Floor plates with straight edges will create facades with planar facade panels (see Fig. 13, left, middle). Curved floor plate geometries will create a cylindrical surface when extruded (see Fig. 13,
right). Enclosure panels on this surface can be single curved, or approximated with planar panels into a faceted facade, by approximating the curve with a line.

Figure 13. Computational Execution: Vertical Extrusions

3.1.2 Revolution
Fig. 14 are surfaces of revolution. In any revolved surfaces, all panels on the same level are identical to each other, but vary from one level to the next with the exception of a circular cylinder. In a cylinder every panel is rectangular, and identical. Panels are single curved, or can be simplified to be planar (see Fig. 14, left). In other surfaces of revolution, panels are trapezoidal or triangular.

Figure 14. Revolution

3.1.3 Transformation
In a tapering building at least one face is sloped, and the slope may vary between faces (see Fig. 15, left). The facade on the left is a rectangle, although the panels are leaning. They are planar, rectangular, and are all identical. The vertical facade is a trapezoid. Subdividing a trapezoid into the same number of panels on every floor creates parallelogram-shaped panels—each is unique. In another approach (see Fig. 15, middle), only the corner panels are trapezoidal or triangular, but the rest of the panels are rectangular and identical. Using another concept (see Fig. 15; right), which is applicable when leaning enclosures are not feasible, sloped panels can be simplified to be vertical. A common scenario is when operable vents are required. However, the stepped stack joint will add additional complexity.
Figure 15. Tapering

Building forms that smoothly transform from one shape at the bottom to another at the top have floor plates which vary from floor to floor. The first example is a transition from a square to a 45° rotated square inscribed by the bottom curve (see Fig. 16, left). We can quickly see that the facade surface consists of eight triangles: four vertical, and four sloped. As triangles are always planar, all facades will be planar. However, when dealing with more complex transformations—for instance, transitions from a square at the base to a circle at the top—computational analysis protocols will support designers in analyzing the panelization solutions and implications (see 3.2).

Figure 16. Transformational

3.2 Computational Investigation

For buildings with many unique conditions, computational analysis protocols are key to understanding the geometric implications for enclosure penalization. For buildings that may have thousands of unique facade panels, the analysis has to be executed in a way that every unique condition can be understood and quantified. Often, customized scripts that customize the functionality of 3D CAD tools are created as part of the design process, in order to understand and visualize results.

3.2.1 Out-of-planeness Analysis

The Tiangxi Nanchang Greenland Central Plaza Tower transforms from a free-form curve through a circle in the middle, to another free-form curve at the top of
the tower (see Fig. 17). The resulting geometry is a free-form surface. However, the tower is 4-fold symmetric, and one-eighth of the skin is sufficient to describe the entire enclosure geometry.

Because the design intention is to maintain a smooth appearance, cold-bent glass is utilized in the curtain wall. The geometry of each curtain wall panel was modeled through a parametric script, and the out-of-planeness of each panel measured. We define out-of-planeness to be the dimension that one corner vertex of a rectangular panel is moved in the direction of its surface normal, while the other three corners of the panels are fixed. The analysis demonstrates a maximum out-of-planeness of 53 mm. The full analysis results were visualized by color coding, displaying measures in 3D CAD, and creating spreadsheets for further analysis and visualization (see Fig. 18).

**Figure 17.** Jiangxi Nanchang Greenland Central Plaza, Parcel A, Nanchang, China

Evaluating the results can be a challenge. In this example a question immediately arises: Is 53 mm out-of-planeness within the limits for cold-bending glass? Early on in the design process, in Schematic Design or Design Development, finding a definite answer can be a challenge considering that the fabricator and installer are only chosen after the enclosure has been bid. Bidding can take place as late as after the Construction Document phase. Thus, accurate and detailed
information that may affect feasibility—such as thresholds—only become available when the overall form becomes increasingly difficult to change.

To establish applicable thresholds, the following research techniques are typically employed and used as a “rule-of-thumb” in the design process:

- **External knowledge base**
  - Literature review
  - Fabricators and installers
  - External consultants

- **Internal knowledge base**
  - Review of previous projects and research
  - Computational deformation and stress analysis
  - In-house mock-ups

Design teams are facing several challenges when researching fabrication constraints. The incentive for a manufacturer to engage during the design process can be based only on the prospect of a future contract. Different manufacturers and installers may use different fabrication techniques, and have different warranties and policies in place that may influence, for instance, the threshold for cold-bent glass. And even after a curtain wall company is selected, it may still be unclear who fabricates the glass—as the fabricator may be a subcontractor of the curtain wall company, possibly selected at a later time. Thresholds are not only based on what is physically possible, but also based on warranty policies and contracts. Although feasible to fabricate, thresholds may still create undesirable visual results which can be difficult to quantify.

![Deformation Analysis](image1)

*Figure 19. Deformation Analysis (left, middle), Physical Testing (right)*

We maintain a flexible analysis process that allows for change, so that we are not slowed down during the design process. In order to understand the implication of different thresholds—from two different fabricators, for instance—results are analyzed and visualized to demonstrate the implications (see Fig. 20). Blue indicates panels that can be considered planar, with no bending necessary; yellow indicates formable panels; and red shows panels beyond the limit of cold-bending. Computational analysis allows us to understand many unique conditions, and quickly evaluate changing constraints.
3.2.2 Panel Uniqueness
Take the rain-screen of the Convocation Hall for Kuwait University as an example for analysis of panel uniqueness (see Fig. 21). Geometrically speaking, the enclosure is half ellipsoid and half spherical. Repetition of panels in the sphere segment is relatively simple to predict by intuition, as a sphere segment is a revolving surface (see 3.1). Analysis of the ellipsoid segment, however, is not as straightforward.

In order to understand the implications of the panelization strategy, the U-dimension of any panel was mapped against the V-dimensions to quantify the number of unique panels, and how different those panels were (see Fig. 22). The analysis shows that there are 3,400 panel types, and that panel dimensions vary between 460mm and 880mm. This analysis helps to clearly understand the problem and can then be used to formulate solutions.
4 Optimize: Improve constructability, reduce cost, maintain design intent

From constructability and cost standpoints, the optimization of enclosures usually focuses on panelization. There are typically three goals: **Planarity, rectangularity, and similarity**. Meeting them will often result in an enclosure that is more economical to fabricate. Possible trade-offs include

- **Aesthetics**: We may want a smooth skin but can only afford to construct it with planar glass.
- **Component complexity**: An edge joint designed to accommodate many panel angles may be more expensive than a unique panel joint.

Optimization may take one of three general approaches:

1. **Optimize Global Form Parameters**: Adapt the global form to maximize equality, planarity, rectangularity, and similarity of panels. This may result in drastic variations from the original design, or may result in minimal change.
2. **Deviate in Local Panel Conditions**: Deviate from the global form locally to optimize planarity, rectangularity, and similarity.
3. **A combination of both strategies**

4.1 Optimization of Global Form Parameters

One of the most effective optimization strategies is to choose a global form that is subdivisible in a way advantageous to the construction technology at hand. While the inner and outer facades of the Al-Hamra tower (see Fig. 23) are simple extrusions, the side edges of the rotating opening—the “flare-walls”—are stone-clad double curved surfaces. The global form has been optimized for fabrication as a ruled surface, called a hyperbolic paraboloid. Ruled surfaces, although double curved, have straight sections [5]. Panel optimization of these walls was
able to produce a result with 94 percent flat and identical stone panels (see Fig. 24).

Figure 23. Al Hamra Tower: Geometry Diagrams

Figure 24. Al Hamra Tower: Panelization

4.2 Deviation in Local Panel Conditions
Local deviations from the global form are an effective strategy to optimize the enclosure geometry. Consider a simple example where a double-curved curtain wall segment was optimized so that it could be build from planar, vertical, and rectangular facade panels (see Fig. 25). As a trade-off, the acceptance of a stepped stack-joint, discontinuous horizontal mullions, and a faceted appearance was necessary.
Figure 25. Faceted Double-Curved Facade

Another option for a subdivision that has a more continuous appearance, while being constructible with planar panels, is to triangulate the double-curved surface (see Fig. 26). Note: triangles are planar by definition. The trade-offs for this solution are increased complexity at the curtain wall nodes, and triangular curtain wall panels.

Figure 26. Triangulation of a Double-Curved Facade

One of the challenges with deviation is that there can be different feasible solutions. Finding the most desirable solution for deviation often requires creating customized scripts. Consider a curtain wall geometry that was described by a B-spline curve-in plan (see Fig. 27). To simplify fabrication of the stack-joint geometry and the glass panels, the B-spline curve was rationalized into arc segments with endpoints falling on the panel joints. Due to the given constraints, there is not one explicit solution. As a trade-off we lose tangency between arcs, and will need to deviate from the original spline curve. Consider two different options for describing the same B-spline with arcs. First, a solution that prioritizes tangency between arcs over closeness to the original curve (see Fig. 27). In this example the maximum deviation from tangency is 0.13°, with a maximum deviation from the input curve of 35 mm. Second, a solution that has a minimal deviation from the original geometry to stay as close as possible to the original gross floor area (see Fig. 28). Here we must accept a larger discontinuity between the arc segments up to 3.4°, but the solution only deviates 6 mm from the original curve.
In another example, the ellipses of the rain-screen at the Convocation Hall for Kuwait University had to be optimized in order to be defined by four points based on the roofing geometry. Consider that a planar ellipse can be defined explicitly by only three points. Hence, there is not one but many different ellipses that can be fit through the four points. We defined the ellipses by utilizing a least-square fitting algorithm [6] executed in R from a customized link to our 3D CAD program (see Fig. 29).

Another form of optimization increased the repeatability of the Convocation Hall’s 6,270 rain-screen panels (see Fig. 30). We developed a script to reduce the
number of unique panels by allowing the gaps between the ellipsoid rain-screen panels to vary. With this technique, the number of panel types was reduced from 3,400 panels to a discrete family of 179 panel types.

Figure 30. Optimizing Repeatability of Rain-screen Panels

5 Documentation

Often, communicating design still centers around 2D drawings. One must find a way to communicate efficiently, especially when documenting enclosure systems with many unique conditions and complex geometries. A common solution is to describe the geometry for form-generation through diagrams (see Fig. 31) or equations. The benefit of this method is that it clearly describes the form generation. However, it is hard to track mistakes when recreating the geometry this way.
Figure 31. Geometry Solution Documented through Diagrams

As an alternative, we can also describe the geometry discreetly by documenting each panel through work points (see Fig. 32). The coordinates can be generated automatically from the model, or linked in such a way that changes to the form or panelization will automatically update the coordinate documentation. We often use computer scripts to efficiently document. In many cases we will document geometry using both diagrams and the discrete panel solution.

Figure 32. Geometry Solution Documented by Control Points

6 Conclusion

In this paper we presented the four key process steps for rationalizing complex building geometries: Form, analyze, optimize, and document. First, we demonstrated the rationale behind complex building enclosures, and highlighted challenges through a series of realized examples. Second, we proposed two methods for gaining insight into geometric problems in design phases. We refer to these analysis methods as *computational execution* and *computational investigation*, and exemplified each method. The analysis results then informed our approaches to optimization with the goal of improving constructability and
reducing cost. Lastly, we showed two options for effectively documenting complex geometries: explaining the form-creation through diagrams, and documenting the discrete panel solution through control points.

Computational tools enable us to realize complex enclosures on a large scale. Many complex buildings utilizing geometrically complex systems would probably not be feasible without computational tools. These tools, however, are only auxiliary agents of the designer, and do not replace a good understanding of geometric principles and visual-spatial skills.

References

Abstract

Sustainability research increasingly tends towards high-technology solutions and often bypasses simpler avenues of inquiry. Less studied are inquiries that draw upon the intrinsic qualities of responsive materials and advance the prospect of architecture to act passively and be instructive in response to environmental fluctuation.

This presentation describes a collaborative effort between Bohlin Cywinski Jackson Architects and the Bio_Logic Design Group to research, develop and implement passive building energy strategies based on the thermodynamic properties of organic phase change materials (PCMs). This strategy incorporates glass PCM containment glass tiles that lower reliance on mechanical conditioning and presents an educational opportunity to convey the beauty of the phase change process to building occupants.

The building application presented is designed to help meet the energy petal of the Living Building Challenge for the Frick Environmental Center in Pittsburgh, PA and contributes to the center’s educational mission to convey sustainable principles to the public. In particular, the team explored the development of glass PCM containment glass tiles that demonstrate the communicative potential of sustainable technology.

Keywords: research and innovation, new technologies, decorative glass, energy performance, demonstration project
1 Introduction

The new Frick Environmental Center (FEC) is a joint venture between the City of Pittsburgh and the Pittsburgh Parks Conservancy. Free and open to the public, the Frick Environmental Center will support a critical need in the Pittsburgh area to significantly increase and diversify participation in hands-on environmental education, attracting visitors from around the nation and around the world. The Frick Environmental Center will serve as a living laboratory for environmental design and educational practice, and reflect a balance between humans and the natural world in a manner that is playful and inspiring. It will integrate innovative educational facilities with a public park that is a complex ecosystem, historic landscape, and recreational property. All aspects of the project are governed by a commitment to the best environmental practices. In addition to anticipating LEED platinum certification, the project is designed to meet the goals of the Living Building Challenge (LBC). The Living Building Challenge is an ambitious standard that challenges those in the design and construction industry to change building practices on a wholesale level. It includes requirements such as net-zero energy and net-zero water, as well as elimination of building materials that contain harmful chemicals. It also requires that the public be made aware of the operation and performance of the project, in an effort to motivate others to become more sustainable.

In response to the education requirements of LBC, the design team (Bio_Logic Design Group, BCJ Architects, and TriPyramid) has designed a display (Figure 1) in the main public Gallery to showcase phase change material (PCM) thermal...
storage devices. The teams’ intent is to address the necessity to lower energy consumption by increasing the energy storage capabilities of the building envelope. Our approach is to use low-tech solid-state phase change material glass tiles for this purpose. PCM is also integrated into the building wall cavity, and helps to modulate internal temperature swings, lower reliance on building mechanical conditioning and met the energy petal of the LBC. The visual and tactile display in the Gallery demonstrates the thermal storage capacity of PCM and showcases the visual aspects of sustainable technology to visitors.

Figure 2. Plan of the Frick Environmental Center with the glass tile heat exchanger location shown in blue.

Children are the primary visitors to the Frick Environmental Center and the challenge of designing a public facility for children is to engage them comprehensively. Towards this goal, the team is interested in the potential of the building to become a learning tool that creatively conveys information haptically and visually. The reasoning is based in studies that show meaning is often more quickly conveyed through imagery and direct physical contact. The importance of demonstrating content visually is most often confined to schools of design and art, and there are no widely accepted standards for visual literacy. There are no significant movements to transfer this mode of learning to other aspects of K-12 education although the role of visual learning is emerging in mathematics, science and engineering coursework. Our project applies visual and tactile learning to technology and building science by engaging children with the physical process of crystallization as the PCM undergoes phase change. The hypothesis is that if children are engaged with sustainable technology in a way that is meaningful that this will influence behavioral change in regard to energy consumption. The more one viscerally understands the operation of a building, the more one is likely to be sensitive to inputting energy to affect internal building conditions. This is a small step in becoming literate in the interface of energy exchange between buildings and the environment.
The glass tiles are effective as they translate thermal information to experience. In both children and adults, we have noticed the glass tiles are visually engaging. When one first sees the PCM under transition (specifically in its liquid to solid phase), generally the person looks more closely at the crystallization phenomena. Upon doing so, the person is very close to the tile, often physically touching it, and attention is focused. Children use this mechanism to concentrate on an object visually and to narrow the field of vision to remove distractions. Adults generally perceive a visual environment differently, usually scanning an entire context. Both conditions are represented in the design for the Frick Environmental Center, the single tile to focus one's attention and the array of tiles such that visitors understand the dynamics of thermal exchange as a field. This field condition is observed as an array of up to 500 tiles in the Frick Environmental Center gallery (Figure 1 + Figure 9). Arranged perpendicular to the glass, ambient light washes the tile surface when the PCM is in its frozen state, reflecting light into the space. Upon entering the building, the visitor first views the array at an oblique angle, seeing the tiles in the densest perspective.

2 Phase Change Materials

Phase change materials (PCMs) applicable to building technology include salts, paraffin and organic fatty acids. They have the potential to offset heating and cooling loads by serving as high mass thermal energy storage. Figure 3 diagrams the energy storage ad release cycles as the material changes phase. Compared to concrete PCMs are far more effective at thermal storage during phase transition. Thermal mass has long been used to stabilize temperature in buildings and developed into a standardized technology by Edward Morse who patented the ‘Trombe’ wall system in 1881. PCMs are a more recent advancement of this system, dating to the 1970’s, and are effective due to the high heat of fusion generated when a material changes states. Today, PCMs are most commonly encapsulated in plaster then applied as an interior surface or encapsulated in plastic sheeting then applied behind drywall.
Figure 3. PCM thermal process.

Figure 4. Recent experiments with PCM crystallization patterns as temperature drops below the PCM set point.

3 Modular and Reconfigurable Glass Containment Glass Vessels

Our team interests were to define geometries that render PCM more effective at thermal exchange with the surrounding environment and to work in the emerging field of making sustainable technologies visible to building occupants. In particular, the project is a study of incorporating PCM into glass containment glass tiles that promote and control the conduction of thermal energy between the glass tiles and the surrounding air. Glass was chosen for the containment glass...
tiles for its transparency and high thermal conductivity. Comparatively, PCM has low thermal conductivity and benefits from thermal transmission through the glass vessel. The operative principle is that more heat is exchanged as the surface area with the surrounding environment is increased. The total heat transfer is dependent upon the heat transfer coefficient of the PCM, the surface area and the average temperature difference between PCM and surrounding air.

Transparency of the vessel allows the building occupant to visually perceive the material as it undergoes phase transition. This is the key aspect of communication of responsive material properties that lower energy consumption to building occupants. As buildings have trended towards technology that operates in the background, the intent of the Frick Environmental Center is to reengage occupants with building operation. The glass tiles are design to convey subtle principles of thermodynamics at a range of scales, quickly and actively. The tile hanging system is designed to be reconfigurable, both in terms of vessel location and density and in terms of material set point within the tile.

![PCM_tiles](image)

**Figure 5.** PCM glass tile undergoing phase transition from liquid to solid.

### 3.1 Sample Bay

A typical glass vessel (Figure 5 + 6) measures 8” x 8” x .4”, has an approximate surface area of 64 square inches and a PCM volume of 16 cubic inches. On the interior of the north façade the daily temperature fluctuation is relatively low and coupled with the low thermal conductivity of the PCM, a strategy that increased air contact was designed. Approximately 70 glass tiles will be arrayed in each bay (Figure 8) (8 bays total) 1120 cubic inches of PCM per bay x 8 bays = 8960 cubic inches total.
3.2 Location and Application

The placement of the PCM containment glass tiles is on the interior of the north façade in the main public gallery. This location ensures high visibility and a high degree of interaction from visitors, allowing for the greatest impact of the tiles as an educational tool. The tile array is designed to temper this thermally dynamic location and to offset cooling loads from the occupied building times to the unoccupied times. The occupied (9am – 5pm) thermal range of the building is between 68F and 76F and the unoccupied range is 64F – 80F. The average set point of the PCM is 72F, the average of the high and low HVAC set points. It is projected that this will be the most active temperature range for the PCM. During the summer months, the glass tile system is designed to effectively keep the temperature in the gallery below 76F until 5pm when the air-conditioning resets to 80F. The absorbed heat within the tiles can then radiate into the gallery, optimally keeping the temperature below the 80F conditioning trigger point.
Figure 7. Diagram of PCM tile and fittings.

Figure 8. Elevation and section of PCM display and development of tile fittings.

Figure 9. The Frick Environmental Center – Public Gallery PCM tile display.
4 Conclusion

Visual expression of sustainable technology, once an integral aesthetic and performative aspect of vernacular architecture, is less prevalent since the invention and widespread use of air-conditioning. Technology, in this case, encouraged dissociation between building and environment. Today there is a shift towards understanding the ecology of building operation and interest in the expressive qualities of technology and the aesthetic integration into high-performance building systems. Our interest is to explore the potential of responsive building systems and convey that sustainable buildings are not well-designed static systems but that they facilitate a dynamic exchange of matter and energy with the local environment — and that this exchange can be visual, educational, and modify our behavior in regards to consumption.

The construction of the Frick Environmental Center will position Frick Park as the urban hub of environmental education programs of the Pittsburgh Parks Conservancy for Pittsburgh region. The Frick Environmental Center site is within three miles of over 170,000 residents of neighboring municipalities including many of Pittsburgh’s most underserved neighborhoods. The Environmental Center is designed to engage the public in environmental issues and use both low and high tech means to convey the interrelationship between the built and natural environments to visitors. The Center will be integral in changing the region's interaction with the environment from a cycle of deterioration to a cycle of stewardship.

Both BCJ and the Bio_Logic Design Group plan to continue this R+D partnership and combine visually expressive responsive materials with other emerging glazing technologies, such as high performance: glass, coatings, interlayers, along with new printing and fritting technologies to create responsive facades that integrate aesthetics, education and building performance.
Dynamic glazing in U.S. Building Energy Codes and Green Construction Codes

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Abstract
The use of dynamic glazing in buildings offers significant energy savings and peak load reductions compared to traditional “static” glazing by being able to optimally control solar heat gains and daylighting throughout the day and year. As such, dynamic glazing represents a key technology on the route to zero energy buildings. This energy saving envelope technology is commercially available and adoption in the market is growing. To support market adoption it has been important to remove potential unintended barriers to its use such as in building code requirements. This paper describes the recent changes in the U.S. building energy codes (ASHRAE 90.1, IECC, and California Title 24) and green construction codes (ASHRAE 189.1 and IgCC) which have been adopted to clarify code compliance for, and encourage use of, dynamic glazing.

Key words: Electrochromic glazing, dynamic glazing, energy codes, ASHRAE 90.1, ASHRAE 189.1, IECC, IgCC,

1 Introduction
Buildings consume 40% of all the energy used in the US. Electrical lighting energy accounts for around 20% of that energy, approximately 38% of total building electricity use and 22% of the total electricity generated in the United States [1].

Fenestration with dynamic solar control has been identified as a key envelope requirement for zero energy buildings by the US Department of Energy [1]. When part of an integrated façade with dimmable lighting controls, dynamic glazings can provide significant energy savings over conventional façades. The DOE estimates that if all of the windows in the current building stock were replaced with those which have dynamic solar control and good thermal performance (U-factor) and integrated with dimmable lighting controls, 2.6 Quads (1 Quad = 1 quadrillion BTUs) of energy could be saved in the US annually. In fact, dynamic glazing on its own could save 0.8 Quads compared to the performance of static windows sold today [2], see figure 1.

Additional field studies and building energy modeling by both LBNL’s Windows and Daylighting Group and others have continued to confirm that dynamic glazing (in particular electrochromic glazing) can result in significant energy savings over conventional static sun management systems [3, 4, 5].
Because of the significant potential to provide a step change in building energy performance for the nation, it is important to remove any potential roadblocks to the commercialization and use of new product technologies that provide such functionality in new and existing buildings.

Figure 1. Annual energy usage across US building stock predicted by LBNL based on the implementation of key façade technologies [1].

In 2005, the National Fenestration Rating Council (NFRC) had the foresight to launch a performance label for fenestration containing dynamic glazing so that the performance of such products could be officially rated (see figure 2). NFRC also provided the first definition of a dynamic glazing which included products with blinds or shades between the panes of a glazing system and chromogenic glazings such as electrochromic glass. However, at that time, if a code official saw a window with a dynamic glazing NFRC label, on which there are two numbers for solar heat gain coefficient (SHGC) – a minimum and maximum number – they would not know how to interpret it. This was because there was no language in the prevailing model codes (IECC or ASHRAE 90.1) that would provide instruction on how to interpret these two numbers against the standard prescriptive table of single maximum SHGC values.

Since initiating the conversation in 2009, significant progress has been made in including interpretation language for dynamic glazing into the US building energy codes and standards, thus removing code related barriers to adoption. This
paper details the language relating to dynamic glazing in the US model codes and the above baseline “green building” codes.

![NFRC dynamic glazing label](image)

**Figure 2.** NFRC dynamic glazing label

### 2 Types of Dynamic Glazing

#### 2.1 Electrochromic glazing

Electrochromic (EC) glass is a type of active dynamic glazing that has the ability to reversibly change its visible light transmission and solar heat gain coefficient at the touch of a button or in response to sensors (e.g. light, occupancy, temperature) or on the command of a building management system. An example of the configuration of an electrochromic dual pane insulating glass unit is shown in figure 3. The dynamic range of EC glazings on clear glass substrates currently spans from a high of 60% visible light transmission (VT) to a low of 1% VT with corresponding solar heat gain coefficients of 0.41 and 0.09 respectively. Other performance ranges are also possible when the EC coatings are used in combination with different tinted glass substrates which can be used to provide different exterior aesthetics. The wide dynamic range performance provides the ability to create an automatic heat and light valve for buildings, capturing needed solar heat to offset heating loads when needed and blocking unwanted heat when in cooling mode, and at all times harvesting daylight to offset electric lighting.
The penetration of dynamic glazing in the commercial market is growing rapidly now that the category has a proven ten year track record and with the availability of larger sizes, higher volumes, improved color aesthetics and other new features. The photographs in figure 5 illustrate the scale of buildings now being glazed with this dynamic glazing technology.

Figure 3. Example of the configuration of an electrochromic (EC) dual pane insulating glass unit.

Figure 4. Graph of visible light transmission (VLT) versus solar heat gain coefficient (SHGC) which demonstrates the heat gain and light transmission range of a high performance EC product compared with examples of standard static glass.
Figure 5. Images of a large scale installation of electrochromic glazing at Butler County Health Care Center, David City, Nebraska. Photos courtesy of Daubman Photography (top and middle images) and SAGE Electrochromics, Inc. (bottom image).
2.2 Thermochromic glazing

Thermochromic glazing is a passive dynamic glazing technology that changes its level of transmission in response to changes in its temperature – becoming darker as the temperature increases. Current commercially available thermochromic technology comes in the form of a thermochromic PVB laminate interlayer material which is laminated between two plies of glass using standard laminating processes. The resultant laminated lite is then generally combined with another lite to form an insulating glass unit. The laminated lite containing the thermochromic material is on the exterior facing lite of the insulating glass unit.

The lowest transmission state is determined by the temperature that the interlayer reaches in the fenestration product, which is in turn dependent on the weather conditions and the incident solar intensity. The product is available in laminated IGU configurations with different tinted or coated substrates. Generally the thermochromic laminate contains a tinted lite which is the exterior facing ply when installed to increase the absorption of the incident radiation. To provide good U-factor performance and improve the SHGC, a low-e coating is also generally added to the inboard lite of the IGU.

The dynamic range of a thermochromic IGU varies depending on the IGU configuration, but the ratio of the highest to lowest transmission state (center of glass) is generally about 5. Depending on the companion tinted or coated lites in the IGU, the clear (low temperature) states range from 27%T on a darkly tinted substrate to 60%T when using clear float glass and the respective tinted state transmissions range from about 6%T to 13%T at 65°C [6].

2.3 Dynamic glazing using mechanical shading systems

The category of dynamic glazings as initially defined by NFRC, and more recently by the model codes (see below), also includes mechanical shading systems that are integrated into the fenestration glazing in-fill system, such as shades or blinds that are installed between two panes of a glazing in-fill (see figure 6). Both manually and automatically controlled systems are available.

Unlike the electrochromic and thermochromic systems, mechanical shading systems when in the closed condition can offer some improvement in thermal insulation, such as at night. For example, a window with a U-factor of 0.40 btu/°F.hr.ft² can reach 0.35 btu/°F.hr.ft² when the shade is pulled [7]. The solar heat gain of such a window can be modulated from 0.47 when open to 0.17 when the shade is closed and triple IG pane with internal shading combinations can have a SHGC range from 0.25 to 0.10 [7].
Figure 6. Example of a mechanical shading system that is covered by the definition of dynamic glazing by NFRC and the model codes. A pleated shade between the panes of glass in the glazing infill. Photograph courtesy of Pella® Windows and Doors.

3 Baseline Codes and Standards

3.1 Introduction

In the United States there are two main energy codes or standards for commercial buildings - ANSI/ASHRAE/IES Standard 90.1 “Energy Standard for Buildings Except Low-Rise Residential Buildings” (commonly known as ASHRAE 90.1) and the International Energy Conservation Code (IECC) developed by the International Code Council (ICC). Within the IECC there is a residential chapter as well as a commercial chapter covering non-residential applications. California has its own energy code called “Title 24” and prides itself as being a leader in energy conservation.

Generally in these codes there are two main pathways for compliance – prescriptive or performance. The performance path requires that the building be modeled with appropriate software to demonstrate that the energy performance is
better than that of a baseline building. Normally the performance path is adopted for larger buildings where the expense of modelling can be borne. The prescriptive path is used for smaller buildings and as the name suggests prescribes minimum or maximum values for specific components of the building. For fenestration, for example, maximum values for U-factor and SHGC are mandated and in some instances visible light transmission is also specified. It should be noted that all the performance criteria for fenestration are based on whole unit values including both glass and framing, not center of glass values. This is important, since center of glass values for insulating glass generally has a higher SHGC and visible light transmission and a lower U-factor than the whole fenestration unit because of the impact of the frame.

Note also that an alternative compliance path for the IECC is through compliance to ASHRAE 90.1.

These codes and standards are mandatory minimums and represent the worst building that can be built according to code. In addition to these baseline codes, there are a set of “stretch” codes and standards often called the “green” codes which represent a higher level of building performance. These standards include performance requirements for other sustainable elements such as indoor environmental quality, life cycle analysis and water conservation as well as energy performance requirements. They are similar in concept to the USGBC’s LEED program, but written in a standard code format instead of a point system. ASHRAE first created ANSI/ASHRAE/USGBC/IEC Standard 189.1 in 2009, which was followed by development of the International Green Construction Code (IgCC) by ICC.

All of the baseline codes and the stretch codes mentioned above have provisions for dynamic glazing which are detailed in the sections below.

3.2 ANSI/ASHRAE/IES Standard 90.1

The 2010 version of ANSI/ASHRAE/IES Standard 90.1 was the first standard to reference dynamic glazing. It created both a definition for dynamic glazing and an interpretation for an NFRC label that had two SHGC values. The definition reads:

*Dynamic glazing: any fenestration product that has the fully reversible ability to change its performance properties, including U-factor, SHGC, or VT.*

For the prescriptive path, the standard says that the lowest labeled SHGC value shall be used to demonstrate compliance with the SHGC requirement. Dynamic glazing is considered separately from other glazing, and no area weighting of SHGC performance can be made with any other fenestration on the envelope is allowed. In the 2013 version of ASHRAE 90.1, there is a requirement for meeting a minimum ratio of VT/SHGC where daylighting controls are used. In this case the highest values of both VT and SHGC are used.

In the performance path, automatically controlled dynamic glazing is modeled as it is to be controlled to give full credit for its dynamic performance. If the dynamic glazing is manually controlled, the glass is modeled using the average of the VT and SHGC.
In the 2013 version of the standard, the definition of dynamic glazing has been updated slightly with 'fenestration' replaced by 'glazing system/glazing infill' to prevent misinterpretation to interior blinds or shades.

### 3.3 International Energy Conservation Code (IECC)

The 2012 version of the IECC was the next to reference dynamic glazing. The same definition for dynamic glazing as was used in ANSI/ASHRAE/IES Standard 90.1-2010 was approved as well as the same interpretation language in the prescriptive path which instructs the code official to use the lower labeled SHGC for compliance. Similarly the use of the highest labeled VT and SHGC for calculating the VT/SHGC ratio was also followed.

In the 2015 version the IECC departed from ANSI/ASHRAE/IES Standard 90.1 and made significant changes to the requirements for dynamic glazing in the prescriptive path in order to ensure that appropriate energy savings were being captured by its use. In particular, a requirement for automatic control and for the ratio of the highest to lowest labeled SHGC values to be at least 2.4 was introduced. Alternately, if both highest and lowest labeled SHGC values both already comply with the prescriptive requirement, then they do not have to meet the ratio requirement. The requirement for automatic control makes a lot of sense because automation will ensure that the dynamic glazing is operating as designed without depending on manual intervention. The requirement for a minimum ratio of SHGC ensures that the dynamic glazing has a reasonably wide dynamic range between high and low values and thus an appropriate level of energy efficiency performance.

In addition, similar language for dynamic glazing was added to the residential energy chapter of IECC 2015 which previously had not been present in the 2012 version, using the updated 2015 language described above.

### 3.4 California Title 24

California was the most recent entity to provide interpretation language for dynamic glazing in their Title 24 energy code and did so in its most recent 2014 version.

The definition of dynamic glazing in Title 24 includes the essence of the definitions in IECC and ANSI/ASHRAE/IES Standard 90.1 but is more detailed. Title 24’s definition specifically includes two kinds of dynamic glazing – chromogenic glazing and integrated shading systems – and specifically excludes internally or externally mounted shading systems that attach to windows whether removable or not.

It defines chromogenic glazings as a class of switchable glazing which includes active materials such as electrochromic glazings and passive materials such as thermochromic which are permanently integrated into the glazing assembly and whose primary function is to switch reversibly between a high transmission and low transmission state.
Integrated shading systems are defined as fenestration products which include an active layer such as shades, blinds which are permanently integrated between two or more glazing layers, through which the U-factor and/or SHGC and VT of an insulating glass assembly can be reversibly altered.

Similarly to ANSI/ASHRAE/IES Standard 90.1-2010 and IECC-2012, it allows for the lower labelled SHGC to be used for compliance, but requires that the dynamic glazing be automatically controlled in order to modulate the entry of light and heat into the building. Similarly, no area weighted averaging with other non-dynamic glazing is allowed.

Title 24 has a requirement for a minimum visible light transmission, and similar interpretation language is included for dynamic glazing, except that the higher labelled VT is used for compliance.

4 The 'Green' Codes

The 'Green' Codes have provisions not just for energy but also for indoor environmental quality. The latter covers the provision of daylighting and views for the occupants which is important for fenestration and envelope design. The requirement to maintain a certain level of daylight and a view to the outside has the potential to balance the downward pressure on window to wall ratio that has been exerted in the last few years in the baseline codes.

4.1 ANSI/ASHRAE/USGBC/IES 189.1

For energy efficiency, ASHRAE 189.1 is designed as an overlay to ASHRAE 90.1 and so the base requirement for ASHRAE 189.1-2011 is compliance with ASHRAE 90.1-2010. Therefore the definitions and interpretation for dynamic glazing are brought in from 90.1. In ASHRAE 189.1-2014, there will be a requirement for the prescriptive performance of fenestration to be 10% better than ASHRAE 90.1 values.

Unlike in ASHRAE 90.1, the prescriptive compliance path of ASHRAE 189.1 has a requirement for permanent horizontal shading for fenestration (using for example an overhang or sunshade) on the east, south and west elevations in climate zones 1 to 5. In recognition of the enhanced solar control provided by dynamic glazing compared to horizontal static shading systems there is an exception to this requirement if automatically controlled dynamic glazing is utilized. The dynamic glazing has to meet certain performance requirements to ensure that good energy performance is delivered: The lower labeled SHGC must be less than 0.12, the lowest labeled VT must be no greater than 5%T and a highest labeled VT no less than 40%. Manual override for the automated system is also a requirement to allow occupant control, and very appropriately, so is acceptance testing and commissioning of the dynamic glazing system. This latter requirement ensures that the performance specified is actually delivered in the as-built design.
4.2 International Green Construction Code (IgCC)

The 2012 version of the IgCC is the other standard for high performance green buildings and like its baseline version (IECC) also allows designers to use ASHRAE 189.1 as an equivalent compliance option. The 2012 IgCC is designed as an overlay to the 2012 IECC with other sustainable design attributes such as site selection, material selection, daylighting etc. added to the energy requirements. As an overlay standard, it brings in the same definition for dynamic glazing and specification for the use of the lowest labelled state for SHGC compliance. As a stretch code, the prescriptive path of the IgCC requires that fenestration have values for U-factor and SHGC 10% lower than the IECC requirement.

Similar to ASHRAE 189.1, the prescriptive path of the IgCC also requires shading by a permanent projection (overhang, sunshade, etc) on the east, south, and west facades. Again, because of the enhanced energy performance, automatically controlled dynamic glazing with certain properties is included as an alternative method of compliance. In this case the performance requirements of the dynamic glazing are slightly different from ASHRAE 189.1. The minimum SHGC must be less than 0.12, but the VT requirement is specified using the ratio of the higher and lower labeled which must be at least 5. Automatic control is required, as is functional testing of the system.

5 Conclusions

Dynamic glazing has the potential to provide a step change in the energy performance of building envelopes and is one of three key façade technologies on the US DOE’s roadmap for achieving net zero (or near zero) energy buildings.

In order to remove barriers to the adoption of dynamic glazing technologies it has been important to provide interpretive language in the US energy codes and standards, especially in prescriptive compliance paths where one value of SHGC is listed yet dynamic glazing has a range of SHGC performance.

Since the first interpretive language that appeared in the 2010 version of ASHRAE 90.1, dynamic glazing is now recognized in all the national building energy codes and standards – both for baseline and “green” construction. The recognition of the product category in this way has effectively removed barriers to adoption and provided a basis from which to refine the performance requirements as the adoption grows and technology advances.

References


Extending the Performance and Design of Laminated Glass Fins using Ionoplast Interlayers

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Abstract

Ionoplast interlayers extend the performance of laminated glass fins and provide improved design solutions for glass façades. The enhanced flexural behavior and strength benefits associated with a stiff, ionoplast interlayer enables longer, thinner and narrower fin profiles with extended structural performance at higher temperatures versus conventional PVB laminates. In addition, ionoplast laminates offer improved edge stability in exterior glazing applications and in conditions where the interlayer comes into contact with structural silicon sealants. While there are no codes and standards addressing the engineering design of laminated glass fins, the Australian standard AS 1288 is an important reference for monolithic glass fin design and treats the buckling/collapse condition for several boundary conditions. Façade engineers often use first principles stress analysis approaches to design laminated glass fins. Such approaches take into account the interlayer shear properties explicitly and can address complexity in the boundary conditions for a specific façade concept. Here we review some of the published analyses and test data for laminated glass fins and show examples of facades that have taken advantage of the properties of ionoplast laminated glass fins.

Introduction

For more than thirty years, architects and façade designers have incorporated transparent glass fins into many types of building enclosures, including store fronts, curtain walls, skylights, and canopies. These glass elements are oriented perpendicular to the main facade glass components thus providing support and resistance to lateral loads. Glass fins may be deployed in both interior and exterior applications and, in some cases, provide a purely decorative function. Glass fins can be fixed at the floor and roof, provide a connection point for glass fittings to hold and position the exterior glass panels, or be part of cable or tension rod supported systems. Early glass fins utilized “thick” tempered glass and were designed with high safety factors and redundancy. We have seen a steady trend in recent years towards the use of laminated glass fins because of residual structural capacity after accidental breakage. Traditional laminated glass is based on polyvinyl butyral (PVB) interlayers and its safety performance is well
recognized in the industry. Since 1998, ionoplast interlayers have extended the structural and durability performance of laminated glass generally and are having a great impact on the design of laminated glass fins.

**Laminated glass interlayers**

Since the 1930s, Polyvinyl butyral (PVB) interlayer has been the industry standard for the manufacture of laminated safety glass. Architects are well aware of the possibilities and limitations of laminated glass in façade engineering, curtain walls and skylights. Ionoplast interlayers, such as DuPont’s SentryGlas®, have expanded façade design beyond traditional applications. Because the interlayer is over 100 times stiffer and 5 times tougher than PVB, the transmission of load between the two sheets of glass in the laminate is highly efficient, even at elevated temperatures. This leads to the near monolithic flexural behavior of the laminated glass even when under load in direct sunlight during summer. Laminates manufactured with ionoplast interlayers show less than half the rate of deflection when compared to laminates with PVB when under the same load, and almost the same behavior as monolithic glass of the same thickness. In general, laminated glass fins made with ionoplast interlayer require less depth, enabling a thinner glass profile.

**Increased Critical Buckling Load**

One of the most common design requirements for glass fins is resistance to buckling. This is a complex subject, as there are different directions in which the fin can bow (lateral, axial, torsional). The typical fin is subjected to each type of loading in normal use. One way to quantify the difference in standard PVB versus ionoplast is through a calculation of Critical Buckling Load under axial loading. As introduced by Johan Blaauwendraad of Delft University in Netherlands, one way to calculate the critical buckling load for a fin is to apply an axial load to the laminate, calculate the moment of inertia to buckle the laminate out of plane, and take into account the shear modulus of the interlayer material. The different interlayer behavior is taken into account in the final stiffness term by using the appropriate shear modulus of the interlayer under the given conditions.

In his example outlined in the paper, Blaauwendraad calculated a critical buckling load (P_{crit}) for PVB as 87kN. The shear modulus used (0.5MPa) equates to roughly the shear modulus of PVB under a short duration (3 second) load at 50°C. Using ionoplast, the shear modulus under a 3 second load and 50C is 26.4 MPa, resulting in a critical buckling load of 238 kN, approximately 2.75 times greater than the PVB example. Using Ionoplast interlayer, rather than the 10mm/1.5mmPVB/10mm construction outlined in the paper, a laminate of 6mm/1.5mm Ionoplast/8mm would have the same Critical Buckling Load as the
10mm/1.5mm PVB/10mm laminate. This is a weight savings of 30%. The overall effect of shear modulus is shown in Figure 1.

**Figure 1.** Effect of Interlayer Shear Modulus on Critical Buckling Load under lateral loading

An additional fin buckling mode analysis is presented by Peter Lenk and Franklin Lancaster in their paper *Stability Analysis of Structural Glass Systems*. A method is first proposed to understand the effective thickness of a 5 ply fin under axial load, similar to Blaauwendraad, based on interlayer shear modulus and the critical length of the laminate. From their results, one can see that the higher the shear modulus, the higher the effective thickness of the laminate. It can be shown, similar to the previous paper, that the thicker the column, the higher the critical buckling load required to buckle the laminate. As mentioned previously, the shear modulus of ionoplast interlayers is much greater than standard PVB, particularly at higher temperatures.

Lenk and Lancaster went on to show the effective thickness calculation for lateral torsional bending. In this method, the dependence of interlayer shear modulus is studied based on a critical moment. The effect of shear modulus of interlayer material is even more dramatic in this condition, as seen in Figure 2.
Figure 2. Effect of Interlayer Shear Modulus on Effective Thickness under torsional loading

The work of Lenk and Lancaster, in addition to the work of Blaauwendraad, illustrate the impact ionoplast can play in the design of glass fins through the use of modeling. Additional approaches have been used to study these effects through physical measurements.

From the work of Delince and Belis, similar results can be shown through measurements of structural glass laminates under lateral buckling loads. In their test setup, a lateral load is applied to the structural glass laminate, with two different interlayer materials compared. One is standard PVB, the other is an ionoplast material. The test equipment measured the load at which initial buckling occurred, as well as the ultimate failure of the laminate. The results indicated a buckling load nearly 3 times higher for the ionoplast laminate (G) in comparison to the PVB (E) laminate. Results from the test are illustrated in Figure 3.
Andreas Luible’s work highlights an additional application of ionoplast interlayer in expanding the functionality of structural glass fins. Through his work in lateral torsional buckling of glass fins, a good comparison can be made between monolithic glass, a PVB laminate, and an ionoplast laminate. These equations, developed from models and measurements, can be applied several different ways. Continuing from the previous examples, a 3 second load will be applied at 50°C. The appropriate Shear Modulus values for each interlayer will be used based on these loading conditions. Figure 4 shows a comparison of calculated Critical Lateral Torsion Buckling Moment (CLTBM) for each construction. The CLTBM of the PVB laminate is 42% less than the monolithic equivalent while the Ionoplast example performs 10% better than the monolithic example, and nearly twice the CLTBM of the PVB construction.

![Figure 3. Measured Critical Buckling Load in PVB Laminate Fin (E) and SentryGlas(R) Laminate Fin (G)](image)

<table>
<thead>
<tr>
<th>Fin Type</th>
<th>Span/Height (mm)</th>
<th>ASTM Minimum Thickness (mm)</th>
<th>Fin Depth (mm)</th>
<th>Critical Lateral Torsional Buckling Moment</th>
<th>Ratio of CLTBM of Monolithic Fin</th>
<th>% Comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 mm Monolithic Glass Fin</td>
<td>6000</td>
<td>18.26</td>
<td>600</td>
<td>20.2 kNm</td>
<td>1</td>
<td>100%</td>
</tr>
<tr>
<td>10 mm + 1.52 PVB + 10 mm</td>
<td>6000</td>
<td>9.02+9.02</td>
<td>600</td>
<td>11.7 kNm</td>
<td>0.58</td>
<td>58%</td>
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<tr>
<td>10 mm + 1.52 SentryGlas® + 10 mm</td>
<td>6000</td>
<td>9.02+9.02</td>
<td>600</td>
<td>22.2 kNm</td>
<td>1.1</td>
<td>110%</td>
</tr>
</tbody>
</table>

**Figure 4. Critical Lateral Torsional Buckling Moment for three constructions**

A different application of the equations laid out in Luible’s work allows the user to calculate the minimum required fin depth in order to achieve a selected CLTBM. Figure 5 shows the comparison between the same three constructions discussed previously, this time in terms of required depth of fin. The PVB fin requires 51% greater depth than the monolithic example, while the ionoplast fin requires 7% less depth than the monolithic example and 40% less than the PVB fin. For many applications, a shallower fin is desirable as it requires less material thereby...
reducing the cost, protrudes into the living space a lesser amount, and provides a lighter weight solution.

<table>
<thead>
<tr>
<th>Fin Type</th>
<th>Span/Height (mm)</th>
<th>ASTM Minimum Thickness (mm)</th>
<th>Fin Depth (mm)</th>
<th>Critical Lateral Torsional Buckling Moment</th>
<th>% Comparison of Depths</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 mm Monolithic Glass Fin</td>
<td>6000</td>
<td>18.26</td>
<td>600</td>
<td>20.2 kNm</td>
<td>100%</td>
</tr>
<tr>
<td>10mm + 1.52 PVB + 10 mm</td>
<td>6000</td>
<td>9.02+9.02</td>
<td>904</td>
<td>20.2 kNm</td>
<td>151%</td>
</tr>
<tr>
<td>10 mm + 1.52 SentryGlas® + 10 mm</td>
<td>6000</td>
<td>9.02+9.02</td>
<td>555</td>
<td>20.2 kNm</td>
<td>93%</td>
</tr>
</tbody>
</table>

**Figure 5. Required Fin Depth for three constructions**

A third way to understand the differences in the constructions is to compare required glass thicknesses to design for the same CLTBM. Holding the 19mm Monolithic Fin as the base case, Figure 6 shows the comparison of glass thicknesses required by each laminate to achieve the same CLTBM design criteria. The PVB fin must be 21% thicker than the Monolithic fin, while the ionoplast fin can be 5% thinner than Monolithic, or 22% thinner than the PVB fin. This thickness difference can result in cost savings through the price of the glass or the cost of the supports.

<table>
<thead>
<tr>
<th>Fin Type</th>
<th>Span/Height (mm)</th>
<th>ASTM Minimum Thickness (mm)</th>
<th>Fin Depth (mm)</th>
<th>Critical Lateral Torsional Buckling Moment</th>
<th>% Comparison of Glass Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td>19 mm Monolithic Glass Fin</td>
<td>6000</td>
<td>18.26</td>
<td>600</td>
<td>20.2 kNm</td>
<td>100%</td>
</tr>
<tr>
<td>PVB Fin Laminate</td>
<td>6000</td>
<td>11.06+11.06</td>
<td>600</td>
<td>20.2 kNm</td>
<td>121%</td>
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<tr>
<td>SentryGlas® Fin Laminate</td>
<td>6000</td>
<td>8.71+8.71</td>
<td>600</td>
<td>20.2 kNm</td>
<td>95%</td>
</tr>
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</table>

**Figure 6. Required Glass Thickness for three constructions**

**Improved edge stability, sealant compatibility and resistance to weathering**

The long-term behavior of PVB laminates constructed with open edges has been an issue in terms of their resistance to weathering. Typical results of insufficient weathering resistance include edge delamination (the delamination of the interlayer at the edges of the glass panels) and haze development or discoloration (yellowing) due to the effects of rainwater (and cleaning agents) or UV exposure. These effects, both in combination and individually, limit the lifetime of the glazing and can render its use ultimately unacceptable. In contrast to PVB, the appearance and condition of laminates made with ionoplast interlayers remains...
almost unaltered despite exposure to such conditions, as demonstrated by prolonged and comprehensive outdoor and laboratory testing. ¹ Certain designs and installation details require fins to be attached to the façade glass via a structural silicone sealant. Compatibility of the sealant with the interlayer used in the laminated glass fin then becomes an important performance requirement for the fin design. A variety of structural sealants have been tested and shown to be compatible with ionoplast interlayers. No discoloration, bubble formation, or delamination effects were noted after testing. These benefits have often resulted in the selection of ionoplast interlayers for minimally supported laminated glass systems, such as Pilkington Planar™. The laminated glass fins on the interior of the AMC Theater in Century City, California, are part of a façade system that maximizes transparency, enabling passers-by to see into the entire inner space of the theater. The frameless look of the glass is enhanced by the use of low iron glass and ultra-clear ionoplast interlayer. Glass fins in Hong Kong’s Causeway Bay Apple Store are 15.5 meters. With glass elements that are this large and slender, buckling is a serious design consideration. The resistance to buckling is governed by the composite behavior of the laminated glass which is directly affected by the stiffness of the interlayer. In this case the stiffness of ionoplast makes this design possible. In addition, the glass fins incorporate fully laminated inserts that attach the fins to the façade panels with no mechanical fixings. Ionoplast interlayer is critical when laminating these inserts.

![Photo 1](https://example.com/photo1.jpg)

**Photo 1.** AMC Theater, Century City, CA  
(Photo: Courtesy of W&W Glass)  
Architect: STK Architecture, Inc.  
System: Pilkington Planar™/SentryGlas®

Design Standards

The standard most often cited as a reference for glass fin design is the Australian standard AS 1288 Glass in Buildings—Selection and Installation. The purpose of Appendix C is to ensure that buckling will not occur when subjected to design loads. Sub-sections provide formulas for calculating the critical elastic value for beams with and without intermediate buckling restraints, and those which are continuously restrained against lateral displacement. According to AS 1288, the ultimate limit state design moment for a particular structural situation is not to exceed the critical elastic buckling moment ($M_{CR}$) divided by a safety factor of 1.14.

Note that the analysis is purely for monolithic glass and does not treat laminated glass. Designers can use AS1288 and consider only one ply of glass in the laminate for calculation purposes. This leads to significant over design of laminated glass fins, especially when using ionoplast interlayers where the stiff interlayer imparts efficient structural coupling of the component glass. Alternatively, finite element methods may be used for first principles approach to fin stability and glass stress analysis.
Conclusion
Ionoplast interlayer properties offer flexural, deflection, and high temperature benefits over PVB interlayers. Glass fins made with laminated glass improve post-breakage safety over monolithic glass fins. There are differences related to edge stability, sealant compatibility, and long term weathering of laminate interlayers. From a structural design point of view, ionoplast interlayers expand glass fin design, minimizing glass profiles and allowing for larger glass. The examples of interior and exterior laminated glass fin projects are numerous. Some supply structural or energy performance, while others are strictly decorative in nature. All require engineering and can benefit from the physical properties of ionoplast interlayer.

Citations
Coupled High-Strength Window and Mullion Model Validation

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Abstract
Glazing in storefront and curtainwall configurations are increasingly used in areas subjected to blast load. Current design approaches typically use single degree of freedom (SDOF) methods to analyse the performance of both the window glazing and mullions. The flexural resistance and mass of each component must be identified to solve the SDOF representation. Then, the resistance curve is calculated based on span, support conditions, cross sectional stiffness, assumed deformed shape, and a failure criterion. This paper addresses the latter two critical parameters.

Dynamic verification of deformed shape is difficult to assess through testing and has historically been calculated through analytical and numerical methods. However, new measurement methods provide high resolution, high speed deformation measurements through the use of Digital Image Correlation, which is a stereoscopic camera setup capable of measuring three dimensional deflections of both the window glazing and mullions simultaneously. This allows analysis of deformed shape and the interaction between the glazing and mullions. The failure point for the resistance curve was determined by modifying the Glass Failure Prediction Model (basis for ASTM E1300) to handle high-strength glass. Together these models were used to validate SDOF and finite element models used in industry for storefronts comprised of high-strength glass.

1. Introduction
Protection Engineering Consultants (PEC) was engaged by the Air Force Research Laboratory (AFRL) to evaluate the performance of window systems consisting of PPG’s Herculite® XP glass installed in commercial grade frames and storefront systems such that a fast running model could be developed to be used as a design tool enabling engineers to specify Herculite® XP glass. Herculite® XP glass is a high strength glass technology developed by PPG Industries with a residual stress about twice that of commercially produced fully tempered (FT) glass. The research program included quasi-static tests of Herculite® XP glass at PEC, shock tube tests of punched windows (insulating glass units (IGUs) with commercial window frames containing Herculite® XP glass) at ABS Consulting, and two full-scale blast tests at AFRL on IGUs containing Herculite® XP glass in punched window and storefront configurations using typical commercial window frames and storefront systems [1].

This paper presents developments in the application of the failure prediction model based on experimental observations of deformed shape and glass fracture.

2. Glass Failure Criterion History, Improvement and Implementation
The AFRL test program was conceived to validate a model capable of predicting glass failure for both static and dynamic loads. The Glass Failure Prediction Model (GFPM) developed by Beason and Morgan [2] was chosen for its incorporation of load rate, empirical flaw probability distribution (validated), and because it is the basis for the industry standard ASTM E1300 design methodology [3,4]. However, the GFPM was originally developed to only accommodate annealed (AN) glass and required modifications to address the increased strength of Herculite® XP glass.

To summarize the basic premise, the GFPM uses a finite difference model after Vallabahn and Wang [5] to correlate the lateral pressure on a given piece of glass to its stress distribution. The stress is then modified to account for load duration and biaxiality, which is referenced as the equivalent stress. The equivalent stress is incorporated into a Weibull distribution where empirical flaw parameters \(m, k\) define the shape of the Weibull distribution and relate equivalent stress to the probability of failure. Two methods of GFPM modifications are presented below followed by a description of the test program and data used for validation.

2.1 SBEDS-W GFPM Methodology
SBEDS-W (Single degree of freedom Blast Effects Design Spreadsheet for Windows) [6] uses the GFPM to predict glass failure for SDOF analysis. Specifically, SBEDS-W uses the method presented in ASTM E1300 Appendix X3. Use of the stress distribution factor, \(J\), eliminates the need to explicitly map the relationship between lateral load and stress in the glass. However, the stress distribution factor is based on testing of AN glass only. To accommodate the increased strength of Herculite® XP glass, a strength
multiplier was added to the model which has a similar effect as altering the \( k \) parameter of the Weibull distribution found in the GFPM. Due to this modification, the \( k \) parameter is fixed at a value of 2.86x10^{-53} in SBEDS-W. Therefore, the \( m \) parameter is the only variable used to calibrate differing strengths of glass (in addition to the embedded strength factor). This parameter was established through both static and dynamic testing.

### 2.2 An Extended GFPM Method

To identify the GFPM flaw parameters for Herculite® XP glass, PEC used an implicit FEA analysis by LS-DYNA to map stress to lateral load on the glass. This supplants the original finite difference model found in the GFPM, but accomplishes the same task. Results were validated for AN glass using static test data to verify model accuracy. Additionally, the deflection data from this model verified the polynomial method for calculating deflection of the midpoint presented in ASTM E1300 Appendix X2. This approach in modifying the GFPM differs from the approach using the GFPM implementation in SBEDS-W, but both yield conservative results when compared to blast test data.

### 2.3 Modified GFPM Model Comparison

Figures 1 and 2 show the cumulative Weibull distribution (failure probability) using both the original and adjusted set of flaw parameters plotted against the lateral pressure on the glass. Both models of the modified GFPM are shown for comparison (SBEDS-W and RCSS).

The SBEDS-W model represents the approach used by PEC over the course of this project and uses an \( m \) value of 6.55 while \( k \) is treated as a constant \((k=2.86x10^{-53} \text{ N}^{-7} \text{m}^{12})\). The RCSS version was run with both original flaw parameters \((m=7, k=2.86x10^{-53} \text{ N}^{-7} \text{m}^{12})\) and adjusted values \((m=3, k=1.56x10^{-23} \text{ N}^{-3} \text{m}^{4})\). To adjust the Weibull distribution parameters, several pairs of flaw parameters were plotted against test data until the cumulative distribution encompassed most test values (minimizing the number of test values in the tails of the distribution curve). This adjustment proved to be robust across multiple sizes, thicknesses, and load durations. Also, notice that that SBEDS-W model is consistently conservative and tuned for better correlation on dynamic test results (compared to the quasi-static tests).

The resistance of the glass was not directly measured in dynamic testing (shock tube and blast testing) as material resistances are extremely difficult to measure directly when combined with inertial resistances. Resistance was thus inferred from measured deflection and known mass distribution based on deformed shape. The deflection was measured over time through the use of a laser gauge and the time of failure was determined from high speed video. The resistance curve relates the deflection to the lateral pressure and the time of failure was used to identify the maximum deflection and subsequent pressure (resistance) on the glass.

![Figure 1. Dynamic Test Validation (152.4cm x 76.2cm x 5.6mm Herculite® XP glass)](image-url)
Figures 1 and 2 show good results from both models based on conservative predictions from the probability distribution. The RCSS GFPM has better handling of load duration than the SBEDS-W GFPM as evidenced by a better probability envelope for both static and dynamic testing. However, SBEDS-W is only used for dynamic events and thus the embedded GFPM method is specifically calibrated for such events and performs well based on test results plotted against the probability distribution. For longer duration loads, the SBEDS-W methodology will be conservative.

3. Testing and Data Collection

3.1 Shock Tube Testing.

Shock tube testing provided an abundance of data with regard to deformed shape, crack propagation, glass deflection at failure, and polyvinyl butyral (PVB) bite considerations. Deflection of the glazing was measured via laser gages. High speed cameras were used to capture crack propagation, which was used to assess glass break timing and to correlate displacement at time of failure. This was used to improve the predictive capabilities of the GFPM found in SBEDS-W. Additionally, stereo cameras were set-up to capture high speed video for use with DIC software to analyse the deformed shape of the glazing, which is further discussed in section 4.

The initial monolithic glass tests were performed to investigate rate effects included in the GFPM model. Layups tested are summarized in Table 1. Shock tube test results and predictions using an $m$ of 6.4 in SBEDS-W are summarized in Table 2. SBEDS-W predicted slightly higher deflections and resistances to first crack than observed in the tests. Additionally, the break point of glass was predicted correctly 57% of the time based on flaw parameters determined from static testing. Using the dynamic test data, $m$ was adjusted to 6.55 to account for these differences which were most likely due to rate effects and assumed deformed shape. The effect of inertia is seen in Figure 3 where the observed test data initially lags behind the idealized window response calculated by SDOF analysis in SBEDS-W. This inertial effect is discussed further in section 4.

Table 1. Shock Tube Tests Glass Layup Types

<table>
<thead>
<tr>
<th>Glass Layup Type</th>
<th>No. of Samples</th>
<th>Nominal Thickness (in)</th>
<th>Frame Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Outer Lite</td>
<td>Air Gap</td>
</tr>
<tr>
<td>1</td>
<td>4</td>
<td>3/16</td>
<td>1/2</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>1/4</td>
<td>1/2</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>1/4</td>
<td>1/2</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>3/16</td>
<td>1/2</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>1/8</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>5/32</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>3/16</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1</td>
<td>1/4</td>
<td>-</td>
</tr>
</tbody>
</table>

* laminates composed of 2 lites of glass
In addition to the monolithic glass tests, several laminated IGU layups were tested. The shock tube pressure capacity was the limiting factor on the thicker glass layups (Type 2 and 3 as shown in Table 1) as higher pressures were needed to break the glass without subsequent over loading of the PVB. Higher impulses with lower pressures could be achieved to break the glass, but this resulted in a lack of control in the testing and caused PVB failure and catastrophic failure of the system, immediately after glass break occurred. Several successful and controlled tests were conducted, however. Table 3 shows the inner lite test results and the corresponding SBEDS-W predictions using an $m$ of 6.4. On average, SBEDS-W predictions were 3% lower than the measured deflections of the inner lite when the glass did not break. However, the GFPM predicted no failure for each of the tests where the glass failed, suggesting that improvements could be made. The test data suggested that an adjusted value of $m$ of 6.55 would account for these differences and provide better predictions for subsequent blast tests.

![Graph showing deflection comparison](image)

Table 3. Shock Tube Results: Laminated IGU Comparison

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Window Type</th>
<th>Glass Break Time (ms)</th>
<th>Max. Defl. (in)</th>
<th>Glass Break Time (ms)</th>
<th>Max. Defl. (in)</th>
<th>SBEDS-W Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>1</td>
<td>6.1 ± 0.15</td>
<td>2.67</td>
<td>no break</td>
<td>2.77</td>
<td>3.7%</td>
</tr>
<tr>
<td>10</td>
<td>1</td>
<td>7.2 ± 0.15</td>
<td>2.40</td>
<td>no break</td>
<td>2.5</td>
<td>4.2%</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>no break</td>
<td>2.37</td>
<td>no break</td>
<td>2.23</td>
<td>-5.9%</td>
</tr>
<tr>
<td>12</td>
<td>1</td>
<td>no break</td>
<td>2.55</td>
<td>no break</td>
<td>2.42</td>
<td>-5.1%</td>
</tr>
<tr>
<td>13</td>
<td>1</td>
<td>6.2 ± 0.15</td>
<td>2.44</td>
<td>no break</td>
<td>2.76</td>
<td>13.1%</td>
</tr>
<tr>
<td>14</td>
<td>3</td>
<td>no break</td>
<td>2.51</td>
<td>no break</td>
<td>2.45</td>
<td>-2.4%</td>
</tr>
<tr>
<td>15</td>
<td>3</td>
<td>&lt;6.7 ± 0.5</td>
<td>N/M</td>
<td>no break</td>
<td>2.9</td>
<td>N/M</td>
</tr>
<tr>
<td>19</td>
<td>2</td>
<td>no break</td>
<td>2.58</td>
<td>no break</td>
<td>2.58</td>
<td>0.0%</td>
</tr>
<tr>
<td>20</td>
<td>2</td>
<td>no break</td>
<td>2.60</td>
<td>no break</td>
<td>2.58</td>
<td>-0.8%</td>
</tr>
<tr>
<td>21</td>
<td>2</td>
<td>no break</td>
<td>2.77</td>
<td>no break</td>
<td>2.66</td>
<td>-4.0%</td>
</tr>
</tbody>
</table>

Notes: †High-Speed Video Estimation  
Laser Deflection; DIC Deflection; N/M - not measured

### 3.2 Blast Testing

Two full-scale blast tests were performed on twelve window assemblies (six per test) at the AFRL test facilities located on Tyndall Air Force Base in Panama City, Florida. Test 1 was performed on August 22, 2012 and Test 2 was performed on October 3, 2012 (Figure 4). Both tests were performed to validate the
PEC performed analysis with measured loads and response data to compare results from the models. SDOF analyses were performed using SBEDS-W. The SBEDS-W glass module was calibrated to match results from previously conducted static tests and shock tube tests with model values of $m = 6.55$, $k = 2.86 \times 10^{23} \text{N} \cdot \text{m}^{-12}$, $POF = 500$, and $LF = 1$. The predicted and observed response of each IGU is summarized in Table 4 (note, predictions were made assuming a single window with rigid supports). In all cases, the SBEDS-W glazing response predictions are conservative as was expected given the assumption of rigid supports.

![Figure 4. Blast Test 2 Results](image)

Table 4. Blast Test Comparison

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Bay</th>
<th>Window Type</th>
<th>Layup Type</th>
<th>Glazing Type</th>
<th>Response</th>
<th>Max. Disp. (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Inferred</td>
<td>Predicted1</td>
<td>Measured2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>Storefront</td>
<td>4</td>
<td>no break</td>
<td>fail glass</td>
<td>2.96</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>Storefront</td>
<td>2</td>
<td>no break</td>
<td>fail glass</td>
<td>3.16</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>Punched</td>
<td>1</td>
<td>break3,4</td>
<td>break3</td>
<td>7.9</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>Storefront</td>
<td>1</td>
<td>no break</td>
<td>break3</td>
<td>3.46</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>Punched</td>
<td>4</td>
<td>fail glass</td>
<td>fail glass</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>Punched</td>
<td>4</td>
<td>fail glass</td>
<td>fail glass</td>
<td>-</td>
</tr>
</tbody>
</table>

1 predictions made with SBEDS-W using $m = 6.55$
2 measured data is from laser gauges prior to rigid body motion of the frame
3 outer lite break, inner lite not break
4 PVB activated and stretched

4. Data Analysis of Deformed Shape

4.1 Digital Image Correlation

Response of the glass and mullions was measured using the 3D DIC method. DIC can make thousands of measurements over the entire visible area of the system thereby providing a full surface representation of deformation in time than is possible and/or practical with traditional deflection measurement approaches. This measurement technique uniquely facilitates detailed analysis of the deformed shape of the glazing.
and mullions and their interaction. Deformed shape is typically assumed to remain parabolic for glazing and mullions over the full history of response. In reality, deformed shape changes in time, significantly altering assumptions of inertial resistance in the predictive models. DIC can also be used to further develop multi degree of freedom (MDOF) or finite element analysis (FEA) models for coupled glazing and mullion system response that incorporate information learned from the deformed shape analysis.

2D and 3D DIC has been used in a number of industries for at least the past 10 years mainly for the measurement and depiction of strain fields as they develop in material specimens or structural components undergoing static testing. The accuracy and reliability of 3D DIC measurements are dependent solely on the quality of the images captured by the stereoscopically mounted cameras. With the recent development of reasonably priced, high speed, high resolution digital cameras (2-4M pixels) over the past 3-5 years, the number of potential applications of this technology has also grown to include dynamic testing. AFRL has since developed specialized implementation techniques that now allow for accurate and reliable 3D DIC measurements in laboratory and full scale air blast environments.

This data from the shock tube and blast tests allowed PEC to verify the deformed shape of the window during dynamic response, analyse strain (and stress) concentrations for FEA validation, and monitor frame movement during the window response. The deformed shape of the glazing and mullions is used for validation of FEA and can be used to determine the load-mass factors in SDOF analysis. In the shock tube tests, only the deflection of the glazing was measured; therefore the deflection of the mullions can only be inferred based on extrapolation from glazing deflection. However, in the blast tests, the mullion response was measured and can be used to analyse the interaction between the glazing and mullions. The coupled effects of the interaction between the mullions and the glazing during dynamic response are discussed further in Alberson et al (2013).

4.2 Glazing Deformed Shape

The deformed shape of the glazing observed from the DIC during the shock tube testing shows that a parabolic deformed shape occurs after inertial effects and a flat plate type of response have been overcome early in the response as shown in Figure 5. Each line represents the deformed shape at a single point in time for the horizontal cross section of the glazing at an interval of 0.153ms. The middle section of the glass is not stressed initially and responds more as a rigid body mass than a plate in flexure. However, the stress incrementally works towards the centre of the window until all glass is contributing to resistance of the load through bending. At this point in time the glazing behaves according to plate theory and the deformed shape becomes roughly parabolic. This is the assumed deformed shape for the load-mass factors associated with SDOF calculations.

![Figure 5. (left) DIC Deflection Contours overlaid on the High-Speed Video and (right) Vertical Centerline Deflection History up to Laminated Inner Lite Failure.](image)

For the size and strength of windows tested in this program, the glazing is capable of withstanding the load long enough to transition into large displacement plate response, which explains the good pre-test predictions from SDOF analysis. With this in mind, the analysis was able to accurately predict the response of the glazing based on plate theory and the failure criteria specified through the modified GFPM. However, for larger or different aspect ratio windows or for different strength glass this may not be true. More work is needed to investigate this phenomena; one possible path forward is to look at the use of a
stress based implementation of the GFPM in FEA rather than the deflection based implementation used in ASTM E1300.

After the glass failed, the DIC data continued to define the response of the glazing through the PVB response phase (Figure 6). Notice the larger deflection of the top and bottom (left and right of the plot) of the glazing compared to the centre of the glazing. The material in the top and bottom of the window is moving faster than the material at the centre of the glass. This was also seen on tests with monolithic lites where the glass debris was monitored and tracked. Regardless of whether the glazing is monolithic or laminated, the tests illustrated that the material that fractures first has the highest velocity after fracture.

Figure 6. Shock Tube Test 13 Vertical Centerline Deflection History – Laminate.

This could be due to energy release from glass fracture or elastic rebound from the unfractured glass. The glass first cracks in the corners, where the stress is the highest (discussed further in the FEA validation section). As the glass fractures, the stored energy in the glass (due to bending and tempering) is released starting in the corners. The effects of the fracture in the corners are two-fold; the energy release propels the fractured glass and the unfractured glass as the centre begins to relieve the bending stress by returning to a flat plate. This all takes place over the course of ~1ms, but this appears to be enough time for the centre of the window to act as an anchor while the edges (where the cracks initiated) accelerate. If this is true, it indicates that the stress relief runs just ahead of the crack propagation. Further FEA and test data are needed to validate this assessment of the observed test data.

If the glazing is laminated, the glass will accelerate until the PVB forms a tension membrane to further resist the load. Again, the deformed shape of the PVB in tension membrane does not occur immediately at the time of glass fracture, but forms gradually. It starts at the edges and moves towards the centre similar to the formation of the deformed shape during the glass dominated response phase.

By differentiating the DIC data, the velocity profile of the glass debris can be analysed. This is useful, along with debris size, in predicting shard fly-out characteristics, which ultimately correspond to injury potential. Coupled with debris size and mass distribution data from the debris fly-out analysis, this data was used to further calibrate debris fly-out models and to link the results to injury potential.

4.3 FEA Validation through Strain Analysis

The immense amount of data on the deflected shape of the glazing allows the slope of the deflected shape and the glass strains to be calculated and compared to the simulation. Figure 8 and Figure 9 show a comparison between DIC and FEA of the deflection and 1st principal stress, respectively. The stress calculation was based on Hooke’s law assumptions and is thus directly proportional to the measured strain.

The fringes shown in Figure 8 are for the same point in time (at maximum deflection). Notice the good correlation on the magnitude of deflection and contour shape in Figure 8 and the stress concentrations in the corners of the glazing in Figure 9. Also, notice the difference in the amount of stress shown in the middle of the glazing. FEA provides the complete surface and through thickness theoretical stress state of the elements in this region which can be compared to the stress state calculated from DIC deflection measurements at the surface of the glass. The measurements are manipulated into surface strains by
calculating the change in distance between the points over time. The strain to stress transform is straightforward for pure bending or pure tension situations. However, as the boundary conditions on the glazing start to produce tension through the cross section, and the assumptions of pure bending begin to add the effects of tension membrane, the strain distribution is harder to identify. To estimate the strain distribution, the curvature (2nd derivative of the deflection profile) was used to attempt to quantify local bending in the vertical and horizontal direction. This method shows promise, but more work is needed to further investigate the capability of measuring the strain distribution through the thickness of the glazing and accurately calculate the stress at any given point.

![Figure 8. Deflection Comparison of (left) DIC and (right) FEA.](image)

![Figure 9. 1st Principal Stress Comparison at Maximum Deflection of (left) DIC and (right) FEA.](image)

5. Conclusions
The test program provided sufficient data to evaluate a resistance function for IGUs containing Herculite® XP glass for use in a SDOF analysis program. Comparisons with test data illustrate that the model can conservatively predict the performance of IGUs containing Herculite® XP glass subjected to shock loads.

Shock tube and blast testing showed good correlation with SDOF predictions made with SBEDS-W based on consistent and conservative glazing failure predictions. Additionally, the resistance curve generation based on the polynomial method found in Appendix X2 in ASTM E1300 was verified with the static test results.

Deformed shape assumptions for the glazing and the mullions can be measured in dynamic load scenarios to capture the deformed shape of the system and each component individually. The deformed shape can be used to identify the mechanics of the material during response, and can allow calculation of strain and stress distribution during elastic and plastic response, and material failure. The deformed shape of the glass is consistent with large deformation plate theory and exhibits a parabolic shape soon after load is applied, and more importantly, during the time of fracture. Therefore, the load-mass factors used to idealize the deformed shape of the glazing for SDOF analysis appear to provide accurate and conservative results for the high strength glass tested in this project.

Acknowledgements
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LLC provided the glazing and mullions, respectively. Shock tube and blast testing was performed by ABS Consulting and AFRL, respectively.

References
Optimized Secondary Seal of Insulating Glass Units for Structural Sealant Glazing Application

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Abstract
New façade structures are more and more demanding. Ensuring a maximum of transparency and lightness as well as respecting the architectural identity it is rather important to use any opportunity of efficient products and existing structural capacity as well as an effective value engineering approach. A coordinated design phase improves the appearance of a façade but also the complexity in production and an economical realization.

For curtain walling facades and insulating glass units the freedom in design and the level of transparency is usually limited by the capacity of structural sealant glazing joints or the secondary seal. Novel high-strength silicones provide new potential for façade applications and optimized width of edge seal. Not only the fact that a lean silicone joint design saves silicone, but also the improvement of load capacity for existing joint sections by using another adhesive are great benefits for increasing feasibility and acceptance of structurally bonded façade units.

The entire interaction of innovative products and appropriate design methods is demonstrated on the example of Hudson Yards – Tower C in NYC.

Keywords:  insulating glass, secondary seal, climatic loads, load sharing, high-strength silicone

1 Introduction
In today’s transparent façade structures use of insulating glass is a standard application limiting loss of energy at colder conditions and protecting the internal area from overheating at warmer conditions. Due to its functionality, members of the IG unit are affected by different external and internal impacts, especially to the edge seal. If those impacts were not considered for the design of the edge sealing system the durability of the IG unit could be affected and fogging of the enclosed space would result. For IG units applied in Structural Sealant Glazing elements any underestimation of load reactions affecting the secondary seal limits not just the serviceability but causes a safety risk, too.

Preventing any risk it is important to look to the details and to take into account the relevant conditions. [1] and [4] point to the fact the load sharing between the lites of a glass unit has to be considered and [4] also highlights that climatic
effects shall be taken into account, especially for smaller units and non-rectangular shapes. Finally, this paper shows how to determine the relevant influences onto the edge seal of an IG unit and how to optimize the necessary secondary seal width by using more detailed calculation approaches and higher performing materials.

2 Dual-Seal system

Insulating glass units used in Structural Sealant Glazing applications are required to be produced with dual-sealed edge sealing systems. Due to different characters of the used materials a primary and a secondary sealing level are differentiated.

Main parts of the primary sealing level are the spacer, which keeps the glasses at a specific distance, and the primary sealant itself, which closes the small gaps between glasses and spacer. The spacer is a rigid metal or plastic profile with a hollow shape, slightly perforated to the inner cavity of the IG unit. The desiccant is installed into the hollow shape where residual water, infiltrating moisture and solvent vapor can be absorbed, immediately. Due to its high level of moisture vapor migration resistance Polyisobutylene-based materials are very suitable for primary sealing. The combination of a rigid spacer profile and a primary sealant is the main barrier against moisture vapor penetration and loss of inert gas.

The structural function of the edge seal is completely taken by the secondary seal, which is not only responsible to transfer the applied loads but also to minimize any mechanical impact to the primary seal and to prevent walking or displacement of the spacer into the vision area. In Structural Sealant Glazing the secondary seal is a structural joint, too. Issues of adhesion onto different substrates, compatibility with adjacent materials and a proper design are mandatory to be solved by the IGU fabricator, the sealant supplier and the design professional avoiding any failure of the IG unit during service life.

![Typical edge seal configuration](image)

***Figure 1.*** Typical edge seal configuration (© Sika).

Referring to the expected service conditions and necessary life expectancy of IG units in Structural Sealant Glazing, use of silicone is required for the secondary seal. Silicone adhesives developed for SSG und IG applications guarantee the
best resistance in terms of weathering impacts like exposure to water, UV and extreme temperatures. Mechanical properties of a silicone adhesive remain rather unchanged in the range of temperatures expected for façade applications (between -40°C (-40°F) and +80°C (+175°F)).

3 Design approach

Usually rectangular and flat IG units are used for Curtain Walling. Calculation of the minimum width of the secondary seal can be determined based on some simplified formulas. For lateral tensile loading (1) can be used. Referring to (1) $C_t$ is the required width of the secondary seal which should be minimum 6mm. $W$ is the relevant width of the glass unit which used to be the length of the shorter glass edge if the glass is 4-sided structurally bonded. $F_t$ is the allowable tensile stress which is limited to 138kPa (20psi) according to [1]. According to [4] permissible design values are determined individually considering the existing product properties. $P_1$ is the value of short-term and uniformly distributed loads affecting the secondary seal. Even if the calculation approach is simplified estimation of the proportional load affecting the outer lite and the edge seal is more complex and can be followed in 3.1 and 3.2.

$$C_t = \frac{P_1 \times W}{2 \times F_t}.$$  \hspace{1cm} (1)

In case of unsupported IG units the outer lite permanently applies dead-load shear stress on the edge seal. Preventing a failure of the primary seal due to significant downward movement of the unsupported outer lite, [1] requires a conservatively limitation of allowable dead-load shear stress $F_s$ to 7kPa (1psi). Further values need for determining the required width of the secondary seal $C_s$ are the weight per unit area $M$, the units area $A$ itself and the length of the edge seal perimeter $L$. If both $C_t$ and $C_s$ gave significant values, a combination of load impacts would be advisable.

$$C_s = \frac{M \times A}{L \times F_s}.$$  \hspace{1cm} (2)

![Figure 2. Sharing of external loads and acting of internal loads according to [3].](image)
3.1 Load sharing of external loads

Lites of an IG unit are not only linearly bonded around the perimeter. They are also connected by the air or gas volume enclosed into the hermetically sealed cavity. This coupling effect causes load sharing between the connected lites. Common SSG guidelines such as [1] and [4] mention this effect but recommend a very general approach of sharing loads equally if the thickness of the inner lite is equal or bigger than the outer lite or charging the total load to the outer lite if the thickness of the inner one is smaller. Even if this approach is easy to use and conservative, the actual behavior and potential of the IG unit is underestimated.

Another simplified approach widely-used in engineering practice is determining the correct ratio of the glass thicknesses. If \( d_1 \) is the thickness of the outer lite and \( d_2 \) is the thickness of the inner lite, \( \delta_1 \) gives the ratio of uniformly distributed loading applied to the outer lite. That means \( P_1 \) is the proportional load affecting the required width of the secondary seal mentioned in (1).

\[
\delta_1 = \frac{d_1^3}{d_1^3 \times d_2^3}; \quad P_1 = \delta_1 \times P_{\text{total}}. \tag{3}
\]

An approach which pursues a very accurate determination of load sharing respecting additionally the shape and the dimension of the IG unit as well as the direction of the relevant loading is stated in [3] and [5]. Covering all the relevant influences Prof. Feldmeier introduced an insulating glass factor \( \varphi \) which depends on the length of the shorter glass edge \( a \) and the characteristic length \( a^* \). \( a^* \) is representing characteristic properties of the IG unit like ratio between width and height \( B_v \), dimension of the hermetically sealed cavity \( d_{\text{cavity}} \) and stiffness of the two lites (outer lite \( d_1 \), inner lite \( d_2 \)).

\[
\varphi = \frac{1}{1 + (a/a^*)^4}; \quad a^* = \sqrt[4]{\frac{E \times d_1^3 \times d_2^3 \times d_{\text{cavity}}}{p_B \times (d_1^3 + d_2^3) \times B_v}}. \tag{4}
\]

<table>
<thead>
<tr>
<th>( a / b )</th>
<th>1.0</th>
<th>0.8</th>
<th>0.6</th>
<th>0.4</th>
<th>0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>( B_v )</td>
<td>0.0194</td>
<td>0.0288</td>
<td>0.0421</td>
<td>0.0587</td>
<td>0.0767</td>
</tr>
</tbody>
</table>

\( a \) – length of the shorter glass edge, \( b \) – length of the longer glass edge

\[
\delta_1 = \frac{d_1^3}{d_1^3 \times d_2^3}; \quad P_1 = (1 - \varphi) \times \delta_1 \times P_{\text{total}}. \tag{5}
\]
If $P_1$ is the proportional load affecting the required width of the secondary seal mentioned in (1) and the applied load is acting from inside the building like a wind suction load (interior pressure $>\$ local external pressure), $P_1$ can be determined according to (5). In Figure 3 and Figure 4 the calculated proportional load acting to the outer lite depending on the method of calculation, dimension of the glass unit and the glass configuration is diagrammed. The figures show the potential of optimizing the width of the secondary seal by checking the real properties compared to the conservative approach of the standards or by turning the glass composition arranging the stiffer lite on the inner position.

![Figure 3](image3.png)

**Figure 3.** Proportional load acting to the outer lite and the edge seal in a glass configuration of glass / cavity / glass: 10 / 12 / 8 [mm] (© Sika).

![Figure 4](image4.png)

**Figure 4.** Proportional load acting to the outer lite and the edge seal in a glass configuration of glass / cavity / glass: 8 / 12 / 10 [mm] (© Sika).

### 3.2 Climatic effects

Climatic effects imply internal load effects caused by the expansion of the air or gas volume enclosed into the hermetically sealed cavity. The expansion of the enclosed volume is confined by the inner and the outer lite. Due to the fact that the lites are not absolutely rigid, the actual state is balanced between an isochoric and an isobaric limit state. The individual loading depends on the external conditions and the geometrical properties. Geometrical properties are the dimension of the cavity, the dimension of the IG unit and the thickness of the...
inner and the outer lite. External conditions are variation of atmospheric pressure $\Delta p_{\text{atm}}$, variation of temperature of the enclosed gas $\Delta T$ and variation of elevation $\Delta H$ which can result in an increasing pressure in the cavity. Variations acting on the glass and the edge seal are also related to changed conditions between production of the IGU just as the edge seal and conditions after installation or during service life. The relevant isochoric limit state $p_0$ can be determined according to (6). The geometrical properties are imbedded into the insulating glass factor $\varphi$ determined in (4). The product of isochoric pressure and insulating glass factor in (7) results the internal load $P_{\text{climatic}}$ acting as maximum climatic load effect on the edge seal.

$$p_0 = (\Delta T \times 0.34 \text{kPa/K}) \times \Delta p_{\text{atm}} \times (\Delta H \times 0.012 \text{kPa/m}).$$  \hfill (6)

$$P_{\text{climatic}} = \varphi \times p_0.$$  \hfill (7)

Figure 5 shows how the required width of the secondary seal is affected by wind loads and climatic load effects. While the bigger IG units are mainly affected by wind loads, the impact of climatic loads becomes more and more decisive for smaller units. In worst case climatic load effects onto the smaller IG units are much higher than wind load impacts onto the bigger units. That’s the evidence that not just the biggest IG units are relevant for a proper joint design. Taking into account climatic load effects and considering also smaller IG units is significantly important for a durable edge sealing system and secondary seal which fulfills the demands on safety and life expectancy.

Figure 5. Required width of secondary seal of wind load, climatic load and combined loading (© Sika).

4 High-performance insulating glass sealants
Advanced calculation methods and design tools help realizing and optimizing sophisticated façade details as well as dimensioning the structural sealant joints for challenging loading. But also demands on transparency, cost-competitive and fast production just as sustainable use of material are increasing at the same time as more and more effort in quality, durability, gas tightness and a long-lasting
energy-efficient performance are required for insulating glass units. To improve the edge sealing system of IG units used in SSG applications Sika AG introduced a new series of high-performance sealants. One of them, specially developed for the secondary seal of IGUs, provides an outstanding performance in terms of higher mechanical strength which is useful to reduce the required width of the secondary seal without reducing the required safety level. Furthermore it is characterized by a higher modulus which limits movements and stress applied to the primary seal. The improved material properties in comparison with traditional standard materials are shown in Figure 6. Benefits for the IGU fabricator, the façade designer and the building user are explained in 4.1 and 4.2.

Figure 6. Sikasil® IG-25 HM Plus: Stress and elongation as well as permissible design values determined in accordance with [4] (© Sika).

4.1 Improved design strength
The improved design stress diagrammed in Figure 6 is result of a higher initial performance of the silicone adhesive. Equal to the common standard sealants the allowable tensile stress is based on a safety factor of minimum 6. A higher design value offers several benefits. First of all the available load capacity of the secondary seal can be improved for the preferred minimum standard width of 6mm.

In Figure 7 the example of a triple-glazed unit made of a configuration of glass / cavity / glass / cavity / glass: 8 / 10 / 4 / 10 / 8 [mm] was sealed with a minimum secondary seal width of 6mm. This IGU was applied to an isochoric pressure $p_0$ of 12kPa and a wind load of 1.5kPa. The left diagram shows that the range of glass dimensions which could be applied with a standard sealant without overstressing the secondary seal is strongly limited. Increasing the secondary seal width for a number of IG units makes the line production for a façade project quite complicated. In most cases the decision of the IGU fabricator is producing all the IG units equal with the maximum required width what increases costs and
decreases the speed of production. In the right diagram the same configuration was calculated but using the allowable stress value of Sikasil® IG-25 HM Plus. The higher allowable stress helps to cover more of the smaller IGUs mainly affected by climatic loads and it also opens the range for more of the bigger IGUs mainly affected by wind load impacts.

**Figure 7.** Standard sealant (left) vs. Sikasil® IG-25 HM Plus (right): Configuration of glass / cavity / glass / cavity / glass: 8 / 10 / 4 / 10 / 8 [mm], 6mm secondary seal, $p_0 = 12$ kPa and wind load of 1.5 kPa (© Sika).

Additionally to the improved capacity of existing joints it is possible to reduce the bite of bigger or higher loaded joints by 25 – 30%. While reducing the required width of the structural sealants it would be possible to reduce the visible width of the bonded frame, as well. All-in-all the savings in material led additionally to a slimmer design and more transparency.

**Figure 8.** Standard sealants (left) vs. High-strength sealants (right): Improved mechanical properties help to reduce the silicone joint bite and the visible width of the bonded frame, too (© Sika).
4.2 Protection of the edge seal

[1], 6.5.1 requires a limitation of outward movements caused by lateral loading to 1.6mm to prevent overstressing and failure of the primary seal. For Sikasil® IG-25 HM Plus a modulus of 4.8MPa (H-specimen @ 12.5% elongation) was determined in accordance with [4]. Applying this modulus to the allowable design stress and a maximum dimension of 20mm for the cavity of an IG unit, one would end-up with a joint movement < 0.8mm which is half of the required value. This excellent behavior to limit movements in the edge seal and mechanical applied to the primary seal is used for IG units filled with inert gas, mainly argon. Just the fact that the spacer profile and the primary seal are properly applied and permanently protected by a compatible and strong secondary sealant makes argon-filled IGU in SSG applications feasible without significant gas loss rates.

<table>
<thead>
<tr>
<th>EN 1279-2&amp;3 (Nov. 17, 2010)</th>
<th>Result</th>
<th>Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Moisture penetration</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average moisture penetration index $l_{av}$</td>
<td>4.7%</td>
<td>20%</td>
</tr>
<tr>
<td>Max. individual moisture penetration index $l$</td>
<td>7.1%</td>
<td>25%</td>
</tr>
<tr>
<td><strong>Argon loss rate</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual argon loss rate</td>
<td>0.56% a$^{-1}$</td>
<td>1.00% a$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>0.38% a$^{-1}$</td>
<td></td>
</tr>
</tbody>
</table>

Figure 9. Gas loss rates < 1% a$^{-1}$ were tested for several edge sealing systems using Sikasil® IG-25 HM Plus. Tests were performed by notified bodies (© Sika).

5 Tower C – Hudson Yards, NYC

Summing up the discussion about the opportunities of optimizing the secondary seal of an IGU Tower C @ Hudson Yards in New York City is a great example for using this knowledge and product know-how practically. The final design of the edge sealing system was developed in collaboration between Enclos, AGC Interpane and Sika.
Figure 10. Hudson Yards, NY: Computer animation (© www.skyscrapercity.com).
Figure 11. Type WT01 (left, 4-sided, 1 intermediate transom) and WT02 (right, 4-sided, 2 intermediate transoms) (© Enclos).

Due to the building height certain areas of the façade are exposed to extensive wind loading up to a maximum value of wind suction of -5.794kPa (-121psf). Dimension of the standard units is approx. 1500mm x 4100mm. In some areas the dimensions can extent up to 2650mm width or 4500mm height. For vision glazing an isochoric pressure of $p_0 = 16.6$kPa ($\Delta T_{cavity} \leq 50$K; $\Delta p_{atm} \leq 2.0$kPa; $\Delta H_{altitude} \leq -200$m) was defined by AGC Interpane.

Table 2. Calculation of the required secondary seal – different methods.

<table>
<thead>
<tr>
<th>Method of calculation</th>
<th>Type WT01</th>
<th>Type WT02</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSG bonded transom</td>
<td>2817mm from bottom edge</td>
<td>SSG bonded transoms 711mm and 3518mm from bottom edge</td>
</tr>
<tr>
<td>$1460$mm x $4069$mm</td>
<td>$2292$mm x $4112$mm</td>
<td></td>
</tr>
<tr>
<td>10 / 12 / 8 wind load: -5.794kPa</td>
<td>10 / 12 / 8 wind load: -4.692kPa</td>
<td></td>
</tr>
<tr>
<td>$p_0 = 16.6$kPa</td>
<td>$p_0 = 16.6$kPa</td>
<td></td>
</tr>
<tr>
<td>Standard method [1][4], only 4-sided,</td>
<td>32mm</td>
<td>39mm</td>
</tr>
<tr>
<td>Standard Sealant</td>
<td>21mm</td>
<td>26mm</td>
</tr>
<tr>
<td>-----------------------------------------------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>Feldmeier [3][5], only 4-sided, standard sealant</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sikasil® IG-25 HM Plus</td>
<td>16mm</td>
<td>19mm</td>
</tr>
<tr>
<td>FEA calculation incl. intermediate transoms,</td>
<td>12mm</td>
<td>9mm</td>
</tr>
<tr>
<td>Sikasil® IG-25 HM Plus</td>
<td></td>
<td>applied: 12mm</td>
</tr>
</tbody>
</table>

The inner lite of the IG units is 4-sided structurally bonded and additionally horizontally bonded to one or two intermediate transoms which significantly reduce the out-of-plane deflection of the inner lite. Due to this effect load sharing with the outer lite is strongly reduced what reduces the loading of the secondary seal, as well. If this effect was neglected one would get a very big width of secondary seal. Two examples of type WT01 and WT02 are exemplarily shown in Table 2.

Checking the required width of secondary seal in a geometrical non-linear FEA model considering also the intermediate transoms structurally bonded to the inner lite, a 12mm silicone joint is sufficient to take the remaining loads affecting the outer lite. Comparing the different calculation methods summarized in Table 2 it is amazing to recognize that we can reduce the width of the secondary seal by 60 to 75% just calculating the accurate situation, taking into account the real conditions and use a high-performing IG sealant.
Figure 12. WT02 (4-sided, 2 intermediate transoms), structural joints presented by spring elements (left), displacement behavior inner lite (middle), displacement behavior outer lite (right) (© Sika).

6 Summery
Pointing onto the opportunity to optimize the load sharing between the lites of an IG unit, showing the need of taking into account climatic load effects and presenting a high-performing IG silicone for reducing the width of the secondary seal and movements into the primary seal we could close the argumentation with the example of Hudson Yards – Tower C where all the discussed instruments were useful to find an optimized and save design for the secondary seal. These instructions are base for customized and efficient solutions provided by Sika and implemented by AGC Interpane.

References


Minimizing steel: utilizing glass as structure to achieve transparency and efficiency

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W&W Glass, USA

Abstract
This paper explores various ways to maximize both the transparency and the structural efficiency of feature facades through the use of glass as main or back-up structure. It investigates what designers can do to reduce the overall structure to its minimum through both design and engineering. Examples include glass beams, columns, struts and diaphragms. Also included is a review of a technical paper which provides an explanation of how glass can reduce the size of steel columns, as well as that paper's current role in glass fin design. Analytical examples from completed projects are presented demonstrating these principles.

Keywords: facade design, structural glass, glass fins, cable-nets, steel

1 Introduction
Lightweight and transparent designs are often desired at the entrance or other architecturally important areas of a building. This desire generally competes directly with the need to keep costs down. How then are designers to reconcile these two seemingly opposite design criteria?

When glass is used as structure it can serve to both lighten the look of the facade by adding transparency, and lessen the cost of the structure by reducing the loads on the surrounding elements. Glass can be both the main structure, such as in glass fin walls, or the secondary structure, such as a stabilizing diaphragm for slender steel mullions. In either case it is systems which use glass to its full capabilities rather than just as a fill-in material which are the most transparent and cost competitive.

What follows is an overview of how glass can be used in this manner as well as a look at when it is appropriate to use the various types of systems. As each building is different it is important for the designer to understand the basic principles outlined herein rather than take a prescriptive approach to design.

2 Typical examples of glass as structure

2.1 Glass fins
Glass fins were introduced as a structural system by Pilkington Architectural in the UK over 40 years ago. The basic premise of the structural system is to utilize glass panels as mullions or beams in order to support facade or roof glass. The main benefits of this system are the increased transparency realized by replacing steel structure with glass, as well as the greater dimensional accuracy of the
glass fins as compared to steel. It is also cost competitive with steel, with the price falling between that of a rolled steel structure and one consisting of plate or built-up sections. The cons of the system rest primarily in the required size of the fins. Tempered glass is approximately 1/3rd as stiff and 1/6th as strong as steel, necessitating greater depth as compared to their steel equivalent.

**Figure 1.** Glass Fin Supported Façade – 2000 Avenue of the Stars – Los Angeles, CA ©W&W Glass

Glass fins are most efficiently utilized in façades due to the fact that there is no de-facto restriction on span. Multiple glass panels can be spliced together to create long fins that can span multiple stories. The span is generally limited by buckling, which will be addressed in more detail in Section 4.

The splices of the fins are now typically done with bolts at the front and back edge of the fins as opposed to a horizontal connection. See Figure 2 for an illustration of this. This allows the transfer of moments from one panel to another with a minimal amount of visible structure.
In contrast to façades, glass fins in roofs are generally secondary rather than primary structure unless the spans are such that a single panel can be used. This is due to the fact that glass fin splices tend to creep when held in the horizontal orientation. The principles of the structure are otherwise the same as for a façade.

Figure 3. Glass as secondary roof structure – Orlando International Airport, Orlando, CA ©W&W Glass
3 Atypical examples of glass as structure

3.1 Struts

When trying to use glass in an innovative manner it is helpful to think about applications where concrete might typically be used, as thin concrete shells and glass plates are structurally similar. In fact tempered glass has the advantage of being about twice as stiff and twice as strong as normal weight, normal strength concrete. Concrete has the clear advantage of being able to be poured into different shapes and to great sizes, whereas glass is limited to flat or gently curved shapes of a finite size. So applications where flat concrete of limited size might be used are good candidates for substituting glass.

One such application is the use of glass as a strut. The concept of the strut-and-tie model for concrete was developed in the 80’s as a way to systematize the design of deep beams and other complicated structural forms made of concrete. The key innovation was treating the internal forces of the concrete beam like a truss, with steel reinforcing “ties” taking the tension forces and concrete “struts” taking the compression forces.

![Figure 4. Figure RA.1.3 from ACI318-11 – Description of strut-and-tie model, ©ACI [1]](image-url)
This finds an application in glass structures when the deep beam is instead a hybrid stainless steel and glass truss, with the stainless steel elements acting as the ties and the glass acting as the struts.

Figure 5. Hybrid Glass Truss – 11 Times Square, New York, NY ©Anton Kisselgoff

This system differs from that of a typical glass fin in that the glass is acting as a compression element only, rather than a bending member. This is due to the connections between the glass and stainless steel chords, which are only able to transmit compression.
Figure 6. Hybrid Glass Truss – 11 Times Square, New York, NY ©Michael Dunham

As the load reverses, rather than take tension, a compression strut develops in the opposite direction.

Figure 7. Hybrid Glass Truss – 11 Times Square, New York, NY ©Michael Dunham
3.2 Diaphragms

Like with struts, concrete is often used as a diaphragm to transfer load to other members. With concrete this is often done by utilizing entire floors or walls of buildings. With glass the application is much smaller, but the principles are the same. The glass canopy shown below is utilized not only as a canopy but as a diaphragm which ties the outer chords of the hybrid trusses together in order to reduce their buckling length and therefore make them more slender. The only sign that the canopy is doing this is the rigid connection between the outer chord and the glass, making it a very inconspicuous way to add additional structure.

Figure 8. Hybrid Glass Truss Canopy – 11 Times Square, New York, NY
©Anton Kisselgoff
4 Steel supported façades and efficiency

A discussion about façade transparency wouldn’t be complete without the mention of cablenet walls. Cablenets are in essence a structural system which moves the structure from the visible area to the perimeter, thereby maximizing transparency. The tradeoff for this transparency is increased perimeter structure and increased construction cost. What follows is an investigation into when cablenets make the most sense as compared to a mullion system. This investigation is limited to cablenets which utilize only vertical cables, which is a system that has become more common than the more complicated two way cablenet.

4.1 Mullion accounting

To begin this investigation one first must look at the design of mullions. The mullion size is governed by both deflection and buckling limits. For slender mullions (as are typically used in a façade) the buckling limit is as shown in eqn (2) below. This assumes a solid rectangular cross section (i.e. a plate).

\[
\text{for } \frac{l \cdot d}{t^2} > \frac{1.9 \cdot E}{F_y} : \quad (1)
\]

\[
\frac{M_n}{\Omega} = \frac{F_{cr} \cdot S_x}{\Omega} = \frac{1.9 \cdot E \cdot C_b \cdot S_x}{l \cdot d \cdot t^2 \cdot \Omega} \quad (2)
\]

Where:

- \( M_n \) = Nominal strength of the mullions
- \( \Omega \) = Safety factor = 1.67
- \( E \) = Elastic modulus
- \( S_x \) = Section modulus about the strong axis
- \( C_b \) = Lateral-torsional buckling modification factor, conservatively = 1.0
- \( l \) = Buckling length of mullion
- \( d \) = Depth of mullion
- \( t \) = Thickness of mullion

And for rectangular cross sections, the section modulus is:

\[
S_x = \frac{t \cdot d^2}{6} \quad (3)
\]
Therefore:

\[
\frac{M_n}{\Omega} = \frac{1.9 \cdot E \cdot C_b}{t^2 \cdot \Omega} \cdot \frac{t \cdot d^2}{6} = \frac{E \cdot d \cdot t^3}{5.274 \cdot l}
\]  

(4)

Setting this equal to the applied loading we have:

\[
\frac{E \cdot d \cdot t^3}{5.274 \cdot l} = \frac{w \cdot l^2}{8}
\]

(5)

The deflection limit of a mullion system is somewhat up to owner preference. Curtainwalls are generally limited to a maximum deflection of L/175, but owners may choose to loosen this limit to L/120 for custom steel mullion systems. For the present investigation L/175 will be used. Assuming a uniformly distributed load:

\[
\Delta_{MAX} = \frac{5 \cdot w \cdot l^4}{384 \cdot E \cdot I}
\]

(6)

Where:

\(\Delta_{MAX}\) = Maximum allowable deflection
w = Distributed load
l = Length of mullion span
I = Moment of inertia of mullion about the strong axis

And for rectangular cross sections, the moment of inertia is:

\[
I = \frac{t \cdot d^3}{12}
\]

(7)

Therefore:

\[
\Delta_{MAX} = \frac{5 \cdot w \cdot l^4}{32 \cdot E \cdot t \cdot d^3} = \frac{l}{175}
\]

(8)

If one wishes to have a balanced system in which the deflection limit is reached at the same time as the buckling limit, eqns. (5) and (8) can be solved simultaneously to determine the ideal aspect ratio of the mullion. First eqn. (5) is solved for d:

\[
\frac{E \cdot d \cdot t^3}{5.274 \cdot l} = \frac{w \cdot l^2}{8}
\]

(5)
\[ d = \frac{w \cdot l^3}{1.517 \cdot E \cdot t^3} \]  

(9)

Next eqn. (8) is solved for \( t \):

\[ \frac{5 \cdot w \cdot l^4}{32 \cdot E \cdot t \cdot d^3} = \frac{l}{175} \]  

(8)

\[ t = \frac{27.344 \cdot w \cdot l^3}{E \cdot d^3} \]  

(10)

And substituted in to eqn. (9):

\[ d = \frac{w \cdot l^3}{1.517 \cdot E \cdot \left[ \frac{27.344 \cdot w \cdot l^3}{E \cdot d^3} \right]^3} \]  

(11)

\[ d = \frac{3.64289 \cdot l^{3/4} \cdot w^{1/4}}{E^{1/4}} \]  

(12)

Therefore:

\[ t = \frac{0.565 \cdot l^{3/4} \cdot w^{1/4}}{E^{1/4}} \]  

(13)

And

\[ \frac{d}{t} = \left[ \frac{3.64289 \cdot l^{3/4} \cdot w^{1/4}}{E^{1/4}} \right] = \frac{3.64289}{0.565} = 6.44 \]  

(14)

Therefore for a deflection limit of \( L/175 \), the ideal aspect ratio for the mullion is 6.44. It can be seen that:

\[ d \propto l^{3/4} \]  

(15)

And

\[ t \propto l^{3/4} \]  

(16)
\[ A_{\text{Mullion}} = d \cdot t \]  \hspace{1cm} (17)

Therefore

\[ A_{\text{Mullion}} \propto l^{3/4} \cdot l^{3/4} = l^{1.5} \]  \hspace{1cm} (18)

And

\[ \sum A_{\text{Mullion}} \propto l^{1.5} \]  \hspace{1cm} (19)

When the width of the façade is increased, more mullions are added in a linear fashion, therefore:

\[ \sum A_{\text{Mullion}} \propto B \]  \hspace{1cm} (20)

Where:

\[ B = \text{Total width of the façade} \]

4.2 Cablenet accounting

Because cables derive their (non-axial) load resistance from their geometry there are no competing design criteria as in mullions. The specification of the maximum allowable deflection will determine the maximum cable force. So for example with a deflection limit of L/50:

\[ \Delta_{\text{MAX}} = \frac{l}{50} \]  \hspace{1cm} (21)

\[ T = \frac{w \cdot l^2}{8 \cdot \Delta} = \frac{w \cdot l^2}{8 \cdot \left[ \frac{l}{50} \right]} = \frac{25 \cdot w \cdot l}{4} \]  \hspace{1cm} (22)

\[ A_{\text{Cable}} \propto T \]  \hspace{1cm} (23)

And

\[ T \propto l \]  \hspace{1cm} (24)

Therefore

\[ \sum A_{\text{Cable}} \propto l \]  \hspace{1cm} (25)

When the width of the façade is increased, more cables are added in a linear fashion, therefore:
\[ \sum A_{\text{Cable}} \propto B \quad (26) \]

In order to do a true accounting of the costs of a cablenet one must take into consideration the added cost to the perimeter structure as well. Assuming a one way system and that the base of the structure is essentially fixed to the foundation, this means the cost of a beam which spans the top of the façade opening and resists the cable forces. Like with mullions the spandrel beam can be governed by either deflection or stress. Unfortunately it is not as simple to determine the ideal shape of the I-beam such that it reaches both limiting criteria simultaneously as it is for the rectangular mullion. However there is another approach as shown below.

If the deflection limit is B/240:

\[ \Delta_{\text{MAX}} = \frac{5 \cdot w \cdot B^4}{384 \cdot E \cdot I} = \frac{B}{240} \quad (27) \]

Solving for \( I \):

\[ I = \frac{w \cdot B^3}{9280} \quad (28) \]

The stress limit is:

\[ \frac{M_n}{\Omega} = \frac{F_y \cdot Z_x}{\Omega} = \frac{w \cdot B^2}{8} \quad (29) \]

Solving for \( Z_x \):

\[ Z_x = \frac{w \cdot B^2}{239.5} \quad (30) \]

The rolled steel I-beams available are as follows:
If one looks only at the most efficient cross sections for main axis bending it is possible to fit a curve to the data.
It can be seen from Figures 14 and 15 that for the most efficient sections:

\[ Z_x = W \left( \frac{lb}{ft} \right) \cdot 4.5027 \quad (31) \]

\[ Z_x = W \left( \frac{k}{in} \right) \cdot 54,032.4 \quad (31a) \]

And

\[ I_x = W \left( \frac{lb}{ft} \right) \cdot 79.854 \quad (32) \]
Where:

\[ W = \text{Weight per foot of spandrel beam} \]

Therefore the weight of a beam controlled by stress can be found by equating eqn. (31) and eqn. (30):

\[ W \cdot 54,032.4 = \frac{w \cdot B^2}{239.5} \]  

(33)

\[ W_{z_s} = \frac{w \cdot B^2}{12,940,760} \]  

(34)

And the weight of a beam controlled by deflection can be found by equating eqn. (32) and eqn. (28):

\[ W \cdot 958,248 = \frac{w \cdot B^3}{9280} \]  

(35)

\[ W_i = \frac{w \cdot B^3}{8,892,541,440} \]  

(36)

Therefore when using the most efficient I-beams as spandrels above a cablenet, stress will control for shorter spans and deflection for longer spans. The point above which deflection controls is found by equating eqns. (34) and (36) and solving for B:

\[ \frac{w \cdot B^2}{12,940,760} = \frac{w \cdot B^3}{8,892,541,440} \]  

(37)

\[ B = 687\text{in} = 57.25\text{ft} \]  

(38)

4.3 Mullions vs. Cablenet

Using these equations and some relative costs of material and installation it is possible to compare the relative costs of the two systems for a given height or width.
As can be seen from Figure 16, the mullion system quickly becomes much more efficient due to the exponential cost of the spandrel beam in the cablenet option. There are more efficient ways to span long distances than a simple beam, but what can be taken away from this graph is that one-way cablenets become much less cost competitive as they get wider unless something can be done to economize the structure above the cablenet.

Figure 14. Relative Cost of Systems – Fixed Height

Figure 15. Relative Cost of Systems – Fixed Width
For a given width, cablenets become the better option as the height increases due to the relative cost of large plate mullions increasing faster than that of the cables and spandrel beam. It may be preferable to use a cablenet well before the point of the cost changeover simply due to aesthetic and practical reasons, as the mullions become quite large and difficult to install at large spans.

4.4 Optimizing mullion systems

It can be seen from the previous sections that mullion systems are often times the best option financially. However the standard mullion supported façade can often be quite bulky and cumbersome looking. Indeed the optimum mullion aspect ratio of 6.44 that was found in Section 4.1 is fairly stout. In order to improve this system, one can borrow from glass fin design.

In the Australian glass design code [2] there are given several equations for buckling limits which are dependent on the end restraints and lateral restraints of the beam. What is helpful to the present design situation is that one of the parameters of the equation is the location of the supports relative to the neutral axis of the cross section. This allows one to calculate the buckling resistance of the fin or mullion based on a support of only one edge.

Nethercot and Rockey [3] developed these equations for multiple end restraints. So then rather than the buckling criteria being that as laid out in eqn. (5), instead we have:

\[
M_{CR} = \frac{\left( \frac{\pi}{l} \right)^2 \cdot E \cdot I_y \cdot \left[ \frac{d^2}{12} + y_0^2 \right] + G \cdot J}{1.7 \cdot \left( 2 \cdot y_0 + y_h \right)} = \frac{W \cdot l^2}{8}
\]  

(39)

Where:

- \( M_{CR} \) = Critical elastic buckling moment for a continuously laterally supported beam
- \( y_0 \) = Distance from neutral axis to point of lateral support
- \( y_h \) = Distance from neutral axis to point of load application
- \( G \) = Elastic shear modulus
- \( J \) = Torsional moment of inertia

If the mullion or fin is siliconed to the face glass, then that is the point of lateral support as well as the point of load application. Therefore:

\[
y_0 = y_h = \frac{d}{2}
\]  

(40)

We also know that
\[ I_y = \frac{d \cdot t^2}{12} \]  
(41)

And

\[ J = \frac{d \cdot t^3}{3} \left(1 - 0.63 \cdot \frac{t}{d}\right) \]  
(42)

Plugging eqns. (10), (40), (41), and (42) into eqn. (39), one can numerically solve for \(d\) and \(t\) in order to find a new ideal aspect ratio of 18.5 for solid rectangular steel mullions supported laterally along one edge.

This requires the bracing of the front edge of the mullion by the face glass. In this way one can use the face glass as structure to stabilize and therefore reduce in size the steel mullion. The stabilizing force can be calculated from eqn. C5(2) in the Australian code [2]. This force must be transmitted through the silicone connection between the mullion and face glass, and then through the glass into the jamb and/or head and sill supports. This again is glass acting as a diaphragm.

The result of this silicone bracing is a much more slender profile as well as a 40% reduction in tonnage, as can be seen in Figure 15 below.

![Figure 16. Comparison of mullion sizes](image)

5 Conclusion

Several methods for maximizing transparency of feature façades have been presented. In addition to using glass as the primary structure, designers should consider how it can be used as secondary and back-up structure to increase transparency further. Glass struts and glass diaphragms were presented as good
examples of how this can be achieved. The key in achieving these innovations is first to consider when glass might be appropriate as structure, and then to insure through careful detailing that the glass is utilized to maximize its inherent advantages of high stiffness and compressive strength. Finally a holistic approach to design which considers every step of the load resolution is necessary to realize maximum structural efficiency and transparency.

References
Application & Possibilities of Triple Layer Insulating Glass Units

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Abstract
Due to improved energy saving regulations within Europe the quantity of triple layer insulating glass units will significantly increase within the next years. Actually 55% of the overall insulating glass unit market in Germany for the year 2012 was served with triple glazed units. With a third pane and a second air space it is necessary to look more closely at several special features of this product. Saying “In the past we did it always in the same way without serious failures” does not necessarily work with triple layer insulating glass units. Among others it should be noticed that the stress of the IGU sealing’s will increase especially for panes with very small sizes, that the insulating glass effect is more noticeable than for double layer insulating glass and the possibility of external condensation increases. Also care should be taken about the coating positions and the resulting energy absorptance if there is risk of glass breakage due to thermally induced stresses. The paper is based on the technical bulletin from the Bundesverband Flachglas e.V. (Federal Association for Architectural Glazing) “Code of practice for the use of triple insulating glass units”. This bulletin describes the principle issues which should be considered when working with triple layer insulating glass units. The original paper and other interesting guidelines and bulletins can be ordered at www.bundesverband-flachglas.de

Keywords Energy Saving, Triple Layer Insulating Glass Units, Insulating Glass Effect, Aspect ratio, coatings

1. Introduction
Buildings have a proportion of the total energy consumption in Europe of about 40%. Part of the European energy saving plan is the European Energy Performance of Buildings Directive (EPBD). One consequence of the 2002 updated directive are nearly zero energy houses for new buildings by the latest in 2020. For commercial buildings it has to be implemented by 2019. Part of a building are windows and facades. Due to the modern architecture they have a great portion in a building envelope. The Energy-Saving Ordinance (EnEV) is the German Federal government’s main body of legislation in the quest for an efficient use of energy in new and existing buildings. The EnEV ordinance of 2007 served to implement the EPBD from 2002. The amendment to this ordinance (EnEV) adopted in 2009 tightens the requirement level for energy demand by 30 %. A new one was following at the 1st of May 2014. A number of innovations – including in the field of glass, windows and facades – are required to satisfy these future requirements. The use of triple insulating glass units to a far greater extent than is previously the case will be an important contribution to improving the thermal characteristics of windows and facades. The production of triple insulating glass units in far greater quantities than before has enormous effects on man-
ufacturing technology and on the quality standards which must be met. The considerably increased use of triple insulating glass units in windows and facades means that many aspects have to be considered and taken into account. The object of the “Code of practice for the use of triple insulating glass units” is to address important questions which the manufacturers and processors of triple insulating glass units as well as the window and façade manufacturers are strongly recommended to consider.

2. Triple insulating glass units

2.1 Design of triple insulating glass units

$U_g$-values significantly below 1.0 W/(m²K) are achieved with triple insulating glass units (3IGU). For this purpose, the design of a triple insulating glass unit of this type must include two low-emissivity coatings (Low-E Coatings), minimum one facing each air space. In addition, both air spaces must be filled with inert gas.

2.2 Standard products

The necessary materials and semi finished products must be available in large quantities for standard products. Krypton or even xenon gas filling for achieving lower $U_g$-values are not available in the quantities required for using in triple insulating glass units as a standard product. For this reason, argon is normally used. As a standard design, a triple insulating glass unit with a 4/12/4/12/4 glass makeup is recommended. With two low emissivity coatings (Low-E) on surfaces #2 and #5 and with an argon filling in both cavities.

2.3 Achievable $U$-values

A triple insulating glass unit with a 4/12/4/12/4 structure, two low emissivity coatings (Low-E) with an normal emissivity $\varepsilon_n \approx 0.03$ (state of the art) and with an argon gas filling (gas filling level 90%) in both air spaces, achieves an $U_g$-value of 0.7 W/(m²K) when calculated in accordance with EN 673. Also according NFRC 100-201 the $U$ value is 0.72 W/(m²K) (0.13 Btu/(h-ft²-F)). Without any further measures for improving the thermal properties, this results in the following $U_w$-values for windows with different frame structures (according to EN 10077-1: 2006, table F.1.):

- $U_f = 1.8$ W/m²K: $U_w = 1.2$ W/(m²K)
- $U_f = 1.4$ W/m²K: $U_w = 1.1$ W/(m²K)

Examples of possible measures for further improving the thermal properties of a window design are:

- improving the thermal properties of the frame sections
- use of a insulating glass units with thermally improved spacer bars (so-called 'warm edge' spacer bar systems)
- thermally improving the glazing system by means of a larger glazing bite, for example.

Figure 1. shows the achievable $U_g$ values for 3IGU and 2IGU glass make-ups with argon and krypton gas filling and different sizes of the air spaces.
2.4 Achievable g-values (solar heat gain coefficient)

With the standard product just described, a total energy transmittance (solar heat gain coefficient – SHGC - or g-value) of about 50% (0.50) is achieved for a triple insulating glass unit. This can vary slightly depending with the glass type and the coating used in each individual case.

2.5 Balance U-values

Ultimately, the balance between heat losses (described by the U-value) and solar heat gain (described by SHGC/ g-value) defines the energy saved with a triple insulating glass unit or window. The balanced U-values for a window can be calculated as follows:

$$U_{W,eq} = U_W - S \cdot g$$

The coefficient S for the solar heat gain depends on the direction in which a triple insulating glass unit or window faces are installed. The following numerical values are used for this according to DIN-V 4108-6:

- S = 2.1 W/(m²K) – south orientation
- S = 1.2 W/(m²K) – east/west orientation
- S = 0.8 W/(m²K) – north orientation

With these figures, the following approximately balanced $U_{W,eq}$ values, which in turn can vary slightly depending on the type of glass and the type of coating used in each individual case, are achieved for the described standard product of a triple insulating glass unit with an U-value of the frame, $U_f = 1.4$ W/(m²K), and an U-value of the window, $U_w = 1.1$ W/(m²K) (cf. Chapter 2.3):

- $U_{W,eq} = 0.05$ W/(m²K) - south orientation
- $U_{W,eq} = 0.5$ W/(m²K)- east/west orientation
- $U_{W,eq} = 0.7$ W/(m²K) - north orientation

2.6 Special coatings

With the help of coatings which have been optimized especially for use in triple insulating glass units, an $U_g$-value of 0.7 - 0.8 W/(m²K) and a g-value of approxi-
mately 60 % (0.60), is achieved in the standard glass make-up described. The window values stated above (see items 2.3 and 2.5) then change accordingly.

3. Factors affecting durability
3.1 Air space and pane format (surface area, aspect ratio)

The loading for the system increases with the size of the air space (insulating glass effect, cf. section 5.2). Two air spaces in triple insulating glass units add up, at least with regards to that effect, in such a way that they can be considered as one continuous air space. (Only for symmetrical make-ups) The resulting loads for the glass panes and the edge sealing depend on the format. Small, narrow panes exhibit the highest loading for glass with an aspect ratio 1:3 and for the edge sealing with an aspect ratio from 1:1. Figure 2. shows the effect of different aspect ratios based on the resulting glass stress depending on the length of the short edge of a glass unit. It was compared a “standard” triple insulating glass unit with a glass make-up of 4/12/4/12/4 and an isochoric pressure $p_0 = 16$ KPa.

![Figure 2. Glass stress as a function of the length of the short edge; effect of different aspect ratios](image)

For standard applications of triple insulating glass units in windows, air spaces of 2 x 12 mm are considered to be technically worthwhile. Smaller air spaces(where argon is used for the gas filling) lead to higher $U_g$-values; larger air spaces lead to greater loads on the glass and edge sealing. For larger sizes it can be reasonable to increase the size of the air spaces. The reason for this is to avoid any contact of the individual lites of an insulating glass unit which can in turn for example probably damage the coating due to the deflection cause, for example by wind or barrier loads.

3.2 Secondary sealant

The load reactions applied on the edge sealing are greater with triple insulating glass units. For this reason, the width of the secondary sealant should be increased, particularly for narrow formats. Figure 3. and 4. shows the principle deformation of larger and smaller glass units.
3.3 Structural calculation of glass

As a basic principle, all standards and directives apply as for double layer insulating glass units. On account of the increased loading mentioned above, special questions relating to the dimensions of glass should be answered with the help of structural analysis software. Examples of load-increasing factors are asymmetrical glass make-ups or the use of special glass types, laminated glass and laminated safety glass, and highly absorbent glasses. Furthermore, patterned or wired glass has a lower mechanical strength than annealed float glass. Tempering is recommended when using patterned glass and highly absorbent glass for the middle lite. Small and narrow glass units increase the loads on the individual lites of a triple layer insulating glass unit as well as the edge sealing. For different glass make-ups we recommend a minimum edge length to minimize this risk. In each individual case this limit must be checked with a structural calculation. But as a first idea during the planning phase this values can consulted (Figure 5.).

<table>
<thead>
<tr>
<th>Glass make-up</th>
<th>Recommended Minimum Edge-Length [mm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>4/16/4</td>
<td>450</td>
</tr>
<tr>
<td>4/24/4</td>
<td>600</td>
</tr>
<tr>
<td>4/12/4/12/4</td>
<td>600</td>
</tr>
<tr>
<td>6/12/4/12/6</td>
<td>700</td>
</tr>
<tr>
<td>8/12/4/12/4</td>
<td>800</td>
</tr>
<tr>
<td>4/18/4/18/4</td>
<td>750</td>
</tr>
<tr>
<td>6/18/4/18/6</td>
<td>900</td>
</tr>
<tr>
<td>8/18/4/18/4</td>
<td>1000</td>
</tr>
</tbody>
</table>

Figure 5. Recommended minimum edge length [mm], reference Prof. Feldmeier in Glasingenieur 1-2010
3.4 Coating surfaces
It is recommended that the coatings on the two outer lites are arranged to face the air spaces (coating on surfaces #2 and #5). Tempering of the uncoated middle lite is then generally not necessary. If a coating is provided on the middle lite (surfaces #3 and #5 or #2 and #4) – for example to affect the g-value of the triple insulating glass unit - the middle lite must usually be tempered. But not necessarily! The level of the maximum energy absorptance, up to which tempering of the middle lite is not necessary was investigated. For example, if the energy absorption of the outer lite of a double or triple layer insulating glass unit is ≥ 50% for horizontal and vertical glazing due to the use of a body tinted glass, AGC Interpane recommends fully toughened or heat-strengthened glass. But in any case this is a range and not a fix value. This recommendation needs to be validated in each individual case. If the energy absorptance of the middle lite is ≥ 10%, also a range and it needs also to be verified in each individual case, AGC Interpane recommends fully toughened or heat-strengthened glass. This recommendation is based on a typical location without any higher thermal loading, e.g. static/serve shadow on the glazing, internal blinds, backups or for triple layer IGU’s with keen asymmetrical glass compositions (e.g. air spaces and/or glass thicknesses). For specific applications, however, an analysis of the thermal glass breakage risk is recommended. The Interpane Consultancy Service (IBC) consulting center would be pleased to assist you.

3.5 Special functions
Empirical values for double layer insulating glass units cannot simply be transferred to triple insulating glass units. Combinations with special functions such as safety (horizontal glazing, protection against falling), sound insulation, solar control etc. impose particular requirements.

3.5.1 Safety (overhead glazing, barrier glazing)
The technical regulations for linear supported glazing and barrier glazing as well point fixed glazing (TRLV, TRAV & TRPV and in future the DIN 18008 standard series) in Germany do not make express mention of triple insulating glass units. In the opinion of Bundesverband Flachglas, the requirements which have been generally formulated for multiple-glazed units therefore apply equally to double and triple glazed units. Safety glazing (burglar resistance, bullet or blast resistance) and glazing for fire resistance must be determined for the individual case.

3.5.2 Sound insulation
Sound insulation characteristics can be combined with the thermal insulating characteristics of triple insulating glass units. The load on the thinner outer glass increases significantly with the asymmetrical structures that are typical for sound insulating glasses. For this reason, tempered glass is recommended with edge lengths up to approx. 700 mm.

3.5.3 Solar control
Solar control characteristics can be combined with the thermal insulating characteristics of triple insulating glass units. This changes the light and radiant heat factors compared with double layer insulating glass units with a solar control coating.
4. Glazing specifications
As with double layer insulating glass units, the basic requirements which can be found, for example, in the BF’s “Guidelines for the handling of multiple-glazed units” apply: protection against the continuous effect of moisture (vapor pressure equalization), protection against direct UV radiation (alternatively: UV resistant edge seal), material compatibility, and use in temperature ranges usually found in buildings and zero-stress installation. Frame designs must be suitable for accommodating the triple insulating glass units. The manufacturer of the insulating glass units does not have to be responsible for defects which are beyond his control and occur as a result of non compliance with these basic requirements. The German glazing trade’s Technical Directive No. 17, “Glazing with insulating glass”, as well as the glazing guidelines of the individual manufacturer must be observed.

4.1 Blocking
The functional properties of the glazing blocks must be maintained throughout the whole period of use. To ensure that this is the case, they must be adequately resistant to pressure in the long-term, resistant to aging and be suitably compatible. When fitting the blocks, it must be ensured that the setting and distance blocks are straight and parallel to the edge of the glazing unit. The block must take up the full thickness of the glazing unit and thus carry the dead-load of all three panes. In systems with free rebates, the block must not impair vapor pressure equalization. The block must not cause the edges of the glass to chip. Shear loading of the edge seal must be minimized. The German glazing trade’s Technical Directive No. 3, “Blocking of glazing units”, or any other advise of the glass manufacturer must be observed.

4.2 Larger glazing bite
With regard to the risk of glass breakage typology caused by thermally induced stresses in high thermally insulated frame systems, a larger glazing bite may be considered acceptably for triple insulating glass units (HIWIN research project, sub-project B: investigations into the risk of glass breakage due to a larger glazing bite, final report April 2003, ift Rosenheim and Passivhaus Institut Darmstadt).

5. Other characteristics
5.1 External condensation
The following applies to any insulating glass unit: the smaller the heat transfer – and the lower the Ug-value – the warmer the room side pane and the colder the external pane. Of course, this applies to triple insulating glass units, too. In addition, the external lite directly exchanges radiant heat with the sky. Depending on the individual installation situation, this radiant heat exchange leads to considerable additional cooling of the external pane, particularly on clear nights. If the surface temperature of the external lite falls below the temperature of the adjacent external air, this leads to condensation and in special cases even the formation of ice on the surface of the external lite. This process is generally known as the formation of dew or hoar frost. The condensation will disappear due to the heating of the external together with the external air, for example by the morning sun. This phenomenon is not a malfunction, but more an indication of the outstanding thermal insulation value of the triple insulating glass units. Because of the even better thermal insulation of triple insulating glass units, it must be expected that condensation will form on the external surface of the glass unit more frequently.
than with the previously common double insulating glass units. To avoid confusion and irritation of customers and users, it is recommended that this phenomenon is pointed out in advance. Further developments lead to products which can decrease this effect. So called “Anti-Condensation” coatings on position #1 can help to minimize, but not fully excluding this effect.

5.2 Insulating glass effect
Section 4.2.2 of the “Guideline to Assess the Visible Quality of Glass in Buildings”, issued by the Bundesverband Flachglas amongst others, describes the “insulating glass effect” which results in concave or convex curvature of the individual lites and therefore optical distortion due to the impact of temperature changes and variations in the barometric air pressure. Because of the larger volume of gas enclosed in the two air spaces, this effect can be greater with triple insulating glass units. Figure 6. shows the principle effect of the insulating glass effect if the temperature, the barometric pressure or the altitude changes. For this $\Delta T$ is the temperature difference between manufacture and installation, $\Delta p_{\text{met}}$ is the difference of barometric pressure between site of manufacture and site of installation, $\Delta H$ is the difference of altitude between site of manufacture and site of installation and $p_0$ is the isochoric pressure as a function of $\Delta T$, $\Delta p_{\text{met}}$ and $\Delta H$.

![Figure 6. Principle of the insulating glass effect](image)

5.3 Optical quality
5.3.1 Inherent color
Section 4.1.1 of the “Guidelines for assessing the visual quality of glass for buildings” describes the inherent color of all glass products, especially those made from coated glass. Due to the presence of a third glass lite and a second coating, the inherent color of a triple insulating glass unit can be seen more clearly than that of double layer insulating glass unit.

5.3.2 Glass Edge of the IGU and muntins
Muntins can also be used in triple insulating glass units. But it is recommended that the use of this vertical and/or horizontal bars are limited to one air space.
Visual impairments (see “Guideline to Assess the Visible Quality of Glass in Buildings”), such as a slight offset of the spacer bars or muntins when arranged in both air spaces, for example, have no effect on the functionality of triple insulating glass units and cannot be completely ruled out.

**Finally**

Since product diversity continues to grow, glass consulting for architects, planners, and clients in building projects is in high demand among glass processing companies.

The AGC Interpane Consultancy Service (IBC) assists national and international architects, engineers, planners, fabricators, and institutional building clients either by phone or on-site. Apart from architectural and technical consulting for window and facade manufacturers, the IBC also offers training courses and coordinates the national and international cooperation of architectural consultants and clients. The IBC can be reached via phone at +49 9931 950 229, fax +49 9931 950 236, or e-mail ibc@interpane.com.

**References**


One Way Cable Systems

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Abstract
In only the last decade, one-way cable systems have become a dominant structure type for supporting high end structural glass facades. These systems now account for more than 40% of structural glass projects we see out to bid, however, the application of this form of structural support to glass façade design is still very recent. The first two-way cable net glass façade, the Hotel Kempinski by SBP, was completed only 19 years ago in 1994. The first one-way cable glass façade, the Kimmel Center by Dewhurst MacFarlane is even younger (2001). Because of the relative infancy of this structural form we as designers and engineers will probably be learning its nuances for some time to come.

Keywords: one-way, cable, warping, boundary conditions, transparent

Introduction
Cable supported walls are well known for their transparency and simplicity. However, that’s only one aspect of the story behind their recent popularity. For example, one-way cable systems are also the shallowest of current structural façade systems. Sometimes simply consuming the least amount of otherwise usable real estate drives the entire choice of structural system. One-way cable systems are also very adaptable and expandable. They easily adapt to multiple floor construction and can be used in a variety of configurations. From an economic stand point, when compared to their two-way cable net cousins, one-way cable systems have far fewer internal and external connections. The costs of these connections - especially the additional end fittings and anchors - add up. Because of this, currently completed one-way systems dramatically outnumber completed cable nets and will probably continue to do so.

The primary task in designing a one-way cable glass facade really comes down to managing the warping of the glass to acceptable levels determined by 1) the glass surface bending stress and 2) IGU’s by shear stress on the edge seal.

Webster’s defines warping as “to twist or curve something that is usually flat or straight”. Warp is an unavoidable consequence for glass panels supported on a flexible structure and joined to a rigid boundary. Rigid boundaries are easily understandable, easy to work with, and make robust weather-tight seals and functioning door portals achievable. Understanding the transition of flexible structures into rigid boundaries is an important topic to understand well and even more important: a continuing opportunity for creative development.

There are generally speaking three fundamental ways to manage warping at the interface between a flexible façade structure and a rigid boundary structure. They are: 1) increasing cable tension near the boundary, 2) using intermediate supports to reduce effective cable span, and 3) softening boundary conditions. Increasing the cable tension reduces cable deflection locally - effectively creating an intermediate transition zone between the stiff boundary and more flexible typical cables. Often it is permissible to have a few boundary cables at much higher tension if the majority of typical cables maintain a lower tension. This strategy is both cost effective and common. However, there are situations when increasing tension is simply not an option. Reducing the effective cable span by introducing intermediate supports reduces the overall magnitude of deflections across the entire system effectively mitigating warp. Softening the boundary conditions also works by creating a transition zone between the flexible and rigid. The unique constraints of a project usually dictate which strategy or combination of strategies will be the most effective. The following case studies illustrate our evolution of approach and strategies for dealing with warping over the last decade designing one way cable systems.

1 Time Warner Center Prow 2002
Our first one-way cable system design was The Prow at Time Warner Center at 59th and Columbus in New York (Figure 1).
The project was tall, a 39m, three sided glass box. The walls measure 14m and 4m wide. The vertical mullion elements are 12mm diameter high strength stainless rods which are braced laterally every 4.9m by steel frames. The vertical tension load is taken into large steel frames at the sill and at the head of the façade. The glass is non-laminated, monolithic, and attached by point fittings to a custom casting and interior glass louvers system (Figure 2).

Warp at the corner and edge boundaries were managed by reducing the effective cable span. Although the overall vertical span was 39m, the vertical rods effectively span only 4.9m between horizontal structural frames. The glass on this project was very flexible 12mm monolithic. At the top of the structure where the wind pressure was greatest, warping was easiest to control as the rod tension was naturally high due to the accumulation of façade dead load.

2 One Bryant Park 2006
There are five cable supported walls at the One Bryant Park project in New York. The largest in terms of area is the main entrance on 42nd and 6th Avenue which spans 11m tall (Figure 3 and 4). The typical glass module was 1.5m by 3.15m laminated monolithic.
The primary strategy for managing warp on the main entrance was increased tension in cables adjacent rigid boundaries. These boundaries were 1) the portal, 2) the corner and 3) at each jamb. The maximum cable force at these locations was around 200 kN where the maximum cable force at typical cables was 112 to 134 kN. As a result, the cables at the boundaries of the façade were 1.8 to 1.5 times stiffer than the typical cables.

Around the corner on the 43rd Street side are two 7m wide by 21m tall cable walls referred to as the Theater Walls (Figure 5). The Theater walls are actually two-way cable systems. There are a total of 6 horizontal cables in the wall, one at each horizontal glass joint. During the design phase, a pure vertical one-way system was studied for these Theater walls; however, the building structure just wasn’t capable of supporting the dramatically increased tension loads that would result from trying to control the glass warp at the jamb with 21m tall cables.

At that time, an interesting hybrid alternate was also studied. The hybrid solution eliminated 4 of the 6 horizontal cables and was probably the most efficient of all designs studies. Although not used on One Bryant Park, that one-way/two-way hybrid concept would later be incorporated into future designs for City Creek Center (Figure 21) and Houston Office Façade (Figure 24).
A good deal of time was spent on this project trying to eliminate the corner column (Figure 7). Special dead load fittings were developed and much analysis work was done trying to develop a structural silicone solution. In the end, the project schedule forced us to move ahead with the column but the studies we did on this project eventually found application on Juilliard (Figure 14) and USC Broad.

3 Center Square 2006

The Center Square Mall in downtown Philadelphia (Figure 8) was W&W's first one-way cable system designed to support insulated glass units. The main wall is 14m tall x 12m wide and the glass module 2m x 3.5m. This project was a renovation and the existing structure simply could not support the tension levels that we would have asked for had this been new construction.

Since increasing cable tension wasn't an option to control warp, the span of each cable was cut in half with horizontal kickers (Figures 9 and 10). Even then, the resulting warp was still very large - almost 114mm of glass corner deflection.
The glass bending stress was within acceptable limits, however, there was great concern about edge seal failure due to shear stress. Extensive testing was carried out on the unit to verify performance (Figure 11 and 12). After three months of daily warping and pressure cycling, the panel was repeatedly checked for condensation and eventually approved by the manufacturer. The insulated units for this project were supplied by Pilkington Architectural and use a patented edge construction developed for the large displacements of point supported glass (Figure 12). The high performance spacer has a reservoir in the extrusion which holds about 300% more butyl than conventional IGU spacers. In the end, the high performance spacer was the key to making a one way cable system possible on this renovation project.

4 Juilliard Alice Tully Hall 2007
Alice Tully Hall at the corner of 68th and Broadway in New York City has a maximum vertical span of 12.2m (Figure 13). The east façade is 40m long and the south is 21m long. The glass type is laminated 6mm-SGP-12mm.

The vertical cables ranged from 19 to 36 mm diameter. Larger cables were used at boundaries where increased tensions were required to control warping. A flexible edge boundary (Figure 15) was also integrated into the cantilevered portal frame near the corner where warping was especially problematic. This flexible edge pivoted at the base of the portal and allowed for an extra 16mm of deflection at the top of the portal (Figure 16). While this may not sound like a lot, the extra flex made a significant difference in the glass surface stress. Without the flexible boundary, the glass bending stress would have been unacceptable.
The corner was structurally glazed. Figure 17 shows a diagram depicting the extreme positive and negative flex of the vertical cable system at mid-height in plan view. Figure 18 shows the mockup test of the corner and flexible boundary portal.

5 City Creek Center
The facades were all initially designed as simple one way vertical cable spans; however, the large tension loads in the vertical cables caused problems for the arch structure.

Figure 21.

The arch was pinned on one side and on rollers on the opposite side. As the cable tension increased due to wind, the arch flattened and shifted towards the rollered side.

Figure 22.

This eventually led to the addition of a single horizontal cable across the spring point of the arch to control horizontal thrust.

This cable was integrated into the façade where it greatly helped limit warping. So while the horizontal cable was originally added to help control deflections of the arch, incorporating it into the façade cable system resulted in lower vertical cable tension values as well. In the end, this wall was a hybrid; not fully a one way cable system but also not fully a two-way net either. It was the design initially conceived for the One Bryant Park Theater wall. Economically, the hybrid was less expensive than a full cable net and structurally much easier on the head and sill than a purely single direction system.
Additionally, because this façade used insulated units, further warp testing was done on the Pilkington spacer to verify edge seal performance (Figure 23).

6 Houston Office Entrance (Currently under construction)
The Houston Office Entrance project is composed of two identical facades 18.3m wide by 31m high (Figure 24). The typical module is 1.75m wide by 2.3m tall insulated laminated glass.

On this façade, warping was controlled two ways: 1) reducing the deflection with intermediate supports and 2) using a wider more flexible panel at the jamb boundaries.
Learning from City Creek Center, the Houston Office Entrance was developed from the start as a hybrid system. Vertical cables span the 31m floor to ceiling height but are braced by two stiff horizontal cable intermediate supports (Figure 25).

The horizontal cables are themselves laterally braced by intermediate kickers (Figure 26). Structurally, the system functions as three stacked 10m spans. So unlike previous one-way cable systems W&W has built, the boundary cables do not carry a higher pretension than the typical cables. Instead, a 22% wider - and therefore more flexible - insulated panel was used at the jamb to bridge between the flexible cable and rigid jamb. In this way, we were able to take advantage of the knowledge gained in previous edge spacer testing and maintain a lower cable tension even at the boundary.
7 Conclusion
In ways large and small every new project builds upon and extends knowledge gained from previous projects. It’s impossible now to imagine the future innovations that will inevitably result as one-way cable systems are introduced to a greater number of designers and developed over a greater number of projects. Hopefully, these simple case studies have helped illuminate in a practical way a few approaches to flexible structure transitions and added to the conversation about the ongoing development of this structural form.
Glass Innovation of Today

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Abstract
Based on today’s trends and advances in glass technology of the construction industry, we notice a shifting need to build innovative and sustainable buildings using glass to steel instead of traditional stone to steel. After the windows were installed into David’s Diamond, it served an aesthetic purpose, filling the diamond with a clear blue sky abstract color, offering viewers and aweing sight. David’s Diamond a top One World Wide Plaza, represented the start of innovative and creative design of glass for skyscrapers, making it’s accomplishments in aesthetics. Innovatively, the Freedom Tower achieves LEED Gold for its glass that is able to absorb direct sunlight while only gaining a small amount of heat, and it special coasting safely freefall during shatters. The Empire State building also achieves honors as the nation’s largest LEED building as it captures LEED Gold for its 6,514 window renovation from prehistoric double-pane windows to triple-pane iWindows, enabling a $410,000 annual energy (38%) savings on life cycle costs.

1 Introduction
Innovation in today’s construction industry continues to grow and reach new heights; installing eco-friendly materials, and incorporating sustainable means and methods are areas proving how the construction industry has innovated sustainability. We can see examples of improvements in the industry’s innovation and sustainability based on two buildings designed by former Skidmore Owings and Merrill Architect, David Child’s. The two building’s designed by Mr. Child’s are One Worldwide Plaza and One World Trade Center (Freedom Tower). Another national landmark, the Empire State Building, incorporated new insights to sustainability by constructing eco-friendly glass windows, thus achieving LEED
Gold. Based on today’s trends and advances in glass technology of the construction industry, we notice a shifting need to build innovative and sustainable buildings using glass to steel instead of traditional stone to steel.

1.1 David Childs, Architect at SOM Designs One Worldwide Plaza

David Child’s, Architect at Skidmore, Owings and Merill, designed One Worldwide Plaza and completed construction by 1989. It's a 50-story office skyscraper, approximately 1.5 million square feet, located in Manhattan, New York [4]. One Worldwide Plaza represents a traditional style of construction of steel to stone connections. 1989 was a time before innovation in sustainability was worldwide trend.

1.1.1 Steel to Stone, and Structural Aspects of One Worldwide Plaza

The steel and stone structural elements are the main components of any building, especially skyscrapers. The initial design of One Worldwide consisted of a maize-colored brick with stone setbacks. The top of the building consisted of this brick exterior, while the bottom exterior consisted of a set granite base, offering one of the highest performances in protection and strength. The granite, marble and stones were fabricated in Italy, and shipped to the United States. Representatives from Skidmore, Owings, and Merrill, and HRH Construction were able to travel to Italy in order to perform a quality analysis and check on selected stones. Because the design called for an expensive granite base, David Childs suggested they apply a thin veneer of stone supported from behind with steel trusses (hidden from view aesthetically, creating a steel to stone connection [4].

Placed on top of this base are columns, pilasters and arches. As the structural steel and stone assembles up 48 stories with repeated stone setbacks, a copper pyramidal crown is formed topped with a pyramid made out of glass. This pyramid made out of glass is called David’s Diamond. In the making of David’s Diamond, a copper base consisting of copper panels were set a top the roof in between its seams. The copper panel system also consisted of mullions, aluminum, and a based fastened with metal
screws. These materials were prefabricated and then manually hoisted 48 stories to the top of the roof, thus minimized field work. One of the problems with erecting this metal and steel structural was its light capacity to hold load; a solutions to the problem was to further reinforce the aluminum, steel, and copper [4].

The structural framework of David's diamond was made up of an assembled white tubular triangle. The white metal tubes were screwed into connecting rods, thus converging to a triangle structure. A series of triangles are formed within the metal triangular structure; the outer skin of the diamond was made up of separate aluminum sections where glass is inserted and assembled into the white structural frame of the pyramid. After the windows were installed into David’s Diamond, it served an aesthetic purpose, filling the diamond with a clear blue sky abstract color, offering viewers and aweing sight. David’s Diamond a top One World Wide Plaza, represented the start of innovative and creative design of glass for skyscrapers, making it’s accomplishments in aesthetics [4].

1.2 Chrysler Building Adds Aesthetic Value
Glass continues to make a strong impact in construction as noted by two of the nation’s most iconic buildings, the Chrysler Building and later One and Two Liberty Place. Aside from David’s Diamond using glass aesthetically as a diamond on just the top of the roof, the Chrysler Building and One and Two Liberty Place expands the use of glass aesthetically and structurally throughout the building’s entire exterior façade [7].

In 1928, following World War I both William Van Alen and Walter P Chrysler designed the Chrysler Building with an Art Deco influenced style; it consisted of a visual arts design modeled with rich colors, abstract geometric shapes, and ornamented finishes. This design was fathered by the Art Noveau style of the Eiffel Tower (Figure .1).
Figure 1. Art Noveau style of the Eiffel Tower, which grandfathers the present design of the Chrystler Builder.

The exterior façade of the Chrysler building was made of symmetrical steel and glass structural shapes, such as triangles, curves, and chevron patterns (Figure 2).

Figure 2. Exterior façade of the Chrysler building

Aside from the architectural exterior art of the façade, the building featured a “jewel-like glass dome,” with windows topped with glass-wrapped corners (cite). The structurally glass-wrapped corners of the Chrysler building was used to create an aesthetic visual emphasis on the exterior aspect of the building; this innovative glass idea and design creates a physical and visual impression to the viewer that the building is light, giving the view and impression that the building “floating in mid-air,” [8].
1.2.1 One and Two Liberty Place Building Adds Innovative Structural Value

Completed in 1990, Liberty Place was designed by Helmet Jahn and Ziedler Roberts. Under heavy influence from the previous iconic glass construction of New York City's Chrysler building, Liberty Place included a spire made out of glass and steel with gables and diagonal setbacks. The gable of both One Liberty Place and Two Liberty Place was set back with diagonal setbacks to create an exterior “step,” visual as designed in both the Empire State and Chrysler buildings. The spire formed by exterior gable wall consisted of glass and steel moment connections.

Now glass is used as a structural aspect in a setback system with steel to distribute downward loads of the building from dead and live loads (Figure 3.).

**Figure 3.** One Liberty Place introduces a structural setback system used with steel to distribute downward loads of the building from dead and live loads.

Here, the masonry structure, along with the steel and glass components, is increased in length to achieve this structural design with glass. Also, to create and increase masonry space along each setback, every individual footprint associated with each floor level is level along the building's spire is “pushed back,” from the ground to give it a step-like feature [6]. This method used under the supervision of Helmet Jahn and Ziedler Roberts ensure that the building’s spire would be able to maintain its glass-to-steel structural integrity from opposing loads.
The exterior design of the towers consists of granite, aluminum, and glass panels; the amount of glass used increased as the building’s spires were constructed for added structural support for loads. Aesthetically using glass and aluminum, the Liberty Place buildings like the Chrysler Building creates an assembly of horizontal and vertical shapes throughout the entire building to the stone base.

The horizontal aluminum bands structurally attaches blue glass and gray granite at the corners of the building, resembling the glass-wrapped corners of the Chrysler Building, but with an addition of an aluminum grid along the entire building for structural support (Figure 4.).

![Figure 4.](image)

**Figure 4.** In Two Liberty place, it’s horizontal aluminum bands structurally attaches blue glass and gray granite at the corners of the building, with an addition of an aluminum grid along the entire building for structural support.

Then the center façade portion is lined with glass and crossed with lines of gray granite every fourth floor (Figure 4.). Aesthetically the silver and blue glass of One and Two Liberty Place produces a decorative mirror-image of the surrounding skies, sunsets, and city skylines (Figure 5.).
1.3 David Child’s Stone to Glass Design on The Freedom Tower

Unlike One World Plaza, many new buildings are starting to incorporate more glass into their designs. The Freedom Tower, a building currently under construction at the old location of the twin towers, is a great example of a building that is using glass to the next level. SOM Architect, David Childs, also designed the Freedom Tower; it had a budget of $2 billion when it was first designed however the final design ended up being over $4 billion. When complete, the total area will be approximately 2.6 million square feet. After the spire is installed, the Freedom will be 1776 feet, Interestingly enough, this building was picked to be thigh high because it was also the date when the Continental Congress adopted the Declaration of Independence. This building will consist of mostly office spaces but will also include a broadcasting center, a large observation deck, and a new restaurant [10].

This building from top to bottom is all glass; under its skin of glass the building is made of a heavily built steel frame. A system of columns and beams are connected to form a moment (connected) frame. Their connection is held together both by bolts and welds. In addition to this steel moment frame there is also a large
concrete shear wall. The combination of these two types of connections structurally influenced the building’s rigidity, causing an absence of usual essential columns in the middle of it. This is a big designed advantage since it provides tenants the most possible occupational space [10].

1.3.1 Political Issues with Basic Conceptual Design of Freedom Tower
When David Childs first designed the base of the Freedom Tower, the opposing New York Police Department weren’t supportive about the building’s structural ability to defend against bombs. A new designed was proposed was a 200 foot base made of steel and concrete. The only occupied space of the first 200 feet of the building would be the lobby. However, many people were not happy with this design since the building looked like a bomb shelter. At first, David Childs from SOM had a plan to cover the bottom in a sheathed metal designed. This however got quickly changed to the idea of using glass. Childs’ came up with a design using a reflective prismatic glass attached to welded aluminum screens. Three companies competed for a bid of $82 million to produce the glass for the base. In the end, it was decided that a Chinese company would produce the glass panels, but this plan did not work out though since the Chinese companies weren’t able to produce a glass panel to match the architect’s specifications. After they had an American company make the glass it was then sent to China for the fabrication of glass cuts for a prismatic effect, as well as glass lamination placement for safety precautions. After the cuts were put into the glass, the glazing’s sharp edge made it very difficult to cut. Also, the large pieces of glass would now bow and not stay stiff. After all of these problems and millions of dollars, the project was cancelled and they had to come up with a new idea.

The idea was to cover the base with glass fins that were not completely flushed into the base. Behind the glass fins was a frosted texture. When the building is lit from inside the glass makes interesting designs. The glass also has a special coating that will not only make it more safe when it shatters but also make it more energy efficient. The glass is able to absorb sunlight while only gaining a small amount of heat.
1.3.2 The Freedom Tower Achieves LEED Gold

Another amazing accomplishment besides for being the tallest building in the Western Hemisphere is the Freedom Tower also achieved LEED Gold. Some of the features that the building used to achieve the award are wind power generation, photovoltaics, sea water cooling and low-emissivity glass. Although all of these are amazing achievements for building one of the most innovative unique achievement was reaching LEED Gold with glass at a historical level [11].

Instead of using spandrel glass like most skyscrapers would use, panes of glass where placed at the height of each story. Each pane of glass weighs about 1,200 lbs with dimensions of 13 feet tall by 5 feet wide. Because most of the building has floor to ceiling glass they are able to take advantage of the sunlight in a sustainable practice called natural daylighting. Natural daylighting is when occupied offices are positioned in the building at a certain orientation to take the most advantage of the natural sunlight [11].

They took it one step further at the Freedom Tower using low emissivity glass, also known as low e class. This glass is able to refract 90% of ultraviolet light and infrared light out. Ultraviolet light fades and wears down material and infrared light will heat up the interior of the building. The only light that the low e glass lets in is visible glass which helps illuminates inside of the building. In addition to using low E glass, they also use a dimming system to automatically sense how much visible light is coming through the windows and sets the light at an optimal level. A dimming system save energy by limited electrical use for lighting on average operating below 100%[11].

Some of the features that were made of glass in this building include a decorative portion at the base of the building, a restaurant with a completely glass room and office floors with glass from the floor to roof.

1.3.3 The Empire State Building Window Retrofit Awards LEED Gold

New York City’s Empire State building achieved LEED Gold for their innovative window-glass retrofit. It’s labeled as the nation’s tallest building to receive a LEED (Gold) certification, established by the US Green Building Council. The primary sustainable design
of the Empire State building enabled a reduction in energy consumption by 38% and costs by a total of 4.5 Million [2,9].

Managed by SKANSKA USA Building, the scope of the window light retrofit was to restore 6,514 thermo-pane glass windows and replace them with triple pane windows [9]. The issue with a thermo-pane window is it enables multiple passages for air leakages. Also, produces a low insulation factor due to its sheer double-pane structure, size and capacity. The solution to this problem involved installing spacers between original windows (double-pane) to incorporate a triple-pane window system, a gas fill and an added layer of coated film for protection against air leakage.

Serious Energy, the manufacturer of the Empire State’s triple-pane windows (called iWindows) planned to install a glass window system that’s adaptable to weather patterns: the glass is able to warm in the winter and cool in the summer, which enables facility managers to accommodate changing temperatures conditions throughout the year. In effect, the building benefits from reduced heating and air condition costs with a total of $410,000 annual estimated energy savings.

Installation time of a high-energy efficient triple-pane window only takes 20 minutes, reducing the cost of labor by a fraction of the average price, making it a superior innovative solution to glass renovations for the future. Another special feature included a reduction of air-polluting carbon dioxide emissions by 105,000 metric tons within 15 years of window use [2] and is projected to be 90% more efficient than other buildings.
References


Decorative Glass - A Process for Expression

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Abstract

Architecture is as much about the technology of making things as it is about place and human response, and the evolving capabilities in architectural glass are of increasing interest in this regard. It can become an important component of design's ability to bring people together in ways that help them interact, inspire, and identify.

Glass, at first thought, is valued for its transparency. In architecture, transparency is both a useful literal quality, and a metaphor for one of the most salient values of our time. We appreciate see-through buildings because they connect us with each other and with the world beyond. But transparency is not the only aesthetically useful quality that glass offers. We can quite easily design and fabricate glass to favor reflectivity, translucency, color, pattern, and visual depth. These qualities, while picking up on ancient applications, offer expansive opportunities to use architectural glazing as a medium – one which can carry messages, mark places, and add visual delight and physical comfort.

The benefit of these technological achievements will be demonstrated through several examples and two case studies of built projects. Each represents the synthesis of functional and aesthetic criteria achieved simultaneously through a single decorative glazing application. The projects illustrate how custom printed motifs, coupled with multi-ply lamination, can accurately reduce glare and heat gain, with greater effectiveness than through traditional decorative glazing fabrication methods.

The accuracy of printing methods and precision of ink opacity also enable the design of visual baffles for the control of sight lines and sunlight intensity. Thus, glass can gain a new functional identity in architecture: it can be designed not only to be a custom expression, but also a selective aperture attuned to performance characteristics.

Printable interlayers and direct-to-glass fabrication methods are also advancing opportunities for richer visual effects. A case study of a recently completed project illustrates the lessons learned vis-à-vis design and construction of a decorative glass package comprised of over ten thousand square feet of custom graphics, which performs as an architectural focal point, but also provides utility. The combination of functional and aesthetic capabilities has created exciting new territory for the application of decorative glass.

Keywords: architectural glass, decorative glass, glass performance, frit, printing
Figure 1. A combination of etching and frit patterns on a glass Brise Soleil shelter, a south facing façade from intense sun, while producing a diaphanous screen and glowing beacon.

Figure 2. Printable Interlayers and Direct-to-glass printing allows continuous spectral color shifts.

Figure 3. Colored patterns printed on glass combine with etched glass to achieve a unique and stunning aesthetic expression, providing architectural focus across a creative campus.

1. Glass as a medium

The use of glass as a communication medium is not new. Since antiquity, glass has been used as an art material offering strong visual impact, color fastness, and permanence. With the advent of the Gothic architectural frame, curtains of glass became possible for the first time. Rather than being used simply for daylight, high religious architecture used colored glass to create the equivalent of major multi-media shows, communicating ideas across language groups and time, without regard to literacy. Many architects, ourselves included, enjoy collaborating with artists to incorporate glass-based imagery in our work. The interaction of space, light, color, and image can produce powerful results.

Increasingly we have been dealing more phenomenologically with how glass can serve as evocative architectural material whose very performance characteristics can be controlled by the designer. Blessed with supportive clients, we have been able to build large-scale examples.
Figure 4. Section through Santa María la Real, Pamplona, Spain.

Figure 5. Shelly Ridge Girl Scout Center, Miquon, Pennsylvania.
Figure 6.  William Nealon Federal Courthouse, Scranton, Pennsylvania.

Figure 7.  Competition entry for the US Embassy in Germany.
2. Case Study 1: Glass Brise Soleil

The Corning Museum of Glass’ Rakow Library is the world’s pre-eminent repository for written and graphic information on the history and technology of glass. The building is oriented almost exactly due south, requiring the design of a high performance shading device that also celebrates the potential of glass construction.

The solution, a glass brise soleil, or screen wall, spanning the building’s entire south side, became a large environmental sculpture, transforming the undistinguished character of the former office building. The panels are 16-mm (5/8 inch) tempered glass spanning about 3.5 meters (nearly 12 feet), each one supported separately only by four point connections. Steel masts bracketed about 1,500 mm (5-feet +/-) from the building face define a floating plane outside the building envelope.

Carefully calibrated linear patterns on the glass allow this floating plane to interact with seasonal sun angles to maximize visual transparency while excluding direct sunlight from the library’s interior. Lines on the front are etched into the glass surface, while those on the back are applied with a nearly opaque ceramic frit. Interacting with both solar angles and the refractive qualities of the glass plates, the patterns exhibit a great variety of environmental, visual and optical qualities. Despite the sun’s seasonally changing altitude, the brise soleil’s line spacing, in a graduated continuum, consistently protects the window from direct rays from the sun.
While specifically intercepting light from the sun, the panels are remarkably transparent when viewed from the ground or from inside the building. They create extraordinary, veiled views of clouds, sky, and the reflected landscape. The combination of back-coating and front-etching interact with changing weather and lighting to produce a great variety of simultaneous visual effects: clarity, reflection, luminosity, and an occasional hint of the subtle green hue made by traces of iron. At night, backlighting passes through the clear stripes on the brise soleil’s inner surface, accurately illuminating the etched lines on the front. The building takes on an even glow, making it an elegant beacon in the landscape.

Figure 9. The screen serves as a glowing beacon at night.
3. Case Study 2: Campus Decorative Glass – Stair and Façade Enclosures

Decorative glass elements were envisioned as expressions of the creative culture and identity of the project, but also as a unifying tool for this quadrant of campus and a wayfinding device. The decorative glass elements occur at key architectural moments or site locations. They are located on the structures or in the landscape as wayfinding and are positioned to simultaneously take advantage of the site axies and views.

The concept for the decorative glass was a continuous gradient based off of a range of colors that are sympathetic to an existing campus pallet and the material pallets of two proposed structures. Blue, yellow, and white were added to the color range to create the gradient. There were many design studies executed to determine the final colors. Printed illustrations, glass samples of gradients, and watercolors were all used.

Printed illustrations and renderings do not accurately represent how color will look once it is laminated within glass. Printing representations can be very useful, but their ability to show color accurately is limited. Ultimately, colors must be calibrated to actual samples from the manufacturer so that colors in the artwork file can be calibrated with their particular hardware. Color is challenging to
predict when applied to glass. Lighting, scale, and ink opacity factors have a big impact on the appearance of any color.

Figure 15. A watercolor sketch depicts the design concept for varied, but related gradient families.

Figure 16. Various samples and prototypes were created throughout the process. Early tests examined color gradient ranges, while later tests expanded to cover a range of variables: opacity, line thickness and patterning, acid etching, layering, etc. By engaging in this process early, the architect was able to make informed design decisions and gain precision in a complex, multi-variable process that otherwise yields uncertain results.

Figure 17. Samples were used for review of the line artwork comparisons, reviewing density, color and transparency.

Various technologies were considered. A sample of the digital artwork was shared with several fabricators utilizing both printable interlayers and direct-to-glass printing technologies and a range of samples were created. The samples received varied greatly, as featured in Figure 15. The samples, along with associated costs, were reviewed and the direct-to-glass printing technology was selected.
Once the methodology was chosen, the design team began working with the contractors and fabricators to calibrate the digital artwork with the output. Many samples were created and reviewed at various scales. A sampling process using the actual glass thicknesses, mostly in 12”x12” sample panels from various points in the collection were produced and reviewed, along with a few full-scale mock-ups. Again, the digital information does not represent the perceived colors of the actual glass. Thus, the sample process is critical to predict color.

Figure 18. 12”x12” control samples were used for color comparison to ensure consistency.
Figure 19. Detail of final panel assemblies.
Figure 20. Detail of final panel assemblies.

The glazing utilized at the building’s leading edge, the east stair, is the main decorative glass element for the campus quadrant. All other types are variations or simplifications of this prototype. This primary assembly is composed of three plies of glass and has two layers of printed line work and a custom etched first surface. The assembly and layered color gradient incorporated into the decorative glass, a linear pattern utilized throughout the entire site, is expressed
below in Figure 21. The alignment of the line work and the custom etching was an important part of design and posed certain challenges.

**Figure 21.** Each panel is composed of three plies with two printed interlayers and one etched surface. The three layers interact to vary opacity and color, incorporating a background line pattern and solid fill for custom artwork. The two-color printed interlayers originate from the same color gradient; however, the interior layer is shifted toward the yellow end of the spectrum. The offset line patterns are engineered such that depending on one’s viewing angle, the color of each panel changes as one moves vertically.

The composition of the decorative glass also varied at each of the elements. Some of the compositions were 3-ply as noted above. This assembly was utilized for the building stair enclosure and landscape elements, while the parking structure has 2-ply composites where the graphic of gradient A and B were compressed (see Figure 21). The surface finish of the composites also was varied depending on the design effect desired at each location.
Figure 22. As part of the documentation and delivery process, the color gradient for each panel was defined mathematically using CMYK values. In order to maintain consistency, the gradient of each element was defined as a value shifted along a “master color.”

In the instances where visual connectivity was not desired, one or both of the exterior surfaces of the glass were acid etched. The etched surfaces also provide a dynamic surface for light and shadow during the day and an elegant surface for lighting at night (see Figure 23).

Ultimately, the glass printing technology provided the opportunity to create enough consistency to tie together disparate elements, while providing enough diversity to respond to unique conditions and offer a visual richness through variation.
Figure 23. Two-ply panels acid-etched on both sides form a screen along the north façade of a garage.

Figure 24. Shingled, three-ply panels, with etched-frit custom artwork on the first surface, form a screen around a South facing stair.

Figure 25. Two-ply panels acid-etched on a single surface shade a stair exiting the garage.

4. Conclusions

The use of architectural glass as a means of making buildings more transparent is of ever-increasing interest, and technologies that increase transparency while minimizing visual clutter are advancing rapidly. However, the glass’ ability to perform in non-transparent ways has also increased dramatically. Through the encouragement of our clients, we have had the good fortune to develop interesting and potentially replicable responses.
Acknowledgements

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An ASTM Guide for Structural Glass

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Keywords: 1. Standards, 2. Structural Glass Design; 3. Robustness; 4. Retention; 5. Redundancy, 6. Post-Failure Capacity 7. Codes, standards and regulations

ABSTRACT

Glass is unique amongst building materials as being both transparent and brittle. Unlike the other common brittle materials, concrete and masonry, cracking of any kind is regarded as a failure. Due to the technology initially available, breakage and fall out were considered to be a necessary risk for the transparency glass offered. The same assumption of sudden failure also precluded glass from structural applications. As technology has advanced, so has the potential for robustness through redundancy and retention. Specialist designers have successfully constructed many glass structures. However, many poor practices are perpetuated because of the lack of code-mandated standards. To make glass as a structural material available to the wider design community, and as a reference to the building authorities that review and monitor them, a new structural glass guide/standard is required. While many of the technical considerations will be common to the other material standards, the nature of glass and its design has many unique aspects that also require philosophical consideration. This paper makes proposals for the consideration of circumstance and consequence to add to the usual criteria of strength, stability and serviceability to develop a design standard that promotes good design of structural glass. By expressing the guide as sound design principles, creative design is enabled and consumers can embrace glass structures with confidence.

INTRODUCTION

(The opinions expressed herein are those of the author and have had only preliminary discussion at a committee level. They should not be regarded as indicative of any future ASTM standards or used for design. While the proposed document is referred to as a standard, it is likely that it will initially be released as a guide.)

There are several ASTM standards concerning glass: ASTM E1300 provides a probabilistic approach to acceptable loads for window glass in buildings, ASTM E997 for statistical methods of testing window glass, ASTM E2353 and E2358 for balustrades, and ASTM E2751 for glass walkways, to name a few. However, despite these numerous standards, specifications and test methods, there is not an overarching guide to the design and engineering of structural glass. Even simple glass assemblies, such as glass fin storefronts, do not have a standard by which their adequacy can be measured. Traditional material design standards are entirely concerned about preventing failure of an item; in the case of glass design, the inevitable failures must also be considered and the consequences controlled.

Glass has been utilized primarily for its attribute of transparency. It differs from other building materials in that it is both brittle and cracks are considered unacceptable. The other common brittle materials, concrete and masonry, are also strong in compression and brittle in tension, but utilize steel reinforcement to provide predictable tensile capacity following small but acceptable cracking of the material. Plastic extension of the tensile reinforcement allows ductility of the system and redistribution of loads to less critical areas. In this way, prediction of the initial formation of cracks is not critical to the overall structural performance of the material and stress-based design gives consistent lower-bound predictions of the capacity. For glass, with few exceptions, cracking is regarded as a form of failure, thus the demands on the material must also take into consideration aging and the flaw distribution of the surface, which initiates the cracks that control the capacity of the system.

Window glass design around the world has separated into two camps: ‘stress-based design’ and ‘probabilistic design.’ To treat glass as a generalized building material, one has to realize that all materials have statistical basis. For ductile homogeneous materials, such as steel, variability is small and failure modes can be predicted consistently on a stress capacity basis. For brittle materials, the addition of tension steel has allowed concrete and masonry to be treated in a
similar manner, but adjusted with material safety factors to account for greater variability. The strength of glass is strongly dependent on the distribution of flaws on the surface, such that there can be wide variability of performance and cracks do not necessarily initiate from the point of greatest stress. The combination of variable overall flaw distributions, variable initiation location and variable wind loading to the individual panels has resulted in a history of statistically acceptable usage. Some countries have accounted for this by allowing higher stress for infill panels, but test for peak stress only; ASTM E1300 has adopted Beason’s Glass Failure Prediction Model, which evaluates the distribution of stress over the surface area to evaluate the probability of failure. It is important to recognize that while reducing design stresses or acceptable probability of failure will reduce the number of breakages, that variances in the manufacturing process, inclusions, flaws, installation errors or in-service damage can result in glass pieces with little or no capacity; as such, the traditional design of individual elements to be less than some limiting stress will not guarantee structural reliability.

Glass design practice has the added complexity that due to the technology available in the past, glass breakage and fall out was considered unavoidable and has become accepted in some circumstances. Glass is unique in this respect, and the risk is regarded as acceptable for the transparency gained. When applied to window glass, the formation of cracks usually has a commercial, rather than structural, risk associated with it, and risk to the public is only associated with glass falling to the ground. While some countries in the world now require laminated glass on the exterior, historic inertia and commercial interests often make it very difficult to change practices, including in countries such as the United States. With this in mind, the idea of this brittle material being used for structural purposes in primary or secondary structures has not been codified, nor have the philosophical questions of designing robust glass been addressed.

ASCE 7 seismic design sections consider structures on the basis of the overall system, rather than the individual elements, taking into account the location and likely performance in a partially failed state. For many of the systems, “special detailing” and reinforcement is required to create suitable behavior. Design of glass for structural reliability, as opposed to statistical acceptability, requires similar principles to seismic standards, utilizing system based design with considerations for circumstance, consequence, redundancy, retention and post-failure characteristics.

This paper outlines the concept of Design Classes for structural glass design, outlines the direction for the strength model and provides a ‘roadmap’ for other sections yet to be developed.

A STRUCTURAL GLASS GUIDE/STANDARD

Design Philosophy

ASTM E1300 is used for the statistically acceptable use of glass under uniform load with continuous support on one, two, three, or four edges. The glass failure prediction model on which it is based takes into account not just the maximum stress within the panel, but an integral of the stress and the area applied with a probability function to take into account the flaw distribution of weathered glass. This performs well to define acceptable usage in windows and allows efficient design taking into account that the critical flaw will probably not be at the point of highest stress, as is often observed in testing. This assumption, however, may not be appropriate for design of elements which serve other structural purposes and where failure could cause greater consequential damage. Design of these systems needs to meet the test of reliability rather than statistically acceptable usage. The new standard does not replace E1300, rather it acts as a guide between two philosophically different design methods, separating infill glass from structurally critical glass applications, referring design to E1300 and other existing standards when appropriate and providing design direction when existing standards are not available.

Design of structural glass will assume that the critical flaw may be at the maximum stress location, thus it will be stress-based design. It will also, however, assume that due to inclusions, surface damage, or for whatever other reason, there may be instances where a glass component performs with capacity much less than anticipated. Much of the standard will be about promoting good design practices that ensure robustness and safety, should one component of an element fail.
The 5 R’s of Glass Design

Glass in various circumstances will need to satisfy the 5 R’s of glass design: Resistance; Retention; Redundancy; Residual Capacity; Regulation

Resistance is controlled by strength, stability and serviceability. That is to say, it must be able to resist the loads without breaking: for stability, it must not buckle, and the deformation of the glass structure must be both aesthetically acceptable and compatible with the structure around it; each with appropriate safety margins. The matters of strength are being well-researched, as are the stability behaviors of both monolithic and laminated glass. These technical aspects are common in all building material standards. While lower loads are often used when designing for aesthetic criteria, where deflection can initiate breakage, loads with appropriate factors for strength design need to be maintained. Glass, in part because of its historical usage as a monolithic infill material, now requires new standards to redefine acceptable behavior in both service and post-failure conditions.

Retention is preventing glass from falling immediately if broken. It does not have any specific post-failure capacity other than not to fall to a location of potential human injury during or immediately following the fracture event. Different classes of retention have been identified and will be discussed herein.

Redundancy is where there are alternate load paths in the event that one element or ply is fractured.

Residual capacity is where the element continues to perform a critical function with all plies broken.

Regulations are required to govern when each of these design attributes are required. This takes into consideration not only the size of the element and the load that it is required to resist, but also the location of the element, its circumstance, and the consequences of failure. As an example of how consequence can influence the design, consider a glass fin secondary element supporting 8ft x 5ft sheets of glass on either side. If this element was in a ground level storefront, the consequences of failure could be considered to be minor. However, the same element supporting the same area of glass subjected to the same loads as part of a 100ft high glass wall could cause significant injury should it fail. Thus, the concept of Design Classes is introduced with limitations or requirements for each Design Category and circumstance tabulated.

Glass Design Classes

Design Class A – Unrestricted
Design Class A is for glass that has no specific post-failure requirements. This is similar to the current window glass standards. In the U.S. regulatory environment (and countries using the International Building Code or ASTM’s), this would be covered by ASTM E1300.

Design Class B – Safety Glass
Safety glass is defined as fully tempered (toughened) or laminated glass with a variety of requirements and exclusions in the existing building codes. This standard does not address “safety glass” requirements; rather it acknowledges the presence of requirements at a Code level.

Design Class C – Retention
C1 – The fall area is limited to areas not trafficable by humans, thus fallen glass is retained within an area where it will not cause human injury.
C2 – A second glass unit or safety screen is placed below the glass to prevent broken glass from falling and causing injury.
C3 – Glass that is retained with an adequate organic coating (safety film) which is adequately anchored or contained within the glazing pocket to prevent fall out.
C4 – The glass is laminated, such that glass is not released when one or all components are broken.

Design Class D – Redundancy
D1 – Load can redistribute to a different element (via an alternate load path).
D2 – Multiple discreet elements in parallel. The load is shared between several elements in such a way that if one breaks, the remainder can resist: a.) a non-extreme event; or b.) a design event with reduced safety factor.
D3 – Multiple plies laminated as a composite. For example, a laminated stair tread with the load perpendicular to the plies; the loss of stiffness and strength may be less than (for interior plies) or much greater (for outer plies) than the number of plies broken / the total number of plies.
D4 – Multiple plies laminated in parallel. For example, a laminated fin with the load applied in the plane of the plies: the loss of stiffness and strength is notionally (ignoring the residual capacity of the broken ply) proportional to the number of plies broken / the total number of plies.

As sub-classifications:
D#(a) where the capacity of the system with one ply broken is not required to exceed the unfactored design load, but provides sufficient capacity to resist non-extreme loads and allow replacement;
D#(b) where the ultimate capacity of the system with one ply broken exceeds the unfactored design load.

Design Class E – Redundancy and Retention
The system has multiple load paths and fractured elements are prevented from falling.

Design Class F – Post-Failure Capacity Required
The system continues to have capacity to perform a critical function with all components of an element broken.
F1 – The system continues to have capacity for sufficient time to make safe evacuation or make the area safe.
F2 – Has the capacity to resist a reduced return period design load (say 1 to 5 years) to allow safe replacement.
F3 – It continues to resist design loads with all plies broken (deflection not considered).

**Glass Design Categories**

With the glass characteristics identified, the design elements of occupancy, circumstance and consequence can be introduced and evaluated to formulate Glass Design Categories. One of the best examples regarding building materials that evaluates the effect of failure modes, circumstance, and consequence, are the seismic provisions of ASCE-SEI-7. This standard takes into consideration the occupancy, the seismic loading, the material ductility and failure modes of characteristic structural systems, including materials such as steel, concrete and timber to ensure progressive and proportional collapse. It indicates restrictions and limitations or permissibility of the systems and special detailing requirements for each of the categories. The Seismic Design Category takes into consideration the occupancy, seismic load and ground conditions to be placed in a seismic design category from A to D, where A is the least demanding, and D is in an area of high seismicity and/or adverse ground conditions. For example, ordinary steel concentrically braced frames are not limited in usage for Seismic Design Categories A to C, but are limited to a height of 35ft (10m) for Design Categories D and E and are not permitted in Design Category F. The permissibility of any given system recognizes the failure characteristics of the system as a whole and not just the strength and stability of the building material or individual element. Extensive tables of standard systems are provided in the Standard. Furthermore, extensions in height are permissible with ‘special detailing requirements.’

As noted, the design of glass is not defined entirely by the strength and stability of the system, but also by its failure mode and suitability for circumstance. Hence, it makes sense for a new structural glass standard not only to include the technical aspects of strength and stability, but also guidelines and limitations on what constitutes good design practice for various circumstances. For many common cases, this can be relatively simply and easily defined, however given the specialty nature of high-end glass design, it should also express this in terms of design principles that govern in the general case, so as to continue to allow creative innovation.

While the technical aspects of strength, stability and probability of failure can be determined through scientific and academic testing, the questions of what constitutes ‘good design practice’, ‘acceptable failure modes’ and the amount of post-failure capacity required are somewhat more philosophical.
As examples of variation in accepted practice in window glass usage, some countries require external laminated lights in high rise structures while others require tempered ‘safety glass’ with the risk of spontaneous fracture and fall out. Some codes around the world, the United States included, continue to consider fully tempered glass as presenting a low risk when it fractures into ‘small harmless dice.’ Monolithic fully tempered glass is currently allowed for glass balustrades (but it has been proposed that it will be prohibited for risky areas in IBC 2015.) However, the mechanical interlock of the dice, particularly in larger thicknesses, causes the fractured fully tempered glass to remain in ‘clumps’ until they are disturbed by impacting a surface. If that surface happens to be a person, there are many documented cases of severe and critical injuries. Unfortunately, when this occurs, and particularly when it makes front page news, it reinforces the public’s opinion that glass is not a safe material for building construction. Conversely, while it would be easy to say “all glass should be laminated,” this approach must be weighed against the economic costs and evaluation of the risks. Thus it is not practical to take such a simplistic approach.

It is the opinion of the author that there are times when each of the Glass Design Classes identified earlier in the paper have appropriate usage. The philosophical dilemma is how to classify the Design Category boundaries and limitations for each Class. The following are some generalized rules:

- Glass that is not laminated should either be supported in a system that promotes a stable fracture pattern or in a location where breakage has limited consequence. As examples of this, fully tempered glass structurally bonded in a vertical insulating glass unit (IGU) tends to retain the glass following fracture, so has traditionally been considered acceptable since it often (but not always) gives time following failure for the unit to be stabilized or the area made safe prior to its collapse. As another example, a monolithic glass fin in a storefront with the highest point less than 3m (10 ft) from the ground has a limited risk in the case of a fracture event. Designers may of course choose more conservative solutions and certainly design guides should recommend them, however building standards need to define minimum requirements for the mandatory sections as a responsibility to cost-efficient design to society.
- Monolithic glass that has free edges will generally not have a stable failure pattern. Thus it should have secondary retention when the highest point is greater than 3m from a trafficable surface or as appropriate. Current provisions in the International Building Code require retention by screens or lamination for glass at an angle of greater than 15° from vertical, however vertical elements with free edges are also unstable when fractured, so should have a similar provision.
- ‘Safety Glass’ provisions can be complemented by the concepts of retention and redundancy requirements rather than treating laminated and fully tempered glass as similar.
- Testing of structural glass assemblies should either be required or promoted through the use of load factors that penalize untested designs.
- Load factors can be used to improve reliability (or reduce the probability of failure), however the possibility of random fracture, however so caused, cannot be excluded in any type of glass. Good design practice should ensure that systems continue to function (or fail in an appropriate manner) should one component have little or no capacity. The level of load factor required may be a function of the level of redundancy embodied in the system, such that a system with high redundancy has a commercial advantage over systems with little or no redundancy.
- Glass design has traditionally recognized any fracture as a failure, however to fully evaluate the safety of the system, the structural capacity of the system in the non-fractured, partially fractured and fully fractured states need also be considered. Appropriate design loads to be considered for each of these states may vary with circumstance.

This final element raises an area of glass design which is rarely considered in architectural building applications. The design of glass in the fractured state as a compression element with a secondary reinforcing tensile element, be it an interlayer or a high-tensile element, is somewhat akin to reinforced concrete design. Utilization of glass in the broken state is already considered in applications such as hurricane glazing and also in automotive windshield applications where the bonded, laminated glass is utilized as a sheer diaphragm to prevent sway collapse of the roof in rollover accidents. A method for analyzing glass in the fractured states still needs further investigative study before design calculation methods can be fully utilized. Until that time, some design requirements may continue to require destructive test-
ing for justification. Many destructive test methods are already described in ASTM standards and elsewhere. Additional test methods may be required as part of a suite of standards relevant to structural glass design.

**Some Preliminary Design Criteria**

A survey was conducted amongst design professional and members of several standardization committees in the United States and internationally. As a result of the survey, the following criteria were found to have a good level of agreement in determining general design principles. Actual language for the guide is yet to be drafted.

1. Is it part of the overall stability system? If so, full capacity of the system is required with the element fully fractured (all plies); element(s) must have residual capacity when fully fractured (Class F), or; system has alternate load paths with adequate factor of safety with one element missing (Class D1).
2. Does the element support live load? If so, the element must be adequate (ultimate) with a sacrificial ply (per ASTM E2751 Design and Performance of Supported Glass Walkways). Test to (unfactored) design load with critical ply broken; no further breakage allowed (Class E).
2a. Is the element likely to have a substantial period without observation of defects? If yes, adequacy for a limited period with all plies broken may be required.
3. Are there people under the element? Retention is required to prevent broken glass falling on people (Class C).
4. Are there people under other parts of the system supported by the element? Redundancy and retention (Class E) is required such that the loss of one element in its entirety does not cause consequential collapse or risk to people.
5. Do other elements rely on this element? How high is it?
   a) If there is immediate collapse without element: If the highest point is greater than 3m then redundancy and retention (Class E) is required; If less than 3m, then redundancy (D) only required
   b) Reduced capacity without element (i.e. system has capacity for 6 month return loads without element): If higher than 3m – retention (Class C); If less than 3m – no requirement (Class A/B)
6. Will the fractured state be unstable? No: design as window glass using probabilistic acceptability (per ASTM E1300), Yes: If the element is above 3m, provide retention (Class C), If the element is below 3m, design as window glass (A/B).

The design classes will typically control the ‘special detailing’ and ‘minimum reinforcement’ requirements, but it is intended that these will be performance-based criteria and should not limit the creativity of the designer. Indeed it is intended that by creating a set of criteria by which glass can be designed, tested and used with confidence, it will promote the adoption of glass as a structural material.

**Load Resistance Models**

Design of window glass and glass that is in Class A or Class B will continue to be designed to ASTM E1300 using the failure probability model as the most efficient and effective way to assess acceptability of behavior, while recognizing that there is a probability (and possibility) of breakage.

For systems requiring structural reliability, stress based design assuming the critical flaw at the critical location will be used. As glass has no ductility and remains elastic to the point of failure, glass does not offer the possibility of load redistribution and breakage is sudden. Additionally, while window glass is designed primary for wind load, glass as a general structural material will be required to support loads with different probabilities of exceedance. Load and Resistance Factor Design is considered to be appropriate for general structural design.

The draft Euronorm prEN 16612 Glass in Buildings provides a good starting point for an LRFD glass code. It provides a characteristic strength, partial material reduction factors and load factors. As the strength of glass is affected by surface pre-compression and load duration, both of these phenomenon are taken into consideration. While the load factors used are different than used by ASCE-SEI-7 and IBC, it can be demonstrated that in general for the relevant loads, load durations and IBC load factors, that the peak stresses allowed by formulas in prEN16612 are similar, somewhat more conservative than design by stresses in ASTM E1300-12a1 Appendices X6 and X7. In addition to sat-
isfying the philosophical differences regarding the location of the critical flaw associated with the LRFD model, using the peak stress as the failure criterion also significantly simplifies the calculations by removing Brown’s integral of stress, area and time from the analysis.

Areas where the structural glass standard is likely to differ from prEN16612 include:

- Load factors will be consistent with ASCE-SEI-7 and IBC
- The process for combining loads of differing durations, where the principles of Appendix X5 in ASTM E1300 are likely to be maintained as a materials reduction factor but only to the component of the strength associated with surface tensile capacity.
- Additional partial factors will be included for systems that are required to have greater reliability.
- Additional test methods for will be created and referenced for systems that are not able to be determined by analysis, or are deemed to be sufficiently variable as to require testing (point fixings for example.)

Good structural glass design has often required testing for structural verification. ASTM standards for glass balustrades and flooring rely entirely on testing. There is an aim that some predictive modeling for post failure behavior will be described, so that the designer will have a basis for calculation prior to commissioning testing. There is a possibility that for certain configurations and circumstances a penalty factor may be used in place of testing. Additionally proprietary systems may, through extensive testing, have an ability to get certification to allow design without further testing.

New test methods will be required to determine: the stability of fractured state, post-failure capacity etc. but these remain as items to be developed.

The stability of monolithic glass follows the standard theories of lowest energy states, however with laminated glass the development of stiffness becomes geometry, time and temperature dependant. It is likely that conservative assumptions will be recommended for loads other than wind load so as to maintain simplicity.

For systems that follow common configurations, for example glass fins, load bearing walls and shear diaphragms, there is an aim to have appendices offering specific guidance.

CONCLUSION

Glass is a material that has been utilized for its transparency, but also has excellent capacity in compression and a limited capacity in tension. Specialist glass structures around the world have demonstrated its ability to be used as a structural element, not just as a cladding or infill element.

The widespread usage of glass as a structural element has been limited by the lack of design standards. This has prevented the adoption of the material by non-specialist engineers and designers and also limits the ability of building authorities to evaluate structures, even those designed by glass specialists. In some cases, the lack of a design standard has resulted in the construction of inadequate ‘copycat’ installations.

The public perception of glass as a structural material has been greatly enhanced by high-profile projects such as the Apple staircases. Conversely, the public perception that glass is either unreliable or dangerous is reinforced by practices such as monolithic tempered glass balustrades falling off buildings.

It is the hope of the author that a new guide for structural glass can promote good design practices and preclude potentially dangerous ones. There are aspects of glass behavior that remain “predictably unpredictable”, however taking this into consideration with the technologies and design principles that are now available to us, it is possible to develop systems and elements with appropriate robustness and reliability.

Many standards around the world have attempted to reconcile what is scientifically justifiable with what is known to be statistically acceptable usage in common applications such as windows. The proposal of the author to the ASTM
committee is that these things should be treated as separate, with the probabilistic class failure prediction model continuing to be used for window glass design and stress-based reliability design for glass structures.

Good global structural system design will take into consideration circumstance, consequence, failure characteristics, and overall system performance to facilitate the design of advanced and exciting glass structures. Putting these principles in a standard/guide will enable designers and owners to design glass with confidence.

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Solar Power - Investment for the Future

James R. Gulnick, USA

Abstract
Solar power is an attractive and environmentally friendly investment that helps lower utility costs, creates a positive cash flow, and builds corporate stewardship. This paper looks at the ins and outs of making a photovoltaic system decision, discusses the financial implications, and provides the results of an actual case study. The yearly environment benefits include energy and pollution reduction, greenhouse gas avoidance, and carbon offset. McGrory Glass, Inc. put in place investments to allow it to serve the industry long-term such as a 30 year high efficiency roof with a photovoltaic system featuring US made Sharp modules that will pay for itself in less than ¼ of the time with positive cash flow from day one.

Keywords: solar, investment for the future, environment, stewardship, Sharp

Background
Bill Hoy thought to himself as he sat at his desk in his medium sized glass fronted office. His hardwood desk faced the sharp and distinctive obscure all glass office front. Silhouetted against a bronzed light which streamed through the tinted windows, Bill contemplated the next investment for McGrory Glass.

In his time with the company, he had seen it grow in capabilities, employee experience, and market reach. The company continued funding new technologies, acquiring top industry knowledge, and penetrating new sectors with its products and services. Where could McGrory get a big bang for its buck?

As the sun streamed through the windows warming the back of his light blue, buttoned-down collar, short sleeved shirt, an idea hit him. Or maybe it was a few million photons that were converted to heat as they warmly lit his back. What if McGrory were to become self-sufficient and 100% powered by solar energy? Was it even possible? What would be the return on investment? How would he even begin to research the idea?

Bill jumped out of his seat and onto his feet to find a fellow employee. Three offices down, machinery drawings around, amidst proprietary process documentation, I busily formulated new procedures to temper anti-reflective glass (<0.5% reflectance) without compromising optical qualities.

Bill appeared in the doorway asking, “What do you think about solar power?”

The above inquiry led to an initial level of interest and thorough investigation into the financial implications of a photovoltaic system project.

Commercial rooftop photovoltaic systems may appear to create a valuation obstacle but may be straightforwardly investigated with the use of a discounted cash flow analysis (Klise, Johnson, & Adomatis, 2013). Expenses were the cost of the system, its operation, and maintenance. Financial benefits included a 30% grant from the government, Solar Renewable Energy Certificates (SRECs) sold to the utility market for every megawatt-hour of solar electricity generated (1 SREC = 1 Mwh of solar electricity generated), and utility offset for the power used that did not need to be purchased from the local utility company. A worksheet was created to evaluate the opportunity and environmental commitment. The first ten years of the project financial analysis are shown in Figure 1. The worksheet shows updated and realistic figures for utility offset and SREC revenue.
Financial Analysis
A Solar Company

Model Assumptions

| Performance: 100% of Expected production | Financial Statistics: Net Cash Flow 1,369,374 |

Utility Cost:
- 2% annual increase
- Payback Period: 6.3 years

SREC: FLAT $150 per year
IRR: 29.50%

Financing:
- 6 years @ 4%
- Principal Payments
- Interest Payments

Present Value: $744,331.54

Year | KWH Produced | $ per KW | Avoided Cost Utilities | SREC Price | # of S REC Revenue | Total revenue | Less Expenses | Net Income (Loss) | Tax Benefit | Add back: Depreciation | Net Cash After Taxes | Cummulative Net Cash Flow after Taxes |
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<td>61,360</td>
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Debt Service

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<td>280,206</td>
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<td>22,603</td>
<td>280,078</td>
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<tr>
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<td>285,214</td>
<td>9,437</td>
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<td>280,085</td>
<td>280,085</td>
<td>280,085</td>
</tr>
</tbody>
</table>

Figure 1. Financial Analysis for A Solar Company Project

Making a Photovoltaic System Decision

The next step after a first look and positive opportunity evaluation was to get a few proposals on the project. A simple RFQ was put together asking each bidder to maximize the generation from the existing roof. Various configurations of various sizes and capacities were proposed. Pricing was received ranging from $3.65 to $4.15 per watt. The merits of each proposal were compared to assess the options on an equal footing. Differences in design, materials, installation, and warranty were noted. Important items such as photovoltaic panel and inverter brands were weighed as well as the mounting schemes, and overall system production. Initial assessment of a solar project focuses on the cost per watt and the robustness of the system. Figure 2 shows the initial assessment used to generate the next round of questions and negotiations.
As evaluated with available 2011 data, commercial sized photovoltaic system projects are cost effective when sun-sourced, self-generation, renewable energy installation paybacks are calculated utilizing comparisons based on retail energy costs, however, these projects still remain cost ineffective for utilities themselves to be able to justify the investment (Reichelstein & Yorston, 2013). Return on investment for companies depends critically on federal funding and incentive program availability as well as the geographic location of the project (Reichelstein & Yorston, 2013). Beyond the incentives made available by the U.S. federal government, businesses are able to recover photovoltaic generation projects in as little as five years through the federal Modified Accelerated Cost-Recovery System (Storey, 2012).

A solar project is an iterative process. Available space, generation capacity, energy needs, and financial commitment must be weighed. The first round of proposals yields additional questions as the learning organization becomes better versed on the obstacles and opportunities. This is where solar panel and inverter manufacturer brand names become investigated as the heart which pumps future revenue streams. Warranties, company history and strength, references, and past track record of smoothly run projects are all central to the decision. Figure 3 presents a blank copy of the solar project assessment which was used to further refine and zero in on the successful partner.
### Solar Project Assessment

<table>
<thead>
<tr>
<th>Company</th>
<th>D</th>
<th>E</th>
<th>F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strength/D&amp;B</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diversity of Bus.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Employee Strength</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Experience</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Years in Business</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Location</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Project base</td>
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</table>

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Make</th>
<th>Spec</th>
<th>Warranty</th>
<th>Make</th>
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<th>Make</th>
<th>Spec</th>
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</thead>
<tbody>
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<td>Panel/W</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inverter/W</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Computer/RIU</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Support/Racks</td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
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<tr>
<td>Monitoring Equip</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Licensing/Cost</td>
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<tr>
<td>Misc.</td>
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<tr>
<td>Misc.</td>
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<table>
<thead>
<tr>
<th>Installation</th>
<th>Who</th>
<th>Relationship</th>
<th>Responsibility</th>
<th>Warranty</th>
<th>Visit Assessment</th>
<th>References</th>
<th>Union/Non Union</th>
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</table>

<table>
<thead>
<tr>
<th>O&amp;M</th>
<th>Equipment</th>
<th>Monitoring</th>
<th>Included</th>
<th>Contract Cost</th>
<th>Location</th>
<th>Ongoing Costs</th>
<th></th>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Financial</th>
<th>Installed kW</th>
<th>SRECs/Year</th>
<th>Watt/Panel</th>
<th>Number of Panels</th>
<th>Area covered</th>
<th>Total price</th>
<th>Price/Watt</th>
<th>IRR</th>
</tr>
</thead>
</table>

**Figure 3.** Solar Project Assessment Focused on Company Strengths
System Decision
After careful review and continued negotiation with two vendors, one was finally selected. The price per watt was higher than originally proposed but with McGrory’s blessing as made in the USA Sharp modules were selected over cheaper imported brands. If Sharp modules were good enough for the space station, they were good enough for McGrory. The system was installed during January through May of 2012 with official start up in June of 2012. The final size was 653.77 kW with 2782 Sharp modules of 235 Watts each. First year production was as predicted with total production in 2013 at just over 100% of estimate. The power output for 2013 plotted along predictions are shown in Figure 4.

Figure 4. 2013 Power Output by Month with Predicted Estimates in Blue

Environmental Impact
McGrory’s photovoltaic system generates enough clean energy each year to operate a television for over 5.5 million hours, reduces the emission equivalent to what is created by 431 cars in one year, and produces enough energy to power over 6 thousand computers each year (Figure 5.). The system reduces substantial amounts of carbon dioxide, nitrous oxide, and sulphur dioxide that would have been produced by coal and gas fired power plants otherwise. The carbon offset alone provides a reduction equal to that of 130 acres of trees.

Figure 5. Over 5,500,000 TV Hours, 431 Cars, and 6,000 Computers Each Year

Summary
Deciding to make a solar power investment can be an overwhelming decision. Fluctuating markets for SRECs, government incentives disappearing, and unknown utility prices make for unclear forecasts. With all that in mind, the results may be promising. For McGrory, financial payback is predicted within 7 years. The 653.77 KW of generating power provides 800 megawatt hours of annual production, creates net zero energy consumption, and reduces the facility’s carbon footprint to nil. At 2.3 acres or 100,000 square feet of solar roof coverage, the 30 year white heat-reducing roof with 6 inches of insulation increases panel output by 2%. Furthermore, at an atypical 15 degree panel angle, the system nets and additional 2.5% increased efficiency. Finally, the 2782 Sharp made in USA modules give the company peace of mind as it invests in renewable energy as part of its continuing corporate stewardship program.

References
Threshold: When Does a Reflection Become Noticeable?

James R. Gulnick, USA

Abstract
This paper will discuss the uses of anti-reflective glass, the theory and referenced material behind threshold, and the implication of threshold in the design and specification of anti-reflective glass in various architectural applications. Humans have the ability to discern color and contrast but there is a range of differences in colors and contrast that are unperceivable to the human brain. The signal strength between the differences has to be great enough for the mind to be able to conclude there is a difference. This phenomenon is known as threshold. This threshold phenomenon is what sets anti-reflective glass types apart. Reflections become unnoticeable when they cause a contrast or color deviance of less than 0.5%. In environments where the glass has been designed for high transparency, the light levels are similar on both sides. This is why it becomes important to utilize materials with the lowest reflectivity possible to minimize the chance for distraction.

Keywords: anti-reflective, threshold, architectural glass, perception, contrast

Anti-reflective glass is widely used in architectural applications such as storefronts, restaurants, display cases, radio and TV studios, museums, office fronts and everywhere separation is required without reflection. The goal of anti-reflective glass is to enable views without distraction, protection without obstruction, and visual impact allowing focus on the design and not the glass. Brightly lit displays will appear open and inviting. Each sheet of anti-reflective glass undergoes an expensive and advanced coating process to provide greater light transmission. The reduction of reflection can make it seem as if there is not any glass between the observer and the items on display in the store, the antiquity being exhibited, or the art on the wall. It can be as if the glass isn’t there!

Threshold: When does a Reflection Become Noticeable?
Humans have the ability to discern colour and contrast. For every light level, there is a range of colours and contrast differences that are unperceivable to the human brain. The signal strength between the differences has to be great enough for the mind to be able to conclude there is a difference. This phenomenon is known as threshold.

One of the standard measurements in colour matching taken from the textile industry is delta E (dEcmc) which is a calculation combining lightness or contrast and colour variance (Hunt, 2004). While differences in contrast are more allowable than colour, there is an acceptable range set in commercial applications. Colour specialties industry standard treats a deviation of less than 0.5% dEcmc as being an indiscernible colour and contrast difference (Green, & MacDonald, 2002). However, not all eyes are the same.

In regards to contrast, the difference in lightness and darkness, there needs to be greater than a 1% difference in order for humans to see an apparent difference nearly 100% of the time (Malm, 1999). According to Malm (1999), in cases of contrast level differences of less than 0.5%, the difference becomes not noticeable to nearly everyone:

- Under 0.5%, the reflection (contrasting light) becomes unseen
- Above 1.0%, the reflection (contrasting light) becomes 100% noticeable

Contrast Threshold of 1%
The ability to detect contrast differences is based upon visual perception sensitivity and delineates the threshold between what is visible and invisible (Pelli & Bex, 2013). Since 1860, scientific tests and research have found and maintained that threshold contrast levels necessary for something to be seen is 1% for most objects within a wide variety of environments (Pelli & Bex, 2013). A thorough review of past measurements show that the threshold contrast has remained at 1% independent of dimensions and light levels (Pelli & Bex, 2013).
The simple test used for research of this phenomenon consists of two candles of the same light level being used to illuminate a screen or wall. One has a simple solid and opaque cylinder placed in front to cast a shadow on the screen. By varying the distance of candles from the screen until the shadow is perceived or not perceived the ratio of light between the unobstructed screen and the shadow cast on the screen can be calculated. The amount of light difference along the edge of the shadow is determined by the far candle with the opaque cylinder in front as the amount of light from a point source varies as a function of the inverse of the distance squared (Pelli & Bex, 2013). The measurement of threshold comes at the point when the observer can just barely see the shadow.

This technique consistently results in observation of a 1% threshold (Pelli & Bex, 2013). Other methods such as using a spinning disc with a black section of a slice that when spun created a black ring have also shown this 1% level as the threshold over a wide range of light levels (Pelli & Bex, 2013).

**Colour Threshold of .44% to .69%
**

Colour differences are detected similarly to differences in contrast but become noticeable when the perceived colour shifts (not just brightness level) enough to reach threshold. The human eye detects colours with differing specialised receptors which are excited by blue, green, and red wavelengths of light. Each receptor reacts similarly to colour and light level changes but follow the same general rules as threshold for contrast.

The required level of cone excitation change for threshold detection of colour signals remains equal for a given background excitation level (Jennings & Barbur, 2010). Each cone reacts independently of each other in the level necessary for detection enabling predictive modelling of detection thresholds necessary for any specified background light level and colour (Jennings & Barbur, 2010).

S-cones are excited by blue wavelengths, M-cones are excited by green wavelengths, and L-cones are excited by red wavelengths. Research supports a significant and strong linear threshold relationship (r^2= .90 and .94 respectively) between the M- and L- cone excitations changes required to differentiate between foreground and background colour and brightness levels (Jennings & Barbur, 2010). Blue cones are much less sensitive to excitation changes. The M (green) and L cones (red) required approximately .44% - .69% excitation change to reach threshold levels necessary to be detected (Jennings & Barbur, 2010).

Light is always reflecting from glass surfaces. The question is whether it is visible or invisible to the observer. When the level of reflection does not reach threshold, it is said to be invisible. The contrast threshold of 1% and the colour threshold of .44% - .69% interplay in the effect reflections have on the observer when looking through glass. When the reflection causes a combined light or colour level difference that reaches threshold, the reflection becomes noticeable.

For simplification purposes, under .5% has been selected as below threshold for contrast and colour as represented in the findings of the referenced studies. Similarly, 1% threshold is presented as a level of contrast or colour difference where the change in level is apparent and seen by 100% of normal observers. It is important to understand these ranges in respect to reflection. The reflection is analogous to the light shadow cast by the far candle in the prior referenced example. Reflections cause changes in perceived light levels, contrast, or colours if they reach the threshold level.

**Not a Reflection of You**

Invisible storefronts create a unique aesthetic appeal. With reflection reduced by up to more than 16 times when compared to uncoated float glass, product displays pop and architectural designs transcend nature. The store blends effortlessly with its surroundings becoming one with the square. Foot traffic swells. As a natural result your client smiles.

Views become breathtaking through anti-reflective glass. The type and application of anti-reflective coating can provide glare-free glass storefronts with visible light reflection ranging from less than 0.5% up to 4% as well as produce little to no discernable colour shift. Anti-reflective storefronts are available in monolithic, tempered or laminated, and insulated units. With large formats also available, the many fabrication options give unrivalled flexibility in aesthetically pleasing applications. Many glass fabricators stock and custom process anti-reflective glass to bring life to architectural designer creations. Imagine an environment where beauty flows effortlessly together without the harsh reflections of unforgiving float glass. Figure 1 is an example of how anti-reflective glass creates separation without reflection.

**Figure 1. Anti-Reflective Glass Example**

Today's anti-reflective coating technologies produce glass that limits glare and unsightly reflections in numerous unique applications. These high-tech coatings remove glass...
distractions from picture frame glass allowing the artwork to leap off
the wall and become the focus of attention. Anti-reflective
storefronts invite customer attention and welcome passers-by to
come in and shop. When used in projection systems or displays,
the light or visual media smoothly transmits through the glass
capturing the viewer’s attention without double images or visual
light-front interference.

**Transparent Communication**
Restaurants, boutiques, and image-conscience retail shops require
their carefully-designed, visual display elements to be
communicated in the most favourable light. Glass provides a
weather-tight, physical barrier that still maintains a visual
connection between the public and the store. Unfortunately,
traditional glass also creates a secondary plane of focus pulling
attention away from what is in the store to the reflections on the glass surfaces.

Anti-reflective glass can virtually eliminate the reflection enabling the store’s inner beauty to speak for itself.
Traditional glass reflects 8% of the visible light. What does this really mean in real life? Only 92% of the outside light
source reaches the inside of the storefront and provides a maximum potential for surface viewing through the same
glass of 84.6% since 8% of light suffers from internal reflection on the way back out. Maximum illuminance becomes
100% when no glass separates the light source and the object and no glass or substance separates the object and
the observer.

**Brightness and Reflection Issues**
The relative brightness of typical outside ambient light is 10 to 300 times brighter than inside lighting on overcast and
sunny days. Figure 2 indicates some common lighting situations and the relative brightness. The impact that the
interior lighting has on noticeable reflectance is negligible for a majority of occurrences. And, when a store is lit up at
night, the inner beauty of the store is released to the street in awe inspiring artistry especially with anti-reflective
glass.

**Figure 2. Relative Brightness of Common Lighting Situations**

<table>
<thead>
<tr>
<th>Lighting Examples</th>
<th>Relative Brightness</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bright Sunlight (Beach)</td>
<td>100000</td>
</tr>
<tr>
<td>Diffuse indirect sunlight</td>
<td>20000</td>
</tr>
<tr>
<td>Overcast day</td>
<td>15000</td>
</tr>
<tr>
<td>Jewelry Making, Small Models</td>
<td>1500</td>
</tr>
<tr>
<td>Restaurant Food Prep</td>
<td>750</td>
</tr>
<tr>
<td>Workshop, Blueprint</td>
<td>750</td>
</tr>
<tr>
<td>Study, Bath, Kitchen</td>
<td>350</td>
</tr>
<tr>
<td>Torrential rains and dark clouds</td>
<td>200</td>
</tr>
<tr>
<td>Dining, Entertaining</td>
<td>150</td>
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<tr>
<td>Walking Traffic</td>
<td>65</td>
</tr>
</tbody>
</table>

**Distractibility Index**
The direct reflection ratio allows comparison of visible light-front distraction between differing solutions. This ratio of
“reflection annoyance” can be measured and provide a “distractibility index” to compare different solutions. Simply
put, the amount of reflection divided by the amount of maximum illuminance gives a ratio that is measured on a scale
of 0 to ∞. Zero would indicate that there is no reflectance no matter how much light reaches the objects within the
storefront and back out to the observer. Infinity would indicate a perfect mirror where all light is reflected at the glass
storefront and no light reaches the objects within the storefront and back out to the observer.

How does anti-reflective glass impact the visual presence of a store, display, or building? When undistracted viewing
is desired, finding a solution that provides the minimum colour, contrast, and brightness differential is the answer. In
the real world, the architect and designer have limitless options at their fingertips. Figure 3 is a real life example of a
storefront with a high performance anti-reflective coating that has visible light reflectance equal to only 0.5%. It allows
display merchandise to be protected from the elements while the colours, textures, and beauty are breathtakingly
presented without glare to distract. Storefront with Anti-Reflective Glass
Direct Reflection Ratio

DR = Direct Reflection (% of Source)

MI = Max Illuminance (% of Source)

DIR = DR/MI = Direct Reflection Ratio

As previously discussed, monolithic float glass has visible light reflectance of 8%. A maximum of 92% of the outside source light reaches the objects within the storefront. Additionally, the brightness of the image of the objects as seen by the outside observer has been reduced by another 8% as the light passes again through the glass and another 8% of the visible light reflects back into the store.

Now, let’s calculate the ratio for a storefront with uncoated monolithic float glass:

DIR = DR/MI = Direct Reflection Ratio

Direct Reflection Ratio = 8%/84.6% = 9.5%

In this example, the amount of reflection distracts the observer from the object displayed within the storefront. The direct reflection already peaks at a substantial 8%. But since the maximum illuminance is only 84.6%, the effect of the reflection is 9.5% of the value of maximum illuminance. When an object is brightly coloured the reflection annoyance is bad enough, but when a darker coloured object with fine detail and nuances is displayed, the “distractibility index” understates the problem.

Now, let’s calculate the ratio for a storefront the uses monolithic anti-reflective glass as shown in the photo:

DIR = DR/MI = Direct Reflectance Ratio

Direct Interference Ratio = 0.5%/99% = 0.51%

In this example, the lower amount of interference does not distract the observer from the object. The difference in “distractibility index” can be significant and the ability to see the item on display is increased dramatically. The two examples show a 1900% difference in harsh glare and bouncing light. Anti-reflective glass provides this type of benefit. The lower the direct reflection ratio of the anti-reflection glass, the higher the ability of the observer to focus on the objects displayed within the storefront.

### Distractibility Index

<table>
<thead>
<tr>
<th>Type of Glass</th>
<th>Reflectance</th>
<th>Max Illuminance</th>
<th>Direct Reflection Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-Reflective</td>
<td>0.5%</td>
<td>99.0%</td>
<td>0.5%</td>
</tr>
<tr>
<td>Anti-Reflective</td>
<td>1.0%</td>
<td>98.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Anti-Reflective</td>
<td>2.0%</td>
<td>96.0%</td>
<td>2.1%</td>
</tr>
<tr>
<td>Anti-Reflective</td>
<td>4.0%</td>
<td>92.2%</td>
<td>4.3%</td>
</tr>
<tr>
<td>Float Glass</td>
<td>8.0%</td>
<td>84.6%</td>
<td>9.5%</td>
</tr>
<tr>
<td>Reflective</td>
<td>20.0%</td>
<td>64.0%</td>
<td>31.3%</td>
</tr>
<tr>
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<td>40.0%</td>
<td>36.0%</td>
<td>111.1%</td>
</tr>
<tr>
<td>Reflective</td>
<td>60.0%</td>
<td>16.0%</td>
<td>375.0%</td>
</tr>
<tr>
<td>Mirror</td>
<td>100.0%</td>
<td>0.0%</td>
<td>∞</td>
</tr>
</tbody>
</table>

This threshold phenomenon is what sets anti-reflective glass types apart. Reflections become unnoticeable when they cause a contrast or colour deviance of less than 0.5%. In environments where the glass has been designed for high transparency, the light levels are similar on both sides. This is why it becomes important to utilize the lowest reflectivity possible to minimize the chance for distraction. The difference between 1.0% and 0.5% may not seem like a lot, but it is the difference between a reflection being 100% perceived and nearly imperceptible. In other words, 0.5% is nearly 0% and 1% is 100% - a huge difference in perception for such a small difference in surface reflection.
Figure 4 shows a white block transition within the darker rectangle above. The left most line represents 0% reflectance/contrast whereas the far right line represents 4% for the transition with the line segments shown. 100% of people surveyed saw contrast differences above 1% (third line from the left). To the left of the second line, the white block became completely unseen.

**Summary**

The long and the short of it is that anti-reflective glass is great when focus needs to be on the objects within the storefront, office, or display and not on the glass. Anti-reflective glass provides beauty by being invisible. It is most valuable when noticed the least. Anti-reflective glass allows more of what is being looked at to meet the eye.

**References**


Glass Structures and Seismic Design in the US: Towards a Practical Approach

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Abstract
The possibilities for use of structural glass are ever expanding and are increasingly enticing to US designers. Despite this, there is a lack of familiarity among designers in the architecture and engineering communities regarding what is possible with structural glass, particularly in regions subject to high seismic loading. Combined with the absence of a US glass design “code”, practicing engineers are faced with challenges on every project, from design through permitting.

The challenges of glass and façade design in regions subject to high seismic loading will be presented. The benefits and challenges of incorporating all façade elements- including structural silicone- to obtain realistic system displacements during a seismic event will be reviewed using the Governor George Deukmejian Courthouse in Long Beach, California as an example.

Keywords: codes, seismic design, testing, practicing engineer

1 Background
The use of glass as a structural material in the United States is a fairly new phenomena in the architectural and engineering industry. While glass structures were built in the 20th century, the medium has been pioneered in a much more visible way by the iconic Apple stores [1] and similar recent structures. Glass as a structural material allows architectural designers the ultimate leeway in regards to transparency and the image of “floating” or non-existent structure.

For some engineers design of glass is an opportunity- for others an unapproachable challenge. There is little guidance in the US for design of glass as a structural element, and there is an even smaller knowledge base among engineers regarding how glass and laminates behave as materials. Understanding failure mechanisms and structural response under different types of loads is a pre-requisite for thorough understanding of the logic behind codes or other design guidelines, and form the basis for sound design practice.

There is a broader knowledge base in foreign design and academic communities, and more guidance in the form of codes for glass design. These resources are invaluable for US engineers, but there are still gaps in the knowledge base. In particular, design of glass structures in high seismic regions requires careful
detailing and significant thought regarding structural behavior- an aspect of design not always covered by foreign codes.

The purpose of this paper is to outline some of the barriers to design of glass as a structural material in the US and particularly in high seismic regions, provide examples of how some of these barriers have been overcome, and to suggest potential solutions for moving beyond these barriers. These suggestions should be seen as part of an explicit attempt to engage the design and academic communities in the US and internationally in a discussion about how to generate a deeper understanding of glass as a structural material in the US, which will help to alleviate some of the barriers to the use of glass in structural applications. In expanding the US knowledge base around these subjects and potentially spurring increased interest in academic communities, we consider it crucial that elements of design, detailing, and testing unique to regions subject to high seismic loading do not get lost.

This paper is written from the perspective of a practicing structural engineer. It does not attempt to describe all of the sources of information currently available for the design of glass, nor does it describe every effort currently being made to develop codes or standards.

2 General Challenges and Barriers

Challenges to the design of glass in high seismic regions generally fall under three categories- deformation compatibility, lack of knowledge regarding material behavior, and lack of code guidance. While they can be overcome, these challenges create barriers that design engineers must face on every project. The first two categories- deformation compatibility and material behavior- are dealt with during the design phase of a project and are often hashed out in the engineering office environment, sometimes with input or guidance from another professional in the field but often on the basis of shared, in-firm engineering experience. Because the extent of glass structural design in the US (and internationally) is relatively small and because glass as a structural material is not taught in schools, this engineering experience is limited to a small number of individuals at a small number of firms.

The current insular knowledge base means that there are not many examples to draw from or booklets of “standard practice” that engineers can utilize during the design process, creating the potential for designs that do not appropriately accommodate seismic drifts or do not correctly apply allowable design values noted in the appropriate standards. The work of the COST Action TU0905 [2] group in Europe, Glass Performance Days, GANA, and other organizations and individuals have helped to raise interest in structural glass, but there is still much work to be done to generate further interest and broaden the knowledge base in this subject in the US.

Research and testing on glass structures in the US has primarily been paid for and completed by private entities on a project-by-project basis. Results of these tests are not typically published and are not readily available for other engineers to learn from. While this is understandable from the standpoint of private engineering firms and owners who would prefer to keep specific types of
information proprietary, it creates an impediment for forward movement on the use of glass as a structural material.

This general lack of understanding of glass- combined with the third category- a lack of code guidance- means that mistakes or potential problems may not be caught by jurisdictions or peer reviewers. To date, there have not been any major structural glass failures that have lead to heightened scrutiny or concern within the industry, but this does not mean that strides could not be made towards a better understanding of structural glass design within the engineering industry. For structural glass applications in both high seismic regions, the design through permitting process would be far easier if design professionals and reviewers had a base level of familiarity with glass as a structural material.

The lack of code guidance has implications on the design side that have been alluded to- namely, engineers designing structures without sufficient knowledge or guidance to fully understand what they are doing. There are further implications for projects in jurisdictions where permitting officials strictly interpret code requirements. As further elaborated below, there is no official code guidance for design of structural glass in applications other than vertical glazing. This can force expensive and time consuming testing of glass structures that can otherwise safely be calculated, but for which there is no “official” code that guides the calculation.

**3 Drift/Deformation Compatibility**

A critical aspect of design of glass and related facade systems in high seismic regions is the accommodation of deformations in the supporting structure induced by seismic loading. Accommodation of these deformations can be required within the system itself- i.e., providing a glass pane in a frame loaded in-plane with enough space for the frame to deform around and not crush the pane- or can occur between elements of the structure, such as providing a slip joint between a glass fin wall and the structure above or below the fin.
Figure 1. Graphic illustrating glass pane and frame displacements. Used to determine the required clear distance around a glass pane in a frame to allow for racking under in-plane displacements. [3].

Figure 2. Detail at the head of a glass pane that allows for in-plane movement and out-of-plane racking of the glass.
Movements to be accommodated can be further broken down to in-plane movements and out-of-plane movements. For example, it is fairly straightforward to accommodate out-of-plane drifts with glass, as systems are typically allowed to rack back and forth as a structure moves. Accommodating in-plane drifts can present more of a challenge, particularly in flexible buildings located in high seismic zones. For a standard (non-critical) occupancy building (Category III per ASCE7-10), a 2% maximum allowable drift for a flexible structure (such as moment frames) with a 15’ (4.56 meter) floor-to-floor height means that systems attached to the building or installed within the building must be capable of accommodating 3.6” (91 mm) of drift. While these types of large drifts would not be expected for a rigid glass structure resisting seismic loads, it does demonstrate the need for accommodating seismic movements.

Details at building corners that allow for movement in each direction are a concern for all facades, and become even more complex when the elements requiring compatibility are rigid and load bearing. Corners in curtainwalls are often tested for systems used in seismic regions, and joints or movement can be hidden to an extent within corner mullions. When glass elements form the structure and racking in one direction needs to be accommodated, corner joints can become large and architecturally unappealing. Accurately analyzing a structure to determine building movement and subsequent joint size becomes critical to the finished look of a structure.

4 Material Behavior Under Seismic Loading

The optimal glass structure would- if possible- use glass elements to resist lateral loads, with the addition of reinforcing elements if needed to resist larger tensile loads. In regions with low seismic and wind loads, lateral loads on these structures may be very small and effectively ignored in designed. In regions with higher seismicity, the response of the component elements of a glass structure are more critical to the overall structural design.

Glass structures exist that have been designed to resist lateral loads due to both wind and seismic loading, and some research explicit to applications beyond traditional vertical glazing has been done regarding this topic [4][5]. These studies have largely been completed with the intent of providing guidance and knowledge for glass structures that resist wind loading. While some of the information from these studies can be extrapolated to high-seismic zones, the behavior of glass and laminated glass under cyclical seismic loading presents unknowns that should be thought through during design.

More research has been completed regarding traditional curtainwall and glazing behavior during seismic loading, and guidance for design of glazing systems to accommodate seismic loading and deformation is provided in code and other resources [6][7]. Some of this information can be extrapolated to other glass structures. Despite this, where laminated glass or silicone is used to resist seismic loading, designers generally must make a leap in assumptions regarding the applicability of provided allowable design values. For example, unless testing methodology is explicitly stated and provided, it is generally unclear whether allowable shear stresses for structural silicone should apply in a seismic case. ASTM C719- Standard Test Method for Adhesion and Cohesion of Elastomeric
Joint Sealants Under Cyclic Movement - is intended for sealant response under slow, cyclical thermal movements, not seismic movements. The response of this critical element in glass structures has been tested many times during dynamic curtainwall racking tests per AAMA 501.6, but there is a lack of literature or a comprehensive survey of the results of such testing as it relates specifically to silicone behavior.

Of the literature that is available, Zarghamee et al [8] recommend an allowable sealant stress of 50 psi for seismic loading on four-sided sealed structural glazing. This recommendation is based on tested data, and is far higher than the 20 psi recommended by many manufacturers for use during short-term (wind or seismic) loading. Zarghamee et al have also completed a thorough investigation of the response of four-sided structural glazing in buildings subjected to the Northridge Earthquake. While useful, this information and research needs to be further extrapolated to silicone and other sealants used in structural applications beyond four-sided glazed curtainwall systems.

Similar to sealants, the out-of-plane behavior of laminates under various temperatures and loading durations has been well studied. In-plane behavior of laminates under shear loading has been studied as it relates to elements such as beams or columns with multiple glass plies laminated together to act as a monolithic element resisting long term (10 minutes or greater) loads. Mocibob [4] contains a fairly thorough overview of this research. As previously noted, there has been some study of the behavior of glass and laminates subjected to in-plane loading, but there appears to be little to no research regarding the behavior of laminates subjected to short-term cyclical shear loading similar to what would be induced during an earthquake.

A hallmark of good seismic design is the ability to reliably predict the failure mechanisms of a lateral force resisting system and, in particular, the order in which those mechanisms occur. The calculation of these mechanisms is based on testing combined with first principles and common engineering design practices. Without comprehensive testing, we do not know the failure mechanisms nor the order of their occurrence when laminated glass systems are subjected to short-term, high-amplitude, cyclical loading. We can use the knowledge gained from existing testing and published data for glass, laminates and silicone to get a fair idea of how a complete system made up of these components will perform, but without all of these components being tested together we do not begin to have a level of empirical knowledge approaching that of the codified lateral force resisting systems comprised of concrete and steel.

Finally, design of glass structures under gravity loading requires an element of thought regarding post-breakage behavior that is not generally required for other structural materials and which is therefore not an inherent aspect of the design process for many practicing engineers. Designing for redundancy for resistance to seismic loads and/or designing redundant gravity-load carrying systems such that if elements of a seismic force resisting system that also support gravity loads fail is a critical aspect of structural glass design that could easily be overlooked by structural designers or by jurisdictions doing review.
5 Code Limitations

ASTM E1300- “Standard Practice for Determining Load Resistance of Glass in Buildings”- is the general standard used in the US for design of structural glass. There are a number of limitations contained within E1300 that become evident regardless of whether seismic design is a concern. In addition to these limitations it is our experience that there is a general misunderstanding within the engineering design community regarding the applicability of this document.

As stated in the scope section of the standard, ASTM E1300 “applies to vertical and sloped glazing in buildings”, and “shall not apply to other applications including, but not limited to, balustrades, glass floor panels, aquariums, structural glass members, and glass shelves.” While the appendices of ASTM E1300 provide general design guidelines for non-vertical sloped glazing applications (i.e., all other applications that would be considered structural glass), the standard is not explicitly meant for use in these applications.

The guidelines for determining maximum stresses in the Appendices of E1300 are based on determining an allowable maximum surface stress based on a probability of breakage for a given loading duration. While seismic load duration could be approximated as somewhere between 60 seconds and 10 minutes, additional thought should be given to the impact of aftershocks, loads imposed by permanent structure displacement, and so on.

Maximum surface stresses and breakage probabilities for typical glass panes are dependent on the existence of flaws in the surface of a given glass pane. There is no guidance in the Appendices for the allowable shear strength of glass. While it seems un-conservative to use the molecular bond strength of glass for this application, using the allowable surface stresses for glass shear strength is overly conservative.

As noted above some jurisdictions review designs based on the letter of the code. As such, they may not consider E1300 to be a design guideline that can be utilized- both for the applicability reasons stated above, and because the document is not explicitly adopted in codes. While this may appear to be a technicality, in some jurisdictions it can lead to an impasse in permitting of glass structures. If and when this occurs, a testing protocol is typically implemented to determine the adequacy of any given design to resist the applied loads. These testing guidelines present their own difficulties, and it should be noted that testing of glass structures subject to seismic loads are potentially much more difficult and costly to carry out than testing of elements subject to gravity loads or impact loads.

6 Glass Tension Wall- Example

The Governor George Deukmejian Courthouse in Long Beach, California consists of two building wings connected by an atrium. The exterior walls bounding the atrium consist of glass tension walls approximately 80' tall x 80' wide, made up of 8'-0" x 7'-6" (2.44 m x 2.29 m) glass panes clamped back to vertical cables via a point-fixed spider connection. The walls creates a transparent effect through the atrium, as an observer can stand in front of the courthouse and see through two glass walls to a courtyard nestled between the two sides of the building.
The courthouse is situated close to the Pacific Ocean, with a design 3-second gust wind speed of 85 mph. Long Beach is located in a region with high seismicity and is located on a site with soil of site class D. Code-level seismic accelerations result in design spectral response accelerations of $SD_5$ and $SD_1$ of 1.086 seconds and 0.622 seconds respectively.

The building superstructure is separated into two structurally distinct pieces, with a seismic joint located at the north end of the atrium as seen in Figure 4. This means that the two structures can move differentially in a seismic event.
In addition to differential building movement, the tension walls will be excited under seismic loading and will undergo in-plane movements that may or may not be in phase with the movement of the structure to which they attach. The total amount of movement (differential displacements of the building superstructure in addition to in-plane movement of the walls) dictates the size of the seismic joints required on each end of the walls to prevent glass to structure contact.

Preliminary hand calculations and simple models of a single cable with point loads at glass pane connection locations indicated movements in the plane of the walls due to seismic loading of more than 12". It was recognized that this was an extremely conservative number that ignored the stiffness contribution of the glass walls themselves, which in combination with the silicone sealant between glass panes would act as large, flexible diaphragms. In an effort to minimize the required joint size at each end of the atrium, a non-linear study of the behavior of the walls under wind and seismic loading was undertaken.
All elements of the walls were modelled using three-dimensional finite element analysis software, although some elements such as the spider fixings were simplified to increase computational efficiency. The glass panes in these walls are connected back to a single vertical cable via a double spider connection at the top and bottom of each pane.
Typically, these spider connections allow for some rotation at the rotule connections to the glass itself, but do not allow in-plane rotation at the cable clamps. During analysis, it was determined that rotation of the spider fixing would allow the walls to move in a manner that reduced stresses on the individual glass panes, as each pane wanted to rotate relative to adjacent panes due to the parabolic shape taken by the cables. Not allowing for this rotation would overstress individual panes in shear and/or would force adjacent panes to contact one another.
Fully modeling the tension wall structure, including the silicone between individual panes, captured a more realistic stiffness of the full system than more simplistic modeling would permit. As the glass panes rotate in relation to each other under a seismic event, silicone transfers load between adjacent panes. This adds stiffness to the system, helping to reduce the total amount of movement. Additionally, it means that the wall behaves as a vertical diaphragm, with load transferred from the middle of the wall (where the cable is subject to the largest amount of displacement) to the upper and lower ends of the wall—where the cable is subject to smaller displacements. Accounting for this behavior during analysis led to a decrease in the required seismic joint size to just under 4" (100 mm).

Figure 8. Seismic and Wind Joint Detail During Wind Induced Displacements (Out-of-Plane Movement)
In a seismic event, the silicone in this system will be subject to cyclical deformations. The engineer of record was comfortable using silicone in this application due to the magnitude of imposed shear stresses—typically less than 10 psi (69 kPa). This application points to the potential cost savings that could be achieved by accounting for the contributions of both glass and silicone used in a structural manner in the analysis of glass systems.

7 Conclusions

There are many barriers to design and construction of glass structures in the US, particularly in high seismic regions. The largest barrier is a general lack of knowledge regarding glass as a structural material in both the design and review communities, followed by a lack of codes and references for design. Additionally, in the resources available there has been little study completed regarding the behavior under seismic loading of glass, laminates, silicone, sealants, and other elements that make up glass structures.

An increase in resources for designers and reviewers in the US would lead to more familiarity and comfort with glass as a structural material, opening the door to wider applications of glass in buildings. These potential applications include the
use of glass systems as elements of the lateral force resisting system in building structures or as components of building structures. The development of code guidelines for glass structures is underway and- in combination with general education on structural glass- should be considered a priority in furthering the efforts of the design community to realize glass structures in the built environment.

References
[3] Courtesy of ASCE Committee on Curtain Wall Systems
European Façade Technology - Functional Optimization and Architectural Integration

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Abstract
At the beginning of the 20th century the development of the technology of mechanical air-conditioning allowed the design of buildings independently of the conditions and parameters of the local climatic conditions. As a consequence the operating and initial costs of such buildings were on the rise as well as the dependency on complex technology. In the late-1980s, a somewhat diverging tendency could be observed in central Europe where it became of significance that buildings have to minimize their energy consumption while maximizing their indoor comfort as well as spatial quality. Moreover the waste of materials, time, and money in the building’s construction and operation should be reduced. In addition, social and cultural aspects gained importance, such as in the exterior design of buildings. In the European sense sustainability in the building sector needs to include all of the above-mentioned aspects. A key component in such deliberations is the façade. Based on outstanding European reference projects the presentation focusses not only on the functional optimization of building envelopes as an essential part of an energy and material efficient building design approach but also on the architectural integration of innovative components into the facade of sustainable buildings.

Keywords: façade, innovation, customer needs, complexity, parametric principle, cyber-physical systems.

1 Introduction
Across centuries, building forms and types have been adapted to local climatic conditions. Only in the 20th century did the development of the technology of mechanical air-conditioning allow the design of building envelopes independently of the conditions and parameters of the local setting. However, this development came at a price. Not only are the operating and initial costs of such structures on the rise but the dependency on complex technology and the increasing need for raw materials are also consequences. In the past forty years, this problematic tendency can be observed across all metropolitan centers around the developing and developed world. If we analyze that period from a greater distance, it is clearly apparent that the building sector has caused a significant reduction of both available natural resources and non-renewable energy. Several factors are responsible for this global condition, including population increase and rising productivity; industrialization and urbanization, paralleled by increases in standards of living and the resulting demands for more living space per capita;
and additionally the greater expectation in regard to comfort and quality of living. Such demands lead to the consumption of primarily non-renewable resources such as coal, crude oil, natural gas, and uranium, which are limited in availability.

In the late-1980s, a somewhat diverging tendency could be observed in central Europe where it became of more and more significance that facades don’t just “look good”, but also serve the need for durability and operation of a building. Daniels [1] pointed out that facades are the key for indoor comfort and operational expenditures. They are not only responsible for the cost related to the operation of the building’s mechanical systems but can determine whether, or to what degree, a building needs such systems in the first place.

2 Energy-efficient and sustainable buildings
Sustainable building design takes into account environmental, economical and social aspects. It considers the relevant needs of people across the entire lifecycle of the building, from design, planning and construction, through operation and usage, updating and upgrading, up to demolition with possible reuse or recycling of building components and materials. In Europe the interest in questions of sustainability is on the rise. Ecological aspects of sustainability include the protection of the natural environment and the care for resources. We first focused on the reduction of primary energy and later included the protection of water resources and the elimination or limitation of pollution. For a long time, only a focus on “initial cost” commanded the thinking; today, however, a careful optimization of investment costs and the resulting operational expenses is the norm in Europe. In addition, social and cultural aspects of sustainability gain importance, such as in the exterior design of buildings, but more importantly in the way buildings are being used and the spatial quality they provide to the user. Sustainability in the building sector needs to include all of the above-mentioned aspects. The current discussions in the public realm can be distinguished according to two different strategies: the so-called “Sufficiency Strategy” and the “Efficiency Strategy.” In very general terms, sufficiency is directed toward personal responsibility, such as the degree to which an individual uses resources, whereas efficiency is a parameter of the design and planning of buildings. In both cases, it is the goal to minimize the consumption of energy within a building, as well as the waste of materials, time, and money in its construction and operation. Today’s European building design has shifted the emphasis towards long-term customer satisfaction. Quality, functionality and capital cost requirements have gradually become tougher as a result. Human wellness is a direct result of the comfort of the surrounding space. At least in office and administrative buildings, the importance of a comfortable temperature, fresh air, the use of daylight and acoustic comfort will grow in the future as the public becomes increasingly aware that they have a direct impact on performance and absenteeism.

Within Europe three trends can currently be observed: passive, active and cognitive building concepts [2]. A key factor in sustainability is having a building structure that is suitable for its location and its use, in conjunction with an appropriate façade.
In a passive building concept (Figure 1) passive façade components seal off the interior from external factors as far as possible. Contemporary building technology ensures a comfortable interior environment. Conversely, in active building concepts dynamic façade components respond specifically to changing internal and external conditions. The aim here is to minimize the use of mechanical systems, especially by means of natural ventilation, passive use of solar energy and daylight. It is important to point out that the knowledge of users and/or operators of buildings, an aspect we may call “Operational Competence” becomes of increasing significance. The most innovative building concept will inadvertently fail if it only performs in theory. It shows that purely passive building concepts are only advantageous when compared to active concepts if the location, the height or the use of the building excludes natural ventilation, as well as solar energy and use of daylight for at least two-thirds of the year.

In many moderate climatic zones, optimum energy efficiency is provided by cognitive building concepts (Figure 1). Their façade and mechanical-system components with dynamically adjustable functions are connected to each other through an intelligent building automation system. Adaptive facade components are capable of reacting to non-continuous, changing external conditions that are in many instances predictable and can be calculated, such as the case with annual or diurnal swings in meteorological conditions (i.e., solar altitude angle) or the times of a building’s operation. However, non-predictable weather and operational aspects - such as variations in cloudiness and spontaneous presence of users - should be included by means of appropriate sensors or via internet through the weather report. But in the end we have to remember the fact that building techniques and methods are to be tailored to the people for whom the building is intended rather than matching the tenants to the newest possible techniques and methods.
3 Functional optimization of facades

A key component in a sustainable building is its enclosure, the façade. It needs to possess and deliver across its entire life span superior resource efficiency, which needs to be the result of energy and material efficiency as well as highly efficient design, construction, and operational processes. A façade that is really optimized for energy and comfort should be able to react to the comfort needs of the user and the changing outside conditions in such a way that the mechanical system is only brought into play in extreme situations [3]. With the help of energy-efficient facades, it is possible to even out the differences between outside climatic conditions and interior comfort. With such solutions, the variations within the climatic situation can be dampened and smoothed out as well.

The more the quality of thermal insulation of a facade is increased, the more important is a focus on thermal loss due to ventilation or infiltration. The overarching goal must be that uncontrolled ventilation due to gaps in the construction needs to be avoided. Sub-optimal operational procedures not only cause an enormous increase in operating cost but also result in non-acceptable interior comfort conditions. The optimization of energy use should not stop at the reduction of thermal losses. Transparent and translucent surfaces of the facade collect thermal gains as well. In the case of buildings with high internal loads and large glass surfaces, solar radiation causes overheating if no additional mechanical measures are considered. External shading systems reduce the solar radiation and the resulting thermal gains greatly. Daylight systems, on the other hand, have the role of evenly distributing the entering daylight within a room and optimizing the daylight quality. European researchers have worked on the development of materials that may control the flux of light, energy, ventilation, and sound in a self-controlling fashion. One such research goal is the invention of glass types that are controllable and adaptable. An additional research goal has been the development of electrically operated ventilation flaps in façades connected to a building management system (BMS). They allow for the accelerated and increased nighttime cooling of internal thermal storage masses within a building. Important here is the accessibility of such thermal masses since they are also important in regard to usable solar gains and the discharge of cooling loads. De-centralized mechanical ventilation components built into the facade can be equipped with regenerative heat exchangers, which work for example with phase-change-materials (PCM). They will be capable of evening out diurnal temperature fluctuations. If the capability to store thermal energy is great and, additionally, the local climate possesses the advantage of diurnal temperature swings even during heating periods, mechanical cooling systems may become obsolete.
Energy efficiency can also be increased if a designer widens the “systemic boundaries” of a design. For example, a weather-protecting enclosure between neighboring building parts may be designed as a large buffer zone, resulting in an atrium or mall-type space. Such buffer zones may be equipped with natural or mechanical systems to provide a general thermal environment ranging in air temperature between 15 and 30 °C annually, independent of external weather conditions. To achieve this goal with the least amount of energy, visual light transmission, solar heat gain, and the degree of natural ventilation through the envelope must be controlled centrally by a building-management system. The internal surfaces of such spaces, their roofs and facades, on the other hand, are relatively simple and do not require any particular attention in regards to wind loads or driving rain. Such a “climate hull” therefore increases also the usability of the enclosed building. In an ideal scenario, the user will be enabled to control the components of the internal facades individually, without negative effects on energy consumption. Important nevertheless are the quality of such hulls with regard to noise control (“sound attenuation”) and thermal storage behavior (“thermal buffering”).

If a facade is optimized with regard to its energy efficiency, it is recommended that renewable energy sources be considered to compensate for the remaining energy consumption. In the case of façades, mainly two available active-solar energy sources are to be considered: electric and thermal. The direct use of solar radiation for space heating and warm water consumption can be achieved with various available systems which work according to various principles, such as air or water collectors or heat absorbers with heat pumps. Their performance can be increased with the addition of thermal storage systems. Especially for the building type of an office building, the generation of cooling energy with the help of thermal heat collectors (absorption chillers/cooling) is of great interest. The
principle is simple: in case of the greatest cooling demand, the sun will provide the greatest heat gain for cooling. This, of course, is an elegant balance between „supply and demand“. Building-integrated photovoltaic systems (BIPVs) today have long passed the experimental phase. Currently, BIPV is available for facades and roofs for fixed and movable solar shading systems. In the meantime, the problems of proper cable routing and electric connectors are solved in detail, and excellent systems are available.

4 Architectural integration of components

We as engineers are accustomed to arguing technical aspects. Nevertheless the architectural integration of technical components into the façade plays a major role in modern European architecture. At this point the so-called “theory of product language” [4] offers interesting perspectives. In the mid-1970s Gros [4] made a distinction between the practical functions (the user’s perspective) of a product on the one hand, and the formal and communicative aspects, the so-called product language functions on the other (figure 3).

Figure 3. The Offenbach Theory of Product Language [4] (figure by Schueco International KG)

Formal aesthetic functions distinguish two antagonistic principles: order versus complexity, and reduction of stimuli versus richness of stimuli in terms of shapes, color, texture and material for instance (the observer’s perspective). Indication functions visualize and explain the various practical functions of a product and how it should be used (the user’s perspective). Thus, they play an important role concerning recognition, usability and self-explanation of products. Symbolic functions are associated with objects in the imagination of the recipient or user, depending on the particular context. They refer to conceptions and associations that come to a person’s mind while contemplating an object: for example,
societal, socio-cultural, historical, technological, economical and ecological aspects (the owner’s perspective). Accordingly products as well as architecture are bearers of meaning, beside their utilitarian functions. In the end facades might be projection surfaces for meaning and the architect as the façade designer could act as the “story-teller”. And a successful story might even become a myth [5].

Figure 4. Examples for formal aesthetic optimized facades; left: Schueco E²-Façade, right: Project Capricorn Duesseldorf / Germany (Source: Schueco International KG)

Steffen [6] analyzed innovations in the 20th century according to that theory. Between the 1920s and the 1960s the modern avant-garde was quite successful in communicating the innovative character of modern architecture. The complexity of traditional forms was replaced by a high order of simple geometric forms and the elimination of ornamentation. Only after the International Style became dominant did high order turn into the negative. Accordingly, at the end of the 20th century we have been facing partial styles not only of high order (i.e. new functionalism, minimalism) but also of high complexity in worldwide architecture. We tried to do manage this variety and especially facades with high geometric complexity in different ways.

Our contribution to the façade of a Tower in Turkey (figure 5) is a good example for state-of-the-art value engineering for mastering the geometric complexity. Our in-house design department, Project Engineering, customized the Schüco-system until a solution was found, that satisfied the formal-aesthetic needs of the architects. After a tough value-engineering process we could reduce the number of project-specific aluminum-profiles by 50 %. As we learned, the two main problems of using the traditional façade engineering methods (concept design and typifying of façade-units) and design tools (2D and 3D CAD AutoCAD) on projects with complex geometry are the time you need and the risk of making mistakes.
Nevertheless process efficiency could be increased within this project by individually configured façade-units that are built up from project-standardized parts and typified modules in the factory. In between these, there are precisely defined interfaces. Unplanned improvisation, wastage and the dependency on weather conditions on site have been minimized, while the consistency of quality was maximized.

In a hotel tower project in Spain (Figure 6) the complexity of the façade has been reduced by decoupling the practical functions and the architectural language functions (formal aesthetic, indication and symbolic functions). As a result a double-layer concept came up, with an inner facade of low geometrical complexity (facetted rectangular facade units with high functional complexity) and an outer facade of high geometrical complexity (curved aluminum-pipes with low functional complexity). While the inner layer is based on system components...
(standardized aluminum and rubber profiles, fittings and accessories with certified quality in regard to air- and water-tightness, thermal- sound- and fire-protection...), the outer layer is optimized in regard to bending technology (the basis for shaping the complex geometry of the building within budget). From the designing architect’s perspective, we are talking about the design strategy of addition (controversy to integration). It is a step away from the modern architecture’s honesty of construction towards Jean Nouvel’s idea of a façade which does not reveal, but conceal [7].

5 Holistic design approach
In current architecture there is a desire for optimum comfort and maximum design freedom on the one hand, while on the other hand there is a need for cost- and resource-efficiency. To find a solution for this challenge we are following a holistic design approach, using parametric methods. The ultimate principle of parametric design is the use of variables and algorithms to generate a hierarchy of mathematical and geometric relations. It serves the automated parameter-based generation of geometries of architectural elements that change their properties based on formal relations. It is the shift from using CAD software as a drafting tool, to an efficient design tool (Figure 7).

Figure 7. Parametric design, the shift from using CAD software as a drafting tool, to an efficient design tool (Source: P.Guenther / Schueco International KG)
The design can be easily controlled and elements can be automatically drawn and eventually produced (Figure 8). It is a first step forward to the continuous digitalization of the process chain in the façade business. By this we first analyze the geometric complexity of the façade. With the method of k-means clustering for the arrangement of similar facade units in groups we reduced the logistic complexity. The actual challenge in the holistic design approach is to decouple the façade costs (material and fabrication) from the functional (especially in regard to air- and water-tightness) and design quality (threedimensionally curved appearance) of the façade.

Figure 8. Parametric design, the shift from using CAD software as a drafting tool, to an efficient design tool (Source: P.Guenther / Schueco International KG)

Nowadays the complexity in the design process is not only geometrical. Our holistic design approach is subjected to a detailed, step-by-step analysis with respect to the following factors: cost-efficiency (investment, operating and maintenance costs), design considerations (practical and language functions), energy requirements (heating, cooling, ventilating, lighting etc.), environmental impact, room comfort (thermal, visual, acoustic etc.), ease of use/operation, cost and ease of maintenance, as well as the flexibility to change use and upgrade facilities. For façade planners and builders the holistic design approach also deals with the optimization of fabrication and assembly, by means of merging digital and physical methods. We assume that in near future smart (on site) factories will allow individual customer requirements to be met. Even one-off items can be
manufactured profitably. They enable last-minute changes and deliver the ability to respond flexibly to disruptions and failures on site. This is the reason, why our technological vision starts with the assumption, that the future of the façade business is based on cyber-physical systems, connecting architects and engineers as well as main contractors, system suppliers, façade and maintenance companies with their specific activities spread all over the world. We are using advanced parametric methods for the holistic optimization of passive, active and cognitive building concepts. The optimization parameters are cost- and resource- efficiency as well as practical and formal aesthetic functions throughout the life-cycle of buildings.

Figure 9. R&D-Concepts, the basis for long term research on advanced methods of façade design and construction (Source: P.Guenther & W. Schulz / Schueco International KG)

To handle the complexity of even more comprehensive concepts with the holistic design approach we team up according to the “open-innovation-principle”. We have realized that the greatest potential for increasing innovation lies in optimizing the cooperation of the individuals. The team-members profit from each other by connecting internal and external ideas, opening their innovation activities. This requires a paradigm change in the way everyone works together. Under those premises the driving forces behind this approach are the challenges and technological innovations that the individual members of the team bear in mind. We try to satisfy the needs of all of our target groups such as architects, engineers, main contractors, and façade companies as well as users, observers and owners of buildings as far as possible. Our concepts consider the entire lifecycle of a building, from design, planning and construction, through operation and usage, updating and upgrading, up to demolition with possible reuse or recycling of building components or materials. More than this we think in terms of
cradle-to-cradle [8]. In our holistic design approach we try to minimize the
unnecessary and useless consumption of energy, materials, time and money, by
using innovative products and building concepts as well as advanced highly
efficient planning, construction and operating processes. In combination with
advanced rendering and visualization tools parametric design and construction
allows designers to quickly explore a much larger solution space through virtual
functional and visual mock-ups, as well as rapid prototyping models. It helps to
predict the final outcome more accurately and permits to take realization
concerns into account at an earlier stage. It is the up to date basis for a fruitful
and dynamic cross-disciplinary optimization process between architects and
engineers.

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Blast Mitigating Design of Glazing

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Abstract
The exterior envelope is the first line of defense that the building has to offer in defending against an explosive attack. Although heavier stiffer elements do resist more load, they also tend to cause brittle failure which can be highly hazardous. Lighter materials which are able to absorb energy through deformation may fail at lower pressures, but the fragments tend to be less hazardous. The lightweight ductile design approach is generally the preferred solution because the solutions tend to be more cost effective and do not alter the appearance of buildings significantly.

Windows and glass curtainwalls consist of a system of components which provide a load path back to the structure. In this paper, the general issues related to blast design of the glazing systems are discussed.

1 Introduction
Windows, once the sole responsibility of the architect become a structural issue once explosive effects are taken into consideration. In designing windows to mitigate the effects of explosions window systems are first designed to resist conventional loads and then checked for explosive load effects and balanced design.

A balanced or capacity design approach is taken meaning that the glass is designed to be no stronger than the weakest part of the overall window/wall system, failing at pressure levels that do not exceed that of the frame, anchorage and supporting wall system. If the glass is stronger than the supporting members, than the window is likely to fail with the whole panel entering into the building as a single unit, possibly with the frame, anchorage and the wall attached. This failure mode is considered more hazardous than if only glass fragments enter the building, provided that the fragments are designed to minimize injuries. In this way the damage sequence and extent of damage are controlled.

Windows are often the most vulnerable portion of any building. Though it may be impractical to design all the windows to resist a large scale explosive attack, it is desirable to limit the amount of hazardous glass breakage to reduce the injuries. Typical annealed glass windows break at low pressure and impulse levels and the shards created by broken windows are responsible for many of the injuries incurred due to large scale explosive attack.

Designing windows to provide protection against the effects of explosions can be effective in reducing the glass laceration injuries. For a large-scale vehicle weapon, a lower pressure range is expected on the targeted building the
surrounding buildings not facing the explosion, or for smaller explosions where pressures drop more rapidly with distance. Generally we do not know which side of the building the attack will occur on so all sides need to be protected. Window protection should be evaluated on a case by case basis by a qualified blast consultant to develop a solution that meets established objectives.

To limit glass laceration injuries, there are several approaches that can be taken. One way is to reduce the number and size of windows. If blast resistant walls are used then fewer and/or smaller windows will cause less air-blast to enter the building thus reducing the interior damage and injuries. Specific examples of how to incorporate these ideas into the design of a new building include: limiting the number of windows on the lower floors where the pressures are higher due to an external explosive threat; using an internal atrium design with windows facing inward not outward; clerestory windows which are close to the ceiling, above the heads of the occupants; and angling the windows away from the curb to reduce the pressure levels.

It may be advantageous to consider the reduction in pressure with height due to the increase in distance and the angle of incidence at the upper levels of a high rise building. If pressure reductions are taken into account at the upper floors, minimum requirements such as balanced design, ductile response and redundancy are to be met to reduce the hazard to occupants in case the actual explosion is greater than the design threat.

Glass walls or windows at emergency exits are to be avoided to facilitate egress. Wire glass is to be avoided because of the severity of the injuries it may cause if it becomes flying debris.

Government design criteria generally specify either the threat or the loading pressure and impulse that blast mitigating windows need to be designed for. Pressure levels given vary from about 0.28 Bar up to about 2.8 Bar depending on the criteria document.

Typically, projectile impact loads are not considered for air-blast as they are for wind loads. However, Dade County certified windows for hurricanes may have a higher level or inherent blast resistance compared with other conventional window types. Impact resistant systems need to be checked to verify that they meet the air-blast design criteria.

## 2 Window Component Design

The load path from the glass to the supporting wall governs the design process of a window system. Each component of a conventional window system is addressed in the sub-sections that follow.

### 2.1 Glass Design

Glass is often the weakest part of a building, breaking at low pressures compared to other components such as the floors, walls, or columns. Past incidents have shown that glass breakage and associated injuries may extend many hundreds of meters in large external explosions. High-velocity glass fragments have been shown to be a major contributor to injuries in such incidents. For incidents within
downtown city areas, falling glass poses a major hazard to passersby and prolongs post-incident rescue and clean-up efforts by leaving tons of glass debris on the street. At this time, exterior debris is largely ignored by existing criteria.

As part of the damage-limiting approach, glass failure is not quantified in terms of whether breakage occurs or not, but rather by the hazard it causes to the occupants.

The glass performance condition is defined based on empirical data from explosive tests performed in a cubical space with a 3 meter dimension. The performance condition ranges from 1, corresponds to no breakage, to 5 which corresponds to hazardous failure. Generally a performance condition 3a or 3b is considered acceptable for buildings that are not at high risk of attack. At this level, the window breaks, fragments fly into the building but land harmlessly within 3 m of the window or impact a witness panel 3m away no more than 0.6m above the floor level. The design goal is to achieve a performance level less than 4 for 90% of the windows.

Figure 1. Glass Fragment Performance Level Conditions

Table 1. Performance Conditions for Windows

<table>
<thead>
<tr>
<th>Rating</th>
<th>Level</th>
<th>Description of Damage</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Safe</td>
<td>Glazing does not break. No visible damage to glazing or frame.</td>
</tr>
<tr>
<td>2</td>
<td>Very High</td>
<td>Glazing cracks but is retained by the frame. Dusting or very small fragments near sill or on floor acceptable.</td>
</tr>
<tr>
<td>3a</td>
<td>High</td>
<td>Glass cracks. Fragments enter space and land on floor no further than 1 meter from window.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>---</td>
<td>-----</td>
<td>------------------------------------------------------------------</td>
</tr>
<tr>
<td>3b</td>
<td>High</td>
<td>Glazing cracks. Fragments enter space and land on floor no further than 3 meters from the window.</td>
</tr>
<tr>
<td>4</td>
<td>Medium</td>
<td>Glazing cracks. Fragments enter space and land on floor and impact a vertical witness panel at a distance of no more than 3 m from the window at a height no greater than 0.6 m above the floor.</td>
</tr>
<tr>
<td>5</td>
<td>Low</td>
<td>Glazing cracks and window system fails catastrophically. Fragments enter space impacting a vertical witness panel at a distance of no more than 3 meters from the window at a height greater than 0.6 meters above the floor.</td>
</tr>
</tbody>
</table>

Design criteria established by the U.S. Interagency Security Council, which governs the antiterrorism requirements for most agencies require performance condition 3a for buildings that are at moderate risk of attack. At this protection level, the window breaks, and fragments fly into the building but land within 1 meter of the window. The design goal for moderate-risk buildings is to achieve a performance level of less than 4 for 90% of the windows. Protection level 4 means that glass fragments will penetrate a witness panel located 3m behind the window for a height of two 0.6m or less.

The preferred solution for new construction is to use laminated glass with structural sealant around the inside perimeter. For insulated units, only the inner pane needs to be laminated. The lamination holds the shards of glass together in explosive events, reducing its potential to cause laceration injuries. The structural sealant helps to hold the pane in the frame for higher loads. Annealed glass is used because it has a breaking strength that is about one-half that of heat strengthened glass and about one-fourth as strong as tempered glass. Using annealed glass becomes particularly important for buildings with light weight exterior walls using for instance, metal studs, dry wall and brick façade. Use the thinnest overall glass thickness that is acceptable based on conventional load requirements. Also, it is important to use an interlayer thickness that is 60 mil thick rather than the 30 mil thick as is used in conventional applications. This layup has been shown to perform well in low pressure regions (i.e., under about 0.35 Bar). If a 60 mil polyvinyl butaryl (PVB) layer is used, the tension member forces into the framing members need to be considered in design.

To make sure that the components supporting the glass are stronger than the glass itself, we specify a window breakage strength that is high compared to what is used in conventional design. The breakage strength in window design may be specified as a function of the number of windows expected to break at that load. For instance, in conventional design, it is typical to use a breakage pressure corresponding to 8 breaks out of 1000. Where we are certain of a lot of glass breakage, a pressure corresponding to 750 breaks out of 1000 is used to have increased confidence that the frame does not fail too. Glass breakage strengths may be obtained from window manufacturers.

Smaller glass panes generally have higher capacities than larger panes. Consequently, smaller panes can cause significantly higher loads to be
transmitted to the frames than larger panes and can have a significant impact on the strength of the frame. Also, since every size pane has a difference capacity, it is desirable to standardize the design as much as is practical to simplify the design analysis.

**Figure 2. Example of Building with Many Window Pane Sizes**

(100 11th Avenue, New York by Jean Nouvel)

There are several U.S. Government sponsored software products available to evaluating the response of window glass, including HAZL, WinGard and WinLAC. These codes are made available to government contractors who have government projects requiring this type of analysis.

Glass block is generally not recommended because of the heavy projectiles these walls may create due to failure at the mortar lines. However, there are blast rated glass block products that are available in which each glass blocks are framed by a steel grate system.

The concepts presented here are for both vision and spandrel glass panels. If a shadow box is provided behind the spandrel panel, the connections need to be designed to resist the capacity of the box structure.

**Punched Windows.** Punched windows often can be designed efficiently to be less vulnerable than other window types because the frame is attached directly into the wall, which is generally of more robust construction.

**Figure 3. Example of Punched Windows**
**Strip Windows.** Strip or ribbon windows generally consist of alternating bands of glazing and opaque material constructed using precast panels, poured concrete, or insulated metal panels. The opaque area conceals the floor structure and is referred to as a “spandrel.” Ribbon windows have thin vertical metal framing separating the individual panes, and are supported by the wall at the top and bottom. For this type of exterior facade, the spandrels are attached to each floor level instead. The system is very economical and a common facade type. To resist air-blast loads, steel angle kicker braces are often needed to laterally support the bottom of the spandrel panel.

**Figure 4. Example of Strip Windows**

![Example of Strip Windows](image)

**Glass Curtain Wall.** For this glazing type, a significant part of the building exterior is covered with windows supported by aluminum or possibly steel framing. This support type has an increased risk of hazardous failure as compared with punched windows because strip window systems are supported by wall on two sides instead of four sides. However, it has more flexibility, which allows it to deform significantly without failing.

Glass curtain wall systems have been determined in recent explosive tests to perform surprisingly well to low levels of explosive loads. These systems have been shown to accept large deformations without the glass breaking hazardously compared to rigidly supported punched window systems. Some design modifications may be required to the connections, details and member sizes to optimize the performance.

**Figure 5. Example of Curtain Wall**

![Example of Curtain Wall](image)
**Point and Cable Supported Window Walls.** In point and cable supported systems, each window pane is connected at points near its corners. The bracket that supports the glass often has multiple arms, forming a spider, so that it can attach near the corner of several adjacent panes. The glass is drilled for a threaded connector to pass through, engaging the interlayer to secure the pane during an explosion. The panes are typically connected using a clear or translucent polymer material instead of the metal framing.

**Figure 6. Example of Pin Supported Curtain Wall**

![Image of a curtain wall with pin supports](image)

**2.2 Mullion Design**

Mullion supports may be designed in two ways. Either a static approach may be used where the breaking strength of the window glass is applied to the mullion, or a dynamic load may be applied using the peak pressure and impulse values. A static approach may lead to a design that is not practical. Using this approach, the mullion can become very deep and heavy, driving up the weight and cost of the window system. It may also not be consistent with the overall architectural objectives for the project.

Sometimes cables or steel bars or tubes are placed behind the glass to prevent the glass from entering the interior. Both the U.S. Department of State and the U.S. Department of Defense have tested such systems for air-blast effects. The Defense Department refers to a similar system with a single bar placed behind the glass as a 'catch-bar' system. For these types of systems the steel members are attached using full penetration welds and are able to experience large ductile deformations. Structural wood mullions have negligible resistance and should not be used for blast mitigating designs.

**2.3 Frame and Anchorage Design**

The window frames need to retain the glass so that the entire pane does not become a single large unit of flying debris. It also needs to be designed to resist the breaking stress of the window glass.
To retain the glass in the frame, a minimum of a 6.35mm bead of structural sealant (e.g., silicone) is used around the inner perimeter of the window. The allowable tensile strength should be at least 1.4 Bar. Also, the window bite (i.e., the depth of window captured by the frame) needs to be at least 12.7mm. The structural sealant recommendations should be determined on a case-by-case basis. In some applications, the structural sealant may govern the overall design of the window systems.

Frame and anchorage design is performed by applying the breaking strength of the window to the frame and the fasteners. In most conventionally designed buildings, the frames will be aluminum. In some applications, where the windows are designed to resist high pressures, steel bar inserts, cable inserts or built-up steel frames may be used. Also, in lobby areas where large panes of glass are used, a larger bite with more structural sealant may be needed.

For reinforced concrete construction designed to resist high pressure loads, as is typical for embassy construction, anchorage of the steel window frames is provided by steel studs welded to a steel base plate. For this type of construction, the frame is typically constructed using a steel stop at the interior face and an angle with an exposed face at the exterior face. The frame is attached to the base plate using high strength fasteners. Coordination is required to verify that the fastener locations for the steel frame, the steel studs and the rebar cage are properly arranged.

For masonry walls, metal straps are recommended for anchoring the window into the wall.

Figure 6. Window Frame Cross Section with Steel Insert

2.4 Supporting Wall Design
A similar approach may be used for checking the supporting wall response. It does not make sense and is potentially highly hazardous to have a wall system that is weaker than windows that it is supporting. Remember that the maximum strength of any wall system needs to be at least equal to the window strength. If the walls are unable to accept the loads transmitted by the mullions the mullions may need to be anchored into the structural slabs or spandrel beams. Anchoring into columns is generally discouraged because it increases the tributary area of lateral load that is transferred into these members and may cause instability.
Some window/wall designs will require additional support around the windows. For clerestory windows, the supporting wall is acting largely as a cantilever and will need to be supported with vertical braces spanning floor to ceiling. For punched wall systems with narrow pilasters between them, vertical braces may also be needed. For lighter wall systems like metal stud systems, double studs framing the window are recommended.

The balanced design approach is particularly challenging in the design of ballistic resistant and forced entry resistant windows, which consist of 25 or more millimeters of glass and polycarbonate. These windows can easily become stronger than the supporting wall. In these cases, it windows may need to be designed for the design threat air-blast pressure levels and implicitly accept that for larger loads balanced design conditions will not be met.

3 Operable versus Inoperable Windows
Although operable windows can be designed to meet modest explosion requirements, keep in mind that they will not keep air blast out of the building if they are open.

Inoperable window solutions have potential to be more reliable for protection during air-blast events, because occupants cannot void the windows’ protective function by opening them. However, there are operable window solutions that are conceptually viable. For instance, if a window is designed to open outward about a horizontal hinge at the sill, the window will tend to slam shut in an exterior explosion. If this type of design is used, the governing design parameter may be the capacity of the hinges and/or hardware.

The controlling design component for sliding operable windows (and glazed doors) often is the supporting track. If possible, the track should be embedded in the supporting structure to provide added out-of-plane support to the system.

4 Skylights/Courtyards
Skylights in roof systems have the advantage of not being subject to reflected pressures from exterior explosions at ground level. Also, skylights are required by building code to be designed using laminated glass, which is preferred for explosion-mitigating design. However, they do create a falling fragment hazard. Therefore, these should be designed with a catch system beneath, or designed to remain in the frame for the design air-blast load. Ideally, skylights should be placed as far from the weapon as possible, to keep the pressures low.

For an atrium with an open courtyard in the center, the windows are protected by the building on all sides, and the glass will be subject to indirect air-blast pressures in the event of an explosion outside the building exterior. Because atria are protected on all sides, these internal window systems may be designed for the reduced pressures from an exterior threat. These reductions in pressures can help significantly in reducing the design requirements imposed by explosion loads.
5 Glazed Doors
Glazed doors and glass panes above a door are to be designed using the same methods as for windows. Glazed doors tend to use tempered glass for safety, in case of accidental breakage due to impact. As a result, they are high-strength and can complicate the design of the supporting system.

6 Global Design Considerations
The placement of the building on the site can have a major impact on its vulnerability. Ideally, the building is placed as far from the property lines as possible. This applies not only to the sides that are adjacent to streets, but to the sides that are adjacent to adjoining properties as well, since we cannot be certain about how access will change for those neighboring properties during the life of the building. A common-practice example of this is the use of a large plaza area in front of the building, which often leaves little setback on the sides and rear of the building. This practice can diminish the vulnerability of the front of the building, but generally will increase the vulnerability of the other three sides.
The shape of the building can have a contributing effect on the overall damage to the exterior envelope. Reentrant corners and overhangs are likely to cause multiple reflections of the air blast, which may amplify the effect of the air blast.

In general, convex rather than concave shapes are preferred for the exterior of the building (i.e., the shock front incidence angle on a convex surface increases more rapidly with lateral distance from a detonation location than on a planar surface, causing the reflected pressure on the surface of a circular building to decay more rapidly than on a flat building. Similarly, the air-blast pressures decay with height, as the angle of incidence becomes more oblique. The sides of the building not facing toward the explosion do not experience reflected pressure and will typically perform with less damage.

Generally, simple geometries, with minimal ornamentation (which may become flying debris during an explosion), are recommended unless advanced structural analysis techniques are used. If ornamentation is used, it is recommended that it consist of a lightweight material, such as timber or plastic, which is less likely than brick, stone, or metal to become lethal projectiles.

7 Multi-hazard Considerations
Under normal operating conditions, windows function in a variety of ways including:

- Permit light to enter building
- Save energy by reducing thermal transmission
- Make the building quieter by reducing acoustic transmission

Explosions are one of a number of abnormal loading conditions that the building may be designed to mitigate. Some of the others are:

- Fire
- Earthquake
- Hurricane
- Gun fire
- Forced entry

In developing a protection strategy for windows to mitigate the effects of a particular explosion threat scenario, it is important to consider how this protection may interfere with some of these other functions or other explosion threat scenarios. Some questions that may be worthwhile to consider are:

- If an internal explosion occurs, will the upgraded windows increase smoke inhalation injuries by preventing the smoke to vent through windows that would normally break in an explosion event?
- If a fire occurs, will it be more difficult to break protected windows to vent the building and gain access to the injured?
- Will a window upgrade that is intended to protect the occupants worsen the hazard to passerby?
8 Conclusion
Moderate levels of air-blast may be resisted through the use of minor modifications of standard construction practices used in conventional practice. The cost impact may be contained through strategic placement of windows in areas which are less vulnerable to explosive loads, such as on higher floors or on the sides of a building which do not face a nearby street.

References
The following references are provided for more information. Although many references within the United States are not publicly available, The U.S. Army Corps of Engineers Protective Design Center has provided extensive documentation for designers on their website.


Fire Safety of fenestration according to international requirements – a huge global demand – principles and options for an own advanced production system for EI and EW glasses

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Abstract

With the right products, top quality and limited production costs together with a complete product range - based on eventually own system solutions fire resistant glass offers a unique, highly profitable important business option - one of the most profitable for the time being in glass processing and glass construction for the upcoming years. But it is a real technical challenge and must be established following a well done master plan to succeed.

There was in recent years for small and medium size companies nearly no access to own Fire Proof Glass Production possible due to a big lack of know how about functionality, production processes and patent access, as well as for supervision in practise and awareness for adequate legal regulations in this market.

But the business prospective globally is bright, the will to change is there, but there is still a certain lack of know-how, how to do it. This belongs not only to the architectural market, also for ships and trains. But there is an option for own safe production based on independent patents and long term knowledge related to all sectors.

Keywords: Fire Proof Glass Systems, Fire Safety, Fire Proof Glass Applications, Fire proof glass Production

1. Introduction

1.1 Basic requirements for space-enclosing fire-resistant components

On the subject of "glass for fire protection" the essential requirements of the partition components must be considered to better understand the prevention of the spread of building fires (Figure 1).
Partition components of rooms in Class "E" according to the CEN standards must prevent in a standard fire test and under one-sided temperature load under the standard temperature curve for the required time period the spread of flames and smoke. A restriction on the heat transfer through radiation or convection is not required.

Components of the class "EI" prevent for the required period in addition the transfer of radiant heat and can therefore be used in escape routes and places where flammable materials (floor, furniture, curtains, etc.) are present, which would otherwise by radiation transfer from the fire room start to smoke and could catch fire.

To accomplish this, the temperature on the side facing away from the fire components may increase by no more than 140 K in average and 180 K at the hottest point on the baseline. The aforementioned standard temperature curve is mathematically defined and clearly describes the development temperature (C) in the test oven, depending on the previously elapsed test time. The following applies:

\[ T = 345 \times \log (8t + 1) + 20 \]

Where “t” is the time elapsed since the start of the experiment in minutes. This curve is also used in ISO and CEN standards, as well as in national standards of many other countries. But there are other temperature curves in alternative fire
test regulations or for so-called oil rigs. The CEN standards have yet another, particularly important standard introduced for class “EW”, which lies in performance between “E” and “EI”. Compliance with the “EW” criterion means that the test specimen during a fire test in accordance with EN 1363-1 at 1 m measured heat radiation on the opposite side to the fire must not exceed the value of 15 kW / m² during the test period.

![Classification of Fire-Resistance](image)

**Figure 2: Classification of Fire Proof Glasses**

### 1.2 Glass for Preventive Fire Protection? How comes that?

- Minimise Danger of Ignition (No Smoke, Safe Electricity Equipment etc.)
- Minimise Use of Combustible Material
- **Stop Fire spread**

Ordinary glass is not combustible, but if subjected to heat it cracks easily due to

- its relatively poor tensile strength
- its relatively high thermal expansion coefficient

Glass is therefore unsuitable for use in components that are designed to prevent the spread of fires. Cause of this property of ordinary flat glass is their low flexural strength (18-30 N/mm²), associated with a relatively large coefficient of thermal expansion (9 x 10⁻⁶K⁻¹). At different heating of different areas of glass tensile stresses which cause spontaneous fracture is produced in the cooler zones (Figure 3).
In order to obtain fire-resistant glass, the inclination of the glass panes to crack under the influence of heat, must either be significantly reduced or compensated by additional measures. This happens for the various fire-resistant glazing’s in very different ways. It is important to understand the individual characteristics and effects of the different systems because they often can only work properly if the type of glazing is optimally adapted to these specific properties.

Figure 3: Generation of tensions in monolithic glass

2. Basic types of Fire Proof Glasses

2.1 E- Glasses
In the reinforced systems (Figure 4), the crack is not prevented, but the resulting broken glass in case of fire are kept by additional structural elements firmly together.

Figure 4: Integrity E-glass Reinforced systems

Laminated systems

Monolithic Glasses

Laminated Glasses

d) Glassceramic pre-tensioned Glass Borosilicateglass

c) Profiled Glass

a) Polished wired b) Glass-Blocks

g) Special Interlayer

Foil

Borosilicate Glass

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In wired plate glass or wired cast glass ensures an inside spot welded wire mesh that these cullet’s are hold together. This is probably the oldest and most widely used fire-resistant glass, but not accepted as safety public areas glass due to low mechanical strength.

Profile glass is also held together after breaking through wires. Because of its greater dimensional stability, longitudinally extending, unconnected wires are sufficient.

For the glass blocks with the great thickness of the individual blocks in communication with the outer reinforcement by means of suitable bonding mortar, the formation of openings in the partition, when the fire heat leads to cracks in the glass blocks, is prevented.

A not to be underestimated advantage of the reinforced glasses is that their fire protection performance is almost independent of the development of the fire. Thus, they provide in suitable systems protection against the spread of flame and smoke for 30, 60, in some cases even 90 minutes in a standard fire test. At places where safety glass properties are required, they cannot be used in general. For monolithic fire-resistant glass (Figure 4) the breakage of glass shall be prevented at all, for which different methods may be applied.

For glass-ceramic, this is achieved by selecting a very specific composition and a subsequent heat treatment by which it is possible to reduce the thermal expansion coefficient so that thermal stresses which could lead to breakage, no longer occur. Since this material also softens at higher temperatures than normal float glass, theoretically very long lifetimes are possible with glass ceramic.

In case of toughened safety glass, the bending strength is greatly enhanced by thermal tempering up to > 160 N/mm², because this creates on the entire area of the glass surface compressive stress, which first have to be compensated by heat stress before it can lead to dangerous tension stress. In contrast to the above-mentioned low bending strength of ordinary flat glass is its compressive strength 70 to 90 N/mm² considerably higher.

However, the tempering as the only action is not enough to get a secure fire-resistant glass usually. Rather, special requirements must be placed on the quality of the glass edges and along the glazing method so that the tensile stresses in the edge region cannot be too large. An often applied, only seemingly simple glazing method is to keep the rim overlap of the glass through the glazing bars as low as possible, so that the temperature differences between the endangered glass edge and the fire-exposed parts of the glass remain as low as possible (Figure 5).

However, it is difficult to achieve, even in practice always maintaining the required tight tolerances. To increase security, thus also special toughening processes are used. Also special “intelligent” glazing systems have been successfully tested, which allow normal installation depth of the tempered glass panes.
Figure 5: Temperature in furnace and on glass

In normal application tempered fire proof glasses have the advantage that they also provide good security glass properties. Some developments aim to reduce by additional coatings on the one hand the transfer of radiant heat while they enhance the fire protection effect of E30 towards E60. But it must be noted that the IR-reflective coatings have a negative impact on the achievable service life in case of fire, if they are applied on the non-fire side!

The fire-resistant borosilicate glasses have an intermediate position between the above two types. On one side they have due to their special, deviating from the normal soda-lime glass composition have a much lower coefficient of thermal expansion, so that only corresponding to lower tensile stresses occur. On the other hand, they can be thermally tempered in contrast to the glass-ceramic and are so used as fire-resistant glass. Due to these properties, they bear much higher temperature gradient between the window edge and the fire-exposed glass areas than the tempered soda-lime glass.

Meanwhile, borosilicate glass can be produced by the float process and can be thermally tempered, thanks to an increase in the expansion coefficient that it meets safety glass requirements. In standard fire tests, borosilicate glasses can because of their higher viscosity at the same temperature, reach generally longer lifetimes as tempered soda-lime glasses and offer depending on thickness and glazing technique, protection against flames and smoke for 30, 60, 90 and > 120 minutes.
E glass reduces the transfer of radiant heat only little. When in use the respective structural situation (escape route, material used, distance between glazing and sensitive combustible components or equipment, etc.) must be critically considered.

### 2.2 EW-Glasses (Figure 4)

“Laminated” glasses consist of two or more panes of ordinary, non-toughened float glass, which are connected by means of a fire-resistant intermediate layer, e.g. of hydrous alkali silicate.

These systems have a very different mode of action, as the fire side glass panels of the composite may crack in a fire such as in the reinforced previously described systems; only the resulting fragments are held together by the in normal conditions invisible interlayer, which occurs only in case of fire, becoming then opaque and foams under steam output. This produces a tight sandwich structure of glass and foam glass.

![Table 1: Classification following EN 13501-2](image)

This process provides an additional benefit, because by the evaporation of the water, fire heat is consumed, and the resulting solid foam increases the isolation effect, so that considerably less heat from the fire zone can be transmitted through the glass in the adjacent room. The risk of spread of fire by radiant heat is significantly less than in the glasses previously mentioned. They belong according to the CEN standard to the “EW” class and offer with relatively simple systems a protection for 30 or 60 minutes at a standard fire test. In locations where such glasses must also meet safety glass requirements, they can be combined with suitable laminated safety glasses. Because they allow less heat transfer and in their mode of action are independent of the compliance with certain maximum temperature gradient, they can be used in other glazing demands better than other “E” glasses and offer additional protection.

Recently versions with 2 x toughened glasses with a nanotech interlayer of only 3 mm thickness as fire protection and safety glass for E/EW 30 up to E/EW 120 was introduced and which can be offered too.
Many of the previously mentioned fire proof glass types can gain additional properties by additional measures so that they can attain in suitable systems a variety of other functions such as sound insulation, sun protection, heat protection etc.

2.3 EI-Glasses

For these glasses (Figure 6) only two basic types have prevailed, at first.

![Image](image.png)

**Figure 6:** EI fire proof glass types

### 2.3.1 Alcali Silicate EI Glass

One of these types is made in principle in the same structure as the laminated glass of the "EW" class described above with the hydrous alkali silicate layers, only that these composites for the different levels of the EI-class at least contain 2, usually at least 3 fire protection layers. For extreme requirements may also much more glasses and fire protection layers be combined with each other. Thus, practically all conceivable demands on fire protection glasses with laminated or insulating glasses can be met at the same.

The mechanism of action of these glasses in case of fire is illustrated in Figure 7: At the beginning the radiant heat of the fire source is completely absorbed in the intermediate layers, which indeed contain water and therefore are almost opaque to the thermal radiation. The fire-side intermediate layer is therefore heated up to reach the typical reaction temperature at which the water evaporates in the layer. In this case, a large part of the heat emanating from the fire power is consumed, and thus rendered harmless. At the same time the intermediate layer expands; it forms a thick, strong, tough foam plate that holds the cullet of the fire-side glass plate. The foam is becoming foam glass, a solid sandwich of glass and foam - glass which even still offers full protection if all glass panels of the composite are cracked. So this is a real heat shield glass, which can maintain an extremely high temperature gradient (Figure 7).
At the higher performance classes the protective effect provided by the EI glasses is quite amazing: while dripping melting glass on the fire side at e.g. 1100 °C after 120 minutes, the side facing away from fire keeps for a long time still cold, also the thin glass panes of EI30 after 30 minutes can be touched safely when inside just hot glass drips.

In this way, a secure protection is given, almost independent of the fire development, ensures not only the direct spread of flame and smoke, but also the risk-free passage of escape routes. Another advantage of this EI fire proof glass is its production from ordinary float glass. This results on the one hand, in a good optical quality and on the other hand in the possibility to produce dimensions limited to approximately 2 x 3 m² and thus being able to cut as needed to final size.

The advantage of low thickness is achieved because the water contained in the fire protection layers is very tightly bound and on its release in the event of a fire consumes a lot of energy. Developments in this fire-resistant glass - type led to colour-free high-performance fire-resistant glass with high light transmission.

2.3.2 Aqua-Gel or Nano-based Interlayer System EI Glass
Quite different structured is the other group of "EI" fire proof glass. The structure is similar to an insulating glass, in which, however, the hermetically sealed space containing the fire protection material replaces the air or other gases. So these are laminated glasses, with the outer panes of toughened glass and with minimum one, but also with several relatively thick intermediate layers consisting of a clear, salty, organic "Aqua Gel" or Nano-based interlayer with very high water content.

The protective effect is based almost exclusively on the heat of vaporization of the water; therefore thicker layers for the same protective effect are required. In case of fire, the fire -side pane cracks soon. The gel layer then reacts only at the interface with the fire room dwindling slowly and evenly, while its side facing away from fire still adheres to the tempered glass pane. Because of the necessary use of tempered glass a production of big sizes for later cut-outs to the final
dimensions required by the customer is not possible here. But individual production lines can be built with almost any capacity. Of course, these heat shield fire protection glasses can also be combined with many other functional glass and so simultaneously with high transparency fulfil several, quite different requirements. They already meet high requirements for sound insulation and security glass properties.

2.4 Glazing Systems

Strictly speaking, there does not really exist a fire-resistant glass, but only fire-resistant glazing systems, because the key is the interaction of all components of a system in case of fire. However, a good framing system can fail in case of fire, even if it is provided with an excellent fire-resistant glass, if the items of the glazing were not matched properly to each other. Therefore, a once given approval relates only to a specific tested system. For example, a replacement of a fire rated glass type with another is not permitted; too different is the interdependence of all components of a fire protection system from each other.

3. Certification and Monitoring

There are mainly in countries with less well-organized fire regulations many examples from the use of completely unsuitable glazing in fire protection components. This makes clear the importance of a registration and monitoring system like it is handled in Europe. The fire protection authorities shall ensure that, in general, only officially approved systems are used. A list of approved fire protection systems is published twice a year, for example, by DIBt (Germany).

Table 3: CEN Standards for Fire Proof Construction.

<table>
<thead>
<tr>
<th>Test Standards</th>
<th>Concern</th>
<th>Important Requirements for fire resistant building components</th>
<th>Possible classifications</th>
</tr>
</thead>
<tbody>
<tr>
<td>EN 1363-1</td>
<td>Basic requirements</td>
<td>Standard-Test-Temperature-Rise: T = 345 log(20000(8)) + 20 Pressure in furnace increased by 0.01 Pa</td>
<td>See below EN 1364-1 to EN 1634-3</td>
</tr>
<tr>
<td>EN 1363-2</td>
<td>Alternative and additional Test-Procedure</td>
<td>a) Temperature-Rise: T = 1000(10.000 - 0.675 (e^{-12})) + 20 b) Temperature-Rise: T = 6000(1.000 - 0.313 (e^{-12})) + 20 c) Heat radiation in 1 m distance: 313 kW/m²</td>
<td>Oil-Fire (not official yet) External Fire (used for ext. walls) Classification: See below EN 1364-1 to EN 1634-3</td>
</tr>
<tr>
<td>EN 1364-1</td>
<td>Partitions (not load-bearing walls)</td>
<td>Integrity: opening ≤ 25 mm² or ≤ 6 x 150 mm², no ignition of cotton-pad, no flames on unexposed side) when tested from one side according to EN 1363-1 Radiation: * Radiation in 1 m distance: 313 kW/m² Insulation: * mean Temp.-Rise on unexposed side ≤ 140 K, maximum Temp.-Rise on unexposed side ≤ 180 K</td>
<td>E 20, 30, 60, 90, 120 EW 20, 30, 60, 90, 120 EI 15, 20, 30, 45, 60, 90, 120, 180, 240</td>
</tr>
<tr>
<td>EN 1365-1</td>
<td>Load-bearing walls</td>
<td>Load-bearing (axial contraction C ≤ 100 mm and velocity of the Capacity: (axial contraction DC ≤ 30/1000 mm max.) All requirements of EN 1364-1, see there. Possible additional requirements: Impact resistance ≥ 300 Nm</td>
<td>RE 20, 30, 60, 90, 120, 180, 240</td>
</tr>
<tr>
<td>EN 1365-2</td>
<td>Ceilings and Roofs</td>
<td>Load-bearing (Bending D a L/400 d (mm) and Durchbiegungs-Capacity (Bending velocity - dDk ≤ L/5000 d (mm/mm) All requirements of EN 1364-1, see there.</td>
<td>RE 20, 30, 60, 90, 120, 180, 240</td>
</tr>
<tr>
<td>EN 1634-1</td>
<td>Fire-Doors and shutters</td>
<td>All requirements of EN 1364-1, with the exception, that the max. Temp, on frame may be either 180°C (EL1), or 360°C (EL2) Possible additional requirement: Automatic shutting</td>
<td>E 15, 20, 30, 45, 60, 90, 120, 180, 240</td>
</tr>
<tr>
<td>EN 1634-3</td>
<td>Smoke preventing doors</td>
<td>Leakage measured at roomtemp. (Sₚ₌ₚₑ) or at 200°C (Sₚ₋₃ₚₑ)</td>
<td>Sₚ₌ₚₑ Sₚ₂₃ₚₑ</td>
</tr>
</tbody>
</table>
Institute for Building Technology), which may be compared to UL in the US. It makes sense to use already approved systems, wherever that is possible, if somewhere in the building fire proof glass is required.

Putting a new system through the testing and approval process is costly and time consuming. One can try to make an approval for a single case for a new system by the local fire protection authorities, but with already approved systems, one has the guarantee of a permanent power control, since only systems are admitted to the regular official monitoring, which are continuously monitored by a Material testing Institute. In addition, the monitoring agreement also regulates that the fire protection components must be assembled only by trained personnel.

4. Examples for Application

An important application find fire protection glazing in fire doors and partitions in the interiors of larger buildings. Wherever the interests of preventive fire protection in buildings to be subdivided into fire compartments is required, extensively glazed fire doors and partitions can be used to allow visual contact and daylight access, or even to realize an aesthetically pleasing interior.

Typical applications in the facade can be found e.g., where closely spaced buildings must be protected at inner corners of buildings, roofs, adjacent to vertical parts of the building and high-rise buildings where the flashover from one floor to the overlying by fire glazing can be prevented.

![Figure 8: Building compartmentation & escape routes](image)

The location of some of the systems shown in Figure 8 and 9 are not only the interior and the facade of buildings; also roofing and other overhead glazing (Figure 10) are becoming more common. Even walk-on fire protection glasses were already demanded and produced.
Figure 9: Building compartmentation & escape routes

The location of some of the systems shown in Figure 8 is not only the interior and the facade of buildings; also roofing and other overhead glazing are becoming more common. Even walk-in fire protection glasses were already demanded and produced.

Figure 10: Building compartmentation & facades

ICE high-speed-trains were fitted to the wagon ends with fire protection glasses of class E30 to prevent the spread of fire to other cars in an emergency.

Fire safety glasses of extreme performance that must reliably withstand in all official tests in appropriate glazing a temperature stress of 1100 °C for more than 120 minutes, are used on oil drilling and residential islands increasingly. Also on ships are A0 (= EW60) and A 60 (=EI 60) - glasses mostly for cruisers used.
Today, you can say that most conceivable demands on fire protection glasses can be met, but just in new, sometimes unusual application areas, it is imperative that planning authorities, manufacturers and processors cooperate closely.

5. **Top Fire Proof Glass Production – The Advantage**

5.1 **Transfer of Top European Technology to a reliable high quality production partner**
- Local glass processor
- Understand local mentality
- New buildings as well as Renovations of existing ones
- Access to other innovations
- Long term high earnings for Licensee

**The Licensee’s Benefit - Local Licensed Production**
- Generate market access close to the needs of the local markets
- Less transportation costs for the ready-made glasses
- Quicker delivery times also with tempered safety glass types
- Multifunctional glasses can easily be combined
- Stepwise Completion of product range for license partner

5.2 **Long term market and product opportunities**
- Own “home-made” added value product
- Producer of world-wide high level fire proof and safety glass
- Competitive against top quality products
- Approach to Ship Building Market
- Production of value added complete product range similar to top suppliers
- Achievable EN/ISO/US and other standard fire testing provides access to international markets

![Figure 10: Fire Protection Glass Products – Solutions for all Applications](GlassCon Global - Page 322)
5.3 The Idea: Successful New Fire Resisting Glass Production
Offer for technical Co-operation / License
- Transfer of the complete production technology
- Permanent production support
- Delivery of the needed / patented materials
- Access to any product improvements

5.4 Realisation: Nano Particle Size Interlayers for all Classes E/EW/EI
Advantages of New Nano Technology
- Clear and with high light transmission
- Only 3 mm thin for applications for class EW
- Fire resistance up to 120 minutes E/EW/EI
- Tempered safety glass with big sizes
- Multiple choice of combination glasses allowed
- Applications in facades – sealed units
- Easy to handle core production technology
- Manageable and inexpensive investment into machinery
- Full flexibility in customer service

8. Summary

About all these norms and rules one should not forget that there are more important things in the handling and use of fire-resistant glazing. A precise knowledge of the different fire protection glasses and their specific properties, a careful selection and implementation of the matching glazing, the account of the particular conditions at the site - these are essential prerequisites for a successful preventive fire protection.

Please contact: helmut.hohenstein@hohenstein.biz

References:
[1] Henning Nolte, Germany; he developed and provided over his long career in fire proof glass a lot of detailed background. I acknowledge the access to his materials which I used in this paper
[2] Werner Hillmann, Switzerland; he offers in cooperation with my Company solutions for new applications, access to different market products, but also for tailor-made, turnkey-ready production facilities with support for standards, testing and certification, additionally for product application and market access.
Super lightweight glass structures – a study

Jeppe Hundevad
APG Europe GmbH, Germany

Abstract

At a time where we strive to make ever larger and heavier glass panels, shouldn’t we pause and question if this really is a modern and forward way of thinking? Wouldn’t it be better to redirect our energy into investigating new ways of pushing technological boundaries in order to save material rather than using more of it, whilst nevertheless retaining its value?

This paper aims to look at new developments in super thin glass technology which in the future, if used wisely, will revolutionize the structural glass industry. We will discuss the nature of super thin glass, its special characteristics, and how it can be used.

1 Introduction

This paper intends to introduce super thin, chemically toughened glass and provide comparisons with the industry standard of soda lime thermally toughened glass. The first part of the paper will focus on the structural characteristics of this new form of glass. As well as explaining the reasoning behind certain design approaches using curved glass in lieu of flat glass applications.

The second part of the paper will present a study of an all glass, super lightweight roof structure which utilizes all the benefits of thin glass technology. Owing to the unique nature of the chosen geometry this structure can be retracted. In conclusion there is a short study comparing the total energy usage of this glass as an insulated glass unit with similar conventional heat treated glass.

2 Super thin glass characteristics

2.1 Manufacturing

Conventional glass used in commercial glass applications is soda lime glass and is produced on a float glass line. The glass is brought to a molten state and floats on a horizontal bath of molten tin (Fig. 1).
Super thin glass panels are usually made from $\textit{Aluminosilicate glass}$. This glass material has the additional content of Aluminium Oxide. The resulting glass has superior visual characteristics, as well as a much higher temperature resistance. This super thin glass contains no iron and is therefore considered to be a `zero iron´ glass.

Instead of the conventional float glass line, which is horizontal, this super thin glass is manufactured using a "drawn" process (see fig. 2). During this process the molten glass is held in a bath and drawn vertically through a long nozzle, similar to the way in which fiber optic wire is made. The main difference between this manufacturing process and that of float glass is that the molten glass never actually comes into contact with any surface. This means that there is no tin or air side to this glass, resulting in an extremely low chance of the glass picking up any impurities. Furthermore there is next to no distortion.

**Figure 1.** Diagram of float glass process.
Figure 2. Drawn glass process.

The glass thicknesses studied in this paper will be 0.7mm and 1.0mm, which are the most readily available thicknesses. The largest sheet size is 1450 x 1800mm.[3]

2.2 Tempering / toughening

Such thin glass is not toughened using an oven process where glass is heated and cooled. Instead a chemical toughening process is used.

Figure 3. Chemical toughening process (blue indicates the glass material).

The chemical toughening process is a more complex process than conventional thermal toughening (fig.3). During this procedure the glass takes in charged particles (ions) which are effectively “stuffed” into the glass surface to increase the surface compression. This process takes place in a chemical salt bath, an image of which is shown in figure 4. The temperature of the bath is around 400 °C and the glass is pre-heated prior to this. In comparison, thermal toughening uses oven temperatures of around 600 °C.

Because the glass is toughened both chemically and vertically no rollers are used, meaning that no roller wave distortion occurs.

The resulting surface compression is much higher than that of the conventional thermal tempering process. The surface compression of chemical toughening can be up to 800 MPa compared to about 80 MPa using thermal techniques.[2]

In purely structural terms this is a very significant increase in strength (factor 10). For a comparison we design steel structures with a design strength of 200-400 MPa.
2.3 Breakage shapes / safe breakage

With such high amounts of energy contained within the glass, the corresponding breakage condition will also change. As a general rule of thumb the more energy that glass contains the smaller the particles are that result in breakage.

The following photos (Fig. 5) show a comparison between broken glass fragments of thermally tempered glass on the left and chemically toughened glass on the right. Here it is clearly noticeable that broken chemically toughened glass breaks into much smaller fragments, almost exhibiting a powder like state.

Figure 5. Broken glass particles from thermally toughened glass (left) and chemically toughened glass (right).

This does open up a further discussion about safe breakage of glass. It is necessary to consider if the glass breaking into a semi-powdered state represents a serious human hazard or not.
At this time it is obligatory for all overhead glass to be laminated. This type of super thin glass presents us with the possibility of using anti-splinter films in lieu of lamination, therefore resulting in a lighter weight solution.

3 Structural applications

3.1 Design approach of super thin glass structure

When assimilating all factors of super thin glass the following fundamental characteristics become the basis for designing new structures:

- Dead load (self-weight) - Glass used is only 1mm. This has a significant effect on the dead load of the structure.
- High strength - Glass can accommodate design stresses similar to steel and up to 10 times stronger than thermally tempered glass.
- High deformation – The combination of thin glass and super high strength means that the glass is able to deform a lot more than conventional glass.
- Cold formed bending – Glass can be bent from flat glass easily to form stable shapes, similar to a membrane.

3.2 Flat panel approach

Until now the concentration of structural glass design was based upon flat panel applications.

An IGU itself is a flat panel application in its purest sense. We take a flat sheet of glass and provide support for the glass in various ways. Where a flat panel design needs more strength the glass is simply made thicker by using thicker glass or adding laminates.

For thin glass this approach is less sensible, as the glass in its flat state, exhibits large deformations but does not break. Such large deformations would be considered unacceptable even though they may not necessarily result in glass failure. There would be a perception of discomfort.

3.3 Deformed / curved Structures

The characteristics of large deformation capability and high strength would strongly suggest that a better approach would be to look at curved structure. Applying a curvature to a flat panel results in an increase in stiffness where the forces inside the glass change from being bending forces to in-plane forces.
Due to the high cost of curved glass, there are few completed curved glass structures. However with thin glass there is little to no cost increase to create a curved structure especially as the glass can easily be cold bent into shapes.

The simplest form of curved structure is an arch shape, using single radius curvature. Such shapes below (fig. 6) show simple geometries with this shape.

![Curved structures using single radius curvature.](image)

**Figure 6.** Curved structures using single radius curvature.

These structures do however rely on frame elements and single curvature structures tend to exhibit certain instabilities when under compression loads.

Below (fig. 7) are shown various forms of arch instability.

![Forms of single curved arch instability.](image)

**Figure 7.** Forms of single curved arch instability.

Due to the resulting instability (fig. 7) it would be better to consider a double curved shape i.e. a shape where this buckling cannot occur so easily. A conical geometry could be used to overcome this problem; it not only provides a form of double curve but also ensures that the panel can be cold bent from a panel that was originally flat. This is important when considering the cost of such future glass structures, as it would be possible to avoid having to thermally curve the glass. Conical shapes which could be considered are shown in figure 8.
Figure 8. Conical shape studies for use with cold bent glass.

The following diagram (fig. 9) shows the simple rules of geometry which generate cone shapes. Each cone can be developed into a flat surface.

Figure 9. Conical surface generation.

Let us then look at similar structures which exhibit a conical geometry. A good example is the Kimmel Center in Philadelphia PA, USA. This building has a unique roof geometry comprising a series of cones connected together into a cylinder.
4 Glass roof structure using super thin glass

4.1 Geometry

The geometry exhibited in the Kimmel Center can be used as inspiration for an all glass structures using thin glass.

The following conical structure (fig. 11) is a similar shape but removes the steel frame. The result is a series of twin arches as cone segments.
Figure 11. Conical frameless structure using thin glass.

Such a structure could be made from cold bending thin glass which is connected to form a barrel vault construction. The proposed prototype structure would have a specification as follows:

- **Span**: 3000 mm
- **Length**: Variable according to number of bays (1000mm per bay)
- **Inter Panel Angle**: 90 Degrees
- **Glass Specification**: 0.7mm Gorilla Glass / 0.38 PVB interlayer / 0.7mm Gorilla Glass
- **Sheet sizes**: 750mm x 1250 mm

The resulting developed panel and complete arch plan is shown below (fig. 12).
**Figure 12.** Conical arch - single panel (above), flattened and curved geometry (below).

**Figure 13.** Complete structure showing 3 conical arch pairs and front / back stiffening caps.
4.2 Connections

Another challenge posed by thin glass is the connection method for adjacent panels. Conventional bolted applications cannot be used at holes in the glass would develop high stresses. The only feasible method is to bond parts to the glass surface. Bonding materials such as a structural silicone, high strength TSSA, UV bonding, adhesion tapes and conventional glue have all been considered for this purpose.

The glass panels are connected together using mechanical fixings. A carrier frame bonded to the glass is introduced in order to distribute loads and to avoid scalloping along the edge of the glass.

Articulated elements are fixed to the carrier frame and are adjustable. The final bonding material used was a 3M VHB tape to fix the carrier frame to the glass as this was easy to fix to a curved surface and exhibited flexible elastic properties to allow dissipation of concentrated loads (fig. 14).

![Figure 14. Arch articulation detail.](image)

4.3 Dynamic properties

Owing to the fact that the structure is symmetrical, and is made from flat panels, it is possible to flatten the structure. This characteristic of ‘fold-ability’ is useful and intriguing as this means the structure can be retractable using motors and sliding bearings. Coincidentally, the structure has a unique additional property, which is the ability to retract from a curved shape to a flat shape. The structure could be contracted from a dimension of 3408mm to 650mm, which is just 19% of the expanded length (fig. 15).

It is therefore possible to envisage such glass structures which are not only extremely light weight but also retractable.
These structures are used for the following applications:

- Interior partition walls
- Shop front facades
- Stadium roofs
- Canopies
- Skylights

**Figure 15.** Side elevation of structure showing open (left) and closed (right) condition.

### 5 Energy considerations

Such structures are extremely light weight. For example the structure illustrated above covers an area of 10.5 m² (utilized glass area is 23 m²). But the total weight of the structure including hardware is only 110kg. This results in a ratio of weight to area of 10 kg/m². With optimization of form this value could be further reduced.

This leads us to the issue of energy savings. The table below is an estimation of the energy savings of switching 6mm tempered glass to 1mm gorilla glass. The
summary is an estimate which includes the energy for making the glass, tempering, and shipping. The summary does not include for savings in installation where units will be significantly lighter. Nevertheless this rough calculation indicates that chemically toughened glass could reduce overall energy consumption up to 20% compared to that of conventionally heat tempered soda lime glass.

![Table](data:image/png;base64,iVBORw0KGgoAAAANSUhEUgAAAQAAAAHgCAYAAAA9444gAAAASUVORK5CYII)

**Figure 16.** Energy comparison of 2x6mm IGU, and 2x1mm chemically tempered glass IGU in MJ.[1], [4]

**Conclusion**

The introduction of chemically toughened thin glass provides a completely new set of design considerations when investigating structural glass. This material behaves in a different manner to conventional tempered glass and therefore the design approach needs to adjust accordingly. We need to emphasize the approach to cold bent curved structural applications, with or without a dynamic function.

Such glass contains no iron and has zero roller wave distortion. The use of this glass can also reduce the energy footprint by a factor of 5, therefore offering enormous savings in CO2 emissions for the future.
References

When is Glass Flat?

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Abstract

The discussion about glass often touches on the subject of glass flatness. The material is manufactured flat, but this property of flatness brings with it the problem of determining and answering the question, how flat is flat?

As the material becomes “flatter”, any unevenness in the surface will become more apparent and that’s why when we call glass “flat”, it’s all a matter of interpretation. This effect can be seen on every glass building with a large area of flat glass façade. The glass, when viewed in reflection is uneven and in some cases extremely so.

This paper aims to provide an up-to-date summary of what causes the unevenness in glass. There are many myths about glass flatness in particular “roller wave distortion” which needs some clarification. This paper will conclude by suggesting alternative ways of measuring flatness in glass, not during the manufacturing process, but more appropriately in the final stage after installation. Furthermore, it will be argued that it is not flatness that is concerning us but the effect of non-flatness, or rather “distortion”.

We will aim to suggest possible new ways to determine a benchmark for assessing “in place glass distortion” which is a way to compare the finished installed glass, as well as some ways to determine an overall distortion factor.

Figure 1. Virtual model of a flat glass with reflection.
1 Causes of distortion

1.1 Glass processing

1.1.1 Glass thickness
We begin our investigation into glass distortion at the float glass line. The float glass production results in glass which leaves the manufacturing line in a flat state.

The glass thickness can affect the flatness of the glass. The following details show the flatness of float glass in relation to their nominal thickness. Upon inspection of this table it becomes obvious that variation in thickness has a significant effect on the glass tolerance levels. The fundamental question that arises is however, over which length is the variation in thickness allowed? If, for example, the range +0.2 mm was allowed over a glass length of 1000 mm this would be likely to cause some significant distortion in the glass panel.

<table>
<thead>
<tr>
<th>BS / ASTM Nominal</th>
<th>Min (mm)</th>
<th>Max (mm)</th>
<th>Tolerance+/- (mm)</th>
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</table>

1.1.2 Lamination effects
In the process of lamination the glass panel is pressed together either in a vacuum or mechanically depending on the lamination process. The pressure is applied uniformly but the panel may deflect unevenly under this pressure. This can result in the panels having an uneven thickness of lamination. In particular the edges of the glass may compress slightly more than the center, thereby creating a pinching effect on the edge of the glass. There are recorded tolerances of lamination thickness, but is unclear as to over which length of glass this tolerance can be applied. Therefore the same dilemma arises with the issue of glass thickness.
Table 2 Glass lamination thickness tolerances

<table>
<thead>
<tr>
<th>Nominal Mm</th>
<th>Min mm</th>
<th>Max mm</th>
<th>Tolerance+/- mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>8,38</td>
<td>7,95</td>
<td>8,81</td>
<td>0,43</td>
</tr>
<tr>
<td>10,38</td>
<td>9,95</td>
<td>10,81</td>
<td>0,43</td>
</tr>
<tr>
<td>12,38</td>
<td>11,95</td>
<td>12,81</td>
<td>0,43</td>
</tr>
</tbody>
</table>

1.1.3 Thermal strengthening - “roller wave”

The heat treatment of glass involves the glass being heated up to approximately 650 degrees Celsius and then being rapidly cooled. This heating and cooling or “tempering”, leads to the associated problem of having to deal with a flat product in a semi-molten state. At this temperature the glass is soft. Furthermore the glass is held on rollers resulting in what is termed as "roller wave distortion" as the glass sags and distorts between the rollers.

You can see from figure 2 that depending on the diameter of the roller with the same peak to valley reading, distortion can be quite different. A nominal roller can be around 80-100 mm in diameter with spacing of 150–250 mm. If a smaller radius roller with a correspondingly smaller roller spacing is used the peak to valley reading may be smaller, but the distortion of the glass would be greater as the deviation from flatness would be little changed.

Figure 2. Rollerwave schemes

For this reason the roller wave value alone does not give a true assessment of the glass flatness and its relative distortion characteristics.
When looking at roller wave distortion there are the following important considerations to be made:

- Distortion values right now are actually extremely low. We currently can comfortably achieve roller wave distortion of 0.08mm for a 80mm diameter roller at 150-200 mm spacing. To put this into context, the distortion is less than the thickness of a human hair (average 0.1mm).

- There is no given roller wave definition for thicker glass. Clearly the roller wave distortion is less using 12mm glass than with 6mm glass due to the increase in strength of the semi-molten glass in the oven. One could assume that if a 6mm glass would have roller wave of 0.08mm, then a 12mm glass has a theoretical stiffness increase of 8x minus the increase in weight 2x. This would result in a roller wave 4x times less, i.e. 0.02mm.

- It is rare that glass distortion is caused solely by roller wave. In relation to other effects the roller wave distortion has a small, in certain cases insignificant, contribution to the overall glass distortion.

Figure 3. Roller wave distortion
Fig. 3 is an interesting photo of a façade where it appears that only one panel shows significant roller wave distortion. These waves are apparently quite close together. The vertical nature of the waves has the effect of making the distortion appear even worse.

1.1.4 Bow tolerances
Current achievable bow tolerances are given for glass as a defined bow mm/m. This is combined with an edge lift factor which is due to the edges of the glass cooling at a different rate compared to the center of the glass. A typical bow tolerance is not specified for each glass thickness, but is given as 0.6mm/300mm, and edge lift of 0.2mm over 300mm.

Figure 4 below shows glass distortion where there is predominantly bow distortion. This can be seen in the distortion of the vertical lines. In addition you can see a further finer distortion which is the roller wave distortion, this is a secondary distortion. This suggests that the bow distortion in glass is more evident than roller wave.

Figure 4. Combined bow and roller distortion
1.2 Post processing effects

1.2.1 Internal pressure in IGU (insulated glass unit)
The second source of bow is thermal bow, which is caused when using glass in an insulated glass application. For this to occur, the cavity of the glass which is air sealed can develop differential pressures to the outside ambient temperature. This will result in deformation of the glass unit or bowing effects. A simple example is a unit of IGU with a size of 2 x 4 m. It could be deformed by up to 2mm with a temperature difference of 30-40 degrees Celsius. This deformation would be due to the temperature alone.

![Photo showing bowing distortion.](image)

The above photo appears in many web sites which describe roller wave distortion, but looking closely at this image you can see the distortion in this case is not caused by roller wave but by pillowing of the glass. In this example the pillowing is most likely caused by the IGU cavity undergoing an increase in pressure, causing the outer panel to bow outward. The roller wave distortion here is hardly evident.

1.2.2 Orientation – sloped glazing
One would consider that when designing overhead glazing that optical distortion is of little significance. However in sloped glazing or inclined glazing the glass surface is still visible. If a 6mm thickness glass was used with a 10 degree incline the glass could bow up to 1mm at center pane due to the dead weight of the glass. This is enough to cause a distortion which may eliminate all effects of roller wave.
1.2.3 Method of installation - Installation tolerances

Many systems require glass to be mechanically fixed in position (see Figure 6 below). Under consideration of the small deflections which cause distortion, this means that the forces applied by the fixings could affect the distortion significantly. When tightening a screw in a screw channel it's almost impossible to control the amount that the glass is deformed in the process, anything more than 0.1mm will affect the distortion of the unit.

![Figure 6. Typical mullion detail with IGU – Wicona]([3])

Furthermore if the sub-structure is laid out in a fashion which is not entirely flat, this will also contribute to visual distortion. One could consider installing a curtain wall to an accuracy of 1mm/m run as effectively the same distortion as that of roller wave distortion.

2 Methods of measurement - modeling of glass distortion

There are certain known methods of measuring roller wave and bow distortion in single sheets of glass. These methods are well documented and include feeler gauges, striped boards, and even online scanners. However, these methods are limited only to glass leaving the tempering oven or during the glass panel manufacturing process. This measurement technique therefore does not provide the full picture of the overall distortion of the panel. It would seem more
sensible to consider a method which measures distortion in the complete assembled panel, both before dispatch as well as in the installed condition.

We need to consider a method by which we can measure this distortion using the most modern technology available today. As the units need to be measured after completion it may not be practical to measure them in a flat horizontal condition but in a vertical condition.

2.1 3D scanning methods

With the introduction of cloud survey technology in buildings we are now able to measure most parts of the building to an accuracy of about 1mm.

Figure 7. 3D Scanning technology – Metrascan 3D – Creaform.[1]

The survey cloud measurement is however not able to measure the surface distortion of the glass to the degree of accuracy which is required for this purpose. Therefore a more accurate method is required. At this time the only technology available is 3D scanning technology (see figure 7). This technology is able to measure smaller areas more accurately, and does not require the measured object to be still. The accuracy of the measured surfaces using such measurement can be up to 22 microns, or 0.022mm.

A hand held scanner is used to measure the surface contours accurately on interior or exterior objects. Using pre-positioned sensors the surface can be
measured accurately even if there is some movement or vibration of the object. The pre-placed sensors are able to retain the relative position of the object. This method offers the possibility of surveying an entire glass curtain wall, perhaps after selecting a few certain areas. In this way the distortion value could be calculated from the survey data. Unfortunately a problem of this technique is that the measuring device has difficulties surveying transparent or highly reflective surfaces. This obviously poses a problem, as glass is selected exactly for its transparency and reflectivity. In order to solve this problem it might be possible to coat the glass with some kind of temporary paint, which can be removed with water after the survey is complete.

2.2 Modeling methods

Current developments in the modeling of light and surfaces enables us to be able to create glass panels which deliberately include distortion to make models more realistic. Rendering software is commonly able to model surface “noise” or roughness, and some applications can even model real life glass distortion. For example the following rendering can be considered (figure 8). In this instance the base model uses a perfect flat glass. The next photo shows a vertical wave distortion of 0.4mm over 250mm.

From the picture it is clear that the software is able to identify the minimal distortion of the glass panels, and is also able to model the reflectivity of such a distortion.[2]

**Figure 8.** Distortion modeling: this distortion has a 250mm wavelength and is oriented along vertical. The amplitude of distortion varies randomly up to 0.2 millimeters (peak to valley of 0.4mm). Ref. Eclat Digital – France
2.3 Distortion coefficient – Cdis

By using the methods described it will be much easier to establish a datum for distortion coefficient. Let us consider an overall distortion coefficient or Cdis.

The Cdis factor not only needs to be able to incorporate all local distortion effects, but also needs to accommodate global distortions caused by bowing and pillowing i.e. global effects over the whole area of the panel.

This Cdis can be measured using 3D scanning techniques and can be applied to virtual models to allow Architects to define levels of surface quality. It could be possible to establish Cdis values which relate to certain quality levels. These Cdis levels can be standardized in order for each level to have a certain requirement of pre- and post-processing tolerances in order to achieve a Cdis factor.

One possible approach to this Cdis value would be to look at the Diopter values which are mentioned in the ASTM. The Diopter value is a value which uses the effect of wavelength and amplitude to calculate a distortion value, similar to the focal length of a lens. This diopter value is calculated using the following formula.

\[ D = \frac{4\pi^2 w}{L^2} \]

w = depth of distortion wave peak to valley, or 2 x amplitude
L = length of distortion wave from peak to peak, or wavelength
D = optical distortion in diopters

Generally the lower the diopter value the less is the distortion.

We can use these basic simplified values and simply add the diopter values together for each possible source of distortion. Some results of this are shown in the table in figure 9 below, in this case showing the effect of changing the roller wave. Here we have reduced the roller wave from 0.08 to 0.02mm, with a corresponding roller wave length of 250 to 150mm, which only results in a difference of combined total distortion of Cdis 7%.

Upon further inspection of the data it suggests that the effect of roller wave on the overall distortion values is considerably less than is generally assumed. In fact the overall bow factor of the panel has a much greater effect. This observation is borne out in photographic evidence where the distortion (figure 5).
**Distortion Comparison using values above**

<table>
<thead>
<tr>
<th>Condition 1</th>
<th>Peak to Valley Length (wavelength)</th>
<th>m diopter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Thickness</td>
<td>0.20 mm</td>
<td>7.89 4%</td>
</tr>
<tr>
<td>Lamination</td>
<td>0.03 mm</td>
<td>1.18 1%</td>
</tr>
<tr>
<td>Bow</td>
<td>1.20 mm</td>
<td>131.46 62%</td>
</tr>
<tr>
<td>Rollerwave</td>
<td>0.08 mm</td>
<td>50.48 24%</td>
</tr>
<tr>
<td>Thermal Bow</td>
<td>2.00 mm</td>
<td>19.72 9%</td>
</tr>
<tr>
<td>Installation Tolerances</td>
<td>1.00 mm</td>
<td>9.86 5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Cdis</strong> 211.52 100%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Condition 2</th>
<th>Peak to Valley Length (wavelength)</th>
<th>m diopter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Thickness</td>
<td>0.20 mm</td>
<td>7.89 4%</td>
</tr>
<tr>
<td>Lamination</td>
<td>0.03 mm</td>
<td>1.18 1%</td>
</tr>
<tr>
<td>Bow</td>
<td>1.20 mm</td>
<td>131.46 67%</td>
</tr>
<tr>
<td>Rollerwave</td>
<td>0.02 mm</td>
<td>35.06 18%</td>
</tr>
<tr>
<td>Thermal Bow</td>
<td>2.00 mm</td>
<td>19.72 10%</td>
</tr>
<tr>
<td>Installation Tolerances</td>
<td>1.00 mm</td>
<td>9.86 5%</td>
</tr>
<tr>
<td></td>
<td></td>
<td><strong>Cdis</strong> 196.10 100%</td>
</tr>
</tbody>
</table>

**Difference Cdis** -15.42
**Difference Cdis** -7%

**Figure 9.** Proposed estimation of overall distortion factor Cdis
Conclusion

There is clearly a great deal of further work to be done in this subject, particularly with the evolution of exciting new measuring and surface modeling techniques. The current codes do not sufficiently describe a relationship between glass tolerances and distortion i.e. what is actually seen. They also do not account sufficiently for either different glass thicknesses or different manufacturing techniques. This has lead to many misunderstandings in this field, in particular an over-emphasis on roller wave distortion. The development of an overall visual distortion factor would solve this problem and provide clarity to the subject of visual distortion in glass.

References

Cooking with Curtain Walls: Assessing Exterior Building Reflectivity and Subsequent Thermal Loading

Brett Jeske
*Curtain Wall Design and Consulting (CDC)*, USA

**Abstract**

In the last five years alone, specular light reflected off of building facades has made headlines and many projects have suffered. 20 Fenchurch St. in London, Museum Tower, The Vdara Hotel and Spa, and The Walt Disney Concert Hall are just a few examples of this phenomenon. With an increasing need for energy efficiency and the popular aesthetics of reflective glass within the architectural community, increases in technology and awareness of conscious design allow us to monitor and predict reflection patterns and the possibilities of hazardous glare as well as heat generated off of a façade.

There are several methods for predetermining glare. In this case study, we have focused on the two most prevalent methods being Radiance, and CFD (Computational Fluid Dynamics). These currently are the only methods for predicting the intensity of specular light due to the complexity of reflections in three dimensional space.

In addition to glare, advances in computing technology and physical calculation modeling allow us to accurately predict surface temperatures due to specular light. These methods have been tested and proved.

**1 Introduction To Reflectivity**

All glass has reflective properties. Even architectural clear glass (roughly 5-7% at a normal angle of incidence) will reflect the light. Specular light follows the basic laws of optics which includes the law of reflection.

Derived from the Fresnel Equations, this law explains that glass will both transmit light into the building as well reflect a portion of this light out away from the building. The portion of the light which is transmitted into the building is evaluated in both daylighting studies and building energy models. For assessing a building’s exterior reflectivity, the portion of light that is reflected off of the building is the only concerning element of this fundamental law.

The law of reflection as it applies to glass implies two fundamental statements:

1. The angle of incidence equals the angle of reflection as it applies to the normal glass surface, refer to Figure 1.
2. The intensity of the reflected light is dependent on the angle of incidence, where the critical angle (reflective intensity = 100%) of the glass is parallel to the glass face. Refer to Figure 2.

![Law of Reflection](image)

**Figure 1.** Law of Reflection

![Intensity of Glass Reflectivity Dependent on Angle of Incidence](image)

**Figure 2.** Intensity of Glass Reflectivity Dependent on Angle of Incidence

The reflective data for each glass type is required by NFRC and is available to designers. This enables use of real glass properties data applied to these studies.

### 2 Developing A Standard For Reflectivity

In the United States and throughout most of the world, there is currently no building code to address a building’s exterior reflectivity. Some local governing bodies, such as HOAs, limit or make recommendations about reflective materials. But these typically do not fall in heavy commercial areas of cities where large buildings are more prevalent.

#### 2.1 Existing Building Codes
The City of Sydney, Australia limits the reflectivity of materials on new buildings to 20%. Singapore has enforced similar code [1]. But there are problems in taking this approach as well. The applicable 2010 Sydney Building Code [2] reads as follows:

- Section 4.5.1. New buildings and façades should not result in glare that causes discomfort or threatens safety of pedestrians and drivers.
- Section 4.5.2. Visible light reflectivity from building materials used on the façades of new buildings should not exceed 20%.
- Section 4.5.3. A reflectivity report that analyzes the potential solar glare from the proposed new development on pedestrians or motorists might be required. (City of Sydney, 2010).

Section 4.5.1 explains that facades should not result cause discomfort or threaten the safety of pedestrians or drivers. Ultimately the safety of the population is the the greatest concern.

2.2 Assessing Building Reflectivity
Given the subjectivity of individuals’ sensitivity to glare, the lack of an industry-wide accepted criteria, and the absence of any precedence related to the limits of this type of nuisance, CDC uses a combination of approaches to assess specular glare. In terms of glare itself, through much discussion it is suggested that since a building site will already see sunlight, the limit of building glare in terms of human safety and discomfort should not exceed the intensity of nominal direct sunlight. This is the standard typically used in these studies.

However, there are many other factors at play than the intensity of the reflected light. These include:

- Assessment of possible sensitivities of surroundings to specular light
- Function of the surrounding environment - roads, buildings, etc. will all have different ways of assessing reflectivity – both glare and thermal concerns
- The reflection pattern in three dimensions - visualization of how the entire building reflects
- Angle of Incidence & Reflection

In recent years we have seen the effects of the effects of building reflectivity on property as well. This should be addressed when assessing reflectivity of building envelopes.
Figure 3. A Jaguar With Damage Caused By A Buildings Glare

Figure 4. Building Reflection into an Adjacent Building and Reflection Pattern Observed from the Building itself.

Figure 3 and Figure 4 convey different levels of damage in popular cases. Without standards or precedence, these cases are becoming more common.

According to the U.S. Energy Information Administration, in 2012 close to 40% of the United States total energy consumption came from commercial and residential buildings [3]. Architects prefer to have as many available options to them in designing a building. This coupled with the fact that buildings have energy requirements that must be met and there is potential for savings for building owners. In general, reflective glass will perform better within an energy model than clear glass as more of the light is expelled back into the environment.

Glass is necessary and fundamental for a healthy and productive building environment [4]. But at the same time due diligence is necessary to protect both building owners, surrounding facilities, the public in general, as well as increased energy cost. Design professionals have more need to increase window to wall ratios (WWR), rather than to be faced with dark buildings. It is these contexts that make reflectivity studies crucial to evaluate the entire building envelope and work with architects and owners to find solutions.
3 Case Study

3.1 Tools and Methods
There have long been tools and methods for assessing reflections in two dimensions and by using more analytical methods, such as the Hassall method [5]. However, these methods cannot account for complex building geometry in today's building design community. Nor are these methods complete in assessing problems associated with reflectivity or protecting building owners.

As part of a case study, both CDC and Hochshule Luzern (Lucerne University of Applied Arts & Sciences) have worked together to analyse the two more modern standards using these two software to come to help form some conclusions about each of their benefits and limitations.

These two software are Radiance and CFD (computational fluid dynamics) software. Both include similar ray tracing methods of analysis and each have their advantages and disadvantages.

Figure 5. Sample Output from Radiance Analysis [6].
Figure 6. Sample Output from CFD Analysis

Both software are incredibly similar in predicting both reflection pattern and intensity of specular light. However both are completely different in their output and calculation methods. Both have advantages and disadvantages to assessing building glare.
### 3.2 Software Comparison

<table>
<thead>
<tr>
<th></th>
<th>Radiance</th>
<th>CFD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intent of Software</td>
<td>Daylighting and Lighting Studies</td>
<td>Solar Load Calculation</td>
</tr>
<tr>
<td>View</td>
<td>Previously limited to perspective view, all viewpoints with special implementation</td>
<td>All Viewpoints</td>
</tr>
<tr>
<td>Output</td>
<td>2D Surface Results</td>
<td>3D</td>
</tr>
<tr>
<td>Temperature</td>
<td>No compatibility for further calculation</td>
<td>Yes</td>
</tr>
<tr>
<td>Modelling</td>
<td>3D CAD</td>
<td>3D CAD</td>
</tr>
<tr>
<td>Ray Tracing Method</td>
<td>Monte Carlo Ray Tracing</td>
<td>Monte Carlo Ray Tracing</td>
</tr>
<tr>
<td>Units</td>
<td>W/m^2</td>
<td>Ratio of Nominal Sunlight, W/m^2, °F, °C</td>
</tr>
<tr>
<td>Advanced Geometry</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Output w/ Fins &amp; Sunshades</td>
<td>Unknown</td>
<td>Yes, shown in results</td>
</tr>
<tr>
<td>Glare</td>
<td>Direct and Diffuse</td>
<td>Direct</td>
</tr>
</tbody>
</table>

Both softwares are very useful. For complete analysis, both could be used to generate a full study. Radiance conveys the impact of both diffuse and direct reflections. This allows for a better understanding of the overall reflection. Using this, aluminium components could be defined and included in the analysis. However, previously Radiance was limited to a perspective view which allows for the analysis of diffuse reflections. This was a limiting point of the software. Though now all viewpoints can be covered. Expansion of the software for additional analysis takes time. This is open source software.

CFD currently only measures direct glare. This is the portion of specular light that is concerning in these studies. However, an overall depiction of the buildings reflection with diffuse light is not included in these analysis. In doing this, it does allow for a 3 Dimensional view of specular light. This currently would be the only option for measuring light in airspace which some analysis is required to meet FAA guidelines for structures. CFD also easily allows for additional calculations with its advanced physics based calculation software.
4 Thermal Load

The linkage between exterior reflectivity and thermal loads on the exterior environment is very relevant when assessing a building from a design standpoint. Spectral light from building facades have been found to cause discomfort, generate heat on pavement to dangerous levels, burn people, melt plastic and aluminium, and more.

Prior to now, the linkage between the two sciences has not been fully investigated. CDC has found and proven a method for combining the two.

4.1 Background

Thermal calculations exist within the curtain wall industry now. Many buildings have thermal performance criteria to meet. Curtain Wall systems are designed to meet this performance criteria and aid in the energy efficiency of the building as well as resist interior condensation.

Taking this knowledge of thermal behaviour and applying it to a building’s surrounding environment gives us new data to help examine the reflectivity of building facades.

4.2 Considerations

In evaluating outdoor surface temperatures within, many factors need to be evaluated. These include:

- Outdoor Ambient Temperature - *ASHRAE*
- Direct Solar Irradiation (Sunlight) – *ASHRAE / CFD*
- Direct Solar Irradiation (Specular) – CFD Reflectivity Analysis Output
- Diffuse Solar Irradiation (Sunlight in Shaded Areas) – *ASHRAE / CFD*
- Wind Speed - *ASHRAE*
- Material Properties of the Surface in Question as Well as Subgrades (absorptivity, emissivity, thermal conductivity, thickness, colour, etc.) – *Historical Data or Material Handbooks*
- Surface Orientation and the Angle of Reflection – *CFD Reflectivity Analysis Output*

All of this data is already standardized for building thermal calculation purposes and can easily be applied to exterior applications [7].
4.3 Calculation

Taking everything into account, we have the following equation for surface temperature:

\[ T_{\text{surface}} = \frac{T_{\text{ext}} \cdot h_{\text{conv}} + T_{\text{sub}} \cdot U_{\text{mat}} + q_{\text{rad}}}{h_{\text{conv}} + U_{\text{mat}}} \]  \hspace{1cm} (1)

Where,

\[ q_{\text{rad}} = \alpha_{\text{mat}} \cdot (q_{\text{direct1}} \cdot \beta + q_{\text{diff}} + q_{\text{direct2}}) \]  \hspace{1cm} (2)

And,

- \( T_{\text{surface}} \) = Surface Temperature
- \( T_{\text{ext}} \) = External Ambient Temperature
- \( h_{\text{conv}} \) = Convective Transfer Coefficient
- \( T_{\text{sub}} \) = Temperature of the Earth Below Grade (In this case 0.73m below grade)
- \( U_{\text{mat}} \) = U-Factor of the Given Material composition
- \( q_{\text{rad}} \) = Total Radiation Heat Flux on Surface
- \( \alpha_{\text{mat}} \) = Absorptivity of Material
- \( q_{\text{direct1}} \) = Total Radiation Heat Flux from Direct Reflected Glare (Normalized for Each Surface, from Reflection Zone)
- \( \beta \) = Output from CFD Results (Ratio of Luminosity Compared to Nominal Sunlight Irradiation)
- \( q_{\text{diff}} \) = Total Radiation Heat Flux from Diffuse Light
- \( q_{\text{direct2}} \) = Total Radiation Heat Flux from Direct Sunlight (Normalized for Each Surface)
4.4 Results

Figure 7. Example of Surface Temperature Calculation.

4.5 Verifying Results

In order to verify CDC’s methods and data, models were tested with an existing structure in which CFD trials and thermal calculations were performed at specific times over a 2 hour period. We then proceeded to go into the field on a clear day to take temperature measurements using both a laser thermometer and a thermal imaging camera. The temperature calculations were adjusted after the fact to reflect real temperature data of area rather than ASHRAE’s suggested 0.4% summer design temperatures.
The CFD and thermal analysis at this point in time (9/24/13 @ 12:00 PM) predicted a surface temperature of 134.1 °F.

The measured temperatures at this time within the same reflection zone convey temperatures of 129.5 °F (Laser) and 130.3 °F (Infrared Camera). The data over a two hour span was consistently less than 5 °F below the predicted
temperatures. Not accounting for changes in wind speed, inconsistency of the concrete, oils and dirt on the concrete, and variations within the atmosphere; the hypothesis proved to be extremely accurate to real time data.

5 Post-Installation Fixes

In recent years, highly reflective curtain walls have made headlines and some in some instances these cases have been pushed into litigation. Without a unified standard within the design community and no precedence, more and more of these cases will continue to appear. There is no simple fix in these cases.

After the curtain wall is installed, it is difficult to go back after the fact to install louvers, sunshades, or fins. This may be a challenge from any of the following standpoints:

- **Curtain Wall Design** – It is not functional for the current system
- **Structural** – The additional loading may require reinforcing system
- **Cost** – The amount of work and design which would be included in a field fix of this magnitude will be significant.

Another option for a post-installed fix would include reglazing. On an IGU system, typically the coatings (which generally have the biggest impact on reflectivity) are found on the number two surface as displayed in Figure 10.

![Figure 10. Typical IGU with Coating on No. 2 Surface](image)

Or additionally, an effective method for a fix here would be an absorbent film on the number one 1 face. Subject to weathering, these films would need to be replaced every few years.

The last option is to find a way to shelter areas where damaging specular light occurs on either businesses or pedestrians. While there have been many inventive proposed methods in doing so (see Figure 11), this can be costly and has been part of heated debate in several cases.
New building construction occurs in areas where development is already in place. The argument in these cases applies to whether existing buildings should have to have to adapt to an issue in which the newer brought upon it. Since no Building Code or requirements are in place, it is extremely vague as to what should be done.

6 Conclusion

All glass is reflective. But in recent years, the constant push for a more energy efficient world and trends in architectural design has led to more reflective buildings. This coupled with some innovative building geometry has led to an increase in issues caused by specular light from glass curtain wall.

The tools to analyze reflectivity of building facades have made great leaps in recent years. Specular light and thermal loads can be predicted with relatively high accuracy. The issues that stem from these cases can be prevented through experience and use of these of these tools.

While measuring sensitivity from person to person or business to business can be difficult, there is need within the community for a reflectivity standard. In order to effectively protect building owners (both in new construction & existing structures), pedestrians, traffic, and the glass community itself; standardization of building reflectivity needs to happen.
References
Iterative Energy Modeling in Facade Design

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Skidmore, Owings & Merrill- New York, USA

Arpan Bakshi, LEED AP PQP  
Skidmore, Owings & Merrill- New York, USA

Abstract
Building energy modeling is not a new tool but its industry role is evolving from code compliance to design assistance. An indicator of this transition is the inclusion of a new credit in the LEED v4 rating system, “Integrative Process” that encourages the use of energy modeling before the completion of schematic design to as a way to reduce energy loads in the building and accomplish sustainability goals by questioning default assumptions. As the design of a project evolves over a series of phases, the building envelope can be thermally analyzed with increasing detail to sequentially inform façade massing and composition, glazing selection, framing system detailing and performance specifications. This paper is intended to identify modeling types and considerations appropriate to each façade design phase. It explains the role of energy modeling in façade design and conveys an iterative process of initial design, modeling, and design revision to make informed decisions.

Keywords: energy model, façade design, curtain wall, thermal performance, ASHRAE 90.1

1 Introduction
Energy modeling is commonly performed at the end of a project documentation process to benchmark the completed design for code compliance or rating system documentation. This paper outlines a workflow for energy modeling to be used as part of the design process of façade design. Iterative modeling is the idea of testing design assumptions using analysis in each design phase against project performance goals. Figure 5 shows how this iterative process informs the façade design in a different way in each design phase. In Concept Design, modeling informs visual and spatial concepts. In Schematic Design, modeling informs facade system selection. In Design Development, modeling informs facade material and component selections. In the Construction Documentation phase, modeling is used to calculate facade thermal resistance values which are input into the whole building energy modeling used for code compliance or green rating systems.
1.1 What is an Energy Model?
A building energy model determines cooling and heating loads by mathematically simulating the thermal performance of the modeled building. It then determines energy use over the course of a year by mathematically simulating the performance of heating, ventilating and cooling equipment in response to these loads. An energy model can calculate energy costs and carbon using energy costs and carbon factors input by the user. A common energy modeling software structure is shown in Figure 2. Building energy modeling is used to test single design variables referred to as energy conservation measures or test sets of design variables referred to as bundles. Building energy models are commonly compared to a code compliant version of the proposed design, referred to as a baseline model.
1.2 Role of Building Enclosure in Energy Models

The amount of energy consumed by building systems is proportional to heating and cooling loads the systems are operating to meet. As shown in Figure 3, cooling load components include heat gains from enclosure, occupants, lights and equipment. Heating load components include heat loss through the enclosure. Loads are often referred to as “external” or resulting from the building skin, and “internal” or resulting from heat sources inside of the building.

**Figure 3.** Primary HVAC Load Components

Low-rise and residential buildings are often “skin-dominated” and façade strategies have a larger impact on energy consumption. High-rise and commercial buildings are often “core-dominated” and façade strategies have a smaller impact on energy consumption – however, they can have a large impact on peak energy use which determines HVAC system size and first cost. Low-rise buildings are defined by the American Society of Heating Refrigeration and Air Conditioning Engineers (ASHRAE) as buildings with three stories or fewer above grade. Figure 4 below demonstrates a design scenario in which the total energy consumed in a single day is comparable between ‘Design A’ and ‘Design B’, however the peak energy use (single hour) is 25% less, resulting in smaller HVAC equipment and first cost savings.

**Figure 4.** Cumulative versus Peak Energy Use
Figure 5. Iterative Energy Modeling Workflow Example
2 Defining Parameters
Building energy models are often referred to as “whole-building” energy models because they simulate the operation of a building using input parameters from all major building systems including opaque enclosure, fenestration and shading, air-side HVAC equipment, water-side HVAC equipment, domestic/service water heating, lighting, and miscellaneous equipment like receptacles, elevators, refrigeration and server rooms. Figure 6 outlines enclosure related parameters.

Figure 6. Building Enclosure Parameters
2.1 Standards and Codes
ASHRAE Standard 90.1, Energy Standard for Buildings Except Low-Rise Residential Buildings (hereby referred to as ASHRAE-90.1) is commonly referenced by building energy code and green rating systems such as LEED. The scope of this paper will be limited to this standard.

2.2 Facade Performance Criteria
ASHRAE-90.1 provides four performance pathways as illustrated by Figure 7. The Prescriptive Building Envelope Option consists of criteria sets provided by climate zone. The prescriptive option is the most restrictive as each envelope component must separately satisfy ASHRAE-90.1 requirements. The Building Envelope Trade-Off Option provides more flexibility as the high performance of one envelope component can offset the lower performance of another envelope component, however trade-offs are limited to envelope components in this option. The Energy Cost Budget (ECB) Method option allows tradeoffs between the building envelope and other building systems such as lighting and mechanical systems. The Performance Rating Method (PRM) is similar to the ECB Method but is used to measure energy performance against a prescriptive baseline case.

Figure 7. Envelope Performance Pathways

The Performance Rating Method is popular among green labeling and rating systems.
### ASHRAE Climate Zone

<table>
<thead>
<tr>
<th>Climate Zone</th>
<th>40% Window-Wall Ratio[^1]</th>
<th>70% Window-Wall Ratio[^3]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ASHRAE 189.1-2011 GREEN BUILDING STANDARD</td>
<td>SELECTIVELY PRORATED[^4], INCLUDING SHADING DEVICES</td>
</tr>
<tr>
<td><strong>1: Very Hot</strong></td>
<td>U-6.81 (SI)</td>
<td>0.25</td>
</tr>
<tr>
<td>e.g. Dubai; Manila</td>
<td>U-1.20 (IP)</td>
<td></td>
</tr>
<tr>
<td><strong>2: Hot</strong></td>
<td>U-3.97 (SI)</td>
<td>0.25</td>
</tr>
<tr>
<td>e.g. Shenzhen</td>
<td>U-0.70 (IP)</td>
<td></td>
</tr>
<tr>
<td><strong>3: Warm</strong></td>
<td>U-2.84 (SI)</td>
<td>0.25</td>
</tr>
<tr>
<td>e.g. Shanghai; Istanbul</td>
<td>U-0.50 (IP)</td>
<td></td>
</tr>
<tr>
<td><strong>4: Mixed</strong></td>
<td>U-2.27 (SI)</td>
<td>0.35</td>
</tr>
<tr>
<td>e.g. New York; Beijing</td>
<td>U-0.40 (IP)</td>
<td></td>
</tr>
<tr>
<td><strong>5: Cool</strong></td>
<td>U-2.00 (SI)</td>
<td>0.35</td>
</tr>
<tr>
<td>e.g. Boston; Denver</td>
<td>U-0.35 (IP)</td>
<td></td>
</tr>
<tr>
<td><strong>6: Cold</strong></td>
<td>U-2.00 (SI)</td>
<td>0.40</td>
</tr>
<tr>
<td>e.g. Toronto</td>
<td>U-0.35 (IP)</td>
<td></td>
</tr>
<tr>
<td><strong>7: Very Cold</strong></td>
<td>U-1.70 (SI)</td>
<td>0.45</td>
</tr>
<tr>
<td>e.g. Kazakhstan</td>
<td>U-0.30 (IP)</td>
<td></td>
</tr>
<tr>
<td><strong>8: Subarctic</strong></td>
<td>U-1.70 (SI)</td>
<td>0.45</td>
</tr>
<tr>
<td>e.g. Fairbanks</td>
<td>U-0.30 (IP)</td>
<td></td>
</tr>
</tbody>
</table>

**Notes:**
- U-factor units: Metric (SI) units in W/m²·°K; Imperial (IP) units in Btu/(h °F ft²).
- Vertical Glazing Fenestration refers to the vertical surfaces on a building enclosure. This envelope component is included in this paper as it is the primary enclosure consideration relevant to projects in this office.
- The total vertical fenestration area as a percentage of the gross wall area.
- Performance Targets prorated to account for diminished performance from increased window-wall ratio from 40% to 70%.
- Prorated SHGC does not have to be met by glass alone – this number includes the shading effect of external devices.
- Performance targets are not required values. There will be performance trade-offs between enclosure and other systems in energy modeling.
Figure 8. Design Guidance for Fenestration Selection
Two examples include the EPA EnergySTAR™ program and the USGBC LEED™ rating system. An example PRM is shown in Table 1.

Table 1: Performance Rating Method Example

<table>
<thead>
<tr>
<th></th>
<th>PROPOSED DESIGN ENERGY MODEL</th>
<th>BASELINE ENERGY MODEL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy Use</td>
<td>900,000 kWh</td>
<td>1,000,000 kWh</td>
</tr>
<tr>
<td>Energy Rate</td>
<td>$0.10/kWh</td>
<td></td>
</tr>
<tr>
<td>Energy Cost</td>
<td>$90,000</td>
<td>$100,000</td>
</tr>
<tr>
<td>% Reduction</td>
<td>10%</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8 provides designers with a starting point to define enclosure performance characteristics. The table on the left provides best practice recommendations from ASHRAE Standard 189.1, the Standard for the Design of High-Performance Green Buildings, Except Low-Rise Residential Buildings. These values are dependent on a glazing ratio of no more than 40% of total wall area. A glazing area of 65-75% is a common client request for which the table on the right provides area-adjusted performance values.

3 Analyzing the Building Envelope

The detail of an energy model is dependent on the amount of design information available and type of question we are trying to answer with modeling. Early design questions require less modeling detail while late design modeling requires construction level material and assembly specification. Figure 9 describes the level of detail needed from the façade designer and the level of output which can be expected from the façade analyst. A list of suggested simulation tools has been provided however this may vary by project location and compliance requirements.
CONCEPT DESIGN

- **INPUT**
  Surface model with opaque and transparent surfaces defined.

- **OUTPUT**
  Climate sensitivity between glazing areas, placement and shading.

- **TOOLS**
  EnergyPlus, Radiance

SCHEMATIC DESIGN

- **INPUT**
  Facade areas identified as transparent, translucent, shaded, opaque, etc.

- **OUTPUT**
  Performance matrices for trade-offs between facade material relationships.

- **TOOLS**
  EnergyPlus, DaySim, EvalGlare, constructions; frame details and glazing selections.

DESIGN DEVELOPMENT

- **INPUT**
  Layer-by-layer constructions; frame details and glazing selections.

- **OUTPUT**
  HVAC sizing impact, condensation risk, thermal bridging.

- **TOOLS**
  EnergyPlus, LBNL Optics, Window, Therm

CONSTRUCTION DOCUMENTS

- **INPUT**
  Updated information from previous phase.

- **OUTPUT**
  Calculated assembly values per National Fenestration Rating Council (NFRC) standards.

- **TOOLS**
  EnergyPlus, LBNL Optics, Window, Therm
3.1 Concept Design Phase Modeling
Massing options are evaluated in this phase by simplifying design geometry into opaque surfaces, projection depths and transparent surfaces as shown in Figure 10. Thermodynamic properties are assigned to surface type and area without specification of material assembly.

Figure 10. Concept design massing example
Transparent surfaces are defined by three parameters (simple glazing):

- U-Factor (1/R-value)
- Solar Heat Gain Coefficient (SHGC)
- Visible Light Transmittance (VLT)

Opaque surfaces are defined by a single parameter – U-factor – unless thermal mass is being analyzed (simple constructions). Façade insets and projections are divided into horizontal and vertical components (simple shading):

- Horizontal projection
- Vertical projection

3.2 Schematic Design Phase Modeling
Selected massing option(s) are articulated into wall and window constructions in this phase by replacing simple constructions with layer-by-layer constructions as shown in Figure 11. Simple glazing surfaces are replaced with detailed glazing assemblies to include effects of varying solar incidence angles, which affects daylight performance.

SAMPLE OPAQUE ASSEMBLY
- Exterior Air Film  U-33.40 W/m²-K
- Exterior Finish  U-70.98 W/m²-K
- Exterior Sheathing  U-10.14 W/m²-K
- Continuous Insulation  U-0.44 W/m²-K
- Batt Insulation  U-0.76 W/m²-K
- Interior Gypsum Board  U-10.14 W/m²-K
- Interior Air Film  U-8.35 W/m²-K

**Figure 11.** Example of a layer-by-layer construction description as defined in an energy model

**SAMPLE GLAZING ASSEMBLY**

**Concept Phase Simple Glazing Model Input**

2.00,  !- U-Factor (W/m²-K)
0.35,  !- Solar Heat Gain Coefficient
0.50;  !- Visible Transmittance

**Detailed Glazing Model Input**

SpectralAverage,  !- Optical Data Type
0.003,  !- Thickness (m)

!-Solar Transmission Properties

0.837,  !- Solar Transmittance at Normal Incidence
0.075,  !- Front Solar Reflect. at Normal Incidence
0.075,  !- Back Solar Reflect. at Normal Incidence

!-Visible Transmission Properties

0.898,  !- Visible Transmittance at Normal Incidence
0.081,  !- Front Visible Reflect. at Normal Incidence
0.081,  !- Back Visible Reflect. at Normal Incidence

!-Infrared Transmission Properties

0,  !- Infrared Transmittance at Normal Incidence
0.84,  !- Front Side Infrared Hemispherical Emissivity
0.84,  !- Back Side Infrared Hemispherical Emissivity

!-Conductivity Properties

0.9;  !- Conductivity (W/m-K)

**Figure 12.** Example of a glazing description as defined in an energy model
Figure 12 shows the level of detail with which a glazing assembly can be described in an energy model to capture the effect of coatings and films, built using tools like LBNL Optics & Window.

3.3 Design Development Phase Modeling

In review, the façade is divided into glazing and opaque areas in Concept Design phase. In Schematic Design Phase, detail is added to opaque areas by creating layer-by-layer constructions and detail is added to glazing areas by creating realistic glazing assemblies. In late design phases, Design Development and Construction Documents Phase, additional detail is added to glazing areas by articulating the frame and edge-of-glazing portions of the glazing assembly, to complete a whole-product (assembly) area weighted U-factor calculation per NFRC Standard 100, Procedure for Determining Fenestration Product U-factors. The Windows and Daylighting Lab at the Lawrence Berkeley National Labs (LBNL) has developed a suite of software tools for performing these calculations. LBNL Optics is used for analyzing optical properties of glazing systems. LBNL Therm is used for analyzing two-dimensional heat transfer through building products including glazing frames as shown in Figure 13. LBNL Window is used for combining frames with glazing units to analyze total product (assembly) thermal and optical performance. Figure 14 outlines this calculation.

Figure 13. LBNL Therm calculation of curtain wall example. The diagram indicates change in temperature as thermal energy is transferred through the assembly.
NFRC 100 whole-product (assembly) area weighted U-factor calculation

Where:

- \( U_t \) = Total product U-factor, W/m²-K
- \( A_{pf} \) = Projected fenestration product area, m²
- \( U_f \) = Frame U-factor, W/m²-K
- \( A_t \) = Frame area, m²
- \( U_d \) = Divider U-factor, W/m²-K
- \( A_d \) = Divider Area, m²
- \( U_e \) = Edge-of-glazing U-factor, W/m²-K
- \( A_e \) = Edge-of-glazing Area, m²
- \( U_{de} \) = Edge-of-divider U-factor, W/m²-K
- \( A_{de} \) = Edge-of-divider Area, m²
- \( U_c \) = Center-of-glazing U-factor, W/m²-K

\[
U_t = \frac{\sum (U_f \cdot A_t) + \sum (U_d \cdot A_d) + \sum (U_e \cdot A_e) + \sum (U_{de} \cdot A_{de}) + \sum (U_c \cdot A_c)}}{A_{pf}}
\]

Figure 14. NFRC Standard 100 Glazing assembly U-factor calculation
3.4 Reviewing Model Results
Energy modeling results should be reviewed for the level of detail with which input assumptions were made and for the consistency of output results. Both inputs and outputs should match the level of detail with which the design has been developed in the design phase for which modeling was performed. Designers should review modeling results particularly because energy modeling is commonly performed by external consultants who are not a part of the design team, motivated by minimizing effort over delivering design excellence.

**Figure 15. Energy Modeling Report Example**
Energy modeling reports are generally divided into three sections, (1) an executive summary with findings and recommendations, (2) modeling results, or outputs, and (3) modeling assumptions, or inputs.
Figure 16. Modeling Results/Outputs Example

Energy modelers often provide a single value – total energy cost – to represent the entire modeling exercise, as seen in Figure 16. This type of minimal results reporting does not provide the design team with a way to perform quality assurance. The following results should be requested of the energy modeler:

1. Electric and gas consumption for each end use on a monthly basis, including:
   - Space cooling
   - Heat rejection
   - Space heating
   - Hot water
   - Ventilation fans
   - Pumps
   - Process equipment
   - Area lighting
2. Building area as reported by the energy model.
Energy model output information should be evaluated against model input assumptions to verify the impact of assumed energy efficiency measures. For the scope of this paper we are interested in building façade related inputs. The following questions for each input type should be posed to the energy modeler:

Walls, Above Grade
- Are walls assigned with a single U-factor value, or were layer-by-layer constructions used?
Certain properties like thermal mass are calculated only if layer-by-layer constructions are modeled.

Vertical Glazing
- Are glazing systems modeled with separately assigned glass and frame areas, or as a separately calculated glazing assembly input into the energy model using the tools LBNL Window / Optic / Therm?
In an energy model, a window assembly can be defining a glass area and a frame thickness. This method relies on model libraries to assign generic frame performance values. For custom curtain wall design, window performance should be modeled as a user-defined, custom assembly based on simulations separately performed in the tool LBNL Therm.
- Are glazing units modeled using the simple three property method (U-factor, SHGC, VLT), or was a detailed LBNL Window / Optic / Therm model attached to the energy model to accurately define glass and film properties?

Geometry and Solar Exposure
Ask for a screen capture of the energy model geometry. Energy modeling tools cannot model curved building forms and consultants often over simplify massing into a “birthday cake” form, which adds additional roof surfaces to the model.

Massing Volumes
A mixed use building is energy modeled using multiple building shells. A common modeling mistake is applying ground and roof exposure to each building shell, even if those surfaces have an interior condition. This mistake amplifies the heat lost to the ground and to ambient conditions. Ask to verify how building shells were assigned with ground and roof constructions.
Energy modelers should also provide a table of modeling inputs to confirm they match design intent and to coordinate modeling inputs with engineering load calculation assumptions. An example is shown in Figure 17.

<table>
<thead>
<tr>
<th>Building Envelope Constructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opaque Assemblies</td>
</tr>
</tbody>
</table>

| Model Input Parameters and Energy Efficiency Measures for Baseline Case, Proposed Case and Energy Efficiency Bundles |

<table>
<thead>
<tr>
<th>Insulation R-value and Assembly U-factor/C-factor/F-factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Roofs</td>
</tr>
<tr>
<td>- Roof SRI</td>
</tr>
<tr>
<td>- Roof Reflectivity</td>
</tr>
</tbody>
</table>
4 Building Enclosure Design

The previous section outlined modeling methods for different design phases. This section provides guidance for corresponding façade design decisions.

4.1 Building Enclosure Concepts – Concept Design

During Concept Design, the design team must formulate a conceptual solution for enclosing the building and establish the performance criteria that will begin to direct the development of facades. These performance criteria will include aesthetic requirements, but will also be comprised of decisions regarding daylighting, natural ventilation, and local climatic considerations. In this project phase, the design team will need to firmly establish a general scheme for opaque walls areas versus transparent/translucent wall areas. It is this data that will be
fed into the first energy model in order to establish a baseline performance level for the initial strategies of the building enclosure design.

4.2 Facade System Selection – Schematic Design

Learning from the baseline results established by the Concept Phase energy model iteration, design decisions regarding façade systems can begin to be made. In most instances, certain façade systems are more appropriate than others for different reasons. Sometimes this is due to market availability or economy, but energy and comfort performance are equally important when selecting a façade system. For example, if a tower is sited in a cold climate and the design concept calls for an aggressively performing façade, the design team may choose to disregard single-skin systems in favor a double-skin that may take more advantage of passive energy efficiency. Conversely in a hot climate, a double-skin may be much less energy efficient and unnecessarily expensive.

FAÇADE SYSTEM SELECTION

- Single Skin
- Window-wall (Stick-built or Unitized)
- Curtain-wall (Stick-built or Unitized)
- Special Enclosures (i.e. Cable Walls, Structural Glass Systems, etc)
- Double Skin
- Stick-built
- Unitized
- Unitized Hybrid

By the end of Schematic Design, the second iteration of the energy model will be able to take advantage of a more refined envelope scheme. While the final components will not yet have been designed or optimized, this energy model shall use input values based on weighted averages of opacity and transparency of the façades, as well as – ideally - preliminary material performance data (i.e. U-value, SHGC, etc). The results of this model analysis will subsequently inform the optimization of the individual façade types during the next design phase as it becomes clearer which areas will require higher levels of energy efficiency and performance. At this point, the energy model will assist in confirming whether the correct façade system design has been selected or how it will need to be refined in the next design phase.

4.3 Facade Material Selection – Design Development

During Design Development, the design team shall use the results from the Schematic Design energy model to refine and optimize the individual façade types comprising the building envelope, including curtain-walls, storefronts, and opaque external assemblies. The bulk of this optimization will occur as material
and component selection and the design of assemblies and frames. For example, it is during Design Development that the design team may decide whether to use laminated or insulating glass in a cable wall, or whether to employ triple-glazed insulated glass instead of double-glazed units in a curtainwall. Similarly, based on the previous energy model, an array of glass coatings or spandrel insulation methods might be examined during this phase until the best solutions are found to meet all the thermal performance criteria. It is intended that as part of this design process, thermal analysis exercises shall be performed on the proposed assemblies using software tools such as THERM and Window. These basic performance tests will facilitate and guide the material decisions. Finally, at the end of Design Development, an energy model shall be run again, this time using façade inputs that reflect the materials and thermal performance of the façade systems as designed thus far. The results of this model can serve as final guide during Construction Documents and for the writing of specifications.

Facade Materials Selection:

**Glazing**
- Monolithic or laminated
- Coatings/fritting/films
- Insulated (IGU): double or triple lite
- Spacers (for IGU): warm-edge vs. cold-edge technology

**Framing**
- Thermally broken (polymer breaks)
- Aluminum extrusions
- Brake-formed profiles (stainless steel, bronze, and other metal alloys)
- Steel or stainless steel solid profiles (built-up or singular sections)
- Exterior exposed components (fins, louvers, shading, pressure caps, glass edge profiles, etc)

**Spandrel/opaque panels**
- Metal
- Wood
- Polymer
- Concrete/GFRC
- Masonry

4.4 Construction Documents and Specifications

Facade performance criteria and design intents are relayed to contractors and fabricators via drawings and specifications. In areas where drawings indicate quantities (i.e. dimensions, number of elements, etc), specifications describe “quality” which includes the thermal and energy benchmarks for the performance of the façade. By prescribing specific thermal criteria for each façade type and its components in the appropriate project manual sections, the architect can maintain greater control over the final façade performance and thereby the overall building energy efficiency. However, to acquire the performance minimums, the façade types will have to be analyzed and developed based on increasingly refined energy models during the design process as described above. By doing so, the design team will have a much better grasp of how well the façade should be performing when it comes time to review thermal analyses submitted by fabricators during the construction process.
5 Conclusion and Summary

The use of energy models as a compliance tools has seen incremental growth as more rating authorities accept performance based submissions. This paper outlines the use of modeling for an integrated design process. There are some challenges to widespread implementation of this workflow. The first step is raising awareness about the accessibility, importance and benefits of design integrated modeling. Contractual boundaries remain a barrier as scope distribution between designers, modelers and rating system administrators do not support rapid feedback from iterative modeling. There are some signs of progress. New utility programs such as Xcel Energy’s Energy Design Assistance Program incentivize the investigation of energy efficient strategies through integrated energy analysis, computer modeling and related charrettes. The fourth version of the LEED rating system will also start to bridge the gap between end-of-project modeling for Energy & Atmosphere Prerequisite 2 / Credit 1, and early design modeling through its new Integrative Process credit area.

5.1 Creating a Design Workflow

This paper outlines a methodology for making performance-based façade design decisions. It is not intended to dictate actual performance standards or recommend specific assemblies or materials. In summary, the façade design process is a multi-objective optimization that requires examination using
analytical methods through an iterative process. The outcomes of those studies are dependent on the ability of the design team to understand design assumptions, develop relevant solutions and work together towards a common goal of designing high performance buildings.

6 Acknowledgements

The authors would like to acknowledge the input and support from several individuals in helping realize this study: Nicholas Holt for his support in this area of study, Teresa Rainey for her guidance on building physics and energy modeling; Christopher Olsen who championed this technical paper topic, assembling a group of potential authors and contributors and for his support of high performance façade design; Benjamin Reich and Christoph Timm for their added input on façade optimization; Nicole Dosso and Julie Hiromoto for their assistance with case study information.

References

Implementing, Assessing and Improving High Performance Design Strategies with the SOM HPD Portal
Leading AIA 2030 Commitment Reporting

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Abstract
Improving the performance of the buildings we design requires guidance, reflection and diligence. By signing the AIA 2030 Commitment, firms agree to publicly predict and report measurements, potentially suffering the disclosures and jeopardizing their credibility. A robust methodology must be enacted to comply with reporting requirements and protect a firm’s legacy. Considering the myriad parameters defining a building’s performance, targets are established for water conservation, energy efficiency and carbon reduction by 2015, with net-zero goals for the year 2030. The SOM High Performance Design (HPD) Portal collects our design predictions for a calendar year, compares them against acceptable benchmarks, identifies possible inaccuracies and areas of improvement, and suggests potential design strategies for achieving the firm’s goals. As project teams continue to enter predicted performance and post-occupancy data, and as the firm continues to update existing strategies and identify new goals, the Portal’s output will improve and serve as the defining resource for high performance building design. This paper examines the challenges of achieving 2030 goals, reviews the how the HPD portal captures and expresses information, and explores techniques for training staff and improving the performance of our projects.

1 Introduction
The American Institute of Architects (AIA) states that buildings consume 48% of the nation’s energy, posing the statement to architects as an opportunity and responsibility. Americans flush 5.8 billion gallons of potable water down the toilet daily. In New York City alone, buildings account for over 94% of the electricity consumed, 85% of potable water consumption and 74% of greenhouse gas (GHG) emissions. Recent studies confirm that high performance design strategies reduced energy consumption by 25% and greenhouse gas emissions by 39% compared to the national average and that 2 trillion gallons of water a year would be saved if all commercial buildings reduced their water consumption by 10%. For the design year 2012, SOM collected data from 97 architecture projects totaling almost 130 million gross square feet (GSF). For the 89% of those projects that were active in the office, more than 5 trillion kBtu/yr is estimated to be saved representing enough energy to power 55,000 single-family homes per year.
By introducing the 2030 Commitment, the AIA compels the design of high performance buildings that use less energy and water, and generate fewer greenhouse gases. This paper will introduce the 2030 Commitment in terms of SOM’s efficiency and emissions targets, the ongoing improvement of design and technology, the effort of modeling and evaluation, future considerations, and the resources available to effectively practice High Performance Design. Additionally, this paper will illustrate the magnitude of impact that design decisions have across the timeline of a project. Emphasizing that high performance initiatives have greater potential when considered earlier will drive the use of resources available to the team and encourage the continuing improvement of building performance.

2 Motivations and Methods
The HPD Portal captures and expresses information required to report to the AIA and requires deliberate input to accurately describe a project’s performance goals and predictions. Familiarity with sophisticated modeling software, the expected inputs and intended outputs, and the concept of energy transfer are essential to accuracy.

2.1 The AIA 2030 Commitment
In December 2005, the AIA called for a 50 percent reduction of fossil fuel consumption used to construct and operate new and renovated buildings by the year 2010 and further reductions of remaining fossil fuel consumption by 10 percent or more in each of the following five years with the ultimate goal of zero fossil fuel consumption by the year 2030. In January 2006, the AIA adopted Ed Mazria’s 2030 Challenge creating the 2030 Commitment. While energy is at the core of the AIA 2030 Commitment, it also tracks a variety of other measurements and outlines improvements that firms should make to their daily operations.

Firms that sign the Commitment are required to implement internal operational policies regarding purchasing, waste and energy. Concurrently, SOM developed a long range sustainability action plan that aligned with the stated 2030 benchmarks. Progress is reported annually to the AIA.

The Commitment’s 2013 Annual Report disclosed that less than half the firms that signed on to the commitment participated in the 2012 reporting process (46%), a seven percent decrease in the reporting rate from 2011. In addition, only 57% of participating firms use energy modeling to predict energy consumption, a consistent value since the release of the 2010 results. For the measurements that were tracked, however, the results are encouraging: 193 projects reduced projected Energy Use Intensity (pEUI) by 60% or greater, including 14 projects that are expected to be net positive – these projects represented 120% increase in GSF from design year 2011.

From these findings, the AIA advises two objectives in order to achieve the Commitment’s goals: to perform an energy model for all projects and to increase the pEUI reduction by 16% in every instance.

2.2 SOM High Performance Goals
SOM relied on the availability of standardized benchmarks to choose energy, water and carbon goals to track and identified waste, materials, human comfort and social justice as optional considerations for design team evaluation. The intent of the goals is to compare performance targets to measured building performance as a means to develop in design teams a more meaningful understanding of how design strategies drive predicted performance and actual consumption.

2.3 Energy Modeling
Incorporating goals for our optional considerations familiarizes our staff. The strictest energy codes and prescriptive guidelines drive only 40% savings over common practice. Properly used, energy modeling can optimize the building design and allow the design team to prioritize investment in the strategies that will have the greatest effect on the building’s energy use.

As we strive for deeper energy use reductions, following the AIA recommendation to perform an energy model with every project is imperative.

The AIA reports that design professionals focus on using modeling to predict performance of established designs, not to influence early design decisions. The Leadership in Energy and Environmental Design (LEED) rating system has increased the use of modeling software but their preparation has been skewed toward the late phases of design to satisfy credit requirements without the benefit of the software’s reaction to inputs, response and advice.

![Fig 1: Rapidly Declining Influence. As the project progresses, the cost of changes increases as the opportunity for influence decreases.](image)
A common set of energy model inputs include criteria for location, envelope, internal gains, equipment and systems but sophisticated software has streamlined the entry of hundreds of inputs needed to ensure the accuracy of an energy model. Especially in the early phases of a project, SOM can now estimate and pre-program many variables based on experience and past performance. Some assumptions such as curtain wall characteristics, occupant behavior, programmatic operation and power densities must be carefully considered.

3.0 SOM High Performance Design Targets
As the science behind understanding the use and operation of our buildings evolves, we compare our designs against established industry benchmarks. Upon SOM’s signature of the Commitment, the agreed standards were able to adequately measure energy, water and carbon

3.1 Energy
Energy Use Intensity (EUI) is the standard unit to compare energy use in buildings and is measured in thousands of British thermal units per square foot per year (kBtu/sf/yr). The industry benchmark for measuring operational energy use is the U.S. Department of Energy’s (DOE) 2003 Commercial Buildings Energy Consumption Survey (CBECS) which records actual operational energy use from meters in existing buildings. Design teams will predict the designed building’s energy use with Predicted Energy Use Intensity (pEUI) in comparison against CBECS, specifically site energy, allowing the design team to focus solely on the strategies that reduce consumption and improve efficiency. The pEUI reduction is reported as a percentage reduction from the CBECS baseline building type.
For the purposes of internal comparison, because of its improved energy efficiency criteria and because of its alignment with LEED certification, SOM also measures our projects’ pEUI against ASHRAE 90.1-2007.

As illustrated in Figure 3, starting in design year 2015, the introduction of on-site renewable energy generation will be required in project design to compensate for the energy loads that we are unable to reduce through efficiency.

### 3.2 Water

In a similar alignment with a LEED credit path to compliance, SOM’s evaluation of designed water use reductions comes from compliance with LEED 2009’s Water Efficiency Prerequisite #1 to reduce water use by 20% over the values in the Environmental Policy Act (EPAct) of 1992 and 2005. A gallon is the standard unit of measurement – expressed in performance as an action such as gallon per flush (gpf) or a flow rate such as gallon per minute (gpm), though depending on the units employed by the project, cubic meters (m3) will be accepted. Evaluation is based on the occupancy of the facility expressed as Full Time Equivalent (FTE).

In addition to the obvious reduction of impact to the limited clean water supply that supports life on Earth, reducing water consumption contributes to significant energy
savings. Water must be treated, cooled, heated and distributed throughout buildings – heating water alone represents nearly 15% of total building energy use. In one study, federal buildings that reduced their water consumption by 40% slashed the related use of energy by almost 60%. Similar to the compensation required to offset ongoing energy use demands versus increasing reductions, starting in design year 2015 we plan to design for the recovery and reuse of water within the building, see Figure 4. Additionally, in design year 2025 we propose that treatment of blackwater on site will be required to offset a dramatic 20% reduction of water use from design year 2020, including eliminating the use of potable water for irrigation.

Fig 4: SOM HPD Water Use Reduction Goals Design Year 2012

3.3 Carbon [Second Level Heading] Units
Global Warming Potential (GWP) is a relative measure of how much heat greenhouse gases trap in the atmosphere. In evaluating GWP, all GHGs are compared to the baseline unit of carbon dioxide (CO₂), and are expressed in mass units (grams, tonnes, etc.) of Carbon Dioxide Equivalent (CDE). For the purposes of this paper, SOM acknowledges the contribution of the construction and operation of buildings to climate change through the emissions of greenhouse gases.

While the project team can apply a simple multiplier to the energy consumption of the project resulting in the CDE of operation of the building over a specified period of time, they can alternately undertake a Life Cycle Assessment (LCA) of the
project. An LCA reports the overall environmental impacts of a building, including the CDE emissions of the construction and operation of the building over a specified period of time.

3.4 Optional Targets
A. Materials
Two primary targets related to materials can be evaluated during the design. Especially relevant to the embodied energy of a design, material use reductions reduce a project’s carbon footprint. As the quality and quantity of data improves related to the energy consumed and carbon emitted by the fabrication, assembly and installation of all building materials, LCA will emerge as the primary method to track a building’s overall environmental performance.

With the increasing industry acceptance of Health Product Declarations (HPD) and the Declare label, material toxicity now has established methods of evaluation for occupant health. This building performance target picks up where the ISO-defined Environmental Product Declaration (EPD) currently leaves off and provides the project team with a methodology to communicate with manufacturers, encouraging the transparent disclosure of information regarding a building product’s occupant health information.

B. Waste
The approach to Net Zero Waste is similar to Net Zero Energy, including the strategy hierarchy beginning with reducing, then reusing and recovering waste streams, converting them to resource values with zero solid waste to landfill. Despite lack of a universally accepted standard, this target’s closest reference is the California AB341 75% Initiative which outlines the statewide strategy to divert 75% of waste from landfills by 2020.10

C. Social Justice
As architects begin to recognize their influence in the reduction of carbon emissions and the improvement of human health in the built environment, some are identifying ways to influence the social equity of those who extract, manufacture and assemble the products and materials that we specify. Similar to the Fair Trade movement in food products, the JUST label is a voluntary disclosure system that evaluates a manufacturer’s policies related to how it treats its employees and where it makes financial and community investments.

3.6 Summary and Conclusions
SOM has led High Performance Design in architecture for 75 years. The following conclusions represent an evolution of the strategies that the firm has driven for decades.

*Master our reliance on technological advancements*
For the deep reductions in resource use, architects must effectively track technological improvements to evaluate their effectiveness in meeting goal milestones. Further, design teams must initiate technology and standards improvements.
Anticipate resistance from the industry
Many of the High Performance Design targets and associated strategies represent dramatic deviations from current industry practice. Major reductions of this scale demand that close consultation with the various jurisdictions our projects are located in and be prepared to advise our clients of the drawbacks and the possibilities associated with each strategy.

Improve ease of energy model preparation and post-occupancy evaluation
As recommended by the AIA, design teams must prepare energy models earlier in the design process to effectively evaluate a minor design decision’s major impact on resource consumption. Encouraging clients to participate in post-occupancy evaluations will deliver data collection that drives the improvement of design strategies.

Why are we building this building?
Finally, consider the future deconstruction, reuse and recyclability of all construction materials. We must question the reason for every material selection and indeed even its necessity in the design. Following the hierarchy of resource stream reduction, we must consider the reuse of existing buildings to utilize the energy embodied in the current built environment.

4. RESOURCES AND TOOLS

4.1 HPD Portal
The HPD Portal is a web-based application, built by SOM to support the consistent practice of High Performance Design (HPD). Accessed from within the SOM network, users may click a link on the SOM Intrasite or follow the URL http://hpd.som.com. Users need not log in to view project statistics but must in order to contribute to a project’s data.

The HPD Portal has the following objectives:
- To capture, document, and share the HPD methodology.
- To provide access to and information on the tools and the application of HPD through the various stages of the project.
- To monitor the various HPD project targets and collect critical project-related data that can be centrally analyzed and shared.
- To provide centralized access to HPD project statistics and firmwide knowledge.

The website allows team members to review project updates at a quick glance on the dashboard, establish the project’s high performance goals, define design strategies, enter detailed criteria, analyze the strategies along each design phase, review goal metrics and record client participation. HPD strategies are aligned along five approaches:
- Absorption harnesses natural sources that exist over, under and around a building and utilizes them to satisfy the building’s operational needs. Wind, sun, and ground water all provide absorption opportunities.
- On-site electrical generation improves transmission and system efficiency. On-site methods of generation include photovoltaic (PV) solar cells, wind turbines, microturbines, fuel cells and reciprocating generators.
- Reclamation is utilized once energy has been introduced into a building. Many opportunities exist to capture and reuse these energy streams over and over again. Harnessing the embodied energy of waste air and wastewater streams can reduce the need for energy generation.
- Reduction refers to a group of strategies that minimize the energy consumption and heat gains within a building. These loads are imposed by climatic conditions and internal gains from equipment, appliances, lighting and occupants.
- Strategies related to general design and construction can reduce material use, improve indoor air quality and reduce or eliminate construction and operational waste. After the completion of construction, building commissioning is essential to ensure the optimal operation of systems.

4.2 Strategy Improvements and Future Trends
A. Tasks
The success of design strategies is evaluated in the Analysis/Synthesis segment of the HPD Portal. Tasks from the template are recommended activities aligned by project phase to achieve project HPD goals and are defined and maintained by SOM’s HPD group. Tasks that are applicable to the project are selected from the template and may be edited to better reflect the particular goals and characteristics of the project. Application, tracking and the input of ongoing feedback of these tasks from the team will systematically improve the design strategies.

B. Post-Occupancy Evaluation
Perhaps the most significant criticism of the LEED rating system was directed toward the absence of required measurement and verification of the energy efficiency strategies in the actual operation of the built environment. It is widely acknowledged that many buildings do not perform as initially anticipated for a variety of reasons, impacting operational costs and employee performance and health. For the design team, learning from the variance between design and performance can be extremely cost-effective and greatly improve workplace productivity.

Post-Occupancy Evaluation (POE) is the process of obtaining feedback on a building’s performance in use. The value of POE is increasingly accepted and it is becoming mandatory on many public projects. Because of the ability to compare design values with actual operational data, the POE may be the single most effective strategy improvement technique available and is planned to become a mandatory LEED prerequisite.

C. Biomimicry
As Figure 4 describes, impressive reductions in water use, processing and distribution will require dramatic measures. Many product manufacturers and architects are turning to nature for clues to incorporate the inherent efficiency in natural systems.
One example is SOM’s Active Modular Phytoremediation System (AMPS). Designed in collaboration with CASE, AMPS is a green wall that increases a plant’s capacity to filter airborne toxins by 2-3 times by utilizing the natural system of phytoremediation to clean the air before it reenters the HVC system. This reduces the quantity and intensity of air filtration, reducing mechanical system motor sizes with all the down-stream benefits therein.\textsuperscript{14}

Biomimicry is a field that spans scales. Where AMPS utilizes a natural process as a component of a system, some techniques consider the design of an entire system. Using a piece of hydrogel, researchers at Cornell University have simulated transpiration – the capillary action that allows trees to wick moisture upward without biological or mechanical effort. Specifically designed to move water by the physical process of tensions between atmospheric pressures, it is intended as a way to distribute water and energy through buildings.\textsuperscript{15}

D. Life Cycle Assessment
International Standards Organization (ISO)-compliant life cycle assessment is the most reliable method to verify environmental impacts and support claims. It provides designers, regulators and engineers with valuable information to explore decisions in each life stage of materials, buildings, services and infrastructure.

Because of the availability of reliable metrics for mainly heavy construction materials like concrete and steel, an LCA of the structural design is often performed by the engineer to evaluate the efficiency of the selected system and configuration. Environmental product declarations (EPD) continue to gain traction in the United States, providing the project team with verified, transparent data enabling educated design decisions. Suppliers to the construction industry are rapidly developing EPDs to meet the market demand but significant gaps and flaws in the data currently prevents the comparison of many materials and products.\textsuperscript{16}
E. Cradle-to-Cradle
Also known as C2C, Cradle-to-Cradle have popularized the concept of material reutilization: the idea that an optimized materials economy can eliminate the concept of waste.

While C2C certification is a type of LCA, the system has promoted the concept of products having the capacity to behave in the materials ecosystem as biological or technical nutrients, challenging manufacturers to design products that may be perpetually cycled or even improve the manufacturing system, consumer health or ecological cycle.17

4.3 Resources
The HPD Learning tab link in the HPD Portal opens a series of lecture presentations by SOM experts.

- SOM High Performance Targets
- Climate Analysis and Climate Tools
- Goal Metrics
- Daylight: Basic Concepts
- Daylight: Tools and Analysis
- Shadows, Solar Access – Design Analysis Tools
- Case Study: Greenland Exterior Wall
- Energy Modeling: Simulation and Analysis
- The Importance of Window to Wall Ratios in Performance Design

The HPD section of the Knowledge Management portal on the SOM intrasite provides the following tools.

- About HPD
- Project Checklist
- HPD in Newforma
- HPD in Internet Explorer
- Learning Series
- Other Resources

5. ACKNOWLEDGEMENTS
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Case Study
The University Club: Using Architectural Glass to Solve a Century Old Dilemma

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Abstract
The University Club, built in New York City in 1899 and designed by Charles McKim of the illustrious architecture firm McKim Mead and White, was considered a masterpiece with one dilemma; a pronounced stack effect brought about by its innovative elevator.

As originally designed, the Club included an immense double-height coffered-arch entry porch leading to the front doors beyond. Soon after completion, a series of canopied vestibules were added to the entrance to reduce the heightened stack effect. These and other subsequent alterations effectively obscured McKim’s original design of the main entrance.

To solve this century-old problem, the Club turned to Bohlin Cywinski Jackson and Eckersley O’Callaghan to design an ambitious new marquee entrance that would restore the monumental presence of the entry. Using the maximum available width of ultra-clear, low-reflective architectural glass, they designed an elegantly curved marquee and single sheet clerestory, allowing unobstructed views of the entry and tempering the stack effect. In keeping with the building’s Landmark designation, these substantial glass elements were designed with minimal structural framing and 'light-touch' connections to the building. Now complete, for the first time in over a century the grand entrance is open and visible to club members and the public.

1 Introduction
At its core, the renovation of the front entrance at The University Club of New York required innovative architectural and structural thinking. Yet, as this was a project imbued with great history and sensitivity, it is important to begin this case study with an account of the significance of the building itself and the conditions necessitating the architectural and structural solutions to the entrance. The intention of this case study is to demonstrate how the great technological work of our fellow engineers, fabricators and researchers can manifest itself in the design of sensitive building solutions.

2 Building History
The University Club of New York was founded in 1883 as a social club celebrating art, athletics and intellectual life. It is located on Manhattan’s prominent corner of 5th Avenue and 54th Street [1]. Over the course of the Club’s existence, this area of 5th Avenue has evolved steadily as New York’s highest profile cultural and retail corridor. It hosts many of the city’s most prestigious organizations and important architectural works, among them: St. Patrick’s Cathedral and St. Thomas Episcopal Church, Rockefeller Center, The Museum of Modern Art, Carnegie Hall and the great Central Park. The Club also shares 5th Avenue with some of the most upscale retail stores in the city. Considering its distinguished neighbors and history, the Club has maintained itself as one of the city’s most illustrious social organizations, and this aura is reflected in the building’s interior and exterior spaces.

Built in 1899, the Club’s current structure was designed by one of its members, Charles McKim, of the pre-eminent architecture firm McKim Mead and White. At the time, this firm was one of the most highly regarded architectural firms in the country, with such important commissions as: Washington Square Arch (1892), Columbia University (1893-1900), The Brooklyn Museum (1895), the Boston Public Library (1895), the Pierpont Morgan Library (1903), The Manhattan Municipal Building (1909-1915), and the ill-fated Pennsylvania Station (1910) [2]. Designed in a Mediterranean Revival Italian Renaissance palazzo style, the University Club’s building was considered a masterpiece when complete, and one of the best of Mr. McKim’s illustrious career [3]. Among its many notable features, both inside and out, it has a magnificent building façade with a double-height coffered-arch entrance porch leading to the front doors beyond.
The Club also included one of the latest technical innovations of its time, the elevator. So celebrated was this new feature, that the elevator's central location in the building replaced the traditional grand staircase which typically accompanied most social clubs and grand residences of its time. As the invention of the elevator was very new, its impact on building design was not yet entirely understood. One such effect of the elevator is Stack Ventilation or 'stack effect', which is created when air is driven through a building by vertical pressure differences developed by thermal buoyancy. Similar to outside weather events when warm and cool air meet, the warm air inside the building is less dense than cooler air outside and thus will try to escape from openings high up in the building envelope as cooler air enters openings lower down. Lower level doors without vestibules, elevator shafts and openings at rooftop mechanical elevator housings provide great opportunities for stack effect and, if unrestricted, can create high wind pressure at the building entrance doorways [4].

It was only after The University Club building was opened that its occupants discovered frequent uncomfortable wind gusts and strong pulling forces when the single pair of entrance doors were opened. While McKim’s monumental
entrance arch and portico were indeed exquisite, the front entrance created an awkward introduction to this important social institution.

![Diagram of Stack Effect]

**Figure 5.** Stack Effect: The buoyancy of warmer air creates high pressure at the top of a building and low pressure at the bottom. Somewhere between the top and bottom of the building is the neutral pressure plane, where air is under neither positive nor negative pressure. Shell holes near this plane cause much less leakage than holes at the top or bottom of the building. The exact location of this plane varies depending on temperature differentials, wind, fans, and the operation of combustion equipment. Generally, leaks at the top and bottom of the building—where stack-effect forces are greatest—are most important and offer the largest potential for energy savings. Top-of-building air leaks are slightly more important to seal than bottom-of-building air leaks, because sealing the former tends to pressurize the building whereas sealing the latter tends to depressurize it. Elevator shafts and stairwells in particular can contribute to the stack effect, because they provide a ready path for air to travel across multiple floors. [5] [6]

**4 Evolution of the Entrance**

To try and solve the predicament, in 1905, a wood-and-glass double door assembly was constructed within the portico to create a vestibule. By 1908, the Club had installed a canvas canopy to provide weather protection for members alighting from vehicles on the street. While the addition of the double door mitigated the stack effect and the canopy provided more shelter from bad weather, these additions obscured the reading of the monumental coffered arch of the main entrance, both from the street and from within the porch itself, effectively cutting off the view of McKim’s grand entry for over a century.
Figure 6. The front entrance of The University Club as it was originally built in 1899
Figure 7. The first wood and glass vestibule installed in 1905

Figure 8. The front entrance as it was before this project. The clerestory, doors and side lites were installed in the 1950’s. The canopy was installed sometime later.
Figure 9. The restored front entrance of The University Club.

5 Effects of glass and fittings
Over the course of the 20th century, the configuration of the canopy changed, but its impact on the building remained. In the mid-20th century, the wooden vestibule was removed and a glass-and-metal entry system was installed within the outer arch of the portal. The large clerestory glass was darkly tinted and highly reflective. And while its 10’-4” by 12’-6” size is notable for 1950’s glass fabrication, it was a single sheet of annealed glass. This assembly posed a potentially unsafe situation if it ever cracked or broke, as the glass would not hold together if shattered. While the glass had been intact for nearly 60 years, innovations in safety glass would remove this concern. Moreover, the clips, bolts and beams that structured the clerestory and entrance doors were cumbersome and damaging to the sumptuously detailed Milford Pink Granite and Indiana Limestone of the archway. Finally, the aluminum profiles around the clerestory and door assemblies were poorly built and had deteriorated over time. This deterioration contributed to continued gusts and strong pulling forces at the doors.
6 Landmark Building
The restoration of the entry and replacement of the vestibule and canopy was a continuation of the Club’s ongoing stewardship of the historic building. Because it is an architecturally distinguished building and registered as a National and State Landmark, it was essential that the solution to the entrance be consistent with the historic context of the building. As the entrance is visually and programmatically fundamental to the building, the solution had to meet the highest expectations.

7 Design Requirements
It was apparent from the beginning that the design solution would require the use of large span architectural safety glass to help mitigate the stack effect, provide shelter from the weather for passersby below and provide clear, unrestricted views of the surrounding building façade and interior portico. With the 11 foot wide by 22 foot high arched opening and a 15 foot projected marquee, the architectural glass elements required the support of structural components that were exceptionally minimal with discrete, minimally invasive connections to the historic building. Though modern in its make-up, the completed structure had to follow the charge of Landmarks to be sensitive to and celebratory of the historic façade, and timeless in appearance. This necessitated great attention to detail and craftsmanship in order to be harmonious with the outstanding quality and meticulous design of the original building.

8 Precedent Structures
Given the challenges of employing the most recent structural innovations within the context of historic architecture, studies were made of the solutions implemented in both past and recent glass and structural works. Precedents leading to the development of this project came from both historic glass and metal structures and the latest advanced use of glass enclosures. Historically, McKim Mead and White made use of their contemporary knowledge of glass and structure in the soaring glass and metal ceiling in the Central Waiting Room at New York’s Pennsylvania Station, and in an elegant glass marquee built at the entrance of the President’s House at Columbia University [7]. In Pennsylvania Station, the glass structure provided not only a breath-taking concourse but it illuminated the space and the surrounding interior architecture. The metal framing of the marquee at the President’s House at Columbia University is elaborately detailed, and the glass canopy provides a diaphanous arrival to this important residence. In each building, these glass assemblies balance with the surrounding stone architecture and highlight it.

Figure 10. The soaring glass and metal skylight ceiling at Pennsylvania Station
Figure 11. Entrance marquee at the President’s House at Columbia University
Recent advanced glass structures used as precedents are the Apple Stores in New York and Shanghai. These and other structures demonstrate the sensitive ways in which detailed glass and metal structures can be used to provide unparalleled transparency while protecting their occupants. They are designed with redundant measures of safety and are equipped to respond to thermal air pressure. In a similar manner to McKim’s glass constructions at Pennsylvania Station and the President’s House at Columbia University, these glass structures illuminate the architectural elements that surround them.

Figure 12. The structural glass enclosure at The Apple Store on 5th Avenue and 59th Street in New York City

9 Clerestory and Supporting Structure
Great care was taken to create a glass assembly that maximized clarity within the archway and diminished reflection from the surrounding streetscape. This included the minimizing of potential rollerwave distortions and coloration. The architectural glass within the clerestory element is a single sheet of laminated safety glass that is 3.6 meters (nearly 12'-0") high by 3.2 meters (10'-6") wide. It is made up of 2 sheets of 6mm thick low reflective, pyrolytic coated product glass, 2 polyvinyl butyral (PVB) interlayers and a 6mm thick sheet of extra-clear, low iron glass. This glass matches the lower glass elements at the side lites and balanced door panels to create a consistent view in to and out of the building.

The clerestory is structured by a galvanized steel perimeter capture detail (60mm x 30mm thick), which is braced like a continuous hoop around the stone archway. This capture is bolted to the surrounding stone with ½ inch and ¾ inch diameter adhesive anchor bolts, which are installed approximately every 24” around the stone. The steel capture is fastened to 6mm steel sheets that clamp the edges of the laminated glass panel with structural silicone.
Figure 13. The assembly of the clerestory entrance façade and marquee indicates the perimeter structural capture around the clerestory and the marquee’s connection points to the façade which employs the use of adjustable compression struts. This image also shows the minimal sizing of the structural elements, and the curved and tapered shapes at the outrigger, described below.

Figure 14. The detail indicates the perimeter structural capture around the clerestory glass, adhesive anchor bolts, adjustable compression struts and bronze cladding.
At the clerestory base, the capture is welded to a 100mm by 60mm by 8mm structural steel tube. This tube resists the lateral forces of the façade and marquee and supports the door header below. Its small 4-inch height allows the bulkhead between the clerestory and entrance doors to be decreased to 12 inches from the 18 inches of the original door bulkhead. This further supports maximum visibility through the glass façade.

The structural system of the perimeter capture evenly distributes the lateral and gravitational forces from the glass façade and marquee, and it does so with minimal effect on the surrounding stone. This was crucial to the strategy of restoring and preserving the historic elements of the original building. By engaging the entire perimeter dimension of arched clerestory glass to embrace and support it, the anchoring system at the historic stone is broadly distributed along the archway and piers, and the anchor imbed sizes are greatly reduced. Another more traditional structural solution for supporting the clerestory would have been to place a large beam at the base of the glass to carry its load. This approach would have resulted in the use of multiple large bolts to anchor the beam, thus marring the historic stone and making it very difficult to restore. Additionally, this beam would have been visually cumbersome.

Similarly to the clerestory glass, the marquee glass is constructed to achieve maximum clear visibility of the surrounding archway and building façade. The architectural glass elements at the marquee are made up of 2 panels of 2.26 meters (7'-5") by 2.95 meters (9'-8") laminated safety glass which are curved in a single direction. Each panel is assembled of 2 sheets of 12mm thick low iron, extra clear glass with a 1.5mm clear SG interlayer. The glass panels are heat treated and contrary to common assumptions about this method, the panels are clear and do not have visual distortions.
The marquee is structured by a series of thin steel profiles that are isolated from dissimilar metals. The combined rigidity of the steel frame and glass panels withstand racking on plan. The two projecting profiles, or outriggers, are custom made as curved stainless steel gutters which support the glass and provide stiffness for live loads as well as snow, wind and seismic loads. These outriggers are tapered so that the resulting form begins as a 9” tall ‘J’ shape at the clerestory that reduces to 3” at the outermost edge. This taper minimizes the structure while capturing rainwater and directing it back to storm water drain leaders. The cross framing is curved to match the shape of the curved structural glass panels and resonates with the geometry of the stone entrance archway and surrounding arched windows.

The marquee structure is mechanically fastened to the structural steel tube at the base of the clerestory. It is also supported by two stainless steel adjustable compression struts, which are 42mm in diameter and have long tapers at each end. These rods are fastened to the marquee and clerestory framing by curved steel tabs. The tab at the clerestory is connected directly to the continuous galvanized steel perimeter capture detail. In this manner, the forces from the marquee and struts are evenly distributed along the internal clerestory framing. At this location, three ¾ inch diameter adhesive anchor bolts are distributed along 15 inches at the capture. Similar to the structural method used at the beam below the clerestory, this strategy avoids the need for larger anchor bolts in the stone by reducing and distributing forces away from the base of the outriggers, and helps to preserve the existing stone work.
11 Cladding and Assembly

Each of these elements is clad in #280 muntz metal (architectural bronze). These cladding pieces are finished as #4 satin and stained as dark statuary bronze with a lacquer coating. The dark patina finish blends with the surrounding fenestration elements of the building façade, including the elaborate balcony railings and windows. The compression struts and interior of outriggers are coated to match the statuary bronze and given a flat finish. This effect of reducing light reflection from the finish lessens the awareness of the rods and harmonizes with the craftsmanship of the building’s original metalwork.
At areas where dissimilar metals are close to each other, the structural steel is coated and plastic tabs are installed to keep metal from touching. The oversized pieces of cladding are installed with as few joints as possible. These are hairline joints with back up splice plates. All assembly items are fastened in a manner so that they can be removed and reinstalled without being damaged. This includes the cladding pieces which are installed with adhesives, sealant and hidden tabs.

12 Additional Works and Restoration
The structural elements of the clerestory and marquee are supplemented by a number of architectural items that aid the performance of the assembly. Below the clerestory are extruded bronze entry side lites and a pair of balanced doors. These doors greatly reduce door pulling forces and they can be adjusted during heightened exterior and interior temperature differentials. To further mitigate pulling forces, the doors are automatic. They also have fail-safe electronic locks.

The 15-foot marquee captures rainwater and directs it through the structural outriggers and back to the clerestory. From there, the water runs through intergrated bronze clad storm drain leaders which are placed within the side lite mullion assembly. The leaders connect to the building’s storm piping beneath the entrance landing.

The areas surrounding the new entrance were meticulously restored. These areas include the stair landing, surrounding archway and the interior portico’s walls, ceilings and rosette and the original pendant lamp. Because of the building’s layered history and the multiple versions of entrance vestibules, this was a very sensitive process, successfully restoring the entrance to its original grandeur.

Within the structure and in the interior portico floor vents are a series of discretely located LED light fixtures. These fixtures are programmed with multiple scenes and work not only to illuminate the entrance at night, but to help balance daylight and reduce reflection from the outside.
Figure 22. Image of the restored front entrance of The University Club with new clerestory façade and marquee.
13 Conclusion

In order to be harmonious with the rich history and elaborate detail of the original building, the renovation of the front entrance called for a design that was technologically innovative yet aesthetically timeless. While its overall appearance is effortless, the design required extensive structural and architectural problem-solving in order to seamlessly integrate and address the
complex factors posed by the dilemma. Within the minimal assembly of the entrance structure lies an intricate system that maximizes the use of each structural element while minimizing its impact on the surrounding historic building. The result reinstates the grand entrance as originally intended and solves the issues which have presented complications over time. Through the innovative use of architectural glass, now, after more than a century, the facade, archway and portico can be viewed as a unified and coherent whole.
Figure 24. Image of the front façade of The University Club.

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Advanced Structural Silicone Glazing

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Abstract

This paper presents an advanced engineering technique using finite element analysis to improve structural silicone glazing (SSG) design in high-performance curtain wall systems for building facade.

High wind pressures often result in bulky SSG aluminum extrusion profile dimensions. Architectural desire for aesthetically slender curtain wall sight-lines and reduction in aluminum usage led to optimization of structural silicone bite geometry for improved stress distribution through use of finite element analysis of the hyperelastic silicone models.

This advanced design technique compared to traditional SSG design highlights differences in stress distribution contours in the silicone sealant. Simplified structural engineering per the traditional SSG design method lacks accurate forecasting of material and stress optimization, as shown in the advanced analysis and design.

Full scale physical specimens were tested to verify design capacity in addition to correlate physical test results with the theoretical simulation to provide confidence of the model. This design technique will introduce significant engineering advancement to the curtain wall industry and building facade.

**Keywords:** Structural Silicone Glazing, Finite Element Analysis, Curtain Wall, High Performance Building, Hyperelastic Material

1 Introduction

Design requirements for curtain walls have been influenced by recent extreme wind events. Design wind speeds and cladding pressures have increased significantly resulting in correspondingly larger material sizes and material strength for sufficient structural capacity. For example, tall buildings in typhoon zones have cladding pressures that now routinely exceed 6kPa.

Over the last several decades, structural silicone glazing has successfully attached architectural glass to curtain wall framing in high performance building facades. Due to the increase in high wind pressures, the result has been an increase in bulky metal extrusion frame dimensions. Architectural desire to enable aesthetically slender curtain frame profiles and increased sight-lines
prompted structural silicone designers to optimize the silicone sealant joint design.

The paper presents empirical and theoretical analysis of structural silicone design to develop an enhanced technique to design structural silicone glazed curtainwall for building façade.

2 History of Structural Silicone Glazing

Use of silicone sealants in structural glazing originated in 1965 with the use of glass-to-glass structural seals in the PPG Total Vision System. The practice further developed into two-sided applications in 1970, which utilized two sides of the glass infill adhered to metal framing members using silicone sealants, typically vertical jambs, with the head and sill of the glazing captured into a glazing channel with compression glazing. Four-sided applications, where silicone sealants were solely utilized to attach glass to metal mullions, were first utilized in 1971. Use of innovative glass products yielded two-sided and four-sided applications of insulating glass units in 1976 and 1978 respectively (Hilliard et. al 1977).

Structural silicone glazing has been studied with respect to high-performance environments for the last several decades with proven durability and performance in areas of high wind zones, hurricane/typhoon prone areas, extreme temperatures, and seismic activity (Carbary 2007).

However, the basic design theory on how to properly size the structural joint has remained the same. The bite calculation as derived from the trapezoidal loading theory is as follows in equation (1):

\[
\text{Bite} = 0.5 \times \text{short span length} \times \text{wind load} / \text{Sealant design strength} \quad (1)
\]

The ASTM article, “Methods for Calculating Structural Silicone Sealant Joint Dimensions,” published in 1989, discussed the structural joint width for a rectangular glazing unit is based on the simple physical relationship of the size of the glass, trapezoidal loading principle, maximum windload, and a maximum sealant design strength of 20 psi (Haugsby et. al 1989).

- The windload is the maximum determined force of pressure due to wind speed
- Short span is the shortest dimension of the four sides of rectangular glazing unit
- Sealant design strength is the maximum tensile force allowed on the sealant
Sealant technology, analytical techniques, and computing technology has significantly advanced over the history of the practice of structural glazing. Sealant technology has progressed with neutral curing formulations, increased tensile strengths, and higher movement capability. Studies have been conducted on the performance of sealants in specialized applications. Several papers have been written on the use of silicone sealants in curtain wall units for seismic activity (Zarghamee et al 1996) including the use of finite element analysis to predict the mode of failure in silicone joint (Broker et al 2012).

A study entitled “Evaluation of Silicone Sealants at High Movement Rates Relevant to Bomb Mitigating Window and Curtainwall Design”, used high-speed photography and specialized measuring devices that illustrated the relationship of the tensile capability of the sealant increases as the speed increases to validate the successful use in ballistic applications (Yarosh et al 2008).

The basis for design strength and method of design are not addressed in these papers. For good reason, as the design has been used in projects over the world that has performed well in excess of 40 years. ASTM C1401 Standard Guide for Structural Sealant Glazing is the most complete reference to the design considerations for structural silicone glazing. This document provides an excellent overview of the practice along with a full list of historical references regarding the subject.

There have been efforts to challenge both the basis of designing structural joints and increasing design strengths as mentioned above. Unfortunately, there have been no thoroughly developed and published technical arguments for proof of challenges. Opportunistic approaches appear to be based on short-term business risks and rewards with no regard to impacts of durability based on sound science and engineering.

Finite element analysis of structural silicone has been used to explore standard (Travis et al 1998) and unique designs (Hagl 2008) coupled with the understanding of the non-linear behavior of structural silicone materials. This tool, which has been used in the aerospace and automotive industries, has expanded the understanding of non-linear materials in the construction industry.

3 Finite Element Modeling of Structural Silicone Sealant
Advanced computer software analysis can provide access to several hyperelastic material properties, as well as curve-fitting subroutines that can be used to automatically generate material property data from physical testing. The services of Axel Products were used to develop accurate tension, shear, and biaxial extension data for Dow Corning(R) 983 Structural Glazing Sealant material. The
Axel data models for tension, shear, and biaxial data were then curve-fitted with several material models within the software analysis to find a curve fit which minimized the scaled residuals resulting from the data provided. An incompressible two-parameter Mooney-Rivlin curve fit was selected because it produced minimal scaled residuals. Independent literature indicates that the Mooney-Rivlin material model can accurately represent a material’s response up to 100% strain.

The Mooney-Rivlin two parameter model was tested against the results of ASTM C1135 tensile adhesion joint samples by Dow Corning to validate the generate model using a 1.27 mm mesh size. Below documents the model used to replicate the ASTM C1135 test sample where the size of the silicone joint was 50.8 mm x 12.7 mm x 12.7 mm. For computational efficiency, the size of the glass adhered to the silicone was reduced to the surface area of the silicone sample itself.

Results of the ASTM C1135 test model were compared to the results of physical specimens of the same batch of silicone used in the Axel Products curve-fitted data. Chart 1 documents the load vs. deflection diagrams of the ASTM C1135 test results and the C1135 ANSYS FEA results. Additionally, results at each 1.27 mm of deflection are provided in Table 1, along with the resultant force error at each point.

![ASTM C1135 Tensile Adhesion Joint](chart)

Chart 1: Induced load versus sample deflection in ASTM C1135 Tension Tests (typical of 12.7mm x 12.7mm x 50.8mm joint size)
Table 1: Estimated error between load determined in the FEA Model and actual load test from specimen prepared with silicone batch used in FEA data model.

<table>
<thead>
<tr>
<th></th>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1.27</td>
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<td>10.16</td>
<td>609</td>
<td>545</td>
<td>11.7</td>
</tr>
<tr>
<td>11.43</td>
<td>654</td>
<td>585</td>
<td>11.9</td>
</tr>
</tbody>
</table>

The results within the curve-fitting regime in a single silicone batch indicated a maximum recorded error of 17.6% in the range of 3.81 mm deflection, or approximately 30% nominal strain. In all cases, the FEA results over-predicted the physical test results. Observation of the percent error within the silicone batch indicated that while the material properties appeared stiffer than the material tested, the offset between the tested and modeled materials is consistently between 11% and 18% through the modeled extensions. It should be noted that the strain rate of the data used to generate the FEA material properties and the data used to generate the ASTM C1135 test results were different; the FEA material properties were generated at 0.01 s\(^{-1}\) strain rate, while the ASTM C1135 test results were generated at 0.0167 s\(^{-1}\) strain rate. It is known that rate of strain of hyperelastic materials affects the modulus properties; the effects of the rate of strain were not explicitly analyzed in this paper [Yarosh et.al].

FEA results were compared across several batches of silicone in addition to the single batch above (Table 2). Dow Corning provided three randomly selected data sets from individual batches for error analysis. Results of the sensitivity study indicate the error between the FEA silicone model and the sample batches has a maximum reported error of 33.3% at 25% strain. Unlike the intra-batch comparison, the inter-batch comparison indicates the FEA model is under predicting the induced loads in the physical tests. The error calculated from the inter-batch comparison lacks the consistent offset between the two materials of the intra-batch study. Again, it should be noted that the strain rate of the historical data was generated at a different load rate than the strain rate of the
FEA model. The historical data was generated at a load rate of 50.8 mm / min, equal to a strain rate of 0.067 s\(^{-1}\).

Table 2: Estimated error between loads determined in ASTM C1135 modeled in FEA and actual results of three historical batches of ASTM C1135 testing.

<table>
<thead>
<tr>
<th>Strain (%)</th>
<th>Force [N]</th>
<th>Percent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FEA</td>
<td>Batch 1</td>
</tr>
<tr>
<td>25</td>
<td>133</td>
<td>173</td>
</tr>
<tr>
<td>50</td>
<td>290</td>
<td>352</td>
</tr>
<tr>
<td>75</td>
<td>455</td>
<td>573</td>
</tr>
</tbody>
</table>

Stress distribution plots in Figures 1 and 2 indicate the results of the FEA models at 0.76 mm deflection and 1.78 mm deflection. At these deflections, the induced forces were 84.1 N and 177.9 N, respectively, which are approximately representative of 100% and 200% of what is typically considered limiting stresses for structural silicones.

Figure 1: Distribution of Stress at 100% of Allowable Nominal Silicone Stress
Figure 2: Distribution of Stress at 200% of Allowable Nominal Silicone Stress

Note that in both cases, stress peaks are calculated around the perimeter, and the stress within the silicone sample is highly non-uniform. The high differential stiffness between the silicone and the adjacent substrate causes the stress to be unevenly distributed. The results shown above are consistent with typical failure propagation starting at the perimeter of the testing specimen as observed in ASTM C1135 tests.

The rationale behind the newly proposed silicone sealant joint can be seen in the results of the ASTM C1135 test samples. In a typical curtain wall assembly under negative loads, where the silicone is adhered in a square geometry, the finite rotation of the glass at the perimeter seal will induce the greatest movement at the edge of the silicone joint. The concept behind the new sealant geometry design allows additional movement capacity for the glass to rotate more freely rather than forcing the sealant to fight against the finite rotation of the glass at the perimeter (theoretically inducing a moment couple within the sealant). Figure 3 schematically demonstrates the anticipated center of rotation of the glass relative to the silicone joint in both cases.
The proposed sealant joint design was tested on a 1905 mm x 1524 mm glass model. One quarter of the glass was included in the model for computational efficiency. Two models were generated: one for the proposed sealant design (trapezoid with 23.81 mm long dimension, 6.35 short trapezoid dimension, and 12.7 mm long trapezoid dimension), and one with a 50.8 mm long rectangular sealant joint, per standard industry practice. The glass was loaded to 9.6 kPa. The results of the models were compared as well as to benchmark stresses in the C1135 model.

Figure 3: Assumed Glass Rotation for Trapezoidal and Traditional Silicone Joints
The results of the trapezoidal silicone models that indicate maximum stress through the gross area of the silicone bite did not exceed 0.38 MPa, with peak stress along the edge of the silicone joint at 0.64 MPa. The results of a similar ASTM C1135 test sample with similar edge stresses were loaded to 2.29 mm deflection and 218.6 N applied force. The results of a “traditional” silicone model indicate the gross area of the silicone bite did not exceed 0.55 MPa, with peak stress along the edge of the silicone joint at 0.91 MPa. The results of a similar ASTM C1135 test sample with similar edge stresses were loaded to 3.30 mm deflection and 293.4 N applied force. Details of these stresses at the mid-span of both the long and short dimensions, as well as comparable peak edge stresses are shown in Figures 4 to 9.

Figure 4: Distribution of Stress at Short Dimension Midspan of Trapezoidal Joint at 23.8 mm orthogonal bond width between glass and sealant
Figure 5: Distribution of Stress at Long Dimension Midspan of Trapezoidal Joint at 23.8 mm orthogonal bond width between glass and sealant

Figure 6: Test Results of ASTM C1135 Tensile Adhesion Joint (typ. 12.7mm x 12.7mm x 50.8mm) with Similar Peak Edge Stresses to Trapezoidal Joint
Figure 7: Distribution of Stress at Short Dimension Midspan of Traditional Joint at 50.8 mm bond width

Figure 8: Distribution of Stress at Long Dimension Midspan of Traditional Joint at 50.8 mm bond width
Figure 9: Test Results of ASTM C1135 Tensile Adhesion Joints (12.7mm x 12.7mm x 50.8mm) with Similar Peak Edge Stresses to Traditional Joint

The results of the preceding figures indicate that a stress reduction can be achieved by allowing the silicone to rotate with the glass under large wind loads. It also shows that safety factors included in the design of silicone joints may not be as high as those indicated when comparing silicone in the traditional configuration to the results of a C1135 sample test.

To confirm that the proposed silicone joint would not compromise the glass under positive loads, the above-mentioned silicone joint was loaded to 6.2 kPa positive pressure to check the effects on the stress distribution within the silicone joint. Corner joint stresses were checked against the stresses in the typical silicone joint; these can be seen in Figure 10. The stresses in both the gross area and the corner of the trapezoidal silicone joint did not exceed those in the traditional silicone joint under negative wind loads.
4 Results of Physical Mock-Up Curtain Wall Assemblies

The unique joint design was scaled up on a real size piece of glass and a design of 9.58 kPa (200 psf) and tested to the Miami Dade, Florida Building Code’s Test Protocol for High-Velocity Hurricane Zones. The protocols that were followed were Testing Application Standard (TAS) TAS 202-94, the procedure for conducting uniform static air pressure test. This test is operated in the spirit of ASTM E330 Standard Test Method for Structural Performance of Exterior Windows, Doors, Skylights and Curtain Walls by Uniform Static Air Pressure Difference.

The loading pressures for this mockup were ± 9.58 kPa (200 psf) with a ±14.37 (300 psf) test to validate 150% overload as specified in the TAS 202-94. The mockup samples were fabricated to accommodate a glass size of 1524 x 1905mm (60” x 75”). Two different laminates we used, Polyvinylbutyral (PVB) and DuPont SentryGlas ® Plus (SGP). Three different monolithic laminated types of glass were used in the mock up testing

1. 5mm clear tempered, 2.3mm PVB interlayer, 5 mm clear tempered (3/16” Clear tempered, 0.090 PVB interlayer, 3/16” Clear tempered)
2. 5mm clear tempered, 2.3mm SGP interlayer, 5 mm clear tempered (3/16” Clear tempered, 0.090 SGP interlayer, 3/16” Clear tempered)
3. 6mm clear Heat Strengthened, 2.3mm SGP interlayer, 6 mm clear Heat Strengthened (¼” Clear Heat Strengthened, 0.090 SGP interlayer, ¼” Clear Heat Strengthened).

The glass was attached to an anodized aluminum frame as shown in Figure 11 with a 23.8 mm structural bite orthogonally projected through the trapezoidal joint configuration. Conventional calculation would have required a minimum structural bond width of 52.9 mm. The frame was constructed out of a standard aluminum tube to which a brake metal shape was mechanically attached with 6mm (¼”) fasteners 200mm (8”) on center. Glass type 1 and 2 were tested exactly as shown in Figure 1. The weatherseal detail used with glass type 3 was altered by omitting a backer rod and filling the rectangular cavity with the structural silicone. In all cases the structural silicone was not in contact with the silicone used at the glass edge.

Figure 11: Detail of horizontal and vertical attachment in tested mockups
During test deflection, measurements were taken of the aluminum frame and the center of glass at the testing laboratory. These deflections are reported in Tables 3 and correspond to the locations noted in the table specific to the glass type listed above. Tables 3 and 4 report the data taken on the air infiltration, water infiltration, and static loading of the glass units.

The three types of glass met the Miami Dade Code requirements for TAS 202-94 at a design wind pressure of ± 9.58 kPa (200 psf) which included a ± 14.37 kPa (300 psf) overload.

This mock up (shown in Figure 12) clearly showed that the unique silicone joint design passed the windload design criteria for ±9.58 kPa (200 psf) and survived the ± 14.37 (300 psf) overload. The silicone material used for the structural attachment of the glass in combination with the unique joint design has demonstrated the potential to perform beyond current accepted methods for SSG design.

Figure 12: Picture of actual mock-up assembly used in testing validation

5 Conclusions on Advanced SSG and Incorporation a New Design
As mentioned previously, the lack of credible technical publications has created a need to properly consider new design methods or increases to design strength of structural silicone sealant. The following is a proposed method for a credible and systematic approach for use of Finite Element Analysis for advanced design of structural bite configuration and appropriate maximum stresses beyond traditional.

1. Establish an accurate FEA model
2. Develop an FEA model of a structural joint designed by the conventional formula and design stress
3. Develop an optimized FEA model for the alternative joint design and sealant design strength
4. Compare conventional joint models and alternative models to determine that distribution of maximum stress has been reduced via alternative design
5. Validate alternative joint design with actual performance mock-up curtain wall units

Finite Element Analysis models are generated by complex computing software that requires two main components. First and foremost is the proper selection of a material model that accurately predicts the behavior of a material over the range of expected performance. Second is an accurate data set that has been tested by conventional test methods recognized by the modeling software to accurately predict real world performance of the material.

Tensile adhesion joints tested to ASTM C1135 have become a standard test method to understand the stress/strain relationship of structural sealants in a prototypical SSG joint geometry in curtain wall units. Given the proven history of the conventional structural design methods with correlation to predicted material performance of a tensile adhesion joint, one should be convinced that the selection of the proper model for predicting material behavior would be predictive of the performance of the tensile adhesion joint.

Next in the process for alternative design would be to predict the distribution of forces in a conventional joint design at maximum loads. Understanding the peak forces generated in a tensile adhesion joint stressed to design load is very important.

Using the FEA modeling software, the next step would be to determine the optimal joint geometry to predict an overall lower cumulative stress distribution within the sealant joint to achieve desirable conditions for reduced aluminum or
metal framing members without sacrifice to damaging loads to the structural silicone sealant’s capability.

Comparison of both models should make physical sense with respect to the expected performance of the sealant including actual test results, reasonable expectation for forces generated within the different joints, and appropriate validation of the different joint geometries such as the tensile adhesion joints tested according to ASTM C1135.

ASTM C1184 outlines the needed performance of a silicone sealant used in structural glazing applications. Of importance is a minimum tensile property of 350 kPa (50 psi) as tested by ASTM 1135 at different potential environmental conditions related to temperature and environmental exposure. Silicone sealants are well behaved over a wide range of expected temperatures, but potential differences exist within the performance expectations of the sealant.

This illustrates an important consideration in selection of the sealant used for alternative joint design. Structural sealants that marginally meet any requirement of ASTM C1184 via ASTM C1135 testing should not be considered as a primary option relative to other choices. Sealants that meet each requirement with a relatively high safety factor should be the primary choices for alternative design and sealant design strength.

Mock-up testing should be used to enable predictive comparison of the actual sealant behavior and predicted behavior from the FEA model to ensure the competency of any deviation from the convention of our current standard that has proven 40+ years of success. Performance to onetime events such as bomb blasts and impact applications still will need proper consideration from current practices of testing actual mock-ups for appropriate building codes and industry accepted test methodologies.

References


Table 3: Deflection measurements of unitized curtain wall units under negative and positive windload during TAS 202 testing method. Glass type corresponds to glass and laminate configurations listed in above text. Glass Type 1 comprised of Tempered and PVB, Glass Type 2 comprised of Tempered and SGP, and Glass Type 3 comprised of Heat Strengthened and SGP.

<table>
<thead>
<tr>
<th>Deflections (mm)</th>
<th>Top Corner</th>
<th>Mid Point of Long Span</th>
<th>Bottom Corner</th>
<th>Center of Glass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Glass Type 1</td>
<td>Glass Type 2</td>
<td>Glass Type 3</td>
<td>Glass Type 1</td>
</tr>
<tr>
<td>50% of Test Pressure 7.19 kPa (+150 psf)</td>
<td>3</td>
<td>5.3</td>
<td>6.6</td>
<td>4.3</td>
</tr>
<tr>
<td>Permanent Set</td>
<td>2.3</td>
<td>3.3</td>
<td>1</td>
<td>2.3</td>
</tr>
<tr>
<td>Design Pressure 9.58 kPa (+200 psf)</td>
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<td>6.1</td>
<td>7.1</td>
<td>5.6</td>
</tr>
<tr>
<td>Permanent Set</td>
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<td>3.8</td>
<td>1</td>
<td>2.8</td>
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<tr>
<td>50% of Test Pressure -7.17 kPa (-150 psf)</td>
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<td>2.5</td>
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<td>0.5</td>
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<td>2.3</td>
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Table 4: Performance data for mock-up assemblies for air infiltration, water infiltration and forced entry.

<table>
<thead>
<tr>
<th>Curtain Wall Assembly</th>
<th>Air Infiltration at 75.2 Pa (1.57 psf, 25 mph)</th>
<th>Air Infiltration at 300 Pa (6.24 psf, 50 mph)</th>
<th>Water Infiltration at 15% Positive Design Pressure (1.44 kPa, 30 psf)</th>
<th>Forced Entry - ASTM F588-07</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass Type 1 - Tempered and PVB Laminate</td>
<td>&lt;0.18 m³/m²/hr (&lt;0.01 cfm/ft²)</td>
<td>&lt;0.18 m³/m²/hr (&lt;0.01 cfm/ft²)</td>
<td>No Penetration Pass</td>
<td></td>
</tr>
<tr>
<td>Glass Type 2 - Temperature and SGP Laminate</td>
<td>&lt;0.18 m³/m²/hr (&lt;0.01 cfm/ft²)</td>
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<td>No Penetration Pass</td>
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</tr>
<tr>
<td>Glass Type 3 - Heat Strengthened and SGP Laminate</td>
<td>&lt;0.18 m³/m²/hr (&lt;0.01 cfm/ft²)</td>
<td>&lt;0.18 m³/m²/hr (&lt;0.01 cfm/ft²)</td>
<td>No Penetration Pass</td>
<td></td>
</tr>
</tbody>
</table>
Evolution of Glazing Technologies in Philadelphia

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Frederick Langezaal  
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Abstract

At its introduction in the early 17th century glass windows were a simplistic building material that was inefficient, costly, and only provided aesthetic value. Moving through time, glass has become ever more useful in construction and has seen many new applications that were unthinkable years ago. The evolution of glass and its functionality, technology, and applications is remarkable. An analysis of the structures in Philadelphia during different centuries will reveal the staggering advancements that have been made to create today's seemingly limitless glass.

In 1770, construction began on what was to be known as one of the most historical buildings in Philadelphia. One of America's greatest stories is Carpenter's Hall which was originally built near sewage and tanning waste but sprung to prominence as a hallmark. Today, Carpenter's Hall is closely related to the American Revolution because it was one of the first privately held structures in any of the thirteen colonies where representatives could meet to discuss important matters. During its design and construction, Benjamin Franklin found it of paramount importance to assure that the building was fireproof. During colonial times, one of the greatest and cheapest ways to fireproof a building was to simply construct it of brick and mortar. Since construction cost during that period was based off of units, and glass was very expensive to manufacture and ship, Robert Smith decided to design the building with a brick veneer. Glass did not have the most important role in building construction during this time due to its high cost, but that would change over the next two centuries.

Philadelphia's roots in Georgian style architecture would take a sharp turn to modernism in the 1930's. 1932, Philip Johnson and Henry Russell Hitchcock hosted an exhibition at the Museum of Modern Arts where they introduced the International Style to America. The international style identified three distinct principles: the expression of volume rather than mass, the emphasis on balance rather than preconceived symmetry, and the expulsion of applied ornament. Occurring concurrently to the art exhibition was the design for the Philadelphia Saving Fund Society Building, famously known as the PSFS building. The PSFS building was designed by George Howe and William Lescaze, and it was the first international style skyscraper in America. Rather than designing a "strong" looking building, Howe and Lescaze used glass to rip through the building's facade and expose the interior workings of the building. The architects are quoted saying "Buildings are no longer structural forms, they must open up for the air and sunlight." Glass was becoming a more popular building material in the 20th century, but the international style and the PSFS building marked the beginning of an entirely new vocabulary for how buildings could be designed.

Today, glass is being utilized in so many different applications. With advancements in technology, glass is being used as entire facades of many of today's skyscrapers. Glass is not only considered for its ornamental purpose, but instead as becoming a versatile building material. With the advent of low emissivity glass, multiple glazed windows, and even windows filled with low conductive gases, designers and owners have an arsenal of options to choose from. Glass has also advanced in many other facets including its ability to resist fires, expanded ornamental use, and even structural applications. Philadelphia is home to many buildings that are pushing the capabilities of glass to the limits. Structures like the Buerger Center show of the complex shapes glass can take on, yet remain both cost and energy efficient. The recently revealed new Comcast Tower will boast an impressive glass facade exposing the entire structure within and providing unparalleled views of the city below. An in depth look at the glass technology used today will help understand where it will advance to in the future.

Keywords: Glazing, Philadelphia, History of Glass, Carpenter's Hall, Philadelphia Savings Fund Society Building, Buerger Center, Children's Hospital of Philadelphia, Cira Center, Energy Performance

1 Introduction

Philadelphia provides a wonderful opportunity to analyze the advancements of glass through unique and architecturally important structures. The evolution of glass in its functionality, technology, and application is remarkable. At its introduction in the early 17th century glass windows were a simplistic building component that were
In 1770, construction began on what was to be known as one of the most historical buildings in Philadelphia. One of America's greatest stories is Carpenter's Hall which was originally built near sewage and tanning waste but sprung to prominence as a hallmark historic structure. Having experienced the fire of London, William Penn found it of paramount importance to assure that Philadelphia buildings be as fireproof as possible. During colonial times, one of the greatest and cheapest ways to fireproof a building was to simply construct it of brick and mortar. Since construction cost during that period was based off of units, and glass was very expensive to manufacture and ship, Robert Smith decided to design Carpenters' Hall with a brick exterior walls.

The PSFS building began construction in 1932. The PSFS building was designed by George Howe and William Lescaze, and it was the first international style skyscraper in America. Rather than designing a “strong” looking building, Howe and Lescaze used glass to rip through the building's facade and expose the interior workings of the building. The architects are quoted saying “buildings are no longer structural forms, they must open up for the air and sunlight.” Glass became a more popular building material in the 20th century, and the international style and the PSFS building marked the beginning of an entirely new vocabulary in building design.

Today, glass is being utilized in so many different applications. With advancements in technology, glass is being used as entire facades of many of today's skyscrapers. Glass is not only considered for its ornamental purpose, but instead glass is becoming a versatile building material. With the advent of low emissivity glass, multiple glazed windows, and even windows filled with low conductive gases, designers and owners have an arsenal of options to choose from. Glass has also advanced in many other facets including its ability to resist fires, expanded ornamental use, and even structural applications. Present day Philadelphia is home to many buildings that are pushing the capabilities of glass to the limits. Structures like the Buerger Center show the complex shapes glass can take on, yet remain both cost and energy efficient. The recently revealed new Comcast Tower will boast an impressive glass facade exposing the entire structure within and providing unparalleled views of the city below. An in depth look at the glass technology used today will help understand where it will advance to in the future.

2 History of Glass in the Thirteen Colonies

Even though it wasn't grossly profitable at first, glassmaking was America's first industry ("Glass in America," 2002). During the first 150 years of America's history there were many attempts at establishing glass factories (Brannon, 2009). After colonists landed near Jamestown, Virginia in 1608 they established a small glass factory that used sand from the surrounding beaches to produce glass. News of this reached England, and many businessmen in London were relieved due to the fact that they needed to manufacture cheap goods in America to be sold for profit. However, it was hard to enlist men from both the homeland and the newly settled colony to work in the glass factory ("The History of Glass," 2007). England knew that the settlers needed glass for windowpanes, so in 1608 they sent eight skilled blowers of Polish and German descent to aid the colonists in their manufacturing. No one knows who those men are today, but it is known that their glassmaking settlement was located in the woods about a mile away from Jamestown (Brannon, 2009). Even after London sent these eight blowers to Jamestown the factory still enjoyed only minimal success ("The History of Glass," 2007). Adding on severe weather and unfavorable economic factors, the factory in Jamestown was forced to close ("Glass in America," 2002). Twelve years later another factory was built and Italian glassblowers were brought in instead of German and Polish craftsmen. To Jamestown's dismay, the Italian workers proved to be hard to work with and less productive. The entire factory ended up blowing down a couple years later, and the Indian uprising of 1622 prevented it from ever being re-constructed ("The History of Glass," 2007). Captain William Norton of the British Navy also took a chance with glass production, but he was ultimately deemed a failure since the only thing he produced was beads used to barter with Native Americans on Manhattan Island (Brannon, 2009).

Over the next hundred years the colonies were forced to import the majority of their glass from England. Even though factories began to sprout up throughout America, they didn’t produce enough glass to eliminate the colonies' reliance on the mother land ("The History of Glass," 2007). In 1639, Quaker Lawrence Southwick, glass-maker Ananias Concklin, and Baptist Obadiah Holmes founded a glass factory in Salem, Massachusetts. Due to a shortage of materials and the religious persecution of Southwick and Holmes, the factory failed within a couple of years. In the 1650’s, New York City's Wall Street was home to several glass factories. Little is known about the accomplishments of these factories, and to this day many are considered unsuccessful (Brannon, 2009). It wasn’t until 1739 that America first started gaining success in glassmaking. It was in this year that the first profitable large-scale operation was established in Salem, New Jersey by Caspar Wistar, a German colonist and entrepreneur. He constructed a
glass factory that produced mostly simple articles for average citizens ("The History of Glass," 2007). Unlike prior glass factories, Wistar had access to skilled Belgian glassblowers and an abundance of materials such as clay and sand. Within a few years, Wistar had established himself as creator of South Jersey Glass; a stepping stone for glass factories in the thirteen colonies. The American Revolution would prove to have a great impact on the glass industry, and the few individuals who achieved success would have their names written down and honored throughout history (Brannon, 2009).

2.1 Glass in Colonial Philadelphia

When the thirteen colonies first started producing glass, they made sure to show off their product in what was to be their future capital. Georgian sashes were used in Penn’s house along with every other historic home and building within the city. At first, windows were made so only the lower sash could be adjusted upward. As time passed, double-hung windows started gaining popularity because both sashes could be adjusted. The diamond paned casement sashes that were used earlier in New England (made in the Elizabethan manner) had gone out of style and were replaced by more Renaissance influenced pieces. At first, window panes were small and often squeezed within larger sized openings. Glass-making advanced over the years, and eventually the prevailing size of window panes increased from 5” x 7” to 6” x 8”, 7” x 9”, 8” x 10”, and 10” x 12”. Philadelphian architects always liked the scale of smaller panes on their building’s façade, so smaller pieces never ceased to exist (Cousins & Riley, 2009, p. 135).

Another common trend of windows that existed within the Colonial period was an equal number of panes in each sash of the window. Due to this fact, twelve, eighteen, and twenty-four paned windows were all popular in Philadelphia architecture. Public buildings and mansions contained windows with more panes compared to houses of moderate size which had less. Significant houses of moderate size which contained small, six-paned sashes included the Highlands, the Powell house, the Evans house, and the Wistar house. Windows with the unusual amount of nine panes on the upper and lower sash can still be seen in a few locations like Northern Liberties and the Wharton house on Spruce Street, but this type of window was not used often since it was uneaesthetically pleasing (Cousins & Riley, 2009, p. 136). Even though the trend of equal panes in each sash was very popular in Philadelphia, there were many instances where this trait was tested.

Many times, houses contained windows with nine-paned sashes on the lower floor and six-paned sashes on the upper floors. The reverse could be found in certain instances, and sometimes nine paned sashes and six paned sashes were combined in the same window. Such is the case at the Bartram house and the Johnson house where nine-paned upper and lower sashes were used on the lower floor and nine-paned lower and six-paned upper were used on the second floor. Many different variations of this same arrangement were also found on Penn’s house in Fairmount Park and the Solitude and Blackwell house on Pine Street. Another common window used in Philadelphia was the twelve paned upper and lower sash window. This type of window was used on the first and second stories at Cliveden, Stenton, and Woodford. It was also used at the Morris and Perot – Morris house, Chalkley Hall, and the Port Royal House in Frankford (Cousins & Riley, 2009, p. 137). Like other window types, the twelve paned windows were also combined with sashes of various panes including six, eight, and nine. The Waln house, Laurel Hill in Northern Liberties, and the Free Quakers Meeting House all featured the combination of twelve paned sashes with six, eight, or nine paned sashes (Cousins & Riley, 2009, p. 138). If architects wanted to reduce the apparent height of the building they were designing, they could foreshorten it by adding square windows. This technique was used in the design of the Blackwell, Powel, Wharton, Waln, and Stocker house; all three story buildings (Cousins & Riley, 2009, p. 138).

In colonial times, electricity was not harnessed for use as we know it today. If you wanted your house to have light, you needed windows and candles. Most colonial roofs were either gable or hip, and in order to emit light within the attic, dormers needed to be built into the roof. Dormers are structural elements of a building that protrude from the surface of the roof. Windows were typically built within dormers so sunlight could enter the attic (Cousins & Riley, 2009, p. 139). Round or square windows were typically used, but lavishing houses of fine detail typically had Palladian windows which provided the building with an ornamental look (Cousins & Riley, 2009, p. 140). Famous structures in Philadelphia which were renowned for their use of Palladian windows were Christ’s Church, Carpenters’ Hall, and Independence Hall; the latter boasting the title of the greatest Palladian window in America (Cousins & Riley, 2009, p. 151). Carpenters’ Hall in particular also took pride in their twelve paned sliding and round topped windows with small ornamental pieces (Cousins & Riley, 2009, p. 148). These windows added aesthetic value to the building since it was constructed of mostly wood and masonry.
Fire prevention was of paramount importance during the construction of every building within Philadelphia. Since firefighting techniques we use today were not present in the eighteenth century, fires in major cities were both common and treacherous. William Penn wanted to prevent both the loss of property and life from major fires. Philadelphia was to be a masonry city. Following Penn’s lead, Benjamin Franklin contributed several additional structural and design improvements within buildings including: 1) he required wood would not penetrate through party walls, 2) he assured that strips of wood coated in plaster were installed on the second story beneath the floor boards to prevent the spread of fire (Karsch, 1995), 3) Franklin recommended access to roofs in order to throw water on a fire should it spread to the attic or roof, and 4) Franklin invented lightning rods to be installed on buildings. Franklin founded the first fire insurance company in Philadelphia, fulfilling one of his lifelong goals. Philadelphia soon established other prominent fire companies during this time, but they were not funded by the public. Instead, they were paid for by individuals who owned buildings or homes they wanted insured. Two of the biggest fire companies in Philadelphia were the Contributionship (founded by Franklin) and the Greentree, created only to insure structures with a “tree” on its property (something the Contributionship initially did not do).

2.2 Carpenter’s Hall

In 1724 the Carpenters’ Company of Philadelphia was founded to share knowledge of construction, determine the price of constructing buildings, and help destitute craftsmen (“Carpenters’ Hall”). The Carpenters’ Company wanted to cement themselves in a thriving community, and they found the perfect opportunity in the city of Philadelphia. On New Year’s Day of 1770, the Carpenters’ Company voted to construct a meeting hall that would showcase their up and coming technical skills. They also planned on renting the newly available space for profit (Karsch, 1995). The fact that they rented the building was imperative because without this the Continental Congress would have had no safe place to meet without being spied on by English Loyalists. Robert Smith, a Scottish master-builder who was born from a family of masons, was assigned the task of designing Carpenters’ Hall.

The task delegated to Smith from the Carpenters’ Company was an honor. He also had the privilege of heading a twelve man construction committee throughout the duration of the project. Smith designed a fifty square foot building, two stories high, with ten feet cut out of each corner (Karsch, 1995). The final building was to be in Georgian style, and if one looked down on it from above they would discover that it was built in the shape of a cross (“Carpenters’ Hall”). Unlike today, glass was expensive to manufacture and undesirable in the assembly of curtain walls. Instead, the thirteen inch exterior wall was built of brick to bear the weight of the hall. A collection of randomly sized stones was also cemented together to construct a foundation known as a “rubble” foundation (Karsch, 1995). Although used very effectively for the transmission of light into the structure, glass had no real consequence on the structural integrity of the building.

Aside from being built of brick and supported by stone, the entire framing of Carpenters’ Hall was done with Eastern White Pine. The first floor was supported by two girders, and joists were customized to fit them for maximum support. In order to avoid the use of columns in the basement and first floor, special trusses were used to sustain the load of the building. On the second floor of Carpenters’ Hall, encased within the huge library and partitions, are two “queen post trusses” which support the second floor. A “king post truss” is located in the attic which supports the roof and the cupola (Karsch, 1995). Over time, all of these trusses began to fail due to many factors.

For the first seventy-five years of Carpenters’ Hall’s existence the roof was covered with cedar shake shingles. At first, this was the cheapest option for the Carpenters’ Company. However over time the wood shingles needed to be replaced and repaired. The cost dedicated to this task became too burdensome, so in the 1850’s the shingles were replaced with slate. The final change to the roof came one hundred years later when the slate was
eventually replaced with fireproof ceramic tiles. With each change to the roof the load increased from three pounds per square foot to twelve for the slate, and from twelve pounds per square foot to fifteen for the tile. The king post truss was not designed to hold this weight, and it eventually began to deflect onto the queen post trusses below. To add more problems onto the already collapsing building, the immense library on the second floor began placing extra stress on one of the queen post trusses. Exactly two hundred years after Carpenters’ Hall was completed, a member and structural engineer of the Carpenters’ Company installed steel rods and beams that transferred the added loads to the corners of the building. Nicholas A. Gianopulos is credited with this excellent work, and without it Carpenters’ Hall certainly would not be here today (Karsch, 1995).

2.3 Glass in Carpenter’s Hall and the Direction it is Headed in Philadelphia Today

As previously mentioned, glass was very expensive in colonial times. Even if it was delivered safely and on time, it still contained defects that were undesirable to occupants. The only real function that glass served in this period of history was to emit light into a building. Electricity wasn’t harnessed, and light bulbs were not yet invented. Candles could be used at night, but it was considered a waste to use them during the day. Carpenters’ Hall contained thirty-four twelve paned upper and lower sashed windows throughout the entire building: nine windows on the north and south elevations and 8 windows on the east and west elevations. Robert Smith intentionally placed the windows symmetrically throughout the building because that was a popular architectural trend during this period of time. Three windows on the front of the building were a small building, but for its occupants, windows was necessary for regular Carpenters’ Hall.

Transitioning from colonial to twentieth century Philadelphia, City Designer Ed Bacon once pointed out colonial structures compared favorably with the shape and use of glass in Society Hill Towers. Society Hill Towers were designed by I. M. Pei, who years later would advance glass design with the John Hancock Tower in Boston even though it was initially famous for its flawed glass design. The PSFS building, also located in Philadelphia, contains glass within its structural grid and the ratio of window panes to sections of curtain walls. The fact that these traits transcend from buildings in Colonial times to buildings constructed in the 1930’s demonstrates that the use of glass has evolved within the city of Brotherly Love.

3 Philadelphia Savings Fund Society

Rewind slightly, to 1926 when conservative to the completely revolutionary style of architecture was International, and the building was PSFS. Fund Society was planning to build a new director at the time was James M. Wilcox. Wilcox had a desire at that time to move away from traditional domes and marble. Up until this time conservative city whose architects styles of architecture including Roman historical ornamentation (PSFS Building Philadelphia Saving Fund Society itself their bank offices Lehigh Ave., rusticated block very few windows, entrance way. their branches built in 1926 at Ludlow and S. 52nd Street.

All banking architecture at that time resembled Greek and Roman monuments, and most banks were built in the financial district of Philadelphia. The Philadelphia Saving Fund Society set out to break that mold. Wilcox was quoted saying the goal for the building would be “ultra-
modern only in the sense that it is ultra-practical”. Wilcox also believed that traditional architecture styles would become obsolete and economic realities would lead to utilitarian designed buildings in the near future. Compiling these radical ideas, the new headquarters was envisioned to be a skyscraper which would impact the style of banking architecture forever.

PSFS contracted the architect George Howe to design the building. Howe had been had been a partner in the firm Mellor, Meigs, & Howe. Howe began his career in architecture by attending Harvard architecture school, and also graduating from the Ecole des Beaux-Arts. Howe took his knowledge and passion for architecture and began designing homes, and then also began designing branch offices for the Philadelphia Saving Fund Society (Tatman, 2014). In 1929 George Howe met William Lescaze. Lescaze was a Swiss born architect who studied under the modernist architect Karl Moser (William Lescaze, 2013). Howe and Lescaze entered into a partnership with the design of a day school in Philadelphia, and during this project Lescaze introduced Howe to his skills in a modern vocabulary. Howe then left his partners Mellor & Meigs and designed the PSFS building with William Lescaze.

With James Wilcox idea for the building, Howe & Lescaze began design for the iconic banking headquarters. They designed a T-shaped skyscraper which would be programmed into three uses: 1) retail, 2) banking, and 3) office space. A distinct change in traditional programming was made when the Philadelphia Saving Fund Society bank decided to be located on the second floor, and the first floor would be retail. Locating retail on the first floor was decided to attract all income levels to the bank’s headquarters. In the 1920’s and 30’s Philadelphia had certain sections of the city which had become retail and financial districts, with banks being built in one area, and retail stores being built in another. Banking at that time was practiced only by the wealthy, and therefore did not interest the middle class. When the Philadelphia Saving Fund Society decided to build their headquarters at 12th and Market, in the middle of the retail district, they were opening their doors to a whole new source of clientele. George Howe is quoted in a 1932 magazine article, “...that a mutual savings bank is the homely refuge of the workingman's dollar and its material dwelling must express above all others, the thought of security and economy” (Zoll, 1932).

The design for the core and shell of the modern architecture styles which were These modern styles would be later Philip Johnson, and Henry Russell International Style to America in 1932 at Modern Art. By the time the International already been in use in Europe. The a response to traditional style style believed they had transcended style which could be implemented in any economic period, hence the name

The International Style was based upon the expression of volume rather than balance rather than preconceived of applied ornament. Architects of this primary feature of their buildings. Where to design buildings which looked Style architects exploited materials for incorporated slender thin columns and ribbons of glass would bind buildings insides. Buildings became very finishes were applied to their exteriors became more reflective and translucent as they rose.

PSFS building was based on new beginning to surface at the time. named: the “International Style”. Hitchcock formally introduced the an exhibition at the Museum of Style reached America, it had International Style came about as architecture. The creators of this traditional design, and found a area, in any climate, and at any "International." three distinct characteristics: 1. mass, 2. the emphasis on symmetry, and 3. the expulsion style incorporated glass as a traditional style architects wanted massive and strong, International their natural abilities and extended cantilevers. Long and completely expose their rectangular, and smooth, flat and interiors. Building facades Howe and Lescaze were architects that were trained in traditional style, as well as open minded towards modern styles. Their design for the PSFS building was 36 story, 557,000 square foot skyscraper. The skyscraper was designed in a T-shape to maximize natural lighting. The first floor of the tower was designed to be retail space. The retail space was exposed to Market Street with a glass storefront system. The second floor bank cantilevered over the first floor, and featured two-story tall flat glass windows set in aluminum frames. These windows were one of the first experiments in pure curtain wall design by recessing the large panes of glass in an aluminum frame assembly. It wasn’t until the late nineteenth century had a technique been discovered
to separate aluminum from other earth metals efficiently. When aluminum became cheaper, engineers began exploiting it for its natural characteristics which were strength and lightness. Widespread uses for aluminum would not be fully discovered until after WWII, but Howe and Lescaze understood mill finish aluminum would give the curtain wall a sleek, utilitarian appeal. The second floor bank exterior features a rounded corner which appears to stretch the glass and polished granite from one side of the building to the other. The office floors of the building feature a façade of buff brick, and closely grouped, double-hung windows of four. These double hung windows were also set in aluminum frames. Not only did the PSFS building attempt to bring life back to a struggling economy, but the businesses involved in construction were very grateful for the work. “The aluminum double-hung windows for the high-rise PSFS Building in Philadelphia were manufactured in 1932 by the Campbell Metal Window Corporation of New York. A bank headquarters, the PSFS Building had more than 3000 separate aluminum window units and incorporated plate glass made by Pittsburgh Plate Glass” (Historic Windows, 2009).

Other architectural features of the PSFS building were long thin vertical spandrels adorning one side of the building to express its verticality, while the north side of the tower features end-to-end windows which complement the interior with natural light. North side windows are especially important on buildings because in this region, the north face of a building will get the least amount of sunshine, and therefore be the coldest in the winter months. On the other hand, the south side of the PSFS building has very few windows to avoid glare heat. Also, the south side of the PSFS building was designed to house the elevators and building system chases. Although America was going through an economic crisis at the time of the PSFS building’s construction, this benefited the project because finer materials had become considerably less expensive; the PSFS building was budgeted at $12,500,000 and was completed at a much lower cost of $7,420,943 (PSFS Historical Marker, 2011).

In addition to modern exterior building improvements, the PSFS interior also featured state-of-the-art amenities. The building attracted companies to its offices by offering radio outlets in every office. The magnitude and location of the building was what attracted companies, but the interior functionality is what made them stay. A large portion of the interior functionality stems from the design of the interior of the office spaces: “Offices project in a narrow wing for favorable light, with columns revealed on either side as vertical shafts. At the front, floors are cantilevered beyond the columns to allow continuous glass for maximum light and freedom of interior arrangement” (Mock, 1945). While the idea of maximum daylighting is very attractive, too much exposure to the sun can lead to uncomfortably hot spaces inside the building. To achieve maximum comfort, the PSFS building was the second building in America to feature centralized air-conditioning.

When the PSFS building was first built during depression era, it was subject to various criticisms. Critics and citizens of Philadelphia were not accustomed to such an austere design, especially at this magnitude. As time went on, and more modern buildings began to appear in America, the PSFS building became a national landmark of revolutionary design. The building has become such a landmark, that when the Loews Hotel Company bought the building in 1998, rather façade, all that was done was replacement of the windows and an addition for parking and meeting space. The PSFS building is incorporated building been seen before. One of equation was glass, degree to increase the building. Increased lower the cost of energy seasons, and thus attract lease the office space, revolutionized with the Glass allowed the world, and it allowed the A special article titled “Acres of Glass, Daylight Modern Philadelphia Structure” by H. E. Zoll was published in the April, 1932 edition of Patton’s Monthly. This article
highlighted some of the completely new ways glass impacted the city of Philadelphia with the PSFS building, and sets the tone for how glass was viewed prior to the PSFS building. The article was named “Acres of Glass” because it brings notice to the fact that 65% of the PSFS building is glass, and the total amount of polished glass totals over two acres. An interesting excerpt from the article shows how people viewed the PSFS building at its time, and how they speculated the future will look:

An eminent scientist envisions a city of the far distant future constructed entirely of Glass. A cubic city two miles wide, two miles long and two miles high, having eight hundred floors with walls, ceilings, floors and roof entirely of Glass, of a quartz type which permits the actinic rays of the sun to penetrate through the entire structure. (Zoll, 1932)

While we may not have quite achieved such a translucent society, our trends and advancements with glass open endless possibilities to match our imaginations.

From the 1930’s to present day 2014, designers and builders have progressed leaps and bounds into new techniques and new technologies. At first modernism meant rectilinear structures with sharp corners and pronounced beginning & ends. Now modernism is taking on a much more liquid form, where buildings bend and melt in their design; all of these architectural feats have come from the progressive minds experimenting with glass and metal.

**Figure 1.** In the neo classic 30th street station and the modern Cira Center behind, we see conservative Philadelphia moving to the “sky is the limit: modern approach to the use of glass. Several other structures in Philadelphia of the 21st century are also taking advantage of more effective uses of glass.

As an example of the changing use of glass, the Buerger Center is a very unique building not only in Philadelphia but in the world. Its curved class facade stands out among the surrounding buildings which are typically linear in their geometry. The 750,000 square foot building was designed by Pelli Clarke Pelli Architects. One of the main features of the building is in fact its curvilinear form. Not only is its facade curved but also its hallways and rooms. The structure also houses a 5-story underground parking garage that will hold 1,560 vehicles, which required the largest excavation in Philadelphia’s history.

According to Douglas Carney, CHOP’s senior vice president for real estate facilities, they wanted to design resemblance to a hospital. Being a wanted to create a design that was children. Hospitals are normally sterile straight geometry with no added thrills. poor in these hospitals. Discussed later daylighting in hospitals as it relates to among workers. Aside from the just the Buerger Center will have a roof top aid in rehabilitation. The Buerger system not only because it is a curved assemblies to be put in place.

No more than four of the glazing assemblies are the same throughout the building. This is because they have decided to add a frit to the glass in the shape of the patients’ hand prints. The designers took the actual handprints of the children and transposed them onto the glass along the top and bottom of
the window. This runs through the entire facade of the building. Each story of the building is also offset as seen in figure 6. This exposes the underside of the floor and maximizes the amount of natural light allowed into the building. The fritted glass also provides a reduction in the solar gain of the building helping achieve the silver LEED certification. It is interesting to see how far the construction industry has advanced to where buildings are specialized machines for their intended purpose. For the Buerger Center, the design has a direct link to the patients’ livelihood and their path of recovery.

5 Philadelphia Today

Philadelphia is seeing a boom in the amount of high-rise buildings being constructed. Many of these feature glass facades that are utilizing the latest technology and installation techniques available today. Now that the economy is recovering, developers are looking to create the next greatest construction spending in the U.S. as a whole (Huesman 1). This is seen by the list of new projects which include Lancaster Square, innovation and Technology Center, Science Center. One of the more interesting aspects of glazing is that although the systems perform relatively similar in regards to energy transfer, they take on completely different looks. The glazing system of a building affects all facets of the building’s mechanical systems, user functionality, and interior and exterior aesthetics.

6 Demands of Glaziers

Both glazing manufacturers and installers are under increasing demand to provide ever more cost efficient, thermally viable, aesthetically pleasing, and reliable systems. This demand is being fueled by society in part because of the shift to becoming more sustainable especially in the construction industry. Another factor of these demands is the economic restraint put on owners over the past several years. Owners are allocating more money towards business expenditures other than buildings, and this restrains construction companies from using quality materials. As the economy rebounds, we see a surge in construction as well as the budgets dedicated to the construction of the new buildings. The creativity of architects is shining as more and more renderings and plans are released of beautiful buildings.

6.1 Internal Aesthetics

The first demand to be addressed is the interior aesthetics of a glazing system. It is important to distinguish and separate the interior and exterior aesthetic of glass. For interior aesthetics there are different goals for the designer to achieve. One is to create a minimalistic barrier between the inside and the outside. Or as Matthew Ziff states, a “visual connection” between the two (Ziff 11). That connection allows the flood of natural light into the building which so many occupants will hold of high value. Buildings lit by bleak fluorescent lights pale in comparison to the color brought in by natural light.

For hospitals, daylighting is such a crucial aspect to a patient’s recovery. It positively impacts the patients both physically and psychologically. “In fact, it has been recognized for many years that light has a significant effect on our circadian rhythm (i.e. biological cycles that repeat 24 hours). Campbell et al. (1988) imply that light is the most important environmental input in controlling bodily function after food” (Aripin 3). For the children in the Burger Center, the glazing system provides a link for them to the outside world, and a healthy environment inside of the building to aid in their recovery.
Natural light not only benefits the patients but also a measurable effect on the 1940’s, daylighting buildings. The next few of electric lighting, are often associated with clauster conducive to a healthy systems became more widely used and research conducted by natural light has a place. “Occupants in buildings reported an Specific benefits in environments include absenteeism, savings, and preference of workers” (Edwards & Torcellini 9). Digging deeper into the idea of financial savings, we find an important marketability aspect of glazing systems. An effectively planned glazing system that maximizes daylighting will have a direct effect on productivity. Salaried workers are the most expensive part of any office building as shown in figure 3. A minimal increase in their productivity will induce huge cost savings. A research group at Carnegie Mellon “has identified 12 studies linking improved lighting design decisions with 0.7-23% gains in individual productivity” (Carnegie Mellon 11). If an employee can output 10% more work at a $100,000 cost of labor per year, the owner can save $10,000 a year per employee. Thus, it can be said the natural light has both an aesthetic and financial value.

Another consideration of interior aesthetics is what light to allow into the building. Natural light is comprised of different wave lengths categorized into ultraviolet, visible, and infrared light. For the purpose of this discussion we will only identify ultraviolet light. Ultraviolet light can cause damage to fabrics, leathers, and other materials. This can have a large impact on buildings with large glazing systems. Until the advent of low emissivity glass there was no way to block UV and allow visible light into the building. Low-e glass is a thin transparent film on glass that will reflect a lot of UV and infrared light limiting solar gain and protecting the furnishings inside. Low-e glass has really become a standard in high rise buildings.

6.2 External Aesthetics

External aesthetics of a glazing system surround a variety of demands on the glazing industry. Completely separate from the interior, the exterior skin of a building affects the community around the structure. For one, there are multiple styles an architect can choose from, being a clear transparent, fritted, or even opaque lites. Improvements in glass technologies allow architects to choose from a wide range of options without sacrificing thermal efficiency. In the past, ornamental features like gargoyles or other statues are what made a building special. Now there is a shift in focus to using the glass to separate a building from others. For example compare the Cira Center, which uses a highly reflective glass, to the Children’s Hospital of Pennsylvania which is fully transparent. The choice of what style of glass to use is up to the architect’s imagination as the possibilities are seemingly endless.

Figure 2. The Children’s Hospital of Philadelphia is on the left, and the Cira Center is on the right.

6.3 Energy Performance

The last major demand on the glazing industry is better energy performance. Society today has increased its attention to decrease the human impact on the environment. Buildings play a major part in our lives. Therefore buildings are key focus for improvement in sustainability. Nearly 40% of total U.S. energy consumption
in 2012 was consumed in residential and commercial buildings, or about 40 quadrillion British thermal units” (EIA). How efficient the glazing system is at resisting thermal transmission directly linked to how hard the HVAC equipment in the building will need to work. The HVAC equipment is the largest consumer of energy inside of a building thus any alteration to its use will decrease the buildings energy demand greatly. This raises another questions for the glazing industry to answer, is it worth it? There are large range of glazing options for clients to choose from, so much so that it may seem overwhelming. There is double and triple glazed, electrochromic, photovoltaic, low emissivity, and windows filled with different gases. There is no set answer as every project and client is different. However some options can be considered more cost effective than others.

In the past, windows have had little to no thermal resistance. This occurred because of two reasons, the glass itself has little u value, and the assembly of sashes was not air tight which allowed air infiltration. There have been numerous advances that address both issues. U-values are measured from the center of the glass pane. Philadelphia’s Carpenters Hall which would have had a u-value of on frame with no proper seal or energy to jump from the exterior interior of the building. Today’s structural glass that has no framing, to pass through. The window itself a low-e coating bringing the u-value glass glazing systems that will bring the is not necessarily cost efficient. can make it difficult to choose an rise buildings have large exposed massive amounts of solar gain. No high rises typically have an overall and will be using a cooling system

The glazing industry is currently which has shifted its focus to Being “green” is now a point that defines a building and also enhances its marketability. As seen in the chart above more and more clients are demanding green construction. In the last decade we have seen increased amount of government subsidies, regulations, and the importance of the Leadership in Energy and Environmental Design (LEED). LEED is a third party verification of a buildings that measures a few main categories of a buildings effect on the environment. These categories include sustainable site, water efficiency, energy and atmosphere, and materials and resources. LEED is an internationally recognized system that adds to the property value and the marketability of a building.

Glazing systems do have their drawbacks, being thermal inefficiency and cost. However, these negatives are being identified and tackled by the entire industry. We are continuing research to provide more efficient glazing systems at a lower cost. It is important to note that these aspects can be changed. What cannot be changed the benefits of an effective glazing system. Firstly, glazing systems are attractive as a modern and sleek building skin. Glazing also provides daylight which leads to a better user experience. As detailed before, daylighting has a notable effect on those individuals inside. The glazing industry is an integral part of building construction and will continue to be so.

7 Conclusion

The glazing industry will need to stay current with the demands of the clients. As we can see through the analysis of Carpenters Hall, PSFS Building, and the Buerger Center, these demands will change over time. In the future we will see more emphasis placed on sustainability and reducing the amount of solar gain allowed through the glass. There are promising new technologies that will undoubtedly become standard in the glazing industry. For instance, translucent solar panels incorporated into a buildings skin could drastically decrease the building’s demand for electricity from utility providers. Combine this technology with electrochromic glass, which is currently cost inefficient,
to reduce the amount of solar gain. This will allow the buildings to become even more self-sustaining. The world is changing rapidly to a point where buildings will need to be self-sustaining. Oil prices have quadrupled over the past 20 years meaning HVAC systems are becoming more expensive to operate (Rubin 2).

From the beginning usage of simplistic glazing technologies in Carpenters Hall to the extraordinary glazing of the Burger Center we can see the remarkable advancements made over the past centuries. Even the past few decades have been incredible years for the glazing industry as a whole. New glazing technology is hitting the market at a phenomenal rate and we will soon no longer consider windows thermally inefficient or a Palladian design feature.

References
Recent US Innovative Glass Projects

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Abstract

The following article describes recent and current projects in the US, where innovative glass applications enhance architectural transparent or translucent design. Technical details and structural engineering concepts are presented from a façade engineering point of view, combining technical requirements with aesthetic expression. LED - Laufs Engineering Design [1] believes in the unity of architecture, sustainability and structural engineering, focusing towards one single integrated enclosure design approach.

Keywords: cold-bent IGU glazing, jumbo-size glass, structural glass half-frame, integrated residential facade swimming pools, glass brick rain-screen façade

Cold- Bent IGU Glazing – OSU Vestibule 'Glass Wave'

1.1 Design Idea Example 1

For a new university chemistry & bio-molecular research building at Ohio State University a glazed free-form entrance vestibule was designed according to Figure 01. In order to avoid triangularisation with associated extra cost and reduction of transparency due to additional diagonal mullions, trapezoidal quads were used and cold-bent into their final shape. Due to thermal and comfort requirements insulated glazing units (IGU) were chosen as glazing type (8mm HS – 15mm argon gas – 5mm/1.5mm PVB/5mm lami HS with solar coating, approx. size 100"*48" = 2,540*1,219mm), where the air- and vapour-tightness of the stainless steel spacer (grade 304/1.4301) is achieved by means of primary butyl sealant around the edges, with structural silicone sealant (type DC 3362) holding both lites together as usual.

1.2 Glass Detailing

In order to avoid exterior pressure caps, a toggle system (M6x20 bolts with sleeve D10x20 and 10mm washer) was used to achieve wind suction supports around the edges, see Figure 02. Toggles are placed according to wind loading and also serve to tie the glazing panels into their final twisted shape, after pressing the IGU onto the interior mullions and transom profiles. The stainless steel mullions are T-profiles in section made up of flat profiles bolted together to achieve sharp corners without any welding distortion; therefore connecting bolts have to be
coordinated with toggle locations not to overlap. Toggles engage into stainless steel local C- profiles that are structurally silicone sealed into the IGU spacer zone.

Figure 1. Free-form glass wave vestibule for Ohio State University (OSU); design by Architect Pelli Clarke Pelli, specialty façade contractor Roschmann Steel & Glass, detail structural façade engineering LED

Figure 2. detail of cold-bent IGU glazing toggle support with dew point study

A Grasshopper model was run to determine maximum twist values for the larger and smaller glazing panels, see Figure 03. Taking three corners of a twisted panel to define a virtual flat surface, the maximum offset measured perpendicular to this plane through the fourth corner was 2.6” (66mm) or ratio diagonal D/45 for the larger panel row and 1.2” (30mm) or ratio diagonal D/59 for the smaller panel.
1.3 Structural Engineering

Glazing, metal elements & connections were verified according to ASTM E-1300 & AISC steel manual with relevant loading to ASCE-07 (wind roof corners = 37psf, wind wall edges = 24psf, snow + drift = 25 + 48 psf, seismic 4% of DL, impact P = 200 lbs, roof live loading = 20 psf). The secondary sealant DC 3362 was verified according to EOTA/Dow Corning Manual (allowable tension in normal direction 0.14 N/mm², allowable long-term shear 0.011 N/mm², including a global safety factor of 5). Currently there is no code reference to structurally verify twisted glazing in the US.

To verify sufficient toggle bending (short cantilever systems), plastic design was applied. A 3D structural model was built (software rfem), adding local cold-bent forces as an additional load case (Figure 3). Lateral torsional buckling of the slender T-profile mullion was verified checking eigenvalues of detailed finite element 3D shell models, with lowest eigenmodes > 3 safety.

Numerical twisting of the IGU panels was performed using finite element modelling in conjunction with settlement load cases and exterior pressing forces, the maximum representative force was found to be in the order of 430 lbs, which indicated that special tooling may be required to achieve a controlled twisting process during installation, which felt too high and led to the decision to perform in-house testing related to the twisting process.
1.4 Testing

A 1:1 test rig was built according to Figure 05. It was found that for the horizontally placed larger panel (initial twist 66mm) only a 20mm gap remained after its own IGU dead loading was active. The remaining gap was fully closed with a sandbag load of 165 lbs at the corner and it was decided that no further tools were necessary for a safe and suitable installation, since a conventional turn-key moment of 3 to 6 Nm was sufficient to tie the toggles one by one, starting from the side with the least distance to the frame, working towards the corner with maximum offset.

For three test panels the initial Argon % was measured through a small pipe in the IGU spacer area and then the test rigs were placed outside (Bavarian winter climate) for a duration of approximately six months and then measured again. Values changed over time from 91 to 86% Argon (large panel), 91 to 86% (small panel) and 77 to 76% (roof panel), however re-connecting the measurement device alone most likely caused the reduction of Argon % rather than a loss of primary sealant butyl vapour tightness – more research would be useful here. No cavity condensation was observed in any of the test panels.

![Image of testing rig with cold-bent IGU, toggled to main framing](image)

**Figure 5.** testing rig with cold-bent IGU, toggled to main framing

**Jumbo Size Glazing – Kimmel Art Center Philadelphia**
2.1 Design Idea Example 2

For the new experimental SEI Innovation entrance on the north side of Kimmel Art Center, a tall entrance with glazed side doors was set up as an all-glass structural half-frame, where a 23ft tall triple laminated glass was cantilevered upwards, structurally silicone sealed to the 5ft wide sloped roof glazing which rests on a recessed metal linear support on the existing building side without any further metal sub-structure, to attract attention while protecting the side entrance from weather at the same time (Figure 06). Special high-capacity suckers had to be used for installation due to high weight of one panel (max weight 2,790lbs = 1,266kg).

![Figure 6. new all-glass side entrance at Kimmel Art Center Philadelphia, design by Architect Kieran Timberlake, specialty façade contractor Roschmann Steel&Glass, detail structural facade engineering by LED](image)

2.2 Glass Detailing

A full base moment connection for the 4x10mm laminated tempered safety glazing (with 3x 1.54mm PVB interlayers) shipped from Europe is achieved by means of a stainless steel shoe that is filled with Hilti Hit HY70 over a height of 8" (200mm), transferring push-pull forces through local stiffeners through the shoe and TZ Kwik bolts (D = ½") safely into the existing concrete floor. Dead loading is resting on setting blocks type Gluske GL-UKS, that are able to handle compression due to large glazing self-weight. The outer top glass connection links the roof glazing with the front facade, using silicone setting blocks and site-applied structural silicone sealant (type DC 895, one-component, site-applied).
The top back connection is concealed under a continuous waterproofing flushing interface detail, where the glazing is structurally silicone sealed to a stainless steel RHS horizontal continuous beam that is bolted back to the main existing structure, able to take both vertical forces as well as lateral forces due to wind and seismic (Figure 07). To avoid sliding ice, a tiny aluminum L-profile (1.5x1.5") can be 3M-VHB taped near the front roof edge as an additional snow stop as needed.

![Figure 7. vertical section through bottom glass shoe, top all-glass corner and top back connection to main building](image)

### 2.3 Structural Engineering

The roof glazing is modeled as a horizontal single span plate hinged both ends. The front facade is modeled as a vertical single-span, rigid at the bottom and hinged at the outer top glass corner. It also acts as a column, with compressive support forces coming from the roof loading. Under full wind cladding loading and assuming partial shear interaction of PVB interlayers for short-term wind gusts, the front facade only deflects max $f = 0.79"$ (20mm) = $H/350$ with max $sp^+ = 2.90$ksi (20MPa).

Under full snow loading including drift (28 + 26 psf), the roof glazing (3x10mm FT) only deflects 0.37" (9mm) = $B/150$ with max $sp^+ = 2.47$ksi (17MPa). The max
linear base moment $M$ was converted to a pair of horizontal line loads ($p = 3580\text{ lb/ft} = 52.2\text{ kN/m}$) that do not exceed Hilti Hit compressive capacity. With stiffeners $t = 3/8'' (10\text{mm}) @ 8''\text{ o.c.}$ the metal shoe (grade A36) stays within stress limit and individual plates do not buckle out.

**Chelsea Residence Façade – Integrated Swimming Pools**

3.1 Design Idea Example 3

A new twelve-storey residential building is currently in construction in Chelsea/Manhattan next to the westside highline. For the first time in New York City, integrated partially exterior swimming pools are combined with the façade design for each double-height floor apartment. Pools start on the inside of the building next to the living rooms, running outward to the exterior to allow residents to swim up to their private façade line with stunning views over the Manhattan skyline.

The northern façade is composed of a double-height steel-glass custom-made unitized curtain wall system with vertical exterior shading fins that add further unique identity to the Residence, see Figure 08.
Figure 8. Soori Highline Residence with integrated swimming pools, design by Architect SCDA, façade contractor TBD, facade engineering by LED

3.2 Glass Detailing

Typical façade details are shown for the swimming pool balustrade junction in Figure 09. A translucent laminated glass balustrade is placed in front of the local pool overflow detail and back-lit at nite.
3.3 Structural Engineering

The exterior façade fins are utilized to help structural stiffness of the double-height mullions perpendicular to the building line, allowing the mullion depth to be only net 6” for a span of 22ft. Parallel wind onto the floating fins torques the mullions, which are therefore rigidly linked to the transoms to add required torsional rigidity to the overall façade structure.
Figure 10. structural facade model with rigid transoms including decorative metal fins, frontal wind suction (left) and sideward wind (right)

Glass Brick Rain-Screen – Tribeca Manhattan

4.1 Design Idea Example 4

In order to create a uniquely transparent/translucent six-storey single family luxury residence in the heart of lower Manhattan, glass blocks are being used in a non-standard rain-screen application with integrated windows, mimicking Tribecca’s historic brick wall pattern in a larger scale, see Figure 11. The interior window wall uses ornamented glass in areas where translucent walls vary with clear vision zones.
4.2 Glass Detailing

Figure 12 shows section details of the open-joint glass brick rain screen assembly with integrated operable window wall units on the inside. RHS hollow sections form the outer structural support, glass bricks with drilled, beveled holes allow to place tension rods that press the assembly together long-term, with pure aluminum pads in between the bricks.
4.3 Structural Engineering

Each glass brick bay segment will be pre-fabricated and then brought to site, where it will be bolted as inserts into the RHS- framing that mimics the large-scale brick pattern in elevation. The large-scale framing is bolted to the slab edges and concrete columns, it effectively spans from floor to floor as a Vierendeel system, even though there is no continuous vertical mullion element present, see Figure 13. This allows to minimize mullion depth on the interior, where a conventional window wall system can be used, which is tied back locally to the outer stiff framing. High dead loading of the outer glass brick elements require special attention to embeds and brackets that are anchored into the in-situ concrete structure. It therefore proofs to be beneficial to model both main structure and façade systems in one single master model.
Figure 13. structural model combining both façade structure and main building structure to study interaction as related to force flow and deflections

Summary and Outlook

The above-mentioned projects illustrate an unbowed joy for new glazing designs that continue to experiment with the material glass and its wide range of applications in new ways.
Further research may be necessary with regards to IGU edge spacer durability as related to cold-bending; also tensile stress capacity perpendicular to compressed annealed glass bricks in conjunction with suitable interlayers in between bricks might be a future research field of interest relevant for practical applications.

While detailed knowledge of glass engineering design & connections to achieve structural integrity is one essential aspect of façade engineering, the overall integration of energy efficiency, water-tightness, buildability, force flow through system components and design appearance as an integrated approach appears to be key to arrive at elegant designs with long-term high performance. In that context, an academic curriculum study separation of Structural Engineering and Architectural Studies appears to be superseded, where both fields have long re-emerged together in everyday professional façade design.

References

[1] LED - Laufs Engineering Design, www.laufsed.com, email W.Laufs@LaufsED.com, 46-01 5th Street, Long Island City, NY 11101, USA, phone +1 212 529 3905
Structural glass beams pre-stressed by externally bonded tendons

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Abstract
In addition to the previously reported experimental results on post-tensioned glass beams [1 - 2], the current paper discusses the results of exploratory bending experiments on 2 series of structural glass beams which are pre-stressed by externally bonded tendons. These tendons – stainless steel or CFRP – are pre-tensioned and subsequently adhesively bonded to the lower edge of the glass beams by means of a two-component epoxy adhesive (3M DP 490). After curing, the pre-stressed glass beams are tested in four-point bending and their results are compared with the experimental results of reference beams without any tendons. From the results it is observed that pre-stressed glass beams demonstrate enhanced fracture strength compared to the reference beams. In addition, the pre-stressed glass beams show significant post-fracture load-carrying capacity. From the study it is concluded that pre-stressing a glass beam with externally bonded tendons is a feasible concept. However, more in depth studies to validate the concept are needed.

Keywords: structural glass beams, pre-stressing, redundancy, experiment

1 Introduction
This paper focuses on exploratory experimental investigations into structural glass beams with externally bonded pre-stressing tendons. It forms an addition to the experiments discussed in [1 - 2] on glass beams which are post-tensioned by means of un-bonded tendons. The main goals of (mechanically) pre-stressing or post-tensioning structural glass beams are 1) to augment the fracture strength of the glass beam and 2) to enhance the post-fracture performance of structural glass beams.
The first goal of augmenting the fracture strength of the glass beam is reached by applying a favourable pre-stress in the glass beams by means of the tendon. In the current study this is envisioned by pre-tensioning a reinforcement tendon and subsequently adhesively bonding it to the lower edge of the glass beam. After full curing of the adhesive the tendon is released and inflicts a beneficial compressive pre-stress and a favourable upwards bending moment on the glass beam. The second goal of enhancing the post-fracture performance of structural glass beams is reached by the tensile capacity of the reinforcement tendons. Upon glass fracture, the tendons will bridge the crack(s) in the glass, thereby carrying the tensile forces. Together with a compressive force in the (unfractured) top part of the glass beam, an internal moment capacity is generated, which enables the fractured beam to still carry significant load. A highly redundant system is thus generated.

The concept of (mechanically) pre-stressing or post-tensioning glass beams has currently been investigated only to a limited extent and in only a limited number of (research) projects \[3 – 9\]. Despite their limited number, these projects clearly demonstrate that there is a potential for post-tensioned glass beams. However, additional and more in depth research is needed.

In the current exploratory study, two series of structural glass beam specimens with externally bonded pre-stressing tendons are experimentally investigated in the scope of an MSc-thesis project. The beams consist of a laminated glass web, with either stainless steel or carbon fibre reinforced polymer (CFRP) pre-tensioned tendons bonded at the bottom edge. After pre-stressing, the beams are tested in four-point bending. In addition, a reference series of identical beams but without tendons are tested.

2 Materials & Specimens

The cross-sections of the investigated beam series are presented in Figure 1. The beams are 1500 mm long, have a height of 125 mm and consist of three layers of annealed float glass (6-10-6 mm) which are laminated by means of 1.52 mm thick SentryGlas® interlayer sheets. All edges of the glass have been polished after the lamination process. Apart from the reference beams, the beams have been provided with either a stainless steel tendon with cross-section dimensions of 3*25 mm or an CFRP tendon with cross-section dimensions of 2*25 mm. These latter series are denoted as STS and CFRP, respectively. The tendons are pre-tensioned following the method described in section 3.1 and are subsequently bonded to the edge of the glass beams with a 2-component epoxy adhesive, 3M DP490, at a targeted adhesive thickness of 0.1 mm.
3 Method

3.1 Pre-tensioning method
To pre-tension the tendons, a custom-made rig was devised, see Figure 2. The tendons are placed in a steel U-section, anchored by a bolt at one side (see Figure 2a) and extended at the other side, (see Figure 2b). During the pre-tensioning of the tendons, the local strains in the tendons were measured at both ends by means of strain gauges, see Figure 2a and b, from which the force in the tendons was derived. Subsequently, the 2-component epoxy adhesive was applied on the tendons, and the glass beams were positioned, see Figure 3. The adhesive was left to cure for at least three days before releasing the tendons. The beams were tested in four-point bending within 7 to 10 days after pre-stressing. The applied tendon force while pre-tensioning is listed in Table 1. It should be noted, however, that these values are only indicative, as they do not take into account any loss in pre-tension after release of the tendons.

Figure 1. Cross-sections of the three beam series; (a) glass reference beams – REF; (b) glass beams with stainless steel tendons – STS; (c) glass beams with CFRP tendons – CFRP.
3.2 Four-point bending method
After pre-stressing, the beams were tested in four-point bending. For this, a custom-made support frame was mounted on a universal tension-compression machine (Zwick 500 kN). The support span amounted to 1.4 m and the load span amounted to 0.4 m. Lateral supports were provided at a centre span of 0.55 m. A fixed displacement rate of 1 mm/min was applied until glass fracture, after which the displacement rate was augmented to 2 mm/min and 5 mm/min, respectively, to reduce test duration. Overall, the duration of a single test amounted to 30-45 minutes. During the test the applied force and machine displacement was measured and recorded.
4 Results
The results of the four-point bending tests are presented in Table 1 and Figures 4 – 9.
Table 1 specifies 1) the applied tendon pre-load, 2) the load at which first glass fracture occurred, 3) the maximum load that occurred after glass fracture and 4) the post-fracture reserve which is expressing the maximum post-fracture load as a percentage of the initial fracture load.
Figures 4, 6 and 8 provide the load-displacement curves of the bending tests on the reference beams, the STS beams and the CFRP beams, respectively.
The reference beams typically show one crack upon glass fracture which opens up as loading is continued, see Figure 5. The STS and CFRP beams typically show repetitive and distributed cracking of the glass, see Figures 7 and 9. Final collapse of the STS and CFRP beams is either due to compressive glass failure at the top edge of the beam, progressive adhesive bond failure, or tendon failure.

Table 1. Results of the four-point bending experiments.

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Applied tendon pre-load* (kN)</th>
<th>Initial fracture load (kN)</th>
<th>Max. post-fracture load (kN)</th>
<th>Post-fracture reserve (%)</th>
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<td>REF #1</td>
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<td>2.6</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>REF #2</td>
<td>-</td>
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<td>2.6</td>
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<td>2.7</td>
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</table>

* indicative values, see section 3.1
**Figure 4.** Force-displacement plot of the reference beam tests.

**Figure 5.** Typical crack development in reference glass beams (REF beams).
Figure 6. Force-displacement plot of the glass beams with stainless steel pre-stressing tendon.

Figure 7. Typical crack development in glass beams with stainless steel pre-stressing tendon (STS beams).
Figure 8. Force-displacement plot of the glass beams with CFRP pre-stressing tendons.

Figure 9. Typical crack development in glass beams with CFRP pre-stressing tendon (CFRP beams).
5 Discussion

From the test results the following is observed. Firstly, it can be seen from Table 1 and Figures 4, 6 and 8, that the initial fracture strength of the pre-stressed glass beams is significantly higher than the initial fracture strength of the reference beams. For the STS beams this increased initial fracture strength amounts to 20.1 \( / 8.8 \text{ kN} \approx 230\% \), whereas it amounts to 16.5 \( / 8.8 \text{ kN} \approx 190\% \) for the CFRP beams. The increase in initial fracture strength can partly be attributed to an increase in moment of inertia of the pre-stressed beams due to the adhesively bonded tendon. Following the Rules of Steiner and assuming a fully rigid bond, the moment of inertia of the reference beams amounts to \( 3.6 \times 10^6 \text{ mm}^4 \) whereas it amounts to \( 4.4 \times 10^6 \text{ mm}^4 \) and \( 4.0 \times 10^6 \text{ mm}^4 \) for the STS and CFRP beams, which accounts for an increase to about 125\% and 110\% for the STS and CFRP beams, respectively. The access/remainder in strength increase is explained by the favourable pre-stress which is applied by the pre-stressing tendons. Due to these tendons a compressive pre-stress as well as an uplifting bending moment is applied, which counteract the tensile bending stress at the bottom edge of the beam due to the applied four-point bending load.

Secondly, it can be observed from Figures 4, 6 and 8 that the STS and CFRP beams develop a significant post-fracture strength reserve. Whereas the reference beams demonstrate a post-fracture reserve of only about 30\% of their initial fracture strength, the STS and CFRP beams reach about 180\% and 220\% of their initial fracture strength, respectively. In the reference beams the post-fracture load-carrying mechanism is generated by crack-bridging SentryGlas® interlayer sheets, which transfer tensile force over the crack. Under continued loading, the SentryGlas® interlayer sheets are stretching and the post-fracture load-carrying capacity gradually decreases, see Figure 4. For the STS and CFRP beams, the post-fracture load-carrying mechanism is mainly provided by the tendons. Due to their relatively high strength and stiffness they are able to carry significant tensile forces over the cracks in the glass. In addition, the adhesive bond between the tendons and the glass is sufficiently strong to transfer these tensile forces. This enables the beams to develop a significant post-fracture reserve. From Figures 4, 6 and 8 it can also be seen that the STS beams develop a more ductile post-fracture response than the CFRP beams. This difference is directly related to the material response of the tendons. Whereas the tendons in the STS beams demonstrate yielding, this mechanism is absent in the CFRP tendons. Finally, it should be noted that the results are merely exploratory. More in depth studies into pre-stressing glass beams by externally bonded pre-stressing tendons is needed. Especially the adhesive response due to thermal expansion differences between the glass and the tendon, and due to long-term loading by the tendon needs to be investigated in detail. For accommodating the thermal expansion differences while sustaining the high forces from the tendon, a strong yet flexible adhesive is needed. And to sustain the long term pre-load in the tendon, it might well be that an additional mechanical anchor is needed. These and many more aspects of (mechanically) post-tensioned and pre-stressed glass beams are currently investigated in an ongoing PhD study at the ICOM-EPFL and results will be presented over the next years.
6 Conclusions
From the experimental investigations it is concluded that pre-stressing structural glass beams, by means of externally bonded pre-tensioned STS or CFRP tendons at the lower glass beam edge, is a feasible concept. Pre-stressing the glass beams results in a compressive stress and an upwards bending moment in the glass beam. This results in an increased fracture strength compared to regular glass beams. Furthermore, due to the presence of the tendons, a significant post-fracture load-carrying capacity is generated. As such, the pre-stressing tendons enhance both the pre-fracture and post-fracture response of the glass beams. However, it should be noted that the current investigations are merely exploratory and do not take into account potential loss of pre-stress due to creep response of the adhesive, nor any stress actions in the adhesive due to differences in thermal expansion between the glass and the tendon. Additional research is thus needed and is foreseen in an ongoing PhD project at ICOM-EPFL focusing on post-tensioned glass beams.

References
Structural glass columns in significant seismic zones

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Abstract

As a building material, glass has evolved from simple infill and envelope elements designed to pick up and transfer wind loads to beams and fins designed to transfer loads supporting members, and, finally, to full self-supporting and self-stabilising glass structures such as stairs, bridges, and sculptures.

The focus of this paper is on the next step in this progression, the use of structural glass as a fully integrated structural element: not only self-supporting and stabilising but also acting as a support for the non-glass structures, bringing glass alongside steel, concrete, timber, and masonry as a viable building material. To this end, the newly opened flagship Apple Store in Stanford, CA, is presented as a case study in the use of glass columns to support a steel roof in a significant seismic zone in California.

Specifically, the paper looks at three parts of the challenge in developing glass columns: the design of glass columns themselves and their capacity to resist the design loads, including brief discussion on redundancy; the accommodation of movements imposed on the glass columns by the main structure as it moves under seismic excitation; and the design of the connections which enables the structural system to work.

Keywords: structural glass, buckling, finite element, seismic movement, redundancy

1 Introduction

The Apple Store, Stanford, is a steel framed building, a “special braced frame”, split into three architectural zones: Zone 1 is the front retail space and storefront with a stainless steel-clad steel-framed roof above a 3-sided façade; Zone 2, separated from Zone 1 by a stone-clad spine wall, is the middle retail space surrounded by four stone-clad walls below a 30ft span stainless steel and glass skylight; Zone 3 is the back-of-house which contains the braced bays and floor diaphragms that give the building lateral stability. This case study focuses on Zone 1, the front retail space, on how the roof is held up by glass columns, and how the whole system is designed to move in an earthquake.

The roof and façade form a lean-to: essentially two sticks connected at 90° with the bottom supported on the ground and the top restrained against the rest of the
structure (Figure 9). The roof spans 32.5ft (10m) with a 7.5ft (2.3m) overhanging canopy built up from braced cellular beams at 7.5ft (2.3m) centres. The glass columns are positioned at the façade line standing at 17.5ft (5.3m) tall, aligned with the façade joints at 7.5ft (2.3m) centres. The connection between the glass and steel is designed to act as a “pin” with no bending forces transferred between the two, only vertical and lateral loads. In this way the roof is supported by the columns and the columns braced laterally by the roof.

Figure 1.  Apple Store, Stanford CA, twilight.

Figure 2.  FE model of the entire structure. Non-linear, transient dynamic, natural frequency, spectral response analysis.
Figure 3. The clear support wall around Zone 1.

Figure 4. The dividing wall between Zone 1 (left) and Zone 2 (right).
Figure 5. Zoning of the Apple Store, Stanford. Zones 1: retail, steel roof, glass façade; Zone 2: stone clad wall, curved glass skylight; Zone 3: back of house containing the lateral force stability system for the building.

Figure 6. Front elevation, Zone 1

Figure 7. Side elevation, Zone 1, Zone 2, Zone 3.

Figure 8. Building section, Zone 1, Zone 2, Zone 3.
Figure 9. Closer section of Zone 1. “Pin” connections at the top and bottom of the glass column and rear connection at the partition wall.

2 Design approach

The first challenge is the approach to the design. US Codes and Standards, at time of writing, do not have provisions for the use of glass in the structural seismic force-resisting system. These provisions are itemised for variations in braced steel frame, concrete shear walls, and similar traditional stability methods and material combinations. Seismic design provisions for glass are reserved solely for cladding or “non-structural components”. While technically it is possible to design glass to act as part of the main stability system, and in this case would have been structurally preferable, bracing the roof through glass shear walls to transfer loads into the ground is not permitted by code. Testing of the material and proposed system is possible however restrictive for cost and schedule reasons – such bespoke testing and certifying is typically reserved for the design of bolts and anchors, not one-off structural systems.

The stability system employed in this case is to brace the roof against the main structure at roof level and have it act as a laterally cantilevering diaphragm, simply floating over the glass columns with no resistance or load transfer into the façade line.

Accommodation of this lateral roof movements can be facilitated in two ways. The first approach allows the roof the slide over the façade with the two moving independently. This is feasible and has been employed on a similar project, though it creates problems at the corners and short edges where the roof pushes the façade out of plane, opening and closing the joints. The second approach is preferred in this case: the façade moves with the roof as the roof moves laterally...
relative to the ground. Because the façade tilts and rocks with the moving roof, this minimises the size of joints between panels and simplifies detailing compared with the sliding connections.

In terms of detailing, pinned/rocking connections are simpler and more reliable than sliding. It is difficult to ensure that sliding mechanisms do not bind and lock geometries thereby generating new and unintended forces.

The approach of pivoting and rocking comes with its own complications, however: the tilting and rocking of the glass columns in and out of the façade planes, while they carry non-trivial axial loads, generates secondary P-Δ effects (change of load effect under global deformations), in addition to the typical P-δ effects (change of load effect under local imperfections).

![Figure 10. Lateral movement of the roof along the plane of the main façade, maximum movement occurs at the glass line causing the façade panels to rack about their support point.](image)

### 3 Buckling of columns

Slender elements loaded in compression are checked for buckling capacity, where the element fails elastically due to geometric instability at lower loads than the material itself is capable of withstanding. This is the typical first order P-δ effect, the "little delta" δ signifying imbalanced loads due to imperfections in the installation.

Basic theoretical buckling capacity is determined by the Euler Buckling equation, which is a function of the material’s stiffness, element cross-section, length, and end-restraint conditions. In this case, the 17.5ft (5.3m) tall columns are pin/pin ended, built up from 5 plies of glass laminated together with Sentryglas. This simple first-pass check gives a theoretical upper limit capacity of approx. 32kip (140kN) (Figure 11).
\[ E := 10 \cdot 10^3 \text{ ksi} \]
\[ t_{\text{column}} := 2.25 \cdot \text{in} \]
\[ d_{\text{column}} := 15 \cdot \text{in} \]
\[ I_{\text{weak.axis}} := \frac{d_{\text{column}} \cdot t_{\text{column}}^3}{12} = 14.238 \times 10^4 \text{ in}^4 \]
\[ K := 1.0 \]
\[ L := 17.5 \cdot \text{ft} \]
\[ F := \frac{\pi^2 \cdot E \cdot I_{\text{weak.axis}}}{(K \cdot L)^2} \]
\[ F = 31.865 \times 10^0 \text{kip} \]

\[ E = 68.948 \times 10^3 \text{ MPa} \]
\[ t_{\text{column}} = 57.15 \times 10^0 \text{mm} \]
\[ d_{\text{column}} = 381 \times 10^0 \text{mm} \]
\[ I_{\text{weak.axis}} = 5.926 \times 10^6 \text{ mm}^4 \]
\[ K := 1.0 \]
\[ L = 5.334 \times 10^3 \text{ mm} \]
\[ F := \frac{\pi^2 \cdot E \cdot I_{\text{weak.axis}}}{(K \cdot L)^2} \]
\[ F = 141.744 \times 10^0 \text{kN} \]

**Figure 11.** The theoretical buckling capacity of an unrestrained column (31.9kip (141.7kN) Euler Buckling calculation);
The pin/pin system is enabled though the detailing at the top and bottom of the fin (Figure 13, Figure 14, Figure 15). The top transfers vertical forces from the roof into the column though bearing in a bolt hole in the glass. A high strength stainless steel pin with internal bushing and resin detailing allows for free rotation of the pin within the hole to move freely in plan directions. This is particularly important during the expansion and contraction of the steel structure as it heats and cools and “breathes” with temperature variations.

The base is similarly detailed as a shear key within the shoe that acts as a pivot point and shear connector into anchors below.

To increase the capacity of the column, intermediate restraint is provided through point connections to the façade panels, particularly for the post-failure case where capacity is reduced by the failure of a single ply in the 5-ply laminate, or indeed complete structural failure of an adjacent fin. These connections to the façade brace the columns laterally and reduce the effective length of the column, thereby increasing the buckling capacity (Figure 12).

More accurate finite element (FE) analysis is carried out to capture the restraint locations, which are offset from the column centreline and plotted to determine the remaining capacity in the columns. Several studies are carried out to further capture load increases and/or reduction in section capacity under post-failure cases (Figure 17).

For real-world elements geometric imperfections, off-centre loads, torsional buckling modes, and safety factors are also taken into account as part of the P-δ effects. These considerations further reduce the design capacity of the columns below the ideal.
Figure 13. Top of column, plan detail;

Figure 14. Top of column, elevation;

Figure 15. Bottom of column, elevation;
Figure 16. Non-linear deflection of the buckling edge, two point restraint on the column edge

Figure 17. Buckling curves of various loading conditions. Blue: service condition; Red: failure of adjacent column at the door; Green: failure of one of 5 glass plies in the column. The effect of reducing the capacity of the column (green) is worse than redistributing load from adjacent fully failed columns. As the load factor is increased (x-axis), lateral shift of the midpoint increases in a non-linear way (y-axis), i.e. a lateral shift is generated which increases faster than the load applied. In the case of
glass, this causes run-away stress increase and material failure below theoretical capacity.

4 Racking of columns and façade panels

As the roof moves laterally under seismic excitation, the axis of the column shifts from vertical. This induces lateral loads at the base from the tilt of the column. This is the P-Δ effect, a result of the changing global geometry of the load path under the selected seismic isolation system, the “big delta” Δ signifying a global effect. By maintaining a pin/pin connection at the top and bottom of the column, no additional moments, which would destabilise and buckle the glass, are generated.

Geometrical analysis, considering even an extreme case of a 4in shift, can be shown to only generate an additional 2% lateral force at the base acting along the long axis of the column (Figure 18). Other than generating additional (nominal) reaction loads, tipping of the columns, provided the load itself (roof) is restrained, has no effect on the capacity of the column.

In a similar way the façade panels must also pivot about a central pin at the base to provide no resistance to roof movements (Figure 19). The pivoting of adjacent elements, which have different pivot points, creates differential movements that are accommodated in the detailing of the interfaces between elements and within the connections themselves.

\[
\begin{align*}
\delta &:= 4 \cdot \text{in} \\
h &:= 17.5 \cdot \text{ft} \\
\theta &:= \tan^{-1} \left( \frac{\delta}{h} \right) = 1.091 \text{deg} \\
P &:= 1 \cdot \text{kip} \\
\text{AxForce} &:= \frac{P}{\cos(\theta)} = 1 \text{kip} \\
R &:= \text{AxForce} \cdot \sin(\theta) = 0.019 \text{kip} \\
\frac{R}{P} &:= 1.905 \% 
\end{align*}
\]

**Figure 18.** Vertical loads on a non-vertical element resolve into vertical and lateral loads at the base. Under an axial load \( P \), considering a notional
lateral movement of 4in (100mm) over a 17.5ft (5.3m) height, a lateral load 1.9% of the vertical load is generated at the base. The axial buckling capacity of the pin/pin element is unchanged by the varying geometry until a bending moment is generated.

The base of the façade panels is detailed in the same way as the base of the columns, by cutting a notch and introducing a “shear key”, essentially a block of steel surrounded by an epoxy, which acts as the support and pivot point and which also prevents sliding under load.

Both situations are modelled and verified by FEA for the bearing surfaces, glass thicknesses, magnitude of movement, and axial load applied (Figure 20, Figure 21). The stainless steel shear keys are profiled with sufficient curvature to prevent knife-edge bearing on the glass edge. Knife-edge or point bearing between steel and glass can generate high stress concentrations; these can magnify relatively low forces into high stresses causing premature failure of the glass.

The resin between the glass and steel provides an intermediary material to prevent glass/steel contact and to take up fabrication tolerances between the layers of glass in the lamination and site installation imperfections.

Figure 19. Pivoting at the base of the fins parallel (left) and perpendicular (right) to the facade
Figure 20. Finite element modelling of the column base. Pivoting about the support point generates stresses as edges meet edges from the changing geometry.

Figure 21. Racking of a doorway bay as the roof moves and pushes the façade at the top – no lateral load is transferred from the roof into the ground through the glass.

5 FITTING

The joints between the panels slide, open, and close as the elements move relative to each other. Detailed drawing of geometry movement analysis optimises the geometry of the connection to ensure no clash occurs between elements on joint closing, no dislodging of connections on opening, or restrained movement on sliding (Figure 23, Figure 24).

There are two fittings per column at quarter points along the height. Their primary function is to capture the façade panels and to transfer the load collected by them
into the ground and roof. Milled titanium blocks are laminated into a notch in the middle ply of the façade and column build-up. Once the glass is in place, toggles are passed through the joint, rotated, and slotted into a channel within the façade inserts. They are then arranged vertically and screwed into the insert within the column to provide a mechanical connection between the three elements.

Their secondary function is to provide bracing for the columns to increase their buckling capacity by providing intermediate restraint. For this bracing to be effective, the fittings need to transfer tension loads so that restraint is provided with only one façade panel in position (typically there are two, one either side of the column, however one of several post-failure scenario assumes only one is effective). In this way multiple redundancies are developed to maintain stability of the glass columns: breakage of a column ply reduces the effective section which is compensated for by the positive restraint to the façade; similarly a complete failure of a façade panel still maintains bracing stability from the remaining panel.

Critically, the fittings must accommodate the racking of the façade in plan directions without resisting movement. The geometry in the inside of the fitting allows for the independent vertical movement of all three connected elements (two façade panels and a column) through sliding of the toggle elements within the fittings. Similarly the column and façade panels are able to vertically slide over each other to prevent tying of the two elements together – such tying would generate push/pull forces in both the base and top, thereby magnifying forces through geometric locking of the elements.

As with earlier examples of this type of insert fitting, originally developed for the Apple Store stairs, the insert is formed from a milled piece of titanium. The block is sandwiched between two sheets of glass in line with the middle sheet before being laminated under pressure and temperature. The result is a piece of metal which can be drilled, threaded, and bolted, embedded within the glass and bonded in place by the interlayer. Titanium is used as it has a thermal expansion coefficient similar to glass which allows the two materials to expand and contract in tandem during the lamination process. A similar piece of steel would expand more than the glass, risking glass breakage.

![Figure 22. Façade/fin connection renders](image)
Figure 23. Clockwise: Toggles are inserted, rotated and slotted into position; plan view of connected elements; racking of the façade relative to adjacent panels and fin behind generates differential movements between the two halves of the connection.
Figure 24. Façade/fin connection Finite element analysis.

Figure 25. In situ connections
6 CONCLUSION

Supporting a steel roof on glass columns is an ambitious undertaking which brings the use of glass up to the ranks of established building materials, particularly when considered in the heavy seismic zones of California. Code limitations are particular barriers for making best use of the structural capacity and opportunity of glass. In fact, we see particular techniques and approaches to design are needed to work around these limitations. In this case, rather than using the façade glass as an integrated shear wall and vertical support, we have had to decouple the lateral behaviour of the potentially stiff glass wall from the vertical support capacity of the glass columns, while accommodating the resulting significant lateral movement of the structure. The result is uncompromised in its design intent. It provides both transparency and mystery to the structure which, when looked at in detail, uncovers various key deliberate design decisions that were required to make the structure work both architecturally and structurally.

Figure 26. Apple Store, Stanford CA, night.
Coating for ribbon and plate: Multi-dimensional inspection ensures highest quality for all types of glass coatings

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Key words:
Coating, inspection, control, defects, detection, quality, production, efficiency

Abstract:
The use of coated glass has risen significantly in many applications during the last decades. This is why perfect coating and highest glass quality are a must to maintain the competitive edge. Here the newly developed, fully automated optical inspection system for COATING by ISRA gives a solution. It provides operators with an easy, efficient and economic set-up for excellent defect detection and exact classification of coating and other irregularities in the surface over the entire glass. The increase in processing efficiency and quality is achieved by applying the completely new, patented multi-dimension, multi-mode and multi-view technology. A 100% in-line inspection can be guaranteed for coating, color, surface, edge and shape - all at the same time, even in mixed batches. All typical coating defects, also smallest color variations for all coating types are detected as well as inclusions of all types and other surface defects. In addition the coating is checked for inhomogeneity and color flow. The system classifies and categorizes all defects and makes a distinction of removable contaminations in the products possible. This helps to react and adjust quickly during the manufacturing process. The overall result: highest quality and maximum productivity with minimized production costs.

Introduction:
The glass industry has been constantly innovating during the last decades to increase the functionality of glass plates, creating new markets and new added value. Coating technology has been one of the main innovation domain that have allowed to developed many new applications for different specialties (electronic, solar,…). But for sure the main domain where coated glass encountered a decisive success has been its development for building applications. Building coating represents today the biggest market for coated glass and offers new opportunities in western and emerging countries. Different type of building coatings have been developed from simple single layers to more complex multiple layers (double, triple silvers…). The development of those technologies (pyrolitic or sputtering) has been challenging for chemical engineers, and heavy investments in machinery and resources remain necessary for each new line. The production of coated glass follows a complex process and defect free coated glass remains today challenging. For that reason coating inspection systems has been rapidly recognized by many glass producers as part of the strategic investments to reduce their amount of claims and preserve their production yield. For more than 10 years the inspection technology has been pushed forward to replace manual inspection, improving the capability of defect recognition and process analysis, helping producers in their quality control and decision process.
Multi-dimensional inspection technology:
The first generation of inspection systems were separated in two classes, simple limited detection systems, and complex, onerous systems using different, separated detection channels. With the strong development of new coating applications, glass producers started to request higher inspection flexibility integrating detection capability for a higher variety of coatings produced on the same lines (Low-E, solar protection, anti-reflective....). In the meantime, the quality acceptance criteria started to evolve taking into account new defect types like color defects or defects on large areas having a low contrast variation with the rest of the plates. This increase of new inspection functionalities was facing another request to improve the cost of ownership of those inspection systems. The multi-dimensional inspection has been the answer that the market was looking for a solution to those tasks.

Different images of same defects are analyzed making recognition a much easier and reliable task. Unmatched detection and recognition rate on all types of coatings defects (fig. 2) are now possible and in a single and flexible system. Moreover core defects or bottom defects (fig. 3) are easily seen even on high reflective coated glass and without missing potential surface coating defects. High reflective coatings are not making systems blind anymore.

![Typical detected coating defects](image1)

Fig. 2: typical detected coating defects (Pinhole, Debris, arcing)

![Typical detected core and bottom defects](image2)

Fig. 3: typical detected core and bottom defects (Bubble, inclusion, conveyor scratch)

The new system generation integrates as well detection functions for large area defects. A second level a data analysis is available. The L.A.I. (Large area inspection) technology permits the detection of defects that are usually not recognized with other systems. Homogeneity, color variation or color angle shift can now be controlled without influence of smaller defects. The visualization of those defects has been as well optimized with MONITOR-MASTER which shows the detection results in real time with simple overview or colored maps.
Despite the increase of treated data, the analysis of the defect types has been simplified with QUICKTEACH new automatic classification software. All defects can be easily and precisely classified using stored defect pictures. The system analyses and determines automatically new class boundaries. The system gather experience from the line with an easy handling for a continuously classification improvement.

**Conclusions:**
The quantity and quality of the vision data is key for glass producers to take the right decisions and to increase their production efficiency, but nonetheless the simplification of the system setup is decisive to assure a successful investment with long term reliability. The multi-dimensional inspection is a new step forward in the world of inspection that gives a solution to both requirements and which prepare the future. We usually hear that about 50% of the products that will be introduced in the next 10 years don’t exist today. The multi-dimensional inspection offers today the flexibility that will be necessary for tomorrow.

**Summary:**
The multi-dimensional inspection has been developed as an answer to the new inspection requirements for coated glass inspection. The multi-dimensional inspection increases the quantity of quality data to be analyzed with a limited amount of electronic components. All coating or glass defects can now be easily recognized using different view channels working simultaneously with same cameras and/or illumination modules. The classification as well has been simplified using the unique automatic classification tool QUICKTEACH.

As a result, inspection capability, system flexibility, and cost of ownership have been strongly improved and give the right tool that the glass industry was looking for.

ISRA innovation has been driven by more than 30 years of experience in glass inspection and by an orientated product development management.
Glass Breakage - Glass Railing System Failures

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Abstract
Glass technology has evolved in the last several decades offering a variety of options. In the last few years many cases of “spontaneous” breakage or catastrophic failures of glass in buildings have been reported throughout the globe causing damages, injuries and even casualties.

Dependent upon the specific use or design intent, glass may also need to comply with additional requirements, especially if used in a railing or guard system.

Our discussion will cite conditions from a few example buildings which have experienced breakage and system failures. Further, the discussion will address the applicable code requirements, design, material selection, engineering, installation and testing. In an effort to identify causes and establish preventative measures, each of these topics will be explored.

Glass in buildings is addressed in current Building Codes, but when it comes to the use of glass in railing systems, the current code leaves some criteria up to individual interpretation. The prevailing question is do current standards and practices applicable to glass in railing systems “adequately” protect the public health, safety and welfare?

It is not only Code Officials’ responsibility to address the use of glass, but it is also ours as design professionals striving for a better-built environment.

1 Introduction
Railing systems are commonly found in building interiors or exterior applications. In the United States, there are several manufacturers that offer multiple solutions for every budget and application. From stock to custom systems, railing systems can be used to meet different design intents that can accentuate aesthetical building features, provide modern appearance, provide unobstructed views, etc.

But aside from all these functions, the majority of the installed railing systems are required to act as a barrier to prevent people from falling to lower building levels. Therefore, the main function of these systems, at least the ones covered in this paper, deal with public safety rather than aesthetical.

There are different types of stock railing systems that utilize different materials such as steel, aluminium, wood, glass or a combination of materials. The most popular systems nowadays utilize glass and metals in different proportions. Aluminium, for example, provides the light weight advantage in combination with
being easily formed/extruded. Glass provides views while maintaining adequate strength when properly designed.

But in order to be catalogued as safe, the railing systems need to comply with different requirements set forth in different standards and codes. It is the responsibility of specifiers and design professionals in general, to understand and address all items that guarantee a safe application.

2 Types of Railing Systems

Amongst the most popular types of railing systems in commercial and high-rise residential construction we find the following types:

- All metal systems, refer to Figure 1.
- Cables railing systems, refer to Figure 2.
- Aluminium-glass systems
- Systems with glass infill panels
- All glass systems

Figure 1.  All Metal Railing Systems

Figure 2.  Cable railing system
2.1 Glass railing systems
The scope of this paper is limited to railing systems that incorporate glass as one of the system’s components. In this paper, these type of systems are referred to as “glass railing systems”, from this point on. This paper is limited to the last three types, from the previous section, of glass railing systems:

- Aluminium-glass systems, refer to Figure 3.
- Systems with glass infill panels, refer to Figure 4.
- All glass systems, refer to Figure 5.

Figure 3. Glass railing system – Aluminium-glass systems

Figure 4. Glass railing system – Glass infill-panels
2.2 Glass Railing Systems Components
Glass railing systems are found at building interiors or exterior applications throughout the world. The majority of these systems incorporate the following components:

- Vertical posts
- Horizontal framing members
- Handrails
- Top rails (guardrails)
- Glass
- Miscellaneous hardware

Depending on the project, system design, building envelope design and some other factors, different glass railing systems can be selected or specified. But let’s keep in mind that these systems are not only a partition or divider at slab openings and balconies. These systems are required to act as barriers to prevent people from falling and in order to do so, there are certain strength and design criterion that must be met. Otherwise, these systems would not be performing nor providing public safety.
3 General Code Requirements

The International Code Council (ICC) develops model codes and standards used in the design, build and compliance process to construct safe, sustainable, affordable and resilient structures. Most United States communities and many global markets choose the International Codes [1]. The International Building Code (IBC), defines and specifies minimum requirements for glass railing systems. Published every three years since 2000, the IBC aims to address safety and good practices in these types of systems. But how are glass railing systems defined by code? And at which locations are these necessary?

3.1 Definitions

Guard: A building component or a system of building components located at or near the open sides of elevated walking surfaces that minimizes the possibility of a fall from the walking surface to a lower level [2].

Handrail: A horizontal or sloping rail intended for grasping by the hand for guidance or support [2]

3.2 Location

As defined by section 1012.1, handrails are required at stairs and ramps. Guards on the other hand and as defined by section 1013.1, shall be located along open-sided walking surfaces, including mezzanines, equipment platforms, stairs, ramps, and landings that are located more than 30 inches measured vertically to the floor or grade below at any point within 36 inches horizontally to the edge of the open side.

3.3 Minimum height

Handrail height per section 1012.2, measured above stair thread or nosing, or finish surface of ramp slope, shall be uniform, not less than 34 inches and not more than 38 inches. While per section 1013.2, guards shall be not less than 42 inches high, measured vertically above the adjacent walking surfaces.

3.4 Strength requirements

Handrails and guards shall be adequate in strength and attachment as follows [3 Section 1607.7], note that these loads are not to be applied concurrently:

- Handrails and guards shall be designed to resist a load of 50 pounds per linear foot applied in any direction at the top and to transfer this load through the supports to the structure. Refer to Figure 6 below.
Handrails and guards shall be able to resist a single concentrated load of 200 pounds, applied in any direction at any point along the top, and to transfer this load through the supports to the structure. Refer to Figure 7 below.

Intermediate rails (all those except the handrail), balusters and panel fillers shall be designed to withstand a horizontally applied normal load of 50 pounds on an area equal to 1 square foot, including openings and space between rails. Refer to Figure 8 below.
3.5 Additional requirements
Where glass is used to provide guard or as a portion of the guard system, the guard shall also comply with Section 2407 [2 Section 1013.1.1].

4 Code Requirements for Glass Railing Systems

Glass in handrails and guards. In addition to all requirements and definitions listed on the previous chapter, and where glass is used as a guard or as a portion of the guard system, there are additional criteria that need to also be fulfilled.

4.1 Materials
The building code specifies that when glass is used as a handrail assembly or a guard section, the glass required is either single fully tempered or laminated glass. There are two laminated glass options allowed: fully tempered or heat strengthened glass.

4.2 Strength requirements
The glass panels and their support system are required to resist the loads described on code Section 1607.7 (refer to Section 3.4 on this paper for design loads).

In addition to this and due to the nature of the material and this type of systems, the code requires a safety factor of four when glass is used.

In addition, Code Section 2404.1 indicates that vertical glass in any exterior application needs to be designed to resist the wind loads.

4.3 Support
Code Section 2403.2 states that when one or more sides of any pane of glass are not firmly supported, or are subjected to unusual load conditions, detailed construction documents, detailed shop drawings, analysis or test data assuring safe performance shall be prepared by registered design professional.

Code Section 2407.1.2 specifies that each handrail or guard section shall be supported by a minimum of three glass balusters or shall be otherwise supported to remain in place should one baluster panel fail.

4.3.1 Support exception
It is important to mention that the 2009 edition of the International Building Code states that, a top rail is not required where the glass balusters are laminated glass with two or more glass plies of equal thickness and type [3]. All previous code editions do not allow for this exception.

4.4 Deflection
As part of the general glass requirements and in order for the glass to be considered firmly supported, Code Section 2403.3 indicates that the framing members for each individual pane of glass shall be designed so the deflection of the edge of the glass perpendicular to the glass pane shall not exceed 1/175 of the glass edge length or 3/4 inch, whichever is less.
5 Considerations When Using Glass

When using glass there is always the possibility of having a microscopic glass contaminant particle that could produce spontaneous glass breakage. This contaminant is called Nickel-Sulfide (NiS) and can affect fully tempered glass. During the manufacturing process, annealed glass is heated during the tempering process which “activates” the NiS particle. When the glass is rapidly cooled in order to achieve the properties of fully tempered glass, the NiS particle remains active. This particle can return to its original state at any given time and when it happens it increases in volume which can lead to spontaneous glass breakage. Glass breakage caused by NiS inclusions can be easily identified by a fracture pattern that is often refer to as “butterfly” or “double D” pattern. Refer to Figure 9 for this pattern.

![NiS breakage pattern](image)

**Figure 9.** NiS breakage pattern

It is estimated that there could be one NiS inclusion per every:

- 220 glass panels of 1/8 inch thick glass,
- 145 glass panels of 1/4 inch thick glass,
- 90 glass panels of 3/8 inch thick glass,
- 60 glass panels of 5/8 inch thick glass,
- 45 glass panels of 3/4 inch thick glass.

It is also important to remember that glass is a brittle material and that the edges are sensitive to impact, especially in tempered glass. Therefore and as a good practice, is recommended to protect all glass edges that could potentially be prone to impact.
6 Lessons Learned

Different glass railing systems across the United States have been observed and studied. Some appear to have address all code requirements, some others clearly expose the lack of knowledge for glass railing systems requirements. But unfortunately, there are more cases that clearly do not meet building code requirements than those that do.

Some glass rail systems have been studied and tested in detail, and findings show that issues are originated due to poor workmanship, material selection, poor engineering, and lack of knowledge. Unfortunately, lack of knowledge has been the mostly observed reason for deficient glass railing systems.

Depending on the glass support conditions, basic engineering can be employed to determined glass stress and deflection under imposed loads. When the support conditions are unusual, tools like Finite Element Analysis (FEA) software can be used in order to determine code compliance. Ultimately, we can no longer argue that due to lack of tools, system performance cannot be determined. While is true that some of these tools are more costly than others, when dealing with public safety, no analysis should be spared. Refer to Figure 10, 11 and 12 for an example of a glass rail system design using second order FEA software.

Figure 10. Glass railing system component modelled in FEA software
Figure 11. Glass railing system component modelled in FEA software

Figure 12. Glass railing system modelled in FEA software
7 Discussion

There are some misconceptions regarding the design of glass rail systems and the appropriate use of all components. It has been argued that the building code has not been very clear regarding the use of a top rail and that is left to the designer’s interpretation. But if carefully studied, the code does define all required criteria for these type of systems.

Some people argue that glass guard systems meet code requirements when handrails are provided as long as the top glass edge is located at 42 inch, which is the height required for guards. The same people say that there is no need for an additional top rail in these cases.

Few ideas are listed below for discussion and consideration:

- The question becomes, what would prevent people from falling in the event of a glass panel failure since there would no longer be an element at 42 inches?
- At 42 inches, the top of the guard would be located above the center of gravity of the average adult.
- Would the handrail provide support when designed to withstand design loads?
- If an adult falls into the glass causing it to break, the handrail would have to prevent the fall.
- At 34 inches, the handrail is below the center of gravity of the average adult.
- Handrails are not required by code at egress/transit/balcony locations.
- Handrails are only required by code at stairs and ramps.
- The code clearly states that the systems need to resist the specified loads applied at the top. Guard minimum height is defined at 42 inches. Therefore, the top is at 42 inches.
- Based on height definition only, handrails are not guards.

Some more audacious people completely ignore code requirements and have installed frameless glass balusters with a beauty cap on top glass. The following ideas are listed for consideration regarding this observation:

- Beauty cap will in fact protect the glass edge from impact, which is a good practice when dealing with glass.
- If the beauty cap is supported by a minimum of three glass balusters, as required by code, can it remain in place if one glass panel fail?
- Does it have the required strength to remain in place to resist design loads?

Different systems are sold by different manufactures in the United States but not all of the systems conform to Building Code minimum requirements. It is in the designers' best interest to study the building code and understand these simple requirements in order understand what the type of systems will prevent any catastrophe. After all, we are trying to build safer structures and promote public safety. Understanding these requirements is our duty as design professionals.
References
Curved Glass in Projects

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Abstract
In the last years a tendency of an increasing number of in building project built-in curved glass could be observed. In a lot of realized projects around the whole world one can find such glass in many different applications with a big number of different geometries. These applications can principally be curved monolithic glass, laminated safety glass or insulated glass. This fact makes it absolute of interest to make much more investigations in this field. The investigations in this field could be focused on e.g. the process of the bending of the glass to bring it into the certain shape, or the very difficult topic of pre-stressing of such glass. How to design curved insulated glass is a big issue too. In comparison to flat insulated glass the internal pressure in the space between the glass layers due to the so called climatic loads is much higher. The state of the art of the production process of such glass shows some different kinds how it is possible to shape glass. The most used way is to transform the glass at a high temperature with more than 550° Celsius. In this case there is a change of the viscosity in connection with decreasing of the Young’s modulus at such high temperatures. Due to the gravity-effect the weaker glass sag down into special designed moulds and get there demanded geometries. Another kind of curved glass is a production in combination with the laminating process. The glass layers are fixed in there demanded shape in special moulds and with the down-cooling at the end of the laminating process the interlayer becomes stiff enough to hold the shape by activated share forces between the glass layers. The last possibility is to produce flat glass and curve it while mounting the glass on the building. The question how to pre-stress curved glass is on the very first beginning of investigations. Thermally pre-stressed curved glass can only be produced as cylindrically shaped. In the case of other geometries this procedure failed. One solution can be a pre-stressing procedure by the means of chemical treatment. This can principally be used for all possible shapes. All these different processes are on the first view very easy but very difficult in the detail. This can be demonstrated by some bad examples.

Keywords: curved glass, curved insulted glass

1 Introduction
The tendency to use curved glass in project shows an increasing number of outstanding realized projects - like e.g. the “Hungerburgbahn” in Innsbruck (Austria), which was designed by the famous architect Saha Hadid. The new cable railway substituted the old railway, which connects the city of Innsbruck with the area of Hungerburg far above the Innsbruck, located in the south of the city.
This cable railway consists of four stops – “Congress” next to the city centre, “Löwenhaus”, next at the riverside of the river Inn, “Alpenzoo”, which is on the half way up to the final station at the very steep hillside and the “Hungerburg” which is the final destination on the very top. The geometries of the glass panels principally follow the raster of the steel grids which are the main-structures in the inner of the glass sculptures. All of the different glass elements are freeforms made of glass, as can be seen in fig1 below. With a special supporting system which is glued to the surface the glass elements were assembled to the main steel structure. [1]

![Figure 1. Nordkettenbahn station Hungerburg, Innsbruck. [1]](image)

### 2 Cold bent glass by assembling

A possibility too is to produce the laminated safety glass flat. During the mounting of the glass panel the demanded shape can be achieved. The simple process can very simple be described as a glass which shall be fixed with 4 glass fittings, as shown in fig 2 below. The glass e.g. a laminated safety glass is produced as a planar panel. In the first step all 4 glass fitting are in the same plane surface. If one of these glass fittings is moved out of this plane surface, a curved surface of the glass can be achieved.

![Figure 2. Cold bent glass by assembling.](image)
2.1 TGV railway station, Strasbourg
One wonderful example for such technique with cold bent glass by assembling is the TGV railway station in Strasbourg, see in fig 3 below. The laminated safety glass was produced flat and these big glass panes were mounted at the building site into their demanded curved shape. [2]

Figure 3. Example for cold bent glass by assembling. [2]

3 Cold bent glass by lamination
Another kind of curved glass is the production in combination with the laminating process. The glass layers are positioned in their demanded shape in special moulds. The typical laminating process can be started. At a temperature of approx. 120°C and a pressure of 1 bar up to 12 bar (depends on the kind of process) the interlayer e.g. polyvinylbutyral PVB becomes soft and connects the glass layers. During the down-cooling at the end of the laminating process the interlayer becomes stiff enough to hold the demanded shape by activating of shear forces between the glass layers. For the elements with a smaller radius this technique was used for the project of the TVG station in Strasbourg, see in fig 3 above.

Figure 4. Cold bent glass by lamination.
4 Hot bent glass

The most used procedure is the bending of glass at a high temperature with more than 550° Celsius. In this case there is a change of the viscosity in connection with decreasing of the Young’s modulus at such high temperatures. Due to the gravity effect the softer glass sag down into special designed moulds and get their demanded geometries.

The process of the deformation of a flat glass pane at high temperatures is the opposite process of the very old technique of glass blowing. The glass is again and again brought in a furnace on a temperature of over 600°C, in order to form it by blowing to a cylinder. The flat glass is produced in the second step of this process.

At temperatures over the temperature of transformation of approx. 550 °C the glass becomes softer. A physical description of the procedure is possible with the viscosity. The viscosity designates the strength, which is required, in order to shift two parallel surfaces in a certain distance with a certain speed. One recognizes the meaning of the viscosity, if one regards the formation of a glass. A melt is a liquid and differs from the solid state by the fact that the bonds between the molecule particles are missing. If individual particles move, then the bonds of the molecule particles must be blown up. The energy required for it is applied by thermal. [3]

![Viscosity behaviour of glass at high temperature.](image)

**Figure 5.** Viscosity behaviour of glass at high temperature.

The higher the temperature is the more molecular bonds are blasted open. This effect results in more curvature in the glass and smaller bending radii. At a temperature of approx. 800°C it is possible to produce such extreme curved glass with e.g. a corrugated or trapezoidal shape as shown in fig. 6 below.
4.1 JCDecaux

Such an extraordinary shaped glass was used for a project in London. A tower for advertising for the company - JCDecaux in Brentford 1000 Great West Road Middlesex TW8.9 – UK was planned by the famous architect Lord Norman Foster, see in fig 7 below. Directly at the exit road to the airport Heathrow in Brentford the tower for advertising is situated. The tower with its height of approx. 29 m has a triangular ground plan form. The lengths of all sides of the triangle are approx. to 6 m. The tower has two large light boxes for advertising at the sides arranged to the road. A structural steelwork is situated in the interior on that the glass cladding is fastened. The structural steelwork consists of 3 vertical columns in the corners and horizontal girders at each glass gap with a vertical clearance of approx. 3 m. With diagonals the steel construction became more stiffness due to the wind loads. The whole tower was shrouded in this corrugated glass. The corrugated glass with an average thickness of 8 mm has a wave length of 76 mm and a difference between valley and peak of 20 mm. [3]
4.2 Joanneumsviertel, Graz
A very interesting project, finished end 2011, is the new entrance of the museum quarter ‘Joanneumsviertel’ in the historical centre of Graz in Austria. The museum was founded in the year 1811 and on the occasion of the 200 year jubilee the government of the Austrian province Styria had decided to renovate this museum. The complex of the museum’s building consists of two wings (museum of natural science and the museum of modern art) of the existing structure. For the connection of those old parts of the museum the architects - eep architects, Graz/A; Nieto Sobejano Arquitectos, Madrid/E - designed the new entrance between them. The visitors of the museum can reach the biggest cone designed as the museum entrance via a specially designed public place. The picture below shows this new entrance with an escalator marked with a red arrow, see in fig 8 below.

The basement with a depth of approx. 10 m was excavated and the two levels were covered with wide spanned reinforced concrete slabs. An architectural challenge of this project was to bring daylight into these two lower floors. The concept of the architects was to let natural daylight flow in via vertical funnels into the basement. [4]
Figure 8. New entrance - ´Joanneumsviertel´.

These funnels have the form of small round courtyards with different diameters of up to approx. 16 m. Laminated safety glass and insulated glass were used for the cladding of these conically-shaped funnels.

The cones have central axis which are inclined up to 15° from the vertical. For this reason the inclination of the glass panes vary from the vertical position to an inclined position of up to 30° from the vertical. Two of the six cones interpenetrate and another one is posed on its top and situated in the centre of a larger one.

Production of conically shaped insulated glass

The used way to produce these conically shaped glass is the process at a high temperature with more than 550° Celsius and with the usage of gravity. In this case there is a change of the viscosity in connection with decreasing of the Young’s modulus at such high temperatures. Due to the gravity-effect the softer glass sag down into special designed moulds and get the demanded geometries.
Figure 9. Production of conically shaped insulated glass.

The procedure of the production of such conically shaped insulated glass IGU can be described with the following steps. The first step was to cut out the glass to the demanded geometry and the edge treatment. After this first step the glass had to be brought into the furnace for the bending process. The bent glass must be laminated, if needed. The final step was the assembling of the insulated glass unit IGU, by usage of soft-spacers for the edge sealing. These laminated safety glass and insulated glass were glued onto the stainless steel sections.

Cone 1 & 2

Cones 1&2 are the cones with an interpenetration located on the northern part of the public place. Cone 1, with a diameter of approx. 9 m, extends into the first basement level and Cone 2, with a diameter of approx. 6 m, extends into the second basement level (see in fig 10 below). For the balustrade, laminated safety glass with a total thickness of 24 mm which consists of 2 x 12 mm conically-curved annealed glass panes was used. The cladding in the basement levels consists of insulated glass with conically-curved 12 mm glass on the outer side, a 16 mm cavity and a laminated safety glass which consists of 2 x 8 mm conically-curved annealed glass on the inner side.

A special detail is the interpenetration of these two glass cones. The guarantee of the tightness against rain for the parabolic curve of the interpenetration was a difficult part, as well as the geometrical challenge which had to be solved. The gap between the glass panes of the different cones is covered with a specially formed stainless steel profile. Which has approximately the same U-shaped cross section as the stainless steel handrails which are used for the balustrade. [4]
Figure 10. Cones 1 & 2.

Cone 3 & 4

The Cone 3 has its larger diameter on the upper side in comparison with cone 4 which was posed on its top and has the larger radius on its bottom edge. Smaller cone number 4 is situated in the centre of cone 3. For the balustrade, laminated glass with a thickness of 24 mm which consists of two 12 mm conically-curved annealed glass panes was used. The cladding in the first basement level was made for both cones of insulated glass with conically-curved 12 mm glass on the outer side, a 16 mm cavity and a laminated safety glass which consists of 2 x 8 mm conically-curved annealed glass on the inner side. The glazing in the second basement level, which is used as a depot for the exhibits, was designed as laminated safety glass with a total thickness of 24 mm. Cone 6 which is located in the very south of the public place is equal to Cone 3. [4]
Figure 11. Cones 3 & 4.

The picture in fig 11 (see above) shows the view from the inner of the museum in the first basement level through the insulated glass units of the cone 3 to top of the insulated glass of the cone 4. The top of Cone 4 is covered with an elliptical, but flat, insulated glass. A very slender steel construction which is positioned in the gaps between the conical glass units carries this insulated glass of the top of the cone. [4]

Cone 5

The biggest cone - Cone 5 - with a diameter of approximately 16 m was designed as the new entrance for the visitors of the museum. Via an escalator the people can reach the first basement level and enter the museum through a sliding door. The central axis of this cone is inclined by approximately 15° from the vertical and for this reason the inclination of the glass panes vary from a vertical position up to an angle of 30° from the vertical (near to the escalator). For the balustrade, laminated safety glass with a total thickness of 24 mm which consists of two 12 mm conically-curved annealed glass panes was used. In the balustrade, a gap for installation of the escalator was positioned (see fig 12 below left).
Figure 12. Cone 5.

**Principle concept of glazing**

The special boundary condition of the great deformation of the wide spanned concrete slabs of more than 30 mm (for the long-term deformation) causes the special structural system of all the cladding. The glass panes of the balustrade had to be staked on the insulated glass of the level below. This means that the lower glass has to carry the vertical loads e.g. the dead loads of the glass above. To keep the distance between the upper and the lower glass level synthetic blocks were used. The calculations made during the design process showed that the additional stresses due to the dead load of the upper glass were not very high and in this case absolutely acceptable. At the lower edge of the insulated glass pane the dead load is supported by steel consoles, which were mounted on the concrete slab. For the horizontal loads, the glass panes were glued to stiff stainless steel ring sections and those were discretely supported at their ends. These hinged supported systems transfer the horizontal loads e.g. wind or human impact to the concrete slabs and guarantee the freedom for vertical movements of the concrete slabs.

**Design of cones**

All the different cones were designed with a finite element model (see in fig 13 below) which covers all glass panes. The loads were defined with dead loads, wind loads and horizontal loads due to human impact. For the design of the
balustrade in the public area a horizontal load of h=3.0 kN/m was used. This level of the load is based on the possibility of a big gathering. Besides these mechanical loads the climatic loads in the insulated glass units were taken into account. These climatic loads include the difference in temperature (summer and winter), the difference in the meteorological air pressure and the difference in the altitude (between the production site and the building site). All these internal and external loads were superposed in the finite element model. [4]

4.3 State Library, Berlin
The 13 storeys old building complex of the Berlin State Library with a length of 170 m and a width of 107 m is located in the heart of Berlin. For the in the Second World War partly destroyed building, a call for tenders was realized by the city-council of Berlin. The famous architect HG Merz won this architectural competition. The cubical structure of the new reading room was situated between two courtyards in the middle of old building complex, see in figure 14 below. The design concept of the architect was to bring as much as possible daylight into the reading room. So as much as possible glass was used for façade. [3]

The vertical cladding of the reading room was designed as a double skin façade. For the outer – secondary skin of the double skin façade 8 mm heat formed toughened glass panes with a lot of small dents according to a special design of the architect were used. The depths of these dents were designed up to approx.
20 mm. For the outer skin with a size of 2834 m² 1215 glass elements were produced. All glass were glued and sealed to aluminium frames. These aluminium frames were mounted at the outer side of the vertical steel structure of the façade, see in fig 15 right.

The space in between the two skins will be used for maintenance. The distance between the inner and the outer skin was given by the architect with approx. 1 m. The gangway for the maintenance staff is covered with a steel grid, and runs in each storey through cut-outs of the vertical steel beams, see in fig 15 left.

The inner - primary skin consists of insulated glass units with a 2 x 6 mm laminated safety glass (tempered glass) on the outer side and 8 mm heat formed toughened glass with a lot of small dents on the inner side. The depths of these dents at the inner skin are up to approx. 10 mm. All insulated glass units were glued and sealed into aluminium frames. The aluminium frames were mounted at the inner side to the vertical steel structure of the facade. For the inner skin with a total size of 1560 m² 661 insulated glass units were produced. [3]
Figure 15. Concept of the double skin façade [3], View of the outer skin on site, cross section.

The right picture in fig 15right shows the outer skin during the process of assembling. The picture shows very well nature of the cladding with the hot deformed glass.

5 Pre-stressing

In some cases e.g. for glass with bore holes pre-stressed glass is demanded. Two techniques are currently available. On the one hand there is a thermally pre-stressing and on the other hand there is a chemical treatment possible. A special technique is the production of e.g. front shield for cars. Very special and expensive ceramic moulds are used for such glass. This is only possible, because such moulds are used for many thousands of such front shields. For thermally heat treated glass there is a geometrical limit. Only for cylindrically shaped glass a thermal pre-stressing is possible.

5.1 Thermally pre-stressing

At the market big machines are available, to thermally strengthen and bend the glass in the same step of the process. At first the flat glass is heated up to more than approx. 550°C. The hot glass is moved to the next part of the machine. In this part the glass will be bent and pre-stressed. Instead of stiff roles a flexible kind of roles like a chain are used to bend the glass. Depending on the direction of these chains with regards to the axis of the machine the glass can be defined as b-shaped or c-shaped. After bending of the glass the surface is blown off with air. In principle the pre-stress process is the same as for flat glass.

5.2 Chemically pre-stressing

Chemically strengthened glass is a type of glass that has increased strength as a result of a post-production chemical process. When broken, it still shatters in long pointed splinters similar to float glass. For this reason, it is not considered as a safety glass and must be laminated if a safety glass is required. However, chemically strengthened glass is typically six to eight times the strength of float glass. The glass is chemically strengthened by a surface finishing process. Glass is submersed in a bath containing a potassium salt (typically potassium nitrate) at 300° up to 400°C. This causes sodium ions (Na) in the glass surface to be replaced by potassium ions (K) from the bath solution.

These potassium ions are larger than the sodium ions and therefore wedge into the gaps left by the smaller sodium ions when they migrate to the potassium nitrate solution. This replacement of ions causes the surface of the glass to be in a state of compression and the core in compensating tension. The surface compression of chemically strengthened glass may reach up to 690 MPa.
Chemical strengthening results in a strengthening similar to toughened glass. However, the process does not use extreme variations of temperature and therefore chemically strengthened glass has little or no bow or warp, optical distortion or strain pattern. This differs from toughened glass, in which slender pieces can be significantly found. [5]

6 Failure

By many different projects curved glass could with defects be observed. These failures can be less critical optically based or very critical mechanically based.

6.1 Optical failure

Such a bad example, but good for the explanation, is the cylindrically shaped heat strengthened glass for a shop window. This glass is mounted with glass fittings to the substructure - the masonry. The fig 16 below shows this cylindrically bent with the distorted glass. These distortions shown in the picture are the so called roller waves in the glass. The reason of these waves is the too high adjusted temperature in the furnace during the heat treatment. Due to the too high temperature the glass was too soft and the waves could occur.

Figure 16. Shop window with optical failures.

6.2 Mechanical failure

In Bolsward, the Netherlands, the “Broerekerk” (church of the brothers), founded before 13th century was completely ruined by a fire in 1980. In 2004 works were started to pre-serve the ruin, and it was decided to fit a new roof designed mainly from steel and glass onto the old church, see in fig 17. Cylindrically shaped heat treated laminated safety glass was used for the glass of the roof.

While assembling the glass on the roof a glass breakage of some glass element could be observed. After investigate this problem the failure could be described. It was a failure while bend and pre-stress the glass. The flat glass panel was placed on top of the mould and put into the furnace. As the glass is heated up, it sags into the mould until it just touches the heat resisting fabric. The deformed panel is not moved in the mould, neither the mould is moved in the airflow. The panel is
directly cooled by cold air from the top. But from the bottom the air was hindered by the steel mould and the resisting fabric. At the supporting point no cold air reaches the hot glass pane and zones of tension instead pressure occur on surface of the glass. These cause an opposite effect of the pre-stressing of the glass and results in much less bending strength [7]

Figure 17. Church Broerekerk in Bolsward (NL) with broken glass panels.

To avoid such failures it is absolutely necessary to have the detailed knowledge about the behaviour of glass during the process at high temperatures. There is a strong relationship between the size and the mass of the glass on the one hand and the duration and temperature of the production process on the other hand. Only with the right justification of the duration and the temperature it is possible to produce a good quality. [7]

7 Acknowledgements
The projects JCDecaux in London, State Library in Berlin and Joanneumsviertel in Graz were realized by the company SFL-technologies in Austria.

8 Summary
In a lot of realized projects around the whole world one can find such glass in many different applications with a big number of different geometries. These applications can principally be curved monolithic glass, laminated safety glass or insulated glass. This fact makes it absolute of interest to make much more investigations in this field.

References
[1] www.strabag.at


New concept for hail testing of glass

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Abstract
Due to the on-going climate change extreme weather conditions such as rain, violent storms and extreme hail are on the increase. These weather changes cause extreme hail scenarios with ice balls of large diameter falling to earth. A demand for a durability verification of is a so called hail testing. Currently only a Swiss standard is available for such testing. In this standard a very simple testing scenario is proposed. Ice ball are shot one after the other onto the surface of the test sample. All these ice balls are shot onto the same position on the surface, which does not in any way represent the scenario which can be observed during a real hail event. For this reason the “Hans Höllwart, Forschungszentrum für integrales Bauwesen AG” developed a testing device, which more accurately simulates the real hail scenario during the test. This special testing equipment was designed with of 10 tubes in total with which ice balls of different diameters can be shot at different velocities onto the surface of the test sample. This enables us to compose our own testing scenario as well as a real hail scenario.

Keywords: hail, hailstorm, hailstone, hail testing device

1 Introduction
In the last few years the damage to buildings caused by heavy hail has increased, because the hail scenarios have become more and more extreme. As the topic is current at the moment, a development of an accurate simulation and respectively a calculation of such an extreme hail scenario is required. Figure 1 below shows a handful of large hailstones and a greenhouse which was completely destroyed as a result of a heavy hail event.

Figure 1. Hailstones, damage caused by hail [1], [2]
Over the past 50 years for example Switzerland registered an increased number of damages caused by hail, as can be seen in fig 2 below. According to surveys by the Swiss foundation for prevention of hailstorms (Präventionsstiftung der kantonalen Gebäudeversicherungen) in most cases buildings are concerned. Along with the expansion of residential estates and a more frequent occurrence of heavy hailstorms the use of sensitive building materials is one reason for the rising costs. [3]

![Diagram showing annual damage](image)

**Figure 2.** Structural damages on buildings with insurances under public law, caused by hail 1961-2005, horizontal bars showing average of five years. [3]

The following questions should be taken into account:

1. How reality can be best simulated?
2. Which factors prevail here?
3. What a load is actually hitting on a building façade?
4. Is there a method available with which such a severe storm can be simulated?

State of testing scenario technology

Currently six European Standards are available, and one of them is a very special, published in the Switzerland. This standard describes the test procedure as the following: a projectile, which represents the hailstone, is shot at a prescribed speed onto the sample by means of air pressure.
A distinction is made between the different types of façade, such as solar panels, photovoltaic or waterproofing details. This rule makes differences in hail material or in used test procedure. Table 1 shows a summary of all existing test scenarios. [4]

Table 1. Summary of the current standards.

<table>
<thead>
<tr>
<th>test object</th>
<th>standard</th>
<th>material</th>
<th>diameter [mm]</th>
<th>velocity [m/s]</th>
</tr>
</thead>
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<td>solar heat</td>
<td>EN 12975-2</td>
<td>steel ball</td>
<td>32-33</td>
<td>2,83-6,32</td>
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<tr>
<td></td>
<td></td>
<td>ice ball</td>
<td>25</td>
<td>23</td>
</tr>
<tr>
<td>photovoltaic</td>
<td>EN 62108</td>
<td>ice ball</td>
<td>25-26</td>
<td>23</td>
</tr>
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<td>EN 61646</td>
<td>ice ball</td>
<td>12,5-75</td>
<td>22,4</td>
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<tr>
<td>terrestrial crystalline silicon photovoltaic</td>
<td>EN 61225</td>
<td>ice ball</td>
<td>12,5-75</td>
<td>16-29,5</td>
</tr>
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<td>13,8-30,8</td>
</tr>
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</table>

A detailed investigation showed that the existing hail tests have some weaknesses. The described methods are too vague and cannot realistically simulate the actual prevailing conditions during a hailstorm. Switzerland is one of the European countries which is affected the most by hail and for this reason, they have developed their own Swiss guidelines concerning the durability of building materials regarding hail. The hail requirements set by the cantons are binding. Only the materials tested by the VKF (Vereinigung Kantonaler Feuerversicherung - Association of Cantonal Fire Insurance) may be used.

During this test, a slope between 45 ° and 90°, depending on where the hailstone can cause the greatest damage has to be adjusted. At an outside temperature of (23 ± 2) °C and relative humidity of (50 ± 10) % the ice balls, which represent the hailstones, are accelerated to the desired speed. A single gun shoots these ice balls with diameters of 10, 20, 30, 40 or 50 mm at different speeds on the test specimens. Each of the experimental specimens is exposed to a total of five individual shots. Depending on the impact on the test item, the materials are divided into five hail resistance classes. [5]

Hail in combination with storm

For all test procedures, the ancillary conditions also play an enormously important role. Neither the effects of wind, rain, temperature or humidity and air pressure nor the firing frequency are taken into account in a verification procedure. Often a
combination of wind, rain and hail occur together, as can be seen in following newspaper clipping:

A headline from an Austrian newspaper

"Once again bad weather in Styria, (Austria): trees fell on houses and cars, roofs were ripped off, the hail was inches high." [...] Not only the great size of the hailstones, but also the enormous density and intensity of precipitation are responsible for a great deal of damage, costing millions of Euros, in the agricultural sector in large areas of Western and Eastern Styria. In Fürstenfeld [...] the hailstorm raged with high winds above the town centre."


Due to the events of the last few years, a more precise examination of hail and its impact on building façades is inevitable at the present time. This article shows that a realistic hail scenario does not only depend on the size of the hailstones, but it also depends on the number of hailstones and their intensity per unit area. A simultaneous impact of multiple objects can cause the façade to vibrate, which significantly increases the level of such dynamic impact forces. In such a dynamic case of multiple impacts, the previously described tests are not suitable. Also, the simultaneous occurrence of hail and storm is mentioned. Most likely hail and wind peaks occur together. The cumulation of all these loads is a key component not only to building damages, but also to the conditions for the impact of hailstones. This aspect is also not taken into account in any standard specification.

2 Methodology

With the above described standards it is not possible to simulate the natural conditions during a hailstorm with wind. Therefore it was absolutely necessary to investigate more thoroughly the influence of these environmental factors. The following diagram illustrates how important the effects of the wind on a hailstone are. Smaller objects will be much more moved by the wind than larger hailstones. Hailstones with a larger mass are more inert and must fall much closer to the façade for the wind to cause an actual impact on the object. For smaller projectiles it is possible to hit the wall from larger distances.
Figure 3. Angles of incidence as a function of wind speed and hail particle diameter.

For the description of the intensity of the hail scenario all the previously mentioned factors must be summarized. The hail scenario is composed of the duration, intensity (impacts per m²), the angle of incidence and the actual weight of the hailstones. This total load is given as energy by the unit Watt per square meter (W/m²) and can be calculated as follows.

Figure 4. Definition of angles for the determination of the energy of impact depending on the wind.

It proved useful to calculate the energy of impact depending on the wind speed and the slope of the test object. For this purpose, the following equation (1) was developed.
\[ E_A = \sum_{i=1}^{N} \frac{m_i}{2} \cdot \left[ \cos \left( \beta - \arctan \left( \frac{v_w \cdot WB}{v_{fi}} \right) \right) \right]^2 \cdot \left( v_{fi}^2 + (v_w \cdot WB)^2 \right) \cdot n_i \] (1)

\[ E_A \] energy of incidence
\[ \beta \] angle of building surface
\[ m_i \] mass of a hailstone
\[ v_w \] wind velocity [m/s]
\[ WB \] coefficient for wind [-36%]
\[ v_{fi} \] fall velocity of a hailstone
\[ n_i \] number of hailstones of same size per square meter
\[ i,N \] index of the classes of hail

The graphs in fig 5 below shows the energy results of calculations according the above described equ.1 for a hailstone with a diameter of 40 mm. Input data are the wind velocity and the angle of inclination. The energy can be read out of these graphs.

![Graph showing energy of incidence depending on the wind speed.](image)

**Figure 5.** Energy of incidence depending on the wind speed.

As can be seen in fig 5 above, it is possible to see how inappropriate a test with only a single-shot at a certain angle is. The wind could be so strong that it might affect an impact speed of the hailstones, compared to the existing standards, up to threefold the speed without wind.
Based on the fact that hailstones of different sizes are differently influenced by wind, it is possible to mathematically simulate this scenario. The assumption consists of ideal hailstones of various diameters and a horizontal wind in a direction perpendicular to the vertical façade. The width of the test surface is kept constant at a meter and the overall height varies from 1 to 7 m, see in fig 6 above. The horizontal area of 1 m² is directly next to the outside of the building. As theoretical values for the number of hailstones and their size, data from ZAMG [7] were used for the different models. Extreme cases taken from last few years were included in the analysis as a reference point.
In table 2 the vertical path a hailstone of certain thickness at a certain wind speed \(v_w\) must take to hit the vertical façade can be seen. The overlapping areas refer to the different wall surfaces from 1 to 7 m\(^2\). The red parts in the table cover the already very low wind speeds with smaller diameters of hailstones. At a wind speed of, for example, 80 km/h and the façade area of 2 m\(^2\) loads of more than 3 joules can arise due to hail. They correspond to two 25 mm thick hailstones on the horizontal floor at 80 km/h impact.

In such extreme cases of the last few years, façades were exposed to strong winds of 100 km/h and an impact energy of up to 6 joules per square meter were possible. This illustrates very clearly the influence of the wind and can be as severe during a hailstorm.

In fig 7 the table 2 is illustrated graphically. There is an exponential decrease of the required height of fall. The inertia of the hailstones of a larger diameter in relation to the wind is recognisable at the bending of the curves.
Another essential topic is the frequency and intensity of the hailstorm. The previously mentioned standards require only single shots onto the test object. As table 3 shows, the frequency of hail storms is much higher. Such a small number of tests would simulate only one event per year. To gain a realistic simulation of a hail scenario, the frequency would have to be increased and also several hail impacts would have to be tested for façades. A simultaneous striking of two hailstones should also be observed. Only using the sum of all impacts over a period of time, it would cover the situation during a hail event together with a storm.

Table 3. Left: number of days with hail events - right: number of hail impacts (in Styria, Austria).

<table>
<thead>
<tr>
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<td>3.2</td>
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<td>10.7</td>
<td>28.6</td>
<td>23.1</td>
<td>15.9</td>
<td>3.7</td>
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</table>

Figure 7. Demanded height of fall as a function of the velocity of wind and the diameter of hailstone.
3 Hail testing device

In order to simulate the reality as closely as possible, a special hail testing device was developed and manufactured. This machine allows an area-wide attack by the means of ten hail cannons spread over one square meter. Another requirement of the examination equipment is the slight adjustability of hail cannons, which must have always the same distance from the test object. Due to the different inclinations of the test objects, machinery for the angle setting of an enclosing framework for the fixation of the hail cannons also had to be developed. [8]

Figure 8. Drawings of the hail testing device.

A device for lifting the hail frame by means of forklift trucks has been integrated specifically to ensure a test at certain heights. Every hail cannon has its own hailstone storage container and can be directly loaded from there. The test facility is programmed manually from a computer by means of SLC (stored program control). So, all scenarios can be simulated by hail impacts in a certain sequence. In addition, wind generated by a turbine and rain generated by spray nozzles could be used for a still closer to reality simulation. So you would have all previously discussed elements of a hailstorm event on a façade included. The hail testing machine developed from the fibag (Hans Höllwart, Forschungszentrum für integrals Bauwesen AG) is shown in figures 8 and 9.
4 Summary and Outlook

All tests carried out with the hail testing device showed that a test with only 5 single-shots, as described in previously mentioned standards, provide no realistic information about the hail resistance of a building element such as a roof construction. Micro-cracks or perforations may arise due to the impact of a hailstorm, which weakens the material to such an extent that the next impact could cause it to break. A more important issue is the influence of surrounding conditions, such as wind, rain or air pressure. Only through the cumulation of all possible loads the material can be designed correctly.

Through a careful analysis of the characteristics of the hailstorm and the development of a special hail testing device at the fibag (Hans Höllwart, Forschungszentrum für integrales Bauwesen AG) it is now possible to create a severe weather simulation with hail, wind and rain which is close to reality.

References

[5] Vereinigung Kantonaler Feuerversicherungen; VKF Prüfbestimmung Nr.00a
[8] Hans Höllwart, Forschungszentrum für integrales Bauwesen AG
Diffusion Barrier Coatings on Glass by Solution Derived Nanocomposite (SDN™) Technology

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**Abstract**

Glass is an integral component for modern technology – from consumer electronics like cell phone screens and OLEDs to large area photovoltaic (PV) panels, glass often serves as the substrate or superstrate in contact with transparent conducting oxides or other active layers. Thus, device performance depends on the chemical composition of the glass: alkali metal ion diffusion can deteriorate device performance over time. Use of a thin coating that blocks ion diffusion relaxes the demands to glass manufacturing and allows to source glass from different suppliers without compromising reproducibility.

Diffusion barrier coatings are generally less than few hundred nanometers thick, dense coatings that have to withstand the subsequent processing steps (e.g. high temperature). Solution Derived Nanocomposite (SDN™) technology can produce barrier coatings that meet these demands without the complexities and cost associated with commonly used vacuum (PVD, ALD etc.) and chemical vapor deposition (CVD) techniques. SDN™ barrier coatings are applied on glass sheets in a specially designed and patented Roll Coater without the need for vacuum technology at any stage of the process. Tuning of coating properties (thickness, refractive index etc.) is achieved by controlling physicochemical properties of the coating solutions. Optical properties and mechanical durability of SDN™ barrier coatings will be discussed.

SDN™ diffusion barrier coating is a single-layer coating that blocks sodium ion diffusion, but also enhances optical properties by reducing reflectivity and improves abrasion resistance of glass.

**Keywords:** ion diffusion, barrier coating, solution deposition, roll coater, antireflective.
1 Introduction

In recent decades, glass has moved from mainly architectural and household material to become an integral component of electronic devices. Displays and touch sensitive screens rely on thin film stacks of electronically active layers deposited on glass for structural support. Glass is chemically more complex than just silica, its main constituent. Depending on raw material (sand) origin and manufacturing process, the concentration of minor constituents like alkali metal ions can vary greatly. Alkali metal ions originate from sodium carbonate and potassium carbonate fluxes, which are used to lower the melting temperature for glass formation. Soda lime glass, commonly used for windows and household items, can contain as much as up to 16% Na$_2$O. Chemically strengthened glass used in displays owes its toughness to potassium ions that are intercalated into glass surface. It is critical to avoid alkali metal ion out-diffusion from glass used in displays because these ions adversely affect conductivity of indium tin oxide (ITO), the predominant transparent conducting layer in display technologies.\cite{1,2}

The diffusivity of alkali metal ions has been monitored by atomic absorption spectroscopy, and it has been suggested that thin metal oxide coatings can block the diffusion. \cite{3,4}

The metal oxide barrier coatings have been previously applied by vacuum technologies, e.g. sputtering \cite{5}, and by pyrolysis of a silane gas on the glass surface above 600°C \cite{6}. These methods generally require high energy input and complex equipment, thus being cost-prohibitive. We present a solution-deposited diffusion barrier coating on glass that offers excellent scalability and is easy to deposit with our patented Roll Coater.\cite{7}

For a thin coating to be effective against ion diffusion, it needs to be sufficiently dense. Since the barrier coating will be used for displays and other optically sensitive applications, it must not deteriorate optical properties of the glass. We will describe below that a thin solution-deposited barrier coating can actually improve optical properties of the glass.

2 Materials and methods

2.1 Materials and coating deposition conditions

PPG Starphire glass, 4 mm thick, was used as the substrate. PPG Starphire is an ultra-clear soda-lime float glass. Its high visible light transmittance (>91% at 6 mm) and its brilliant azure edge are two characteristics unique to Starphire glass. This glass is a low iron composition with mechanical and physical properties similar to ordinary clear soda-lime float glass. PPG Starphire glass consists of 73% SiO$_2$, 15% Na$_2$O, 11% CaO and 1% of trace elements.

Glass slides were subjected to Sparkleen detergent cleaning protocol in Branson 8800 ultrasonic bath for 20 minutes, followed by rinsing with deionized water and isopropanol, and drying in clean dry air (CDA) flow prior to coating. Coating formulation was prepared at room temperature in ambient conditions. Sol-gel precursor concentration was varied to obtain optimal thickness. Prior to coating on glass, coating formulation was filtered through 1 μm filter membrane.
Coating solution was applied on two sides of the glass simultaneously at room temperature ambient conditions, and subjected to heat treatment in a custom-built oven.

2.2 Characterization
Coating thickness and refractive index were characterized with Filmetrics F20 thin film analyzer.
Optical transmittance and reflectance spectra were measured on Shimadzu SolidSpec-3700 spectrophotometer using a Spectralon integrating sphere, and a UV-enhanced aluminum mirror as the reference for reflectance measurements. Coating cross-hatch adhesion test was performed according to ASTM D3359 protocol.
Abrasion testing was performed on Taber 5135 Rotary Abraser using CS-10F wheels at 72rpm with 500 g load for 1000 cycles. Wheels were refaced for 50 cycles using an ST-11 refacing stone before each sample was tested. Before and after abrasion, samples were cleaned by rubbing with wipe in running DI water, rinsing with DI water, and blowing dry with CDA. Haze measurements were performed on a BYK Haze-gard Plus haze meter. A Taber haze attachment was used to adjust the measurement area to include only the abrasion arc.

3 Results and discussion
3.1 Preparation of glass surface
Sparkleen detergent cleaning rendered glass surface hydrophilic as verified by spreading area of a water droplet with a fixed volume. Hydroxylation of glass surface is critical for achieving good adhesion of the diffusion barrier coating. Hydroxyl groups on the activated glass surface facilitate chemical bonding of the coating.

3.2 Optimization of the coating formulation
Development of the coating formulation was carried out by investigating two different sol-gel precursors and their combinations. It was found that a single precursor coating yielded a mechanically harder film that provided higher abrasion resistance, although optical performance was similar for both formulations. Coating properties and performance presented below is obtained with the formulation using the selected precursor.
Precursor concentration is relevant for tuning the coating thickness, but also for coating density: there is an optimal precursor concentration for obtaining sufficient coating thickness and density. At higher precursor concentration, solution deposited coatings start to become porous and are no longer effective against ion diffusion. We found that a thickness of about 85 nm was optimal for the diffusion barrier coating. Refractive index of 1.44-1.45 was measured for the barrier coating at this thickness; this value is close to dense bulk material value.
The coating formulation has good shelf-life and can be stored at room temperature in ambient conditions. Aging study of the formulation and its effect on coating properties is on-going.

3.3 Optical properties
Since glass is used for highly visible applications, optical properties of barrier coating were subjected to thorough inspection visually and by spectrophotometer.

**Figure 1.** Light transmittance of double-side diffusion barrier coated (red solid line) and uncoated (blue dotted line) PPG Starphire glass. The inset shows the curves in greater detail.

**Figure 2.** Reflectance of double-side diffusion barrier coated (red solid line) and uncoated (blue dotted line) PPG Starphire glass, UV-enhanced aluminium mirror was used as the reference.
Fig. 1. shows optical transmittance spectra of the uncoated and double-sided barrier coated PPG Starphire glass. The barrier coating enhances transmittance of glass throughout the collected data range (up to 2500 nm), but the gain is the highest in the visible range where the glass with double-sided barrier coating has up to 3% higher light transmittance.

Fig. 2. shows the reflectance spectra of the uncoated and double-side barrier coated glass. It can be seen that reflectance is reduced for the coated glass, especially in the visible wavelength range. The refractive index of PPG Starphire glass is 1.51 at 632 nm. Hence, our diffusion barrier coating with lower refractive index of 1.44-1.45 also acts as an antireflective coating on glass.

![Barrier coated 8X8 inch glass.](image)

**Figure 3.** Barrier coated 8X8 inch glass.

A digital photograph of a barrier coated 8X8 inch glass is displayed in Fig. 3. It can be seen that the thin coating is highly uniform without visual imperfections or defects across the whole surface, including edges. This supports scalability of the coating formulation and its application method.
Figure 4. Digital photographs of uncoated corroded glass (top) and barrier coated corroded glass (bottom). The photographs have been digitally converted to greyscale and contrast has been enhanced equally on both photos to show defects (indicated by arrows where observed).
Due to its antireflective properties, the SDN™ barrier coating is also well suited for optical defect elimination. Fig.4. top photograph displays corroded glass with visible line defects (pointed out by arrows), and the bottom image shows the corroded glass coated with the barrier coating. Because the barrier coating reduces refractive index contrast with air and also reduces defect depth by backfilling, the majority of line defects are no longer visible under the coating. This allows better utilization of glass that would otherwise not pass quality control and would have to be discarded because of cosmetic defects.

3.4 Mechanical properties
Mechanical properties of the barrier coating are important for their final use but also for handling of the back side during the ITO film deposition stage (e.g. abrasive action from rollers that transport the glass along the production line). Although the Roll Coater is intended for producing single sided coatings, we have also fabricated double-side barrier coatings that offer the advantage of blocking alkali metal ion diffusion into ITO, and preventing cosmetical abrasion defects on the backside of the glass.

Table 1. Abrasion test results for uncoated glass and glass coated with the best barrier coating formulation.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Initial T (%)</th>
<th>Initial H (%)</th>
<th>Final T (%)</th>
<th>Final H (%)</th>
<th>Δ%Haze</th>
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</thead>
<tbody>
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<td>PPG Starphire glass</td>
<td>93.0±0.00</td>
<td>0.04±0.00</td>
<td>92.1±0.00</td>
<td>1.64±0.04</td>
<td>1.60</td>
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<tr>
<td>Barrier coated glass</td>
<td>96.0±0.05</td>
<td>0.04±0.00</td>
<td>94.8±0.10</td>
<td>0.71±0.03</td>
<td>0.67</td>
</tr>
</tbody>
</table>

Table 1 shows light transmission and haze measured before and after 1000 abrasion cycles. Compared to uncoated glass, abrasion is very low for barrier coated glass and it was verified under light microscope that while some of the barrier coating gets abraded, it still protects glass from abrasion after 1000 Taber cycles.

The barrier coating also has excellent adhesion to glass, cross-hatch adhesion resulted in 5B, the highest adhesion rating.

3.5 Barrier performance and thermal durability
The barrier coating was tested for sodium ion diffusion at an external customer facility where it was also subjected to thermal processing. The SDN™ barrier coating passed the sodium ion diffusion test using X-Ray Fluorescence analysis, and displayed excellent durability after thermal processing of up to 700°C.

3.6 Coating deposition using Roll Coater
Advenira’s patented Roll Coater [7], featuring Solution Derived Nanocomposite SDN\textsuperscript{TM} technology, has been designed to accommodate up to 1 m by 1 m square sheets of glass with straightforward scalability to larger sheets in subsequently manufactured machines. The use of liquid precursors allows for a wide range of materials tunability. Overall design of the Roll Coater is depicted on Fig.5. Roll Coater consists of the main system, and loader/unloader carts placed at each end of the main system. Each cart can hold up to 24 sheets of glass. The main system, in turn, consists of pre-treatment module, process module, and post-treatment module. Solution delivery is facilitated via Advenira’s proprietary, patented Chem Box with integrated security features designed to prevent the use of unauthorized chemicals and/or counterfeit cartridges. Roll Coater is designed as a self-contained, HEPA-filtered system with built-in provisions for cleaning and periodic preventive maintenance. These features ensure optical quality coatings without particulate defects.

Without the typical size constraints and facilitation requirements commonly found in vacuum (PVD, ALD) and non-vacuum (CVD, CBD, electroplating, screen-printing) deposition systems, Advenira’s Roll Coater showcases low footprint and easy installation and integration to virtually any facility. The processing speed provides for viable throughput rates by coating-specific curing profiles.

4 Conclusions

Two different precursors and their combinations were studied for formulating a coating solution for deposition of diffusion barrier coatings on glass by use of a patented Roll Coater. A single diffusion barrier precursor formulation was chosen, and further optimized for its concentration to yield a coating of sufficient thickness with maximal density. It was found that an approximately 85 nm thick coating with
refractive index of 1.44-1.45 was effective against preventing sodium ion diffusion from soda-lime glass. Additional benefits were also demonstrated with the coating. Due to the lower refractive index of the barrier coating than that of the glass substrate (1.51), the barrier coating acted as an antireflective coating, increasing visible light transmittance for a double-side coated glass by 3%. Moreover, the barrier coating visually eliminates surface defects from previously corroded or abraded glass, which allows reuse of scrap material and improves economics. Lastly, the barrier coating also provides protection against surface abrasion if deposited prior to handling. The SDN™ diffusion barrier coating thus offers multiple benefits for glass used in displays and devices.

A patented Roll Coater was specifically designed for high-throughput coating of glass of up to 1 m² size by SDN™ coatings. In addition to the diffusion barrier coating described in this paper, the Roll Coater can be used to deposit other functional coatings on glass, e.g. transparent conductors, electrochromic films, abrasion resistant and antifogging coatings.

References

The Millennium IGU: Regenerative Concept for a 1000-Year Insulated Glass Unit

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Abstract
Glass is a ubiquitous material in the built environment. But over the past few decades the use of unprocessed float glass as a façade material has virtually disappeared. Raw float glass is a remarkable material not only for its transparency and optical properties, but also for its durability and recyclability. It will last indefinitely in the building façade, until removed or broken, at which time it can be recycled into virgin material with relative ease, improving the energy efficiency of the float line in the process. Unfortunately, post-consumer architectural glass is not recycled, at least partially because the secondary processes—coating, laminating, insulation—render the practice impractical. In addition, the insulated glass unit (IGU) has an average lifespan of only around 30-40 years, effectively collapsing the durability of architectural glass by at least an order of magnitude—from centuries to a few decades or less. Such realities are seldom questioned or discussed; yet they grow unacceptable as civilization steps towards a sustainable built environment. These issues are explored herein, and a concept is presented for an insulating glass assembly that poses no compromise to the recyclability or durability of float glass and optimizes the lifespan of the IGU. The concept is intended to illustrate an alternative way of thinking about the challenges presented by the pursuit of green building practices.

Keywords: insulated glass, IGU, double-glazing, durability, curtainwall, embodied energy

1 Introduction
Net lifecycle performance gains are conceptually possible through the adoption of maintenance and renovation planning that increases the durability of buildings and building systems. Such a premise mandates the design of buildings and building systems that facilitate the maintenance and renovation process. Current practices do not support this. There is considerable urgency in moving toward a more sustainable and resilient building sector, yet the required technology and know-how to accomplish this are largely unavailable. Pervasive innovation is
required throughout the building process, from design practices to materials, products, and construction methods. Innovation requires different ways of thinking, questioning the conventional manner of doing things, consideration of ideas that may seem unrealistic or impracticable. One specific area that bears consideration is the insulated glass unit (IGU), a ubiquitous component of commercial building facades since the 1980s. Alternative means of providing the functionality of the conventional IGU while mitigating the undesirable lifecycle impacts associated with its production, use, and disposal are possible. Design methods developed within this context may be applicable to a broader range of challenges presented by the built environment.

Specific metrics for durability and recyclability of IGU’s were chosen as development goals as these attributes are problematic in conventional insulated glass products. A first objective is for 100% recyclability of all materials used in the unit design. A second is the adoption of a 1000-year service life. Kesik comments that building structural systems are engineered to perform for the long term, with precedents pointing to a typical service life of "several hundred years." He further remarks that, "the skins of buildings are ideally intended to last the life of the whole building, in particular its structure, or skeletal system." [1] Given the massive investment of resources characteristic of large residential and commercial buildings, this typical structure lifespan has been deliberately stretched to a goal of 1000 years. The IGU concept developed here has therefore been designated the millennium IGU, or *M-IGU*. These goals are embraced as design constraints that demand a different way of thinking about the problem of providing a highly insulative glass assembly that is sustainable in terms of lifespan and recyclability.

2 The Problem With the IGU

The highly glazed façade is largely a product of the advent and widespread adoption of curtainwall technology in the mid twentieth century. Early curtainwall buildings were single glazed. Energy was cheap, and the building types were generally office buildings occupied only during the workday. Consequently, energy efficiency was only a minor consideration. It was not until after the first oil crisis in the early 1970s that a widespread adoption of IGUs commenced. The IGU is a strategy to improve the insulative value of the glazing unit by capturing a hermetically sealed cavity between two pieces of glass. The production process involves separating two panes of glass with a continuous perimeter spacer and seal (Figure 1). In addition to the insulating cavity, the IGU construct provides protected interior surfaces for the application of the many performance coatings produced by the glass industry over the intervening decades.
Figure 1. Makeup of a typical insulated glass unit (IGU). Wet seals permanently fix the glass to the spacer assembly, creating a hermetically sealed cavity. (Source: Advanced Technology Studio – Enclos)

2.1 High Performance Glazings

Selkowitz and others credit the developments provided by the glass industry—particularly the advent and application of thin film coatings—with the significant improvements in solar and thermal performance of highly glazed building facades.

Glass is a remarkable material but its functionality is significantly enhanced when it is processed or altered to provide added intrinsic capabilities. [2]

Today’s spectrally selective thin film coatings are most frequently applied to the interior surfaces of the glass, usually the number 2 surface (surfaces are counted from the outside in; 1 being the layer of glass in contact with the exterior), and the cavity is often filled with a gas (i.e., argon, krypton) less conductive than air. These developments are reflected in center-of-glass U-factor improvements promoted by suppliers ranging from 1.02 with clear single glazing to 0.24 in a 25mm IGU with low-e coating and argon gas fill. [3]
3 Unintended Consequences

The unintended consequences upon glass of the processes and alterations referenced by Selkowitz are twofold: first, the collapse of service life and wasted durability, and second, the float material is rendered unrecyclable. These combine to effect embodied energy.

The primary focus of green building has long been reducing energy consumption during the operational phase of building lifecycle. The widespread application of low-e and spectrally selective coatings on the surface of IGUs has become a common solution for high-performance building facades. There are energy efficiency gains resulting from the solar and thermal control provided by these high-performance glazings when considering a building’s operational phase. The emerging practice of lifecycle assessment (LCA) is bringing growing recognition that there is more to it than just operational energy considerations.

3.1 Embodied Energy

A building begins its occupancy phase with an accrued energy debt—referred to as embodied energy—comprised of the energy consumed in material extraction, processing, manufacturing, transport, and erection activities involved in constructing the building. Added to this accrued energy debt is the embodied energy resulting from maintenance, renovation, and disposal, over the lifespan of the building. LCA is a strategy to account for this energy debt and the environmental impacts associated with embodied as well as operational energy. While embodied energy is of a lesser magnitude that operational energy in a typical building lifespan, the ratio of embodied energy to operation energy increases as operational energy consumption is reduced through high-performance design strategies and the use of increasingly energy efficient technology. In short, embodied energy and the associated impacts are becoming an increasingly important consideration of the green building dialogue.

3.2 Durability and Service Life

Durability is a primary factor of the embodied energy equation; associated impacts are reduced as they are spread over a longer timeframe. Service life is the measure of durability in buildings and the systems that comprise them. The concept of differential durability recognizes that buildings and building systems are assemblies typically comprised of subassemblies and components, and that the service life of any system may be limited to its least durable component. The least durable component of an IGU is generally the perimeter sealant that provides the hermetic seal of the cavity. The failure of an IGU is most commonly caused by air leaking into the cavity bringing moisture that results in condensation, fogging, and oxidation of aluminum and metal oxide coatings, and airborne particulates that result in deposits on the interior glass surfaces. Occasionally even mold can develop within the cavity. While this may not constitute catastrophic failure of the product from a performance standpoint, it reduces service quality to the extent that replacement is often implemented for aesthetic reasons, thereby limiting the service life of the product.
3.3 Service Life Collapse and Wasted Durability

Float glass is a remarkably durable material with an indefinite service life in the building skin that can be measured in centuries. The IGU has an approximate service life of 30-40 years, with a failure curve that begins within the first year and accelerates as the product ages. A field correlation study reported by Lingnell shows a 14% failure rate in class C+CB certified units, and 3.6% in CBA units at 25 years. [9] Accelerating failure rates eventually result in the decision by the building owner for a complete façade renovation. The IGU construct, with its lack of repairability and with the seal as the weak link, effectively collapses the service life of unprocessed float glass from centuries to a few decades. The reduction in service life in the glass represents wasted durability: latent durability that goes unrealized.

IGUs are a common component of contemporary unitized curtainwall systems. No provision is typically made in the design of these systems to facilitate the removal and replacement of the IGUs. The change-out of an IGU can present a significant challenge; access can be difficult, and re-glazing a new IGU in place problematic. Consequently, renovations of curtainwall facades typically involve removal of the existing façade and its replacement with a new one (Figure 2). It can be seen, therefore, that the seal of the IGU not only defines the service life of the IGU; it may define the service life of the entire façade.

Figure 2. The 1980s curtainwall of the New York Javits Convention Center was recently replaced. The estimated cost of renovating the existing façade exceeded the cost of replacement. The old IGUs ended up as landfill. [10] (Source: Mic Patterson)

3.4 Recyclability

Float glass is remarkable not only for its durability: it is also a perfectly recyclable material capable of producing new virgin material at a reduced energy premium over production from raw materials. But unprocessed float glass is extremely rare in contemporary building facades. Most people—even those within the building construction industry—are surprised to find that architectural glass is generally not recycled. It is occasionally down-cycled (e.g., ground up and used as asphalt fill or landscaping material) but most often enters the solid waste stream and ends life in a landfill. It is ironic that the very enhancements referenced by Selkowitz above—secondary processes implemented to improve the functionality of the material (coatings, laminating, insulating)—result in at least an order of magnitude
collapse in durability and render the material unrecyclable. These considerations tend to necessarily broaden the definition of performance.

4 Design Assumptions for the M-IGU

The use of high performance glazing products have contributed positively to energy savings and thermal comfort in buildings, but durability and recyclability are fundamental sustainability attributes that should not be ignored. Yet the current design of the IGU puts thermal and solar performance into opposition with durability and recyclability. What alternative design strategy could equal or better the performance benefits of coated glass while using unprocessed float glass, resulting in no compromise to durability or recyclability of this primary material?

4.1 Service Life

The glass industry has been working toward establishing a service life of 40 years for IGUs. Recently, there has been talk of doubling that goal, certainly an ambitious undertaking with the current IGU design configuration. The question remains, however, as to whether even that is adequately ambitious in the context of achieving a sustainable built environment, especially without a clear solution to the recycling limitations. Conventional assumptions about durability are commonly inadequate, and doubling the current IGU service life, while certainly helpful, may undershoot the need as well as the potential. It reduces but does not dispense with the wasted durability of the current IGU, and does nothing inherently to establish recyclability of the product. An entirely new approach may be required if current high performance systems are to be transformed to the sustainable systems of tomorrow. Adopting constraints, even seemingly insurmountable constraints, may sometimes provide the motivation needed to alter mindset.

4.2 Constraints are Good

The following design constraints are adopted for this exercise:

- the use of unprocessed float glass.
- the use of fully recyclable materials.
- service life – 1000 years (effectively indefinite).
5 Makeup of the M-IGU (Figure 3)

5.1 Material

Various material components impact the durability of the IGU: glass, spectrally selective films and coatings, seals and gaskets, and the spacer/cassette framing among them. Material assumptions and suggestions follow, but should be considered preliminary, as an evolution of material definitions will be developed in response to future research. Materials need the capacity to be favorably recycled, and embodied energy must be evaluated through a comparative LCA process. Even with a smaller relative embodied energy value, glass is clearly the dominant material comprising conventional IGUs by virtue of its mass (Table 1), increasing the value of its extended service life.

Table 1: Preliminary embodied energy analysis for baseline IGU. Embodied energy values from ICE database. [11]

<table>
<thead>
<tr>
<th>Component</th>
<th>Embodied Energy (kBtu/lb)</th>
<th>Weight per SF</th>
<th>Embodied Energy Use Intensity (kBtu/ft^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Glass</td>
<td>10.10</td>
<td>6.00</td>
<td>60.60</td>
</tr>
<tr>
<td>Argon</td>
<td>2.92</td>
<td>0.10</td>
<td>0.29</td>
</tr>
<tr>
<td>Stainless Steel Spacer</td>
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<td>0.25</td>
<td>6.10</td>
</tr>
<tr>
<td>Sealants</td>
<td>26.51</td>
<td>0.20</td>
<td>5.30</td>
</tr>
<tr>
<td>Desiccant</td>
<td>0.86</td>
<td>0.20</td>
<td>0.17</td>
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<tr>
<td>Unit total</td>
<td><strong>10.73</strong></td>
<td><strong>6.75</strong></td>
<td><strong>72.46</strong></td>
</tr>
</tbody>
</table>

*averaged kBtu/lb for IGU assembly
5.2 Glass

Annealed or heat strengthened glass is used with the M-IGU, without coatings or lamination to assure optimal ease of recycling. The use of annealed glass would provide for greater ease of reuse, as the material could be recut to smaller size to fit a new application. Thermal stresses may require the use of heat-strengthened glass, which cannot be cut after heat treatment. In any case, the use of unprocessed float glass, or minimally processed heat strengthened glass, without the application to the glass surfaces of coatings, laminates, or sealants, eliminates all technological barriers to reintroducing the material to the float process for the production of new material, thereby rendering the glass in the M-IGU fully recyclable.

5.3 Films and Coatings

The strategy here is to keep the coatings from being applied directly to the surfaces of the glass lites. Instead, the coatings are applied to a film suspended within the cavity of the IGU. A precedent for this is the Heat Mirror product, which claims a U-factor as low as 0.05 for a multiple film application. [12] The solar and thermal improvements result in part from the spectrally selective coatings, and part from the cavity partitioning provided by the suspended films, similar in effect to a triple or quadruple glazed IGU, but without the added weight (triple glazed IGUs are 50% heavier than conventional products) and dimensional thickness resulting from additional glass layers. Suspended film IGUs were used in the recent renovation of the Empire State Building. [13]

5.3.1 Durability Harmonization

In any case, the durability of the film would not limit the durability of the M-IGU assembly. The film is envisioned as being loaded in a cartridge within the assembly cavity that can be removed, new film installed, and the cartridge replaced. Thus, neither the service life nor the recyclability is compromised by the application of a coating to the glass surface. It is conceivable that coated glass is someday widely accepted by float producers for reintroduction into the float process. Some claim that thin film oxides readily burn off from the glass melt, and there are reports that some producers do recycle coated cullet. Such developments could render the use of coated glass as a viable consideration supporting the goals of this conceptual exercise. There is, however, still the problem of the durability of the film limiting the service life of the glass.

5.3.2 New Tech Ready

The suspended film strategy as suggested in the M-IGU has the additional benefit of readily adopting the advances in material science so frequently produced by industry over the past three decades. The use of new high-performance low-e coatings could be accommodated simply by changing out the suspended film cartridge, as opposed to changing out the entire IGU, or in the case of unitized curtainwall systems, replacing the entire façade system, a formidable barrier to the adaption of new glazing technology.
5.3.3 Recycling the Chemical Soup
The polymer film with various metal oxide coatings will likely present a recycling challenge to the chemical industry, but one that should be more manageable owing to the separation of the coatings from the glass and the material handling benefits thus provided. However, the viability of this approach as a recycling strategy requires further research.

5.4 Compression gaskets
Wet-applied sealants do not promote ease of maintenance, and are at least part of the reason that the glass in IGUs ends up as landfill. Therefore, compression gaskets are used as an alternative means to provide the seal for the M-IGU. The dry gaskets accommodate the partial disassembly and reassembly of the M-IGU for maintenance purposes.

5.5 Cassette frame
The cassette frame is key to the M-IGU. It combines the primary functions of spacer between the glass lites, replacing the conventional IGU spacer, while also providing a minimal frame designed to facilitate the installation and removal of the IGU from a curtainwall unit.

5.5.1 The cassette frame provides the following functions in sum:
- separates the glass lites to create the air cavity using an integral suspended film cartridge.
- holds the compression gaskets that provide the seal to the glass lites, thereby sealing the cavity between the lites.
- holds the pressure equalization filter that links the cavity to the ambient atmosphere.
- holds the suspended film(s) cartridge with spectrally selective coatings.
- accommodates partial disassembly for maintenance of the interior cavity and components.
- facilitates the installation and removal of the entire assembly within a curtainwall module.

5.5.2 Materiality
The cassette frame is conceived as an assembly built up from extruded, coextruded, or pultruded plastic rails. Various adhesives are available to join the framing members at their corners. Plastics provide the advantage of low thermal transfer, the reason for their application as thermal breaks in the aluminum extrusions that comprise conventional curtainwall units. The use of thermoforming plastics would present advantages in material recyclability. Multiple material types can be configured within the same section using a co-extrusion process as a means to optimize performance attributes. Alternately, wood could be considered as an appropriate framing material, perhaps as part of a composite assembly that incorporated more moisture resistant materials in surfaces directly exposed to the exterior environment or at likely areas of condensation.
5.5.3 Mechanisms
The cassette frame incorporates two important mechanisms not developed as part of this conceptual exercise. The first compresses the seals between the glass and the spacer component (suspended film cartridge) of the frame, and is indicated in the sketch (Figure 3) as a perimeter capture that screws into the frame. It is also easily conceived as discontinuous clamp plates screwed to the frame with a snap cover plate. More elaborate mechanisms may be considered, like a hinged frame subassembly for the inboard lite that would allow for easy opening of the IGU assembly and could facilitate ease of interim maintenance. The benefits of a more elaborate approach to facilitate ease of maintenance would have to be carefully balanced against added cost and complexity.

The second mechanism provided by the cassette frame facilitates the primary cassette function: the easy installation and removal of the IGU assembly within a modular unit of the curtainwall system. One of the significant shortcomings of contemporary curtainwall systems is the challenge presented by post-production removal and installation of an IGU, thereby limiting the design quality and even the service life of the curtainwall system to that of the IGU. Cassette strategies afford the opportunity to adopt new glazing product developments without the need to replace the entire façade system. This is a highly desirable attribute as the development of higher performing products accelerates and the uptake of these emergent products becomes vital to increasing the performance of the building sector. While other design strategies are possible, one precedent is found in the use of toggle glazing systems, in which a toggle mechanism is used to fix the IGU within the curtainwall framing systems. [14] In this concept, the cassette frame could facilitate a toggle connection between the IGU and the curtainwall module into which it is fitted. A gasket seal would also be required between the cassette frame and the curtainwall unit as indicated in Figure 3.

5.5.4 Resilience Attribute
The ability to change out an entire M-IGU assembly with relative ease and rapidity is an important resilience attribute. Storm damage to the glass caused by high wind or impact from airborne debris, or manmade damage resulting from forced entry or vandalism, can be quickly replaced with relative economy. In comparison, IGU replacement in conventional curtainwall systems will typically require the complexity of façade access from outside the building, and present a removal and replacement challenge depending upon the curtainwall unit design, which typically fails to anticipate this eventuality. [15]

5.6 Vented Cavities in Façade Systems
Vented vs. unvented: Earlier researchers explored the potential advantages of a vented IGU cavity. [16] As a precedent, vented shadowbox constructs are used in contemporary curtainwall systems in spandrel areas. The practice is controversial, with some designers preferring the use of unvented variations. [17] The biggest problem with vented shadowboxes is the lack of easy access for cleaning if moisture and particulates in the cavity negatively effect the appearance of the façade. The debate takes place with the assumption of zero-maintenance. Maintenance access to the spandrel area is complicated by the floor slab, mechanical systems, and interior finishes that typically occupy this
zone. Setting the aesthetics of the all-glass façade aside, the spandrel area is an excellent opportunity for a highly insulated, low maintenance, rain screen panel system. This would lower the window-to-wall ratio, affording the benefit of an improved façade system U-factor and providing enhanced building resilience and energy efficiency.

5.6.1 Consideration of a Vented IGU
The advantages of a vented IGU include:

- the elimination of pressure differentials significantly reduces stresses on the cavity seals, virtually eliminating the likelihood of the seal discontinuities that compromise service quality and service life.
- elimination of visual distortion in the IGU caused by the bowing—or “pillowing”—of the IGU resulting from the pressure differential inside and outside the cavity.
- pressure equalization cycles allow any moisture that enters the cavity to dry out.

These are significant advantages. The reduced stresses applied to a pressure gasket approach, as proposed with the M-IGU, diminishes the importance of the cavity seal; even if there are minor discontinuities in the seal, the air exchange is designed to occur through a filtered port, minimizing the potential for lasting effects like trapped condensation and particulate deposits on the glass, which, in any case, are easily removed through routine maintenance procedures.

The pillowing characteristic of a conventional sealed-cavity IGU results in an optical effect in the exterior glass, an often pronounced visual distortion of reflections from the glass surface that is frequently objectionable to the building designer and owner (Figure 4). The sole option to mitigate this affect is to employ a thicker glass lite (i.e., 9mm instead of 6mm) for the outboard lite of the IGU, certainly an undesirable practice from a sustainability and cost perspective. This phenomenon would be eliminated with a vented IGU.

Figure 4. The effects of IGU pillowing are apparent in the reflection of the building (left) in the glass façade (right). (Source: Mic Patterson)
5.6.2 Gas Fills
A vented cavity prevents the use of low conductivity gas fills like argon and krypton commonly used in high-performance glazing products, but the M-IGU also eliminates the need for such gases, as effective U-factors are achievable without them. Service quality is enhanced in the process, as the performance of the gas fill is easily compromised by minor discontinuities in the hermetic seal of an IGU.

5.6.3 Cavity Ventilation Filter
Cavity ventilation is actualized through a filtered port to outside air (Figure 3). The filter material and the size of the port are important design considerations to be determined in future development. The port size should be just large enough to facilitate pressure equalization. The filter should accommodate air passage while trapping particulates and blocking moisture. There are a number of material options for this application with varying behavioral characteristics. Accelerated environmental testing of a mockup or prototype will be required to determine the optimally suited material. The filter would be designed for easy removal and replacement from within the building. The used filters should have the capacity to be cleaned and reused, or recycled, depending upon the filter material employed.

6 Maintenance as a Strategy for Renewal

Order of magnitude service life increases demand a reevaluation of maintenance as a strategy for renewal and regeneration, but maintenance has its own impacts that must be considered.

6.1 Minimizing the Impact of Maintenance

A renewal strategy as diagrammed in Figure 5 allows for maximizing the service life of each component within a system. Maintenance is evaluated in LCA as recurring embodied energy, and adds to the lifecycle embodied energy debt of a building. Design and planning are required to harmonize component service life and facilitate maintenance requirements. Analysis is required to investigate the tradeoff between increased durability and recurring embodied energy.
Figure 5. A renewal strategy using maintenance and restoration (only as needed) as a strategy to extend service life and minimize differential durability. (adapted from Kesik. [18])

Maintenance can also enhance system performance, however, resulting in improved operational energy efficiencies. The aging of air and water seals in unitized curtainwall systems certainly has the potential to compromise performance. Identifying and remedying such a problem presents a considerable challenge, as the seals are concealed from inspection, and impossible to repair in any case. If such systems are to be designed for durability, seals must be easily inspected and replaced as required. The same must be true of the components that comprise the façade system, thus the IGU must incorporate seals that are accessible and replaceable.

The maintenance strategy with the M-IGU is threefold:
- balance maintenance requirements to maximize service life while minimizing recurring embodied energy.
- facilitate ease of maintenance through product design.
- focus on minimal maintenance provided on an as-needed basis.
- maximize the lifespan of each component within the assembly to minimize the effect of differential durability.

6.2 Maintenance Planning: Procedure and Cycle

The actual maintenance requirements for the M-IGU are the most critical unknown, so a conservative approach has been taken in their accommodation. While mechanisms are not detailed, strategies for both incremental maintenance and complete unit replacement have been incorporated, although the incremental maintenance holds the potential to render the complete unit removal an unnecessary redundancy. Unlike conventional IGUs and curtainwall systems, all component parts are intended for easy inspection and replacement, most especially those critical to performance and/or subject to wear, or simply of lesser durability, as with the various seals and suspended films.

6.3 Ease of Maintenance

The assembly is to be designed so that all maintenance procedures can be actuated from inside the building, avoiding the necessity of accessing the façade from the exterior, a generally favorable attribute with high-rise buildings. Maintenance access is provided through the temporary removal or displacement of the inboard lite. Only the replacement of the outboard lite and the inspection and replacement of the seals between the cassette frame and the curtainwall unit may require the removal of the entire assembly.

6.4 Frequency of Maintenance

Minimal maintenance is the goal, but frequency of the maintenance cycles is a critical unknown. Most particularly, how often would the units have to be opened up for cleaning? The pressure equalization filters can be designed for easy servicing, but the removal or displacement of the inboard light, cleaning, inspection, and reassembly would be more involved. Procedures and equipment
could be designed to optimize the process. IGUs, for example, can be quite large in contemporary facades, particularly large residential and commercial buildings. This could present a challenge to the maintenance program envisioned herein. Figure 6 shows a concept for a simple semi-automated device that facilitates the removal, installation, and cleaning of either the inboard glass lite for cleaning of the IGU cavity, or the removal of the entire IGU cassette. The device accommodates local maintenance procedures or the transport of the inboard lite or the entire IGU cassette to a specialized maintenance area.

![Figure 6. A conceptual semi-automated device to aid in the maintenance of the M-IGU by facilitating the removal of the inner lite, or alternatively, the entire unit if required. (Source: Advanced Technology Studio – Enclos)](image)

6.5 LCA and LCCA

Building lifespan is the appropriate but seldom used measure of building performance—resource utilization and environmental impacts—and cost. LEED v4 for the first time rewards LCA. Buildings, however, have rarely been evaluated over lifecycles as long as the 1000 years proposed, and a methodology for this is not readily available and will have to be advanced. Recurring patterns of maintenance will define recurring embodied energy over the building lifecycle. Comparative analysis can then be undertaken with variations in maintenance and renovation cycles, as well as with zero maintenance strategies that require complete façade replacement on a periodic basis.

As with LCA, life cycle costing analysis will be an important aspect of any further development. It is evident that the M-IGU will be more expensive than a conventional IGU on a first-cost basis, but not necessarily when compared with other cassette glazing systems. Either option, however, is likely to be excluded from consideration on many projects simply on a first cost basis. Institutional building owners and other owner-occupiers are more amenable to a lifecycle perspective, but they are likely to be challenged by a lifecycle measured in centuries. Yet it is entirely conceivable that this is what the evolution of a sustainable built environment will demand.

7 Conclusion
A framework for a conceptual prototype has been proposed for an IGU that fulfills stringent sustainability goals. Design constraints include the use of unprocessed float glass, fully recyclable materials, and a service life of 1000 years. Initial proposals for material selection for glass, films and coatings, compression gaskets, the cassette frame, and the treatment of the cavity are outlined. Maintenance planning is added as a new feature for lengthening the effective lifespan of the IGU. Feasibility testing would be done with LCA and LCCA.

The identification of a design approach to the problem of an insulated glass unit that might yield a novel solution with advantages over the conventional approach is the first step. The next steps would involve the preparation of a proposal to enter a rigorous concept development phase as represented in Figure 7. This phase would involve further definition of design and performance criteria, refinement of assumptions regarding material selection, design configuration, maintenance and renovation cycles, design development and material selection in support of performance criteria, costing and market evaluation, and feasibility analysis including preliminary LCA and LCCA. Proof-of-concept studies would also be included in feasibility analysis involving small-scale prototypes as precursor to a comprehensive mockup testing program as part of a following product development phase.

**Phase 1: Concept Development**

![Figure 7. Mapping of concept development process suggested as possible next phase. (Source: Advanced Technology Studio – Enclos)](image)

### 7.1 Feasibility Analysis

At any stage the concept as framed could be proven unfeasible. In particular, the frequency and cost of maintenance is a key variable with many unknowns until a mockup testing program is initiated to deliver performance data. The maintenance requirements will directly impact the LCA and LCCA results, ultimately determining the savings in embodied energy and marketability of the product. Unfortunately, because of the low value the current market places on durability, convincing others of the adoption of a maintenance strategy may prove to be
overwhelmingly difficult, even as landfills overflow. At some point societies must proclaim recyclability as a required prerequisite for production. This conceptual exercise assumes that day has come. Similarly, as recycling processes carry their own energy debt and environmental impacts, materials extracted and used in production must be designed for optimal durability so as to reduce the recurring embodied energy associated with maintenance and end-of-life recycling.

7.2 Constraints Drive Innovation

The embrace of constraints involving durability and recyclability can drive innovation. A service life of 1000-years started out as deliberate hyperbole, but as the consideration of this concept progressed, it has come to seem increasingly reasonable and perhaps even viable. The commitment of resources represented by the building sector demands a level of responsibility in the application of these resources that is only beginning to be confronted in current practice. Considerations of cultural resilience and sustainability will eventually comprise a context where such sensibilities become not only compelling but also mandatory. One thousand years may be an appropriate service life for many building types. It can certainly be argued that changing conditions of use over such a time period must necessarily render any discrete building obsolete. Perhaps, but if buildings are designed to adapt to the evolution of occupancy and use as suggested by Stewart Brand in *How Buildings Learn* [19], then this impact could be minimized, yielding buildings not only designed for longer service life but to facilitate adaptability.

7.3 Renewal and Regeneration vs. Service Life

In a sense, the approach taken here renders the concept of a service life at the scale of building and major building assemblies obsolete, replaced instead by a renewal process that results in perpetual regeneration. An M-IGU may still be operational 1000 years out, yet not contain one component from the original assembly. Yet the assembly was never out of service. Does the concept of service life even apply? The regeneration process required to push the limits of durability may in fact transcend service life, reducing the term’s applicability to the smaller materials and components that comprise these assemblies, parts that can be designed for ease of maintenance and replacement as required, and consequently do not limit the service life of the up-stream systems. Here this regenerative strategy is applied to a singular but ubiquitous glass product. How might this notion translate to other building systems or to the building itself? The *millennial curtainwall system* may well be the next investigation!

References


[4] Selkowitz op.cit., p.4


Cold-bent Glass Laminates Analysis

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Abstract
Glass cold bending consists of deforming the glass elastically prior to lamination or on site, after lamination. The purpose of this study is the monitoring of the spring-back deflections and internal stresses in a cold bent laminate under several temperatures and geometries. A numerical model was built on the basis of material properties found in literature.

Keywords: Glass, Cold bending, Laminated, Interlayer, FEM Model

1 Introduction
Curved glass can be obtained by hot bending above the softening temperature of the glass plies or cold bending above the melting temperature of the interlayer. Curved glass laminates can be obtained either by lamination of hot bent glass, by cold bending of flat laminated glass, or by a “two step” cold bending (also called “warm bending”). The interest of glass cold bending methods comparatively to hot bent method, lies in lower fabrication cost and the final increased optical quality.

Cold bending glass laminates consists in deforming the laminate by pushing a point out of plane and fixing it to the structure on site. This method has been used for the insulated glass units of the Avignon train station façade and the IAC Headquarters Chelsea facade (Figures 1,2). The “two step” cold bending consists in bending the flat panes of glass before lamination. The method has been used for the Strasbourg train station (Figure 3). The interest of this method is the fact it that takes less force to bend a thin layer of glass than a laminate.

The present study focuses on this second method and its objective is to monitoring the behaviour of the interlayer which prevents the glass from becoming flat again.

For this purpose, a numerical model representing a two glass ply laminate was built. Two interlayer materials were modelled: PVB and ionoplast. These products have been extensively tested; their mechanical properties are easily accessible and they are by far the most commonly used interlayers in the construction industry for such applications.

The viscoelastic behaviour of the interlayer depends on time and temperature. The present study assumes an instantaneous loading and a constant temperature and the variable is the relaxation time.
2 Material properties

Sodocalcic glass is currently used in the construction industry. Its mechanical properties are defined by EN 572-1. The glass is modelled as an elastic isotropic material with $E = 70\text{GPa}$, $\nu = 0.22$ (thus $G = 28.7\text{GPa}$).

The mechanical properties of the interlayer depend on the polymer itself and vary widely from one manufacturer to the other. The interlayers are modelled as an isotropic viscoelastic material with time-dependent properties at a given temperature. The mechanical properties of the PVB are derived from the following equation [1]:

\begin{align}
G \ (T > 20^\circ\text{C}) &= 0.008 \ (100 - T) - 0.0011 \ (50 + T) \ \log(t) \\
G \ (T < 10^\circ\text{C}) &= 2.0 - 0.2 \ \log(t)
\end{align}
The Poisson coefficient of the PVB varies from $v=0.23$ below 10°C up to $v = 0.49$ and the $E$ values are derived from $E = 2G(1+v)$. This approach gets round the numerical singularity issues related to inversion of the stiffness matrix of the interlayer. However, the non-commercial FEM software used for this study showed relatively good results with nearly incompressible materials as opposed to typical commercial softwares.

The ionoplast mechanical properties are based on values provided in [2] and summarized in Table 1.


Table 1. Interlayer mechanical properties

<table>
<thead>
<tr>
<th>Temperature</th>
<th>PVB</th>
<th></th>
<th>Ionoplast</th>
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<td>20°C</td>
<td>1.34</td>
<td>0.230</td>
<td>567</td>
</tr>
<tr>
<td>24°C</td>
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<tr>
<td>30°C</td>
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<td>0.330</td>
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<tr>
<td>80°C</td>
<td>0.05</td>
<td>0.490</td>
<td>2.49</td>
</tr>
</tbody>
</table>

3 Models construction

The model is made out of 2 glass plies measuring 2400x800x4mm bound together with 1.52mm interlayer thickness. The size of panel was selected in order to compare the numerical results to that of cold bending experiments made by other teams. The target curvature for the initial shape corresponds to R=5m. The moment can be expressed as $M=EI/R$ where $I$ stands for the second moment of inertia.

Two sets of boundary conditions were considered for the model. In the first set the panes are simply supported at mid span and free at the ends, where the couple is applied. In the second set, the panes are supported at both ends and let free to slide away as the interlayer creeps. The couples are applied at the same location as in the first set. One technique used in the industry consists of forcing the plane glass panes onto a cylindrical jig by applying linear forces on the edges. The true deformation under a load applied onto the short edge only is not perfectly cylindrical but parabolic: $f=p(l/2)^2/384EI$. The difference between the parabolic deflection curve and the 5m radius circle is about 0.4% at ¼ of the span and does not exceed 1% close to the ends for the 2400x800x4mm panes used in this case. This discrepancy is acceptable for the purpose of this study.

The finite element mesh is made out of 50mm large hexahedron cells. Each one of the three layers is one element thick. Parabolic hexahedrons (HEXA20) are used in order to accurately represent the variation of the shear in the thickness of each component.

It was verified that meshing with HEXA20 elements is satisfactory by performing a comparative model of 4x4x4mm large elements versus the 50x50x4mm elements. Specific attention is drawn to the numerical error since the model involves elements with small thickness and where the stresses range from 1 to 1000 in the constitutive components.
The glass elements are assigned elastic isotropic properties. The time-dependent properties of the interlayer were obtained by a step by step variation of E and v in time, for each sub step of the calculation. A non-linear static Newton Raphson type analysis is performed to model for the non-linearity of the time-dependent interlayer material. The overall computation is subdivided into 10 steps. At each step the mechanical properties of the interlayer are updated. The analysis also takes into account the variation of the deflection and stresses which are computed at each calculation step. Each step is a static analysis which reuses the deflection and stresses from the previous step.

The Figure 4 provides the computation scenario for the non-linear static analysis. In the first step (statnl0), the glass in bent with the application of the couple at the short edges. In this case the interlayer properties are artificially set to low values in order morph the displaced nodes during the staged analysis. The deflection and stresses in each pane are exactly the same as for one single sheet of glass.

In the following step (statnl01) the interlayer is assigned its full mechanical properties. The model is not yet unloaded and the deflections are unchanged since the previous step.

In the following step (statnl1) the couple is removed and the instantaneous elastic spring-back is observed. A shear transfer occurs at the interface of the interlayer.

In the following steps (statnl2 to statnl10) the mechanical properties of the interlayer change. N corresponds to different steps in time for the computation of the viscoelastic behaviour of the interlayer.
<table>
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<th>Step number</th>
<th>Description</th>
<th>Springback</th>
</tr>
</thead>
<tbody>
<tr>
<td>statnl 0</td>
<td>Two separate sheets of glass are cold bent. <strong>Interlayer</strong>: absent. <strong>Boundary conditions</strong>: each sheet is has its own isostatic supports at the angles. <strong>External load</strong>: bending torque at short edges. <strong>Internal load</strong>: induced by torque in the glass.</td>
<td>None</td>
</tr>
<tr>
<td>statnl 01</td>
<td>After lamination, before suppression of the torque. <strong>Interlayer</strong>: present. <strong>Boundary conditions</strong>: each sheet is has its own isostatic supports at the angles. <strong>External load</strong>: bending torque at short edges. <strong>Internal load</strong>: induced by torque in the glass, not instantly transferred through interlayer since no unloading.</td>
<td>None</td>
</tr>
<tr>
<td>statnl 1</td>
<td>Removal of the torque, first stress transfer in the interlayer, creep of the interlayer. <strong>Interlayer</strong>: present. <strong>Boundary conditions</strong>: underside sheet has isostatic supports at the angles, no support on other sheets of the laminate. <strong>External load</strong>: none. <strong>Internal load</strong>: induced by previous stress field in the glass, instantly transferred through interlayer.</td>
<td>Primary</td>
</tr>
<tr>
<td>statnl 2</td>
<td>Creep of the interlayer, under stress field. <strong>Interlayer</strong>: present. <strong>Boundary conditions</strong>: underside sheet has isostatic supports at the angles, no support on other sheets of the laminate. <strong>External load</strong>: none. <strong>Internal load</strong>: induced by previous stress field in the glass, instantly transferred through interlayer.</td>
<td>Secondary</td>
</tr>
<tr>
<td>...</td>
<td></td>
<td></td>
</tr>
<tr>
<td>statnl N</td>
<td>Creep of the interlayer, under stress field. <strong>Interlayer</strong>: present. <strong>Boundary conditions</strong>: underside sheet has isostatic supports at the angles, no support on other sheets of the laminate. <strong>External load</strong>: none. <strong>Internal load</strong>: induced by previous stress field in the glass, instantly transferred through interlayer.</td>
<td>Secondary</td>
</tr>
</tbody>
</table>

**Figure 4.** Calculations steps
4 Results analysis

The FEM analysis shows an expected reduction of the internal stresses with time, along with the reduction of the deflections.

The deformation of the compound at stage 0 (statnl0) corresponds to the cold bending of two separate sheets of glass, since the sheets are freely moving before they are bound together.

After the lamination step, the total stiffness is different and the deflection after the laminate is unloaded corresponds at first to the elastic spring-back. The elastic spring-back depends on the initial properties of the interlayer (E0, G0 and v0). The delayed spring-back corresponds to the relaxation of the laminate in time. The deflections are given in Figure 5.

![Figure 5. Out of plane deflection monitoring in the samples](image)

The observation of the axial stresses SXX shows that the maximum axial stress in the extrados and intrados of the laminate are approximately +/-30 MPa initially and decrease to +/-25 MPa at 160s. The axial stresses generally decrease as the deflection of the laminate reduces with time.

The observation of SXX in one glass panel shows that the stress in the top surface is different from the stress in the bottom surface. The difference is due to the interlayer opposing resistance to the glass from recovering a planar shape. This asymmetry corresponds to the displacement of the neutral axis in the thickness of the glass. It is verified that as long as the laminate remains curved, the residual elastic bending moment in both glass plies is balanced by shear forces occurring at the interface of the interlayer.

The Figure 6 shows the relationship between all the parameters. The shear force is obtained through integrating the actual shear stress over interface area.
Figure 6. Normal stresses at glass at the face of glass and equivalent resisting moment in the interlayer

The observation of the shear stresses in the glass/interlayer interface plane shows SXY stresses of about 1 MPa while the intrados and the extrados of the laminate show alternate symmetrical tension and compression. Figure 7 shows the stress patterns observed in the PVB laminate.

The behaviour of the ionoplast laminate is slightly different from that of the PVB laminate. Due to a higher elastic modulus, the instantaneous spring-back is much smaller and the overall creeping of the ionoplast is slower. Transverse shear stresses are also higher and well distributed transversely.

Figure 7. Axial and shear stress fields in laminate, intrados and extrados lites
5 Conclusions and further development

This FEM analysis gives out results corresponding to our expectations about the behaviour of the creeping of the interlayers in laminated panels. The outputs of the model corroborate the level of resisting shear stress at the interface of the interlayer. The numerical model acknowledges that cylindrically cold bent laminates are able to keep their shape for a long time. We have noticed a stabilization of the variation of out-of-plane deflections (DZ) after 360 seconds. This behaviour occurred for both PVB and ionoplast laminates.

Our study depends on a precise description of the evolution of the shear modulus with respect to time and temperature. This numerical study raises the following questions, which are still under investigation and shall be supported by further experimentation on actual samples:
- How does the system react under an additional stresses?
- How does the system react under external loading, such as permanent load, dynamic wind load or construction loads?
- What about cyclic variation of temperature, prior to installation and during the life cycle of the building?

6 Summary

This study consisted in modelling the relaxation of a laminated cold bent glass laminates. The models show the variation in time of the deflections, the effective shear transfer at the interlayer and residual stresses in the components of the laminate. It has been verified by calculation on the basis of material properties found in the literature. The research presented in here has been followed by sample testing at the ITKE - Institute of Building Structures and Structural Design, University of Stuttgart [3].

Acknowledgements

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References

Dynamic façades: Solving the green building challenge without design compromise

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Abstract
Green building standards such as LEED, ASHRAE 189.1 and the International Green Construction Code (IgCC) recognize the need for windows to provide natural daylight and views, yet this requirement is often at odds with the need to reduce building energy and can impact occupant comfort creating a significant design challenge. Indeed there is significant controversy currently over data that suggests that buildings meeting the green building standards do not actually have lower energy usage than conventionally designed buildings. This is adding additional fuel to arguments for the reduction of allowable window area in both baseline and green buildings codes. Electronically tintable glass can offer a solution which avoids having to trade off daylight and views with energy performance and occupant comfort, allowing more glass to be used without energy penalty AND without causing thermal or visual discomfort for occupants. A range of new case studies is reviewed where dynamic glazing has been used to solve acute solar control problems through retrofits, and also used in new construction where the architect has been able to execute on their design vision of a highly glazed building without having to compromise either energy performance or occupant comfort.

Keywords: dynamic glass, electrochromic glass, green building, daylighting, views

1 Introduction
From the very beginning of architecture, man has sought to bring sunlight into his buildings and thus was born the window. So what drives the use of windows? Although glass is a wonderful design tool, the main reason we put windows in buildings is for people; because people love the view and connection to the outside and the access to natural daylight, and the way it makes them feel. In fact, the more we understand about the impact of changing daylight patterns on the body’s circadian rhythm and the influence of daylighting and views on the health, well-being and productivity, the more we understand about the importance of windows in buildings.

Green building codes and standards such as BREEAM in the UK, the U.S. Green Building Council’s LEED program, which is codified through IES/ANSI/ASHRAE 189.1, and the International Green Construction Code (IgCC), recognize that a sustainable design is not just about energy efficiency and all have sections that require the provision of daylight and views to the outside. However, the provision of more daylight can come with unintended consequences to occupants in the form of thermal and visual discomfort. This is often due to too much heat gain and glare coming through the windows since the conventional static building envelope...
can’t respond to the ever-changing exterior environment. As such, the benefits of access to natural daylight can often be offset by thermally and visually uncomfortable spaces. In the case of glare, occupants pull blinds and shades and then block the admission of daylight and the view to the outside, negating the benefits of daylighting and views. The use of manual blinds also causes the building energy use to go up compared to the design loads because of the increased use of electrical lighting to compensate for the fact that the blinds remain drawn long after the glare condition has gone.

Indeed, in recent years, it has come to light that a number of green certified buildings are actually not any more energy efficient than their non-green designed counterparts. This has led to the initiation of energy performance verification requirements of the as-built designs.

![Figure 1. A pictorial representation of the Green Building Challenge. How to optimize both energy efficiency and daylight and views without compromising occupant comfort.](image)

In parallel, the push for increased energy performance in buildings has also given rise to significant debate about the role of windows, and more importantly, the amount of glass that should be used [1, 2]. Windows are often seen as the weak link in a building because of their lower insulation value and higher solar heat gain compared to a solid wall. Indeed, in both Europe and North America we are seeing an increasing trend to reduced window area in new building codes through increasing stringency of insulation values and whole building energy efficiency targets (Part L of the Building Regulations in the UK), or through specific window area limits as in the International Energy Conservation Code (IECC) 2012. These trends are also being mirrored in the green codes as demonstrated very recently by the highly public debate over the proposed reduction in the allowable window area from 40% to 30% in the prescriptive path of ASHRAE 189.1 [3]. After significant pushback from the daylight design and research community as well as the glass industry it was withdrawn, but the debate continues.
The window to wall ratio debate within the green codes especially is leading to a dichotomy between providing acceptable window area for daylighting and views and achieving energy efficiency targets, all while providing occupant visual and thermal comfort. This is a major challenge for “green building” design as is pictorially represented in figure 1.

2 An Elegant Solution
Electrochromic (EC) glazing can provide an elegant solution to this design challenge. At the touch of a button, a command from its control system or a building automation system, EC glass can modulate its solar heat gain coefficient (SHGC) and visible light transmission (VLT) over a wide range, stopping at points in between. Current products provide a VLT range of, for example, 60%T to 1%T with a corresponding change in SHGC of 0.41 to 0.09 respectively (see example in figure 2). Moreover a range of products with different dynamic ranges and color aesthetics are available as needed to suit the application and design requirements.

EC glass saves energy in all climate zones by providing passive solar gains during heating seasons, minimizing cooling loads during cooling seasons and providing maximum daylight harvesting potential, replacing the use of electric lights with natural light in all seasons. Additionally, because products today can achieve transmissions of 1% VLT or less, they can control glare without using shades or blinds, thus preserving the view and connection with the outside in contrast to mechanical alternatives which block or mar the view. Studies have shown that 1% VLT is required to be able to control the glare [4, 5].

Figure 2. Graph of visible light transmission (VLT) versus solar heat gain coefficient (SHGC) which demonstrates the heat gain and light transmission range of a high performance EC product compared with examples of standard static glass.
EC coatings can be cleanly integrated into a double or triple glazing unit just like traditional coatings (see figure 3) and different exterior aesthetics can be achieved by adding tints or another coating to the exterior glass pane.

Figure 3. All ceramic thin film electrochromic insulating glass unit.

The ability to modulate the sun’s light and heat provides the designer with a controllable heat and light valve for their building; the amount of light and heat coming into the space is tuned depending on the exterior environmental conditions and the needs of the occupants. By dynamically controlling the light and heat flow, significantly more energy savings can be captured than when using a static façade solution as well as providing enhanced occupant comfort whilst maintaining exterior views. As a result the use of EC glass provides an architect with the ability to design with more glass, thus providing the needed access to daylight and views, without energy or comfort penalty.

The following case studies demonstrate how dynamic glass can be used to provide architects with a tool that can expand design possibilities for the use of glass and allow for optimum daylighting and views while compromising neither energy efficiency nor occupant comfort.

3 A “Green” Glass Cube

The use of glass cube structures in architectural design is all the rage currently. With such a large area of glass, ensuring both energy efficiency and occupant thermal and visual comfort is a challenge, especially in harsh climates. An example of how EC glazings can meet this challenge is demonstrated in figures 4, 5 and 6 which show EC glass implemented in the Morgan Library expansion at Colorado State University (CSU), a LEED® Silver certified modern glass cube designed by architects at Studiotrope. Preserving the transparency of the glass building was a key design objective for the project yet the university also wanted
to showcase sustainability and efficiency while reflecting the virtues of an open and safe campus.

**Figure 4.** Exterior view of the Morgan Library at Colorado State University where EC glazing has been installed in a modern glass cube design to tame the intense western sun. Photo ©Kevin Eilbeck Photography.

**Figure 5.** Interior view of the Morgan Library at Colorado State University. The glass is shown here in the highest transmission state. Photo ©Kevin Eilbeck Photography.

In Colorado the sunlight is intense due to the high altitudes, especially on the west elevation in the afternoon, which is challenging to mitigate using
conventional shading methods. In fact, daylight modeling of the space showed that an extremely dense high coverage shade solution would be needed to control the western sun, which would have negated the openness and transparency objectives of the design. As a result, making such a highly glazed design work with the conventional solutions would have been extremely difficult.

![Figure 6. Interior view of the Morgan Library at Colorado State University showing the glass being controlled in two zones. The upper zone is in the fully tinted state whilst the lower zone is in an intermediate transmission state. Photo ©Kevin Eilbeck Photography.](image)

A second example of a glass cube design using EC glass is shown in figure 7. Here Florida East Coast Realty (FECR), the developer of the property, was inspired by Apple’s now iconic cube design of their Manhattan store when planning the addition to their high profile building on Miami’s Brickell Avenue. However, they were also keenly aware of the negative aspects of highly glazed walls on two sides of the cube in the even more challenging climate of Miami, Florida. EC glass was the solution selected for the project because it could provide the aesthetics of an all glass wall while not sacrificing the visual and thermal comfort for TD Bank, FECR’s sustainable minded tenant. Even with the two story glazing facing south and west, EC is capable of controlling the light and heat entering the space, blocking 91% of the solar heat gain and 98% of the
visible light entering the space keeping the space comfortable for the bank employees and customers even on Miami’s brightest and hottest days. The EC glass tints and clears automatically based on the amount of solar energy that is present on the exterior — and desirable on the interior. The automated system allows an entire elevation to be tinted individually or in tandem and they can also be controlled manually with just 2 wall switches.

4 Energy Efficient Historic Preservation

Figures 8 and 9 illustrate another application for EC glass where energy saving performance is a requirement along with daylighting, but yet without risk of fading, as well as preservation of the historic building appearance. Pictured in the figures is one of the renovated skylights containing EC glass over the St. Johnsbury Athenaeum in St. Johnsbury, Vermont. The St. Johnsbury Athenaeum is the oldest art gallery in the U.S. that still maintains its original design. One distinctive element of the building is its Victorian skylights which flood the gallery’s interiors with natural light and uniquely enhance the viewing experience of the well-known masterpieces such as Albert Bierstadt’s Domes of Yosemite. Unfortunately, though, natural light poses a threat to the Athenaeum’s art collection and when the skylights deteriorated beyond repair the leadership needed to find a better solution for protecting the gallery’s contents. Replacing the skylights with traditional static glass would have required the addition of mechanical shades or sun controls that would have not been in keeping with its original appearance as well as severely compromised the appeal of the gallery and the experience of the visitors.
**Figure 8.** St. Johnsbury Athenaeum skylight renovation using triple pane EC glass with a textured inboard lite to match the look of the original glass. The EC installation provides excellent energy performance, as well as fading protection and thermal comfort. Photo ©Bob Jenks Photography.

**Figure 9.** Inside view of the skylight with EC glazing at St. Johnsbury Athenaeum. Photo ©Bob Jenks Photography.

The project architect, John Mesick, specified triple pane EC glass to provide fading protection as well as dynamic light and solar control combined with excellent thermal performance and protection from condensation. The U.S. DOE
has identified low U-factor windows with dynamic solar control as a key element of zero energy facades [6] and EC combined in a triple pane provides the optimum energy performance. Modeling studies have shown that in this configuration EC glass can result in building energy savings greater than 50% compared to a building glazed with single pane glazings and 15% more than a building glazed with standard triple pane low-e [7].

EC glass also provides excellent protection against fading and sun damage which is important for sustainable design as it can help preserve the lifetime of interior finishing products. Damage to fabrics and artwork occurs not just from exposure to UV light, but also from exposure to visible light and direct heat. In addition to laminated glass on the inboard lite (needed by code for sloped glazing) which blocks out most of the UV, the EC coatings block the other wavelengths of light that cause fading and reduces direct heating of the objects in the space. In the fully tinted state, EC glass in this configuration blocks 99% of the light (UV and visible) that causes fading and 87% in its fully clear state [8]. This compares to ~80% for a double silver low-e glazing with a laminated inboard lite.

In addition, the inboard laminated lite contained textured glass to match the look of the original glass. Mesick stated, “It was critical that the skylight preserve the authentic atmosphere people experience when they visit the Athenaeum. (EC) glass allows us to do that.”

Often in museum and art gallery applications color rendering is an important requirement. Even though in its tinted states EC glazing has a blue hue, when the EC is zoned and controlled appropriately and there is sufficient mixing of light in the space, good color rendering in a space can be achieved to meet the stringent requirements for viewing artwork [9].

5 A Solution for a Most Challenging Problem

Figures 10 and 11 illustrate the application of EC glass at the State of Wyoming’s Torrington Port of Entry, located near the Nebraska border in Southeastern Wyoming. While not strictly a “green” design project, this case study illustrates how EC glass can be the only fully effective solution to some acute design challenges. The Port of Entry serves as a busy weigh station at the intersection of U.S. Highways 26 and 85 where agents promote traffic safety by monitoring commercial vehicles and ensuring compliance with state and federal laws. To best perform their jobs, the agents need clear and unobstructed views – from all angles, at all hours of the day, and in all weather conditions. The existing weigh station had significant sun management issues. Intense sunlight and heat presented challenges during the summer, while snow glare added complexity in the winter such that baseball caps and sunglasses became mandatory accessories for agents monitoring traffic from inside the building.

When a new port of entry facility was required, architect, Douglas Selby, of Douglas Selby and Associates worked with daylighting consultant, Paul Hutton of Hutton Architecture Studio (now part of the Cuningham Group) to develop an elegant solution with EC glass. They evaluated conventional methods of sun control such as interior blinds or shades and other design ideas that involved exterior shrubbery and trellises and rejected them because all would have
blocked or significantly obstructed the view. They felt that using EC glass was the only effective solution to the problem.

Figure 10. Torrington Port of Entry where EC glass has been used to solve an untenable design challenge of preserving the view at all times of the day and year. This image shows the glass in the highest transmission state. Photo ©Kevin Eilbeck Photography.

Figure 11. Torrington Port of Entry, showing the EC glass in the fully tinted state and demonstrating the preservation of an unobstructed view to the outside. Photo ©Kevin Eilbeck Photography.

In this application the EC glazing automatically tints or clears in response to changing daylight conditions, managing glare and solar heat gain while maintaining unobstructed views outside. In the Torrington facility, sensors are
programmed to tint the glass automatically to let the appropriate amount of light in through the glass throughout the day which was a feature critical to the visual success of the Port of Entry.

Since then, EC glazing has been used in multiple different types of port of entry including at international border crossings such as is shown in Figure 12 at Ajo, Arizona (2012) and at the US Border Patrol's Land Port of Entry at Donna Texas, and for the Minnesota Department of Transport (2014).

![Figure 12. Ajo Border Station in Arizona where EC glazing is used to control solar heat gain and glare, allowing officers a clear view outside at all times. Photo ©SAGE Electrochromics, Inc.](image)

### 6 EC Glass in Retrofits: Fixing Design Problems

EC glass can also be used in retrofit applications to solve heat and light control problems associated with existing designs. Take for example the renowned Kimmel Center for the Performing Arts located in Philadelphia which was designed in 2001 by Raphael Viñoly. Located on the Avenue of the Arts, it is an architectural icon with a huge barrel vaulted fully glazed roof housing multiple concert halls, theatres and large public spaces. However, the Dorrance H. Hamilton roof top garden, which was originally designed as a rentable space for private functions with amazing panoramic views of the arts center and the surrounding city, was almost uninhabitable from May to September with temperatures up to 50°C (122°F). The Center’s management had to turn away a thousand inquiries annually for renting the space.

In a renovation designed by BLT architects completed last summer, the rooftop garden has been enclosed in a glass box structure. The design employs EC glass in the roof in order to maintain the views of the Center’s vaulted dome and of the city and public spaces, yet maintain a comfortable temperature year round (see figures 13 and 14).
Figure 13. The exterior view of the Dorrance H. Hamilton roof top garden in the Kimmel Center for the Performing Arts. EC glass is used in the roof to control the heat gain and provide a comfortable space year-round.

Figure 14. The interior view of the Dorrance H. Hamilton roof top garden, showing the EC glass installed in the roof.
7 Conclusions
The impact of being able to design with more glass without energy or comfort penalty should not be underestimated. Glass is a key architectural design tool and provides significant design flexibility for architects. Sustainable design standards and codes recognize the need to use glass to provide occupants with access to daylight and views, because of the positive impact that it has on people's health and well-being, yet doing so often requires compromising energy performance and at times occupant thermal and visual comfort. Dynamic glazing can relieve the constraints enforced on designers by static building envelopes when balancing architectural design with occupant comfort and energy efficiency. The above mentioned case studies clearly demonstrate that EC glass can provide an elegant façade solution which achieves both the competing goals of high energy performance and access to daylight and views, without compromising occupant thermal and visual comfort. The ability to maintain architectural design freedom while still providing an energy efficient AND comfortable building is invaluable. This value will continue to increase as energy efficiency targets rise and as the importance of creating people friendly work spaces is further appreciated.

References
[9] Based on the Krochmann damage function which is the weighted average of the wavelengths from 300-500nm that cause fading and damage to materials. Calculations done using the LBNL developed Window 6 program.
Integrated façades: How technology development and building codes are shaping the future

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Abstract
The building envelope is the cornerstone of a high performance building design. Without it building energy efficiency is poor even with the most advanced lighting and HVAC systems. The building envelope also has many functions. From an energy efficiency perspective it provides thermal insulation, control of radiative heat gains and losses, and daylight to offset electrical lighting. In addition, fresh air crosses the building envelope to improve indoor air quality; windows provide not just views to the outside but also a connection to the external world, and through the various degrees of transparency communicate a corporate image to the outside. The building envelope is also the starting point for the thermal and visual comfort for its occupants. The design of a commercial building has to take all of these – often conflicting – objectives into account.

The DOE roadmap for zero energy buildings names three necessary envelope technologies: Low U-factor fenestration, dynamic solar control and integrated facades with dimmable lighting controls. High performance building standards, such as ASHRAE 189.1-2011, already recognize the use of dynamic fenestration as an efficient design element, and we can expect minimum energy codes to adopt similar approaches in the future. The US Green Building Council's LEED standard requires provision of daylighting and views as well as high energy efficiency. These requirements can be contradictory to each other because providing sufficient useful daylight through glazed areas often means uncomfortable glare and heat and increased building energy use. The need to provide dynamic control for light and heat is critical in minimizing the tradeoffs between providing daylighting and views and energy efficiency.

This paper examines how high performance buildings must be designed to dynamically respond to daylight to both achieve optimum energy efficiency and provide a comfortable environment for its occupants. It also examines how the energy codes need to change in order to achieve near net-zero buildings.

Key Words: Integrated facades, dynamic glazing, dimmable lighting controls, dynamic shading, dynamic glare control

1 Daylighting and Views

Human development has for millennia involved bringing light into shelters, and until fairly recently the only tools were daylight and fire. This was expressed well by John Pierson in an article in the Wall Street Journal [1] when he observed that
'Ever since the first cave people crept indoors for safety, humans have sought to bring sunlight in from the outside'.

Since then, the positive health and well-being benefits of daylight of entraining our circadian rhythms have been proven and well documented [2]. It is, therefore, understandable that we crave for daylight in our buildings, and perform best when it is given to us, whether we are performing office tasks, factory work, school work, shopping (well, we buy more!), or recuperating in a hospital.

The challenge in today’s “green building” design is to attain a good balance between energy savings, occupant visual and thermal comfort and the access to daylight and views. For example, a number of LEED certified buildings, while providing good access to views have no better energy performance than non LEED certified buildings, and with large expanses of glass have the potential to cause significant thermal and visual discomfort if there is insufficient solar control and a planned dynamic response for glare. Any two of the above can be relatively straightforward to achieve, but achieving all three is significantly more challenging and requires the help of technology developments.

2 Energy Benefits of Integrated façades

The energy efficiency of a building is largely dependent on the design of the building envelope, or façade. Energy can be transported across the building envelope by three different physical mechanisms. These are (1) conductive transport, which is the term used for describing how energy is gained or lost in the building because of temperature differences between the inside and outside, (2) radiative energy gain or loss, which describes how solar heat during the day may help or hurt the energy balance of the building, and (3) convective heat loss or gain, which occurs when the building envelope is fairly open or leaky. In this paper we focus on contributions from the first two physical mechanisms. While the third continues to be important, it needs to be addressed by technologies that are beyond the scope of this paper.

The pathway to net zero energy buildings has partly been defined already by U.S. Department of Energy [3] (see figure 1). As can be seen, improvements in the building envelope performance are critical but are not sufficient. A significant portion of the energy savings occurs when those improvements are coupled with daylight responsive lighting controls. By using the term integrated insulating dynamic façades, or integrated façades for short, we refer to building design that has:

1. Effective daylighting design
2. Energy efficient fenestration with
   a. Low U-factor (as appropriate for the climate zone) and
   b. Dynamic solar control, including thermal comfort for occupants
3. Dimmable lighting control
4. Dynamic response for glare
Figure 1. The impact of Integrated façades on energy savings in the US building stock. Integrated façades represent the pathway to net-zero energy buildings. From Arasteh et al., LBNL report number 60049 [3].

The impact of dimmable lighting controls, which is substantial, is also seen in the following figure (figure 2) that was the result of building simulations performed by researchers at Pennsylvania State University on the standard 3-story office building which is routinely used to verify the performance of the model building energy code ANSI/ASHRAE/IES Standard 90.1 [4].

In this figure, we see that, for the case where no daylight responsive lighting controls are used, the total building energy consumption increases approximately linearly when the window-to-wall ratio (WWR), defined as the percentage of the exterior wall that is glazed, is increased. This makes sense, because the glazing area of the building is typically not as highly insulating as the opaque portion of the envelope, and in addition the windows permit the solar load on the building to increase if nothing is done about managing the overall energy balance.

However, when you harvest the daylight and allow the electric lights to be dimmed or turned off, the energy usage of the building can actually go down as window area increases. At a certain window area, when there is sufficient daylight in the space and all the electric lights are turned off, additional window area will then cause loads to start to increase because of additional solar gains and conductive losses/gains. This explains the characteristic “U” shaped curve that you see in figure 2 when continuously dimming lighting controls are utilized. The exact depth and location of the minimum depends on several factors, such as climate zone, building orientation, fenestration performance, insulation of the
opaque wall, depth of daylight penetration, interior design and reflectances, to mention a few.

Figure 2. Effect of lighting control on building energy savings. Information from a modeling study in 2010 by S. Treado, R. Mistrick et. al. at Penn State University

Ideally, each building is modeled in a parametric fashion to determine its optimum window-to-wall ratio. The better the daylighting design and fenestration performance the greater the optimum window area and the flatter the minimum is, such that increases in WWR over a wider range have little impact on the building energy. In a well-designed integrated façade the optimum WWR can exceed 50%. In fact higher window to wall ratios can have building energy performance better than an opaque wall as long as the façade and interiors are designed well and effectively integrated into a good daylighting design.

As an example of the performance an integrated façade can achieve, we refer to the paper published by Lawrence Berkeley National Laboratory regarding an installation in a conference room at the Department of Energy in Washington DC which is fitted with automated electrochromic glazing in a high performance window system integrated with automated dimmable lighting controls [5] (see figure 3).

In this case, the total lighting energy savings were 91% compared with the base design, and the total energy savings were near or over 40% compared with the base design.
3 The Importance of Good Daylight Design

Implementation of good daylight design is critical in achieving the optimum energy savings potential that integrated facades promise. A superior daylighting design achieves all of the following objectives:

1. Superior daylight performance by
   a. Bringing as much daylight as possible deep into building to maximize daylight harvesting
   b. Providing views and “connection to outside”

2. Occupant comfort by
   a. Avoiding direct sunlight on critical visual tasks and other types of glare.
   b. Avoiding thermal discomfort

3. Superior energy performance by
   a. Minimizing electric lighting energy use (see 1.a.)
   b. Controlling radiative gains and losses
   c. Controlling conductive gains and losses

4. Design interest

Several techniques are known that help achieve the above objectives. For example, windows should be placed high along the wall to allow daylight to penetrate deeper into the space (by, for example, using clerestory glazing) with light shelves and sloped ceilings. Skylights should be used whenever possible to get daylight into the core of the building. Perimeter offices as well as interior offices and conference rooms should have glass walls to permit daylight penetration further into the building, thus creating a larger daylit perimeter zone. Good interior design consisting of high interior reflectances and low partition...
heights also promote good daylight design. An example of good design is shown in figure 4 below.

![Figure 4](image1.jpg)

**Figure 4.** An example of a good daylighting design with glass walled perimeter offices. Photo © Bruce Damonte.

![Figure 5](image2.jpg)

**Figure 5.** An example of the solutions occupants will create if there is not a planned dynamic response for glare. Security checkpoint at Chicago Midway Airport, where bins have been balanced on the horizontal mullions of the curtainwall to block the glare.

In all cases, once you admit light into the building, the light must be effectively managed in order to avoid unwanted glare and uncomfortable heat. A dynamic response for glare is essential: Otherwise the performance of a, in other respects, great daylighting design, will be negated by occupants who will be creative in developing their own methods for glare control such as cardboard, paper, or manual blinds etc! Such an example is shown in figure 5 which shows the lengths TSA officers are going to in order to deal with disabling glare on their
computer screens at Midway airport. These “creative” glare control solutions generally remain in place long after the glare condition has abated and block daylight admission and any energy or human factors benefits that the original design intended.

Other pitfalls related to glare should also be avoided. Especially critical is the avoidance of contrast glare such as is shown in figure 6 which demonstrates the unintended consequences of using small punched opening windows in a façade. The lights in the room have to be turned on or blinds pulled in order to counteract the contrast between the bright window openings and the dark walls, negating any energy savings and human factors benefit from harvesting daylight and also blocking the view to the outside.

Figure 6. Excessive contrast glare caused by the use of small windows in a classroom. Photo courtesy of TRC (formerly Heschong Mahone Group).

4 Technology Solutions

The availability of advanced façade technologies now provide designers with the tools to design façades that can meet the “green building design challenge” by providing the trifecta of high energy performance, daylighting and views without compromising occupant comfort. We will discuss here technology availability in the key elements of a zero energy integrated façade; low U-factor fenestration with dynamic solar and glare control and lighting controls.

4.1 Low U-factor fenestration:

Currently there are a number of different methods for achieving improved thermal performance in fenestration, many of which focus on the insulating glass package. Standard double pane insulating glass units which are argon gas filled have a center of glass U-factor of 0.24-0.25 BTU/ft².hr.°F. Multi-cavity insulating units (generally triple pane, but some quad panes are available) can improve this performance significantly by increasing the number of cavities and low-e coatings
in the glass construction. U-factors in the range of 0.11-0.23 BTU/ft².hr.°F can be achieved with triple pane units.

More recently durable coatings have been developed that can be used on the room-side surface of an insulating glass unit (surface 4 of a dual pane unit). With low-e coatings on surface 2 and surface 4, now U-factors of 0.19-0.23 BTU/ft².hr.°F can be achieved in a dual pane unit, attaining performance similar to that of some triple pane units. The advantage of this configuration is that unlike integrating a triple pane, no frame modifications are necessary to accommodate wider and heavier glass. When using a fourth surface low-e, the room side pane will be colder than the equivalent dual pane without a room-side low-e and so considerations relative to condensation should be made.

Vacuum glazings which promise improved U-factors without additional weight and thickness are in development. Much thinner than a conventional dual pane unit – more like single pane glass in terms of thickness – commercial availability is currently limited and, where available, there are some limits to climate applicability. These products can currently offer center of glass U-factors of 0.21-0.26 BTU/ft².hr.°F and when used as the inboard pane of a dual pane unit (hybrid vacuum insulating glass unit) can achieve U-factors of 0.10-0.14 BTU/ft².hr.°F. Further advances in vacuum glazing are being developed but are not yet commercially ready.

In some cases depending on the fabric being used, the use of interior shading systems can also reduce the U-factor to as low as approximately 0.2 BTU/ft².hr.°F, when used in combination with a standard argon filled double pane IGU. This combination is useful for controlling night time thermal losses when view is not a requirement.

The overall performance of the fenestration is determined not just by the glazing package but also by the framing system. Driven by the increasing stringency of the building codes, curtainwall and window manufacturers are offering higher thermally performing systems using better thermal breaks which still meet the all-important air, water and structural performance requirements.

4.2 Dynamic solar and glare control solutions

There are two distinct ways that dynamic solar control can be provided to fenestration, either through motorized moveable exterior louver systems (including automated venetian blinds inside a double skin wall) or through the use of dynamic glazing. There are many automated exterior systems that have been developed and which have been utilized in European markets for a number of years. Whilst exterior systems do a good job of modulating the solar gains, they interrupt the view, some cannot be used in certain weather conditions and mechanical systems require on-going maintenance.

The main type of dynamic glazing is electrochromic (EC) glazing which has been commercially available for over ten years. Electrochromic glazing provides both dynamic solar control and dynamic glare control with no moving parts. Significant developments for EC glazing have been made in the past few years which have provided increased flexibility for designers. The most important of these include
increased size availability (up to 5'x10'), increased manufacturing volumes, availability of a range of colors that architects can choose from to match their project color aesthetic (see figure 7) and the ability to control up to three different areas of a single EC pane as different segments (see figure 8).

Figure 7. Examples of different exterior color aesthetics in EC glazing now available for designers to compliment the designer’s color palette for the building (from top left to bottom right – Classic, Gray, Green and Blue). Images courtesy of SAGE Electrochromics, Inc.

Figure 8. An example of one of the new advances in electrochromic glazing: In-pane zoning. This figure shows an EC product installed in a building with the top of each pane in a tinted state and the bottom of the pane in a higher transmittance state. Photo courtesy of SAGE Electrochromics, Inc.
This latter feature is essential in floor to ceiling glass to provide for effective co-optimization of glare control, light color quality, daylight admission and energy performance. For effective glare control, the EC glass needs to be tintable to 1% visible light transmittance, yet if the whole façade is at 1%T, there will be insufficient daylight admission, the lights will have to be turned on and the light color quality will suffer. With the ability to zone the EC within a pane, optimized performance across multiple dimensions can be achieved as well as the architect’s goal of reducing the number of mullions in the framing system.

Dynamic glare control can also be achieved with the use of automated interior shading systems. They typically track the location of the sun in the sky and the shades are deployed when the sun is incident of the façade to limit the direct sun penetration to a predetermined distance along the floor from the window wall. A large range of fabric choices are available. The most suitable glare control fabrics have an openness factor of approximately 1%. Openness factor refers to the fabric weave. The lower the openness factor, the denser the weave and the less light passes through. A 1% openness factor fabric allows approximately 1% of the visible light through. Light blocking fabrics are also available when that is desired. Figure 9 gives an example of dynamic glare control with an interior shading system. As part of an integrated façade, this solution is normally used in conjunction with exterior shading for solar control.

![Figure 9. Dynamic control of glare using automated interior shades. The direct sun penetration is typically limited to a predetermined distance along the floor from the window. Photograph © Barry Halkin Photography.](image)

### 4.3 Lighting control solutions

Recent developments for lighting controls include (1) standards for dimming fluorescent lamps; and (2) wireless lighting control solutions motivated by a reduction in the number of new construction projects and an increased importance of improving the energy performance of existing buildings.
The lighting industry in the US agreed in 2011 [6] on the electrode heating requirements for fluorescent lamps when under dimming conditions. This means that the most common commercially used light sources and the dimming ballasts that operate them are standardized and therefore their performance in installations will no longer be dependent on the specific lamps and ballasts.

Wireless lighting control and window shade control solutions are now well established for applications in commercial buildings. They greatly reduce the labor costs for building renovations and retrofits, making it practical to have automated daylighting systems that use continuously dimmable lighting controls and automated shade controls in these applications.

5 Commissioning

The importance of commissioning integrated façade systems cannot be overstated. The Energy Center of Wisconsin demonstrated that commissioning daylight control systems alone can lead to energy savings which often exceed 60% [7]. Indeed, there are plenty of examples where, because of insufficient commissioning and post occupancy adjustments, occupants have disabled either light or occupancy sensors, negating the designed energy performance of the daylighting system.

For integrated façades to deliver their true potential performance not only must the individual systems be commissioned, but the lighting controls and façade controls must be integrated and commissioned together to ensure that they are not fighting against each other and deliver the expected performance. Monitoring and adjustment of the performance through post occupancy feedback and building metrics in the first year of operation is also very important since needs for daylight admission and glare control may change during the four seasons and are also occupant and application dependent.

It is important to identify at an early stage and in the project specifications that systems, such as EC glass or shading systems, lighting controls and building management systems, be integrated. It is also essential to identify clearly who has responsibility for the integration and delivering the specified performance. A sequence of operation should also be defined in the specifications so that the commissioning entity understands how the systems need to interact and be controlled. For example, when integrating EC glazing and lighting controls, it is important to identify what both systems will do under different combinations of circumstances. For example, what will the systems do when the building is occupied versus when it is vacant, and in heating mode versus cooling mode, and if glare is present or not, and if it is night or day etc. Normally the rule of thumb is, if occupied, the systems will focus first on delivering occupant comfort (daylight sufficiency or glare blocking) and secondarily on energy performance. Conversely when vacant, the system will focus entirely on building energy load minimization with no concern for the human factors.

It is also critical to note that whilst physical integration of façade and lighting systems through hardware interfaces is important, it is not sufficient. Providing a communication link and having the systems speak the same language is one
thing, but providing the correct commands, programing the correct responses and sharing data between the two systems is the key to having systems work well together.

6 Building Code Development

The developments of minimum building codes, such as ANSI/ASHRAE/IES Standard 90.1 or the International Energy Conservation Code (IECC), have not sufficiently addressed the challenge of providing energy efficient buildings whilst also promoting good daylighting design, views and occupant comfort expressed above. The general direction in minimum building codes is to reduce the window-to-wall ratio (WWR) as far as possible, in spite of the evidence that dynamic façades improve the performance of the buildings considerably. In the ANSI/AHSRAE/IES Standard 90.1-2013 prescriptive compliance path, the maximum WWR is 40%, while in the International Energy Conservation Code (IECC-2015) it is 30%, with a provision for 40% when using daylight responsive lighting controls. Modeling studies using minimally code compliant buildings do indeed show that the energy efficiency improves with decreasing window size in almost all climate zones. Primarily this is because minimally compliant designs feature neither good daylighting design nor the best performing light dimming systems.

![Energy Plus Splitflux_100pec_Dim_LPDP_HIVT](image)

**Figure 10.** Dimming control gives good energy performance even in an average building with poor daylight design. Even at 40% window area the energy performance is the same or better than the windowless building. Note that if the prototype building had a larger perimeter zone with better daylight design and improved fenestration with dynamic solar control the optimum window to wall ratio would be significantly higher than shown here.

Good energy performance can be achieved even in an average building design when using high performance dimmable lighting controls, as shown in figure 10 [8]. The building models used in this study were the same medium office building models used by Penn State researchers (see figure 2), representing an average mid-size office building design.
The results in figure 10 are from simulations performed by researchers from the Pacific Northwest National Laboratory and from the Heschong-Mahone Group (now part of TRC Engineering Services), presented to the ASHRAE Standards Standing Project Committee 90.1 in January 2012. The main changes, compared to minimally code compliant design, are somewhat better window performance with higher visible light transmission (although no dynamic solar or glare control), daylighted areas around the entire perimeter of the building, and continuously dimmable lighting controls including lights being turned to off when sufficient daylight is available.

Even though the model energy codes have not yet reached a point where they are requiring fully integrated façades as described herein, they do now recognize the use of dynamic glazing and provide interpretation language for the code official when such products are used. In the green codes such as ANSI/ASHRAE/USGBC/IES Standard 189.1 and the International Green Construction Code (IgCC), dynamic glazing is allowed as an alternative to the requirement for horizontal exterior static shading.

In order to continue to increase the stringency of building energy codes without compromising the quality of the space for the occupants a new look at how codes are developed is required. For example, finding ways to collaborate across the typical silos of lighting and envelope to create combined requirements that promote better daylighting designs without continuing down the path of reducing window area is important. Also, as we know, any good daylighting design can be negated by poor interior design choices and lack of a dynamic response for glare. Interior finishes is currently outside the scope of building energy codes and so an examination of how we can include such requirements in the scope would provide an opportunity for ensuring the anticipated energy savings are actually captured when the building is completed.

7 CONCLUSIONS

Dynamic integrated façades are the way of the future for high performance building design. These designs depend on high performance fenestration with low U-factor and dynamic solar control together with a dynamic response for glare control and continuously dimmable electric lighting control. No other solution will get us to (near) net-zero energy buildings nor provide the occupant wellbeing and comfort and design flexibility that architects and building owners desire.

There are a range of proven commercially available solutions that provide designers with the tools that they need to meet the green building challenge and to deliver low energy buildings which have good access to natural daylight and views and yet which also provide good occupant visual and thermal comfort.

However, the current minimum building codes do not encourage designs towards this goal with their prescriptive paths. They set limits to the window-to-wall ratio primarily because minimally compliant buildings increase energy use as the window-to-wall ratio increases in almost all climate zones. But the electric lighting energy use in buildings with completely opaque walls will be too high to support
the net-zero energy goal and building owners and occupiers will simply not accept
the design of window-less (or very low window area) buildings.

Therefore something about our building energy codes has to change. In addition
to recognizing the need for dynamic glare and solar control in code development,
more cross-silo integration to promote the use of best practices in daylight design
in the minimally compliant buildings will be necessary if we are going to maintain
buildings that are people friendly as well as energy efficient. Another sensible
change would be a change in scope that would allow give code officials
jurisdiction over interior design as well as the first year of occupancy. These
changes would enable many energy efficient changes to minimally compliant
buildings, such as good daylighting design. And the occupants would be happier,
more motivated and more productive, too!

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School security: advanced glazing solutions to protect people and property

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Abstract
Our nation's schools should be safe havens for teaching and learning, free of crime and violence. Any instance of crime or violence at school not only affects the individuals involved, but also may disrupt the educational process, affects bystanders, the school itself and the surrounding community.” (Stuart Henry 2000 – Wayne State University) This paper and presentation will look at understanding school security needs as they relate to structure, understanding security threats and how to protect people / property for school environments and compare glazing options for enhanced security. We will look at applying the right glazing solution for vulnerable points of entry (windows & doors) and review legislative actions and trends to make schools more secure through glazing selection. We will present an overview of applicable standards and discuss specification of new and retrofit opportunities.

Keywords: Security, schools, laminated glass, protection, impact, ballistic

Introduction
“Our nation’s schools should be safe havens for teaching and learning, free of crime and violence. Any instance of crime or violence at school not only affects the individuals involved, but also may disrupt the educational process, affects bystanders, the school itself and the surrounding community.” Stuart Henry 2000 – Wayne State University

Schools require unique characteristics to ensure a proper atmosphere is created and maintained to achieve their primary objective of intellectual growth. In the process of school commissioning, design and construction, cities, towns and counties face tremendous trade-offs and are forced to make decisions that could prove lifesaving during a catastrophe.

School pool in the United States
A school is more than just a facility; it is a place where families send their kids for the majority of their day to learn, participate in sports and clubs, and perform in musicals and plays. Schools can be why families buy a home in a specific neighborhood, and they can be what ties a community together. The buildings are frequently used as emergency management centers or shelters in times of crisis, making security an important attribute, even after teaching hours or when the building surveillance may not be as rigorous.

In 1998, data collected in surveys conducted by the National Center for Educational Statistics (NCES) suggested the average public school building in the
United States was 42 years old. This suggests many of the country's schools may now be at an age where frequent repairs and upgrades are necessary. Due to the burst in school construction during 1950-1969 (the Baby Boom Era), study report the building of nearly half (i.e. 45 percent) of the currently in-service schools. Seventeen percent of public schools were built between 1970 and 1984, and only 10 percent after 1985.

These older schools were not envisioned with modern day security and safety measures in mind, after all, the Federal Safety Glazing requirement did not go into effect until 1977 – far after the boom of building was over. The schools built during this time may have been wrestling with safety upgrades and have had to move right into energy conservation, leaving security as a known and desirable upgrade, but stifled by what they could improve. Educator A.C. Ornstein found by the time a school is 20 to 30 years old, frequent replacement of equipment is needed. In fact, Ornstein observed, most schools are abandoned by the time they reach 60 years of service. When the NECS study was published, most of those facilities were already about 50 years old and experiencing serious decline. The opportunity to renew, rebuild and protect properly is here and now. While there is pressing need for building better schools, funding and time constraints abound. Since new buildings may not be able to be readily erected, the architectural community must use available options to modernize, update, and safeguard the buildings that we use. More importantly, we do want to avoid specifying materials out of old specifications in a world that has so drastically changed. All specifications for school materials needs to be reviewed and renewed. Laminated glass remains one of the easiest and most cost-effective measures available for enhancing school structure, fostering learning and especially contributing to student and faculty safety.

**Background on attacks**

In recent years, schools are not being thought of as the safe havens they once were. Security is a more serious concern than ever.

School shootings are not new, nor are they isolated to the United States. The first recorded shooting inside a school occurred in July 26, 1794, known as Pontiac's Rebellion School Massacre. It occurred in the Greencastle, PA area and 10 people were killed. Although they are not new, the recent level of awareness and tragedies are prompting much closer examination of protective measures, especially from glazing.

From 1992 to March 2013, [www.stoptheshootings.org](http://www.stoptheshootings.org) has shown that there have been 387 shootings in U.S. schools. That publicized statistic has not changed, however, there have been 50 additional recorded incidents through other media since that time. One of the more tragic and recent events occurred at Sandy Hook Elementary School in Connecticut in December 2012, where 20 children and six adults were killed.

Immediately following the Sandy Hook shooting, discussions across the country started about how this tragedy and future shootings could be prevented. There
were conversations about gun control, awareness and care for the mentally ill, as well as improving safety at schools through better communication systems, security measures, intruder drill training, and more. School districts everywhere are looking at how they can keep their students, teachers, and faculty safe. Design/construction professionals are the key in the important role of providing protection of our school age children and confidence in our community icons.

Design Considerations
Schools are not used for one purpose, and as such, one material cannot be the protective security charm cast on a school. There are many aspects of good, productive and secure school design.

The securing of schools needs to happen well beyond just the structure. The Federal Emergency Management Association, FEMA, has been publishing a guideline with recommendations for safer schools for several years. Part of the Buildings and Infrastructure Protection Series, the Primer to Design Safe School Projects in Case of Terrorist Attacks and School Shootings (FEMA-428) was last updated in January 2012. In the document guidance is provided to think in terms of layers for the protection of school campuses, starting with the topography of the site and moving toward barrier structures around the campus such as fencing and restrictive landscaping. The next step is the layout of the building and access, making sure there is adequate spacing between parking lots and the entry way and using the building as a shield for external activities. The final barrier is the building structure itself. This involves layout and visual access through glazing, hardening of the structure and locked and deterrent windows and doors.

The structure is deemed the last layer of defense for the school. As such we first discuss the externally glazed portion of the façade. Not all fenestration systems have the same requirement for protection depending upon their role in deterring an assailant. Entry doors have been the most vulnerable in many school shootings. Doors are the most logical and commonly used pathways to enter a building. Glazed doors provide the much needed sightline benefit that helps in surveillance, but using standard glass or even tempered safety glass in the door can leave it vulnerable to the break and reach tactic of entry even if they are locked. By impacting these types of glass, quick entry can be had by the assailant reaching through the door or side-lite and opening it from the inside. As in the case of Sandy Hook, the shooter penetrated the side lite of the door and proceeded to open the door. The “break-reach-release” ability of the intruder must be delayed or eliminated. High-performance glass provides resistance, and the anti-shatter capability can aid in preventing the reach through and release tactic that is sometimes used to gain entry through doors while still providing the much needed visibility.

Hurricane-rated high-impact (i.e. large-missile) glass or even ballistic glass could be considered for these areas depending upon the protection requirements and
level of risk. High-performance glass provides resistance, while still providing much needed visibility. Although doors are the most common access point, the sidelights of doors and glazed lobby areas also need to be considered as candidates for enhanced protective capabilities. Typically floor to ceiling panels, these panels also can serve as an open entry point, once cleared of glazing, for an assailant to “walk” into the building. First floor windows without obstacles (i.e.: shrubbery), and accessible windows from elevated walkways are also significantly vulnerable to forced entry. A protective glazing to deter entry through fenestration in these areas is highly recommended as well. Although there are many of types of glazing systems found in schools – skylights, transom lights, balconies etc…, the accessibility to forced ingress needs to be a key consideration if the budget is limited and security is desired.

Performance Glazing and Deterrence

With the existing stock of schools being older and not able to offer reliable security systems through the structure, recent tragedies involving school shootings, and the knowledge that there are products that can help available, a surge of parents and administrators across the country are clamoring for ways to make K–12 facilities more secure.

Areas of the schools under significant scrutiny are doors and windows—and more specifically, the glass being specified. Outdated glass, in the older stock of schools, may lack basic safety, sound control capability and may lack insulation features to control classroom temperature. In short, it cannot offer much more than protection from outdoor elements. However, the installation of laminated glass can immediately update an aging school and offers safety, security, sound and UV protection to students and teachers. Existing doors may need to be replaced completely if bullet-resistant glazing is specified, as the framing system for such heavy configurations is specialized.

With numerous studies over the years indicating the benefits of natural daylight on improved attention span, alertness, learning capacity and overall well-being, it is not a coincidence that more and more efficient glazing is being used in schools. The size, complexity and demands on windows and doors, including the frame and hardware have undergone a transformation in recent years to accommodate this desire for more glass and more attachment with the outside. Not only does the system have to provide adequate screening from wind, rain and snow, it now has to be designed with the climate in mind, provide energy efficiency, sound control, and aesthetics, all while meeting the federal and building code requirements for safety. Choosing the proper glazing for a system is critical. For these applications, glazings that can be impacted but still deter the attacker for some amount of time from entry need to be considered. The deterrence provided by the glass can provide very critical time for reaction on the part of the trained staff.
Glazing Standards

From a glazing standpoint, school architects and administrators may consider the following when designing new or retrofit glazing systems:

- glass should provide inherent health, safety, and security benefits that can help mitigate disasters;
- natural daylight is essential for optimal performance among students. For example, a study by Heschong, Wright and Okura (2002) identified positive effects of natural light on students as evidenced in significantly improved standardized test scores for elementary students. The same study concluded that daylight contributed positively to overall health and well-being of students;
- glass should provide visibility for critical passageways and entry areas; and
- sustained functionality—basic functions of the school can operate following a natural disaster or incident.

The standards related to glass in buildings are numerous. The international arena of standardization between ASTM International and ISO conveniently cover the basic glass products, test methods and specifications as well as the use considerations of such products. Although both organizations are international in reach and acceptance, there are other for-profit and independent organizations that also propagate standards for security glazing. Many of the standards leave the selection and use of the product to the specifier. Some of the common standards referenced for school security have in the past been: ASTM F1233 – Standard Test Method for Security Glazing Materials and Systems and UL 972 – Burglary Resisting Glazing Material. Both standards center around attack of the glazing material with little attention to the frame. ASTM E2395 Voluntary Security Performance of Window and Door Assemblies with and without Glazing Impact however encompasses the attack and performance of the entire window or door system. This test includes the manual manipulation with and without tools to force open a frame, followed by impact to the glass in order to assess the ability to “break and reach” to gain entry. ASTM E2395, due to its completeness in the attack scenario, although still leaning towards protection from an opportunistic attack, has grabbed the attention of specifiers for schools. Through this one standard they can specify windows and doors for both forced entry via manipulation and force as well as glazing targeted entry through impact.

In use considerations

Laminated glass with polyvinyl butyral (PVB) breaks when impacted with enough force, but the glass shards are contained by the interlayer which helps to deter entry. The interlayer may even hold the glass together when impacted by a missile as in hurricane applications or a bullet. Laminated glass is made from a tough plastic interlayer bonded between two pieces of glass. The interlayer is not typically noticeable between the glasses (windshields are laminated glass), so laminated glass offers the same benefits of allowing occupants to see someone approaching the school as ordinary glass. From the outside, the ability to clearly see through can help responders locate intruders or victims.
What makes sense for a building? Single solutions do not exist. As the structure is the last defense, the topography and other physical barriers and actions also come into consideration. Zoned protection is recommended. The most vulnerable and most likely entry ways need to be hardened; they need to have good and permanent visibility that cannot be rendered inactive in a time of need. They must have safe break characteristics and deter ingress. Secure lock down is a necessity. Locked entry doors are becoming mandatory at most schools, however “break and reach” techniques need to be taken out of play with a deterring glazing. The systems must provide reaction time. Even a few minutes could mean the difference between many fatalities. Awareness and visibility are also key – the ability to easily survey the surroundings and see an approaching assailant can provide precious time to enact a well devised security plan.

Laminated glass in these systems does not need to be complex to offer a level of safety and security. A thin laminated glass, about 6 mm (0.25 inches), about the thickness of your windshield, can meet safety glazing requirements and provide a level of deterrence that would be desirable. It may take several shots from handguns like a 9 mm, .357, or .45 calibers to make an opening large enough to put a fist through to unlock a door or window. In some cases, the intruder may be temporarily confused, as the glass does not ‘behave’ as expected. There are many documented smash and-grab attempts where would-be intruders give up because they are generating too much noise and attention and things just didn’t go as they had planned.

Thicker laminates with additional interlayer (as is used in hurricane applications) can be used for higher levels of securing a facility. Most of these glazing fit well into exiting frames and a can be used in insulating glass configurations to achieve not only the desired security, but also the energy efficiency and sound control that is an integral part of the overall school’s capability of being an efficient learning facility. Bullet resistant glazing can also be considered if deemed attainable and appropriate for the anticipated risk and threat. This may be deemed necessary for certain areas of a particular school, but tends to need substantial framing.

Access doors with a double-entry lobby to the school should be equipped with laminated security glazing having forced entry/burglary resistance capability in accordance with Underwriters Laboratories (UL) 972, Testing for Burglary resistant Glazing Materials, or Class I of ASTM F1233, Standard Test Method for Security Glazing Materials and Systems. For new systems, ASTM International standard E 2395 Standard Specification for Voluntary Security Performance of Window and Door Assemblies with and without Glazing Impact should be specified to a minimum level of 3, and preferably higher.
First-floor glass should be, at a minimum, equipped with basic laminated glass, which typically requires a 0.76 mm (0.03 in.) thick interlayer. This type of glass will deter ingress; retain glass; and slow break-and-reach attempts. Forced ingress glazing will offer greater protection, and uses a thicker interlayer. Laminated glass can be retrofitted into most existing window and door systems and can contribute to compliance for security windows per ASTM E2395. Egress through laminated glass has been studied in depth over the years due to its popularity in the hurricane market. It has been shown that entry into the building or exit from the building by fireman with standard tools is readily possible. The concern for laminated glass use and egress arises with the use of bullet resistant glazing as non-traditional tools are needed for access.
Protecting our future leaders

Laminated glass does not have to be bulky, hard to install or expensive to provide a level of deterrence and “buy” some time to initiate the trained response.

Robert Ducibella, a security consultant and member of the Sandy Hook Advisory Commission, suggested reinforcing but not necessarily bullet-proofing glass entry points to schools. He suggests reinforcing glass at the logical entry points to schools with laminated glass citing the weight and expense of bullet resistant glazing.

“You can discharge your handgun or a long gun, small rounds or large rounds, multiple times and you will likely not fail the laminated glazing adequate to gain immediate access into the building,” he said. “An individual will need to show up with a number of attack tools in order to gain entry quickly.” Ducibella said laminating glass at points of entry might add two to four minutes to the time it takes an attacker to enter a school. He said the hope is that law enforcement will be able to arrive at the scene of an attack between three and eight minutes after it starts. Although the time to penetrate laminated glass is affected by the configuration and the tools used, the tendency of not shattering upon initial impact is an attractive characteristic when combating a security issue.

Along with its safety and security enhancing features, laminated glass offers other benefits for schools. Most laminated glass dampens sound coming in from the outside, making it an ideal choice for schools located in noisy neighborhoods or urban environments. Numerous studies have shown children concentrate and can learn better in a quiet space. A study by Earthman and Lemasters (1998) found that higher achievement is linked to schools with less external noise. Laminated glass has successfully protected public facilities and major works of art for many
years. It is commonly used in high-risk facilities such as embassies and federal buildings, as well as museums. Laminated glass protects great treasures such as the Mona Lisa, the U.S. Constitution, and the Crown Jewels in London and is a top choice for protection against severe storms in hurricane regions.

For extra school security, laminated security glass can be an easy and cost-effective measure to assist in resisting forced entry and the threat of bullets. Compared with traditional annealed or tempered glass, laminated glass can aid in securing a building by offering deterrence and therefore time. It is commonly available and is fast becoming the standard specified product for new school design in an effort to protect people as they study to become our future leaders and the property they are educated in.

Citations


Additional Information

About the Author

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Sealants, Testing and Laminated Glass

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Abstract
This paper will look at the development of the testing method for sealant compatibility in laminated glass. The natural correlation and accelerated methodology will be reviewed. Studies and summaries of factors and results will be explained and examined.

Keywords: sealants, laminates, edge effects, compatibility, durability, testing

Introduction
Polyvinyl butyral (PVB) interlayers are plasticized interlayer films that are laminated between two or more plies of glass. The PVB interlayer can react with non-compatible materials with which it may come in contact. As such, direct contact between PVB interlayers with chemicals used in sealants or adhesives should be carefully examined and in some cases avoided.

Compatibility testing is conducted between commercially available and experimental sealants and laminated glass with PVB interlayers as warranted by product introductions or modifications. It is not possible to test every sealant on the market, due to space and resource constraints, however a concentration on commonly used families of sealants from major manufacturers has been done and testing continues on an annual basis. The testing is conducted and reported to provide the industry with guidance on one aspect of sealant selection, as it is recognized that product compatibility is a substantial consideration in building design.

Results are reported from the testing; however, sealant recommendations include more consideration than compatibility alone. Data, but not recommendations are provided as the interlayer manufacturers cannot and do not control variations and modifications in the sealants as tested. Our tests are also performed under a strict protocol so that comparisons can be made between products tested, but may not reflect actual performance as installed due to variations such as humidity, moisture, adhesion, movement, attack etc...

Sealants and other adhesives are tested for edge effects with laminated glass made with PVB interlayers in accordance with the procedures documented below. The sealants and adhesives are made available by suppliers, fabricators and manufacturers. Commercially available sealants have not consistently and repeatedly tested as 100% compatible with laminated glass under these conditions.

Evolution of the test procedure
Once the need for compatibility of sealants at the laminate edge was recognized, several studies were set out to develop a reliable and predictive test. Natural exposure in both a humid climate such as Florida, USA and a hot dry climate such as Arizona, USA were the climates from which edge effect data would be analyzed. Samples with various sealants were placed in standardized exposure fields where the sealants are in intimate contact with the laminate edge. This study showed that exposure for 12 months in either climate yielded approximately the same results for the same sealant family (Figure 1). The Arizona climate took slightly longer to reach the plateau, but the sealant stabilized with the near exact results. The depth of the edge effect tended to plateau during this time and
longer durations did not yield appreciably enhanced results. The results were also similar to what was being seen in the field in a well glazed fenestration system.

Figure 1

The next step was to duplicate the edge effects seen in natural exposure with accelerated weathering chambers. An ATLAS QUV chamber was used with UVB-313 bulbs. Several UV, heat and condensations cycles were trialled. It was determined that a cycle with long UV exposure at high temperature, followed by a shorter cycle with no UV, condensation and high temperature provided the optimum correlation to natural exposure, but in an accelerated timeframe (Figure 2). The cycle is 16 hours UV at 66C, no condensation, followed by 8 hours no UV at 60C and condensation.

Figure 2

The correlation between natural exposure and accelerated exposure was demonstrated between the QUV and Florida. Although in an accelerated environment, the data and curve between these two exposure methodologies fit nicely (Figure 3). Based on this data, approximately 100 hours QUV is equivalent to 1 month natural exposure – although it is not a linear relationship. It should be noted that this equivalency statement takes into account close examination of the dynamic rate of change that occurs between start and 1000 hours followed by the plateau. Therefore it is recommended that no assessment be made until a minimum of 1500 hours of exposure. This
correlates with the 12 month nature exposure plateau as well. Based on this data, a 3600 hour accelerated test can show what may be expected in 3 years.

As in all accelerated exposure programs, variables such as sample preparation, installation and formulation may affect the results. Newly engineered materials must constantly be evaluated against this rule of thumb to ensure it holds true and therefore accelerated data on fixed samples should be used only as a predictor.

![Figure 3](image)

**Test Procedure**

This test method is a laboratory screening procedure for determining the compatibility of elastomeric glazing sealants when in contact with the laminated glass edge after exposure to heat, humidity and ultraviolet light. In order to achieve the best results, the sealant must be in intimate contact with the edge of the laminated glass so that it has the most direct access to the interlayer throughout the test duration. An assessment of the sealant or glazing tape itself or the sustainability of sealant properties through the exposure is not evaluated during this study. This test method includes the observation of two parameters as follows: changes in color of the interlayer, and changes in the glass to interlayer interface as depicted by bubbles, let-goes or other visual anomalies at the edge. With the correlation to natural exposure completed, all testing is done in the accelerated QUV chamber with 16UV @ 66C and 8 dark @ 60C with condensation cycle.

Flat laminated glass panels have sealant applied to the edges ensuring intimate contact between the sealant and the laminated glass edge with the sealant having the most direct exposure to the interlayer. Sealants are allowed to cure at room temperature 21°C ± 5° for 21 days. Visual ratings are reported at predetermined intervals and/or at the completion of the exposure program which include: maximum depth of edge effects, average depth, average area, the presence of a plateau and any discoloration. If any edge effect is seen during this time, the materials are deemed incompatible and the testing of that sample is terminated.

A minimum of two identical laminated glass specimens, flush trimmed, for each type shall be used. Each specimen shall be a minimum of 52 mm wide and have a minimum of two continuous edges which are 305 mm in length. No voids or bubbles are allowed between the sealant or glazing tape and the laminate edge. Laminates without sealant are also exposed as controls.

Laminate glass edges shall be cleaned with white spirits and a clean soft cloth. A two (2) cloth method is to be used whereas the first cloth, slightly dampened with spirits is rubbed along the edge to remove any residue or contaminate present. The second soft clean cloth is to be used to immediately wipe the edge dry of any persisting spirits. No standing solvents shall be left on the laminate edges. Laminates need to be masked off prior to sealant application (Figure 4). This masking is to be completely removed after curing to ensure accurate visibility of the sealant and edge
interface during rating. Prepare a flat surface with a material that prohibits the adhesion of the sealants (such as polyethylene sheeting) to allow for easy release and removal of laminate systems after sealant or tape application and curing. The removal of the laminate from the surface must not disturb or adversely affect the bond between the sealant and/or tape and the laminate. A moulding or framing system needs to be utilized to ensure the intimacy of the sealant bead with the laminate and the quantity of sealant allowed to react with the laminate. In this testing the side channel is 6 mm². Sealant was caulked into this channel and tooled for proper wetting and removal of excess material.

Figure 4

After room temperature cure, the samples are de-masked, rated and subjected to the QUV weathering. Visual ratings of edge effects occur at 500 hour intervals (every 3 weeks), for a total of 3500 hours.

Measurements

The following measurements are physically done at each interval (Figure 5):

Average Depth Edge Effect: - The average depth of anomalies is selected on one edge. A measurement is made from the laminate edge to the center point of the anomaly. This is recorded as the average depth for the side being rated. This procedure is repeated for the opposite side, and for any additional specimens of the sample set. These recorded values for all edges in the sample set are then averaged to get the average depth of edge effect for the set. This number is reported for each rating interval.

Length Affected – measure and sum the length of edge affected by any anomaly. This is rated per specimen and not per side. For this test procedure the maximum length affected is 610 mm. This is also report as a percent of the edge affected.

Maximum depth – The maximum depth of penetration of an anomaly rated from the laminate edge inward to the innermost portion of the anomaly. This is the maximum depth. The maximum depth is rated for each side, but only the highest value from all sides of the sample set is reported for that interval. At the end of the study, the highest
value reached at any interval is reported as the maximum depth, even if it is not recorded during the last exposure interval.

Figure 5

The following measurements are calculated from measured data at each interval:

Average Area – product of the length affected per sample multiplied by the average depth.

Percent Length affected – Total length of specimen subtracting total length affected, divided by total length of specimen.

\[
\frac{(T_l - T_a)}{T_l}
\]

Where:  
T_l is total length of specimen  
T_a is total length of specimen affected

Delamination Plateau – The maximum and average depth (when rounded to the closest full integer) of edge effects remain the same for the last two rating periods of the exposure.

Results

Edge effects are normally seen as clear, very small, 2 mm – 12 mm (0.08 in – 0.50 in), edge bubbles, sometime continuous along an edge, other times very distinct and isolated depending upon the sealant or adhesive. Edge effects from sealants and adhesives are typically maximized in depth at approximately 10 mm (0.39 in) from the edge. Although a slight discoloration can occur with sulphide containing sealants and adhesives, normally the edge effect is clear.
Sealants may contain solvents that can be harmful to the interlayer edge. In most cases investigated, the sealants considered neutral in curing are routinely better performers in a compatibility assessment than those sealants that have acids (i.e.: acetic acid).

Occasionally a test cycle will result in minimal to no interaction between the laminate and the sealant or adhesive under the controlled test environment. This does not guarantee the same results in field as application, environmental and material deviations can occur.

Some typical results from testing are shown below:

<table>
<thead>
<tr>
<th>Sealant Type</th>
<th>Total Length Affected (mm)</th>
<th>Percent of Edge Affected (%)</th>
<th>Area Affected (mm2)</th>
<th>Edge Affected Plateau</th>
<th>Average Depth (mm)</th>
<th>Max Depth (mm)</th>
<th>Depth of Defect (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Silicone Hybrid</td>
<td>18</td>
<td>3%</td>
<td>36</td>
<td>N</td>
<td>2</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Silicone Neutral</td>
<td>5</td>
<td>1%</td>
<td>15</td>
<td>N</td>
<td>3</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>Silicone 2 part</td>
<td>29</td>
<td>5%</td>
<td>116</td>
<td>N</td>
<td>4</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Silicone Acetoxy</td>
<td>28</td>
<td>5%</td>
<td>112</td>
<td>N</td>
<td>4</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Conclusions

In most installations where the sealant is used as a weather seal, the sealant material rarely comes into contact with the laminated glass edge. In butt joint glazing, structural glazing, some point fixed glazing systems, installations where a heel or toe bead is applied, and in sealed insulated glass units, the sealant could come into contact with the edge of the laminated glass and potentially with the interlayer. Reactions between the sealant, glazing tapes and interlayer may occur and could cause a visual anomaly.

The accelerated weathering chamber allows close control of alternating cycles of UV radiation and condensation at selected temperatures. The cycle used to predict natural Florida exposure is: 16 hours of UV (no condensation) at 66C, followed by 8 hours of condensation (no UV light) at 60C. The UV lamps are UVB-313. Due to their shortwave UV emission, and high energy, these lamps can quickly induce sealant curing reactions which can propagate migration of volatiles and/or plasticizers into or out of the interlayer. They can also cause aging and other changes in the sealant which could promote edge effects in the laminate edges contacting the sealant.

The condensation cycle, which alternates with the UV cycle, serves as an accelerator in the curing and aging of the sealant. It also helps to detect glass-to-sealant adhesion loss which could be detrimental to a laminate if left undetected. The effects of water vapor transmission are assessed through use of the condensation cycle. The test protocol was specifically designed to give a severe sealant-interlayer exposure condition to accelerate possible interactions and permit comparison of results among various sealant types.

The effects of accelerated aging do not mean a sealant showing edge effects from sealant compatibility in the accelerated tests cannot be used successfully in a properly designed system. It also does not guarantee good performance with a sealant showing good performance in these tests. Other factors in preparing the glass or frame in an actual installation, sealant production, sealant formulation changes and shelf life which were outside the scope of this program also may have an effect. For the conditions tested, however, the results provide a reasonable basis for comparing and predicting the interactions of these sealants with interlayers in laminated glass. Consideration of the visible effects of sealants and an understanding of their development by the party accepting the design is recommended.

Sealants should be selected firstly on a basis for their desired performance (i.e.: compression, tensile strength, weatherproofing, structural, cosmetic), with edge effects being a consideration after a performance class or family has been established.
Analytic design approach to maximize panel dimensions in horizontal 2 hrs fire-resistant & thermally insulated glass assemblies

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Abstract
High performance Fire resistant glazing pertains to a common standard of today’s architecture. This is due to the high demand for light flooded, but fire safe open spaces inside of the building. The main application of fire resistant glazing applies to vertical windows, doors and curtain walls where advanced production technologies and testing experience offer a vast range of solutions.

However, when it comes to horizontal glass assemblies such as flooring and skylights, the whole game changes as the extreme impact of fire loads as well as the critical response of the glass system is significantly different compared to vertical applications.

This paper shows an evaluation concept and analytic design approach for horizontal floor/ceiling fire-resistant glazing, targeting maximum panel dimensions within a closed and thermally insulated application under extended fire impact durations up to two (2) hours. The procedure is being explained with a Case Study, reflecting the analytical design, material engineering, fire testing & benchmarking, custom fabrication and installation of the world’s largest two hour fire-rated & thermally insulated, walk-able floor glass (by single panel size) within the New York University Campus - main gymnasium & library building in Abu Dhabi.

Keywords: fire, safety, horizontal glazing, public areas, testing

1 Introduction
Opening public spaces for light and transparency has been the credo of modern architecture. Designed by Rafael Vinoly architects New York, the new campus of the New York University (NYU) on Saadiyat Island, the new cultural hub of the Emirate Abu Dhabi as capital of the United Arab Emirates falls into the category of innovative architecture, applied into an environment where light and shade require a strong balance.

The harsh and hot weather in this region during summer times predefines the local building architecture by using fewer openings in order to control energy consumption for cooling and air conditioning. The sports and library building of the new NYU campus has been designed as a multiple floor complex offering...
large indoor spaces for purpose orientated education. An intelligent strategy between natural and artificial light lets this massive building floating. External roof skylights catching natural daylight which is going to be further distributed through internal skylights into lower floors. This ‘light well’ strategy reaches down to the basement level where students will receive the enjoyment of sitting around a massive swimming pool, successfully flooded with natural light through six (6) floors of a building structure.

1.1 Light architecture vs. fire safety
Open areas below the internal glazed skylights are not furnished with automatic sprinkler systems nor are there any separate metal fire shutter designed to prevent against smoke and fire spread between the building floors in an event of fire. Due to their size and function as building floors, these internal skylights have been rated with a fire resistance of 120 minutes towards system failure and/or collateral damage. The insulation spectrum has been classified as a physical barrier against flames, hot gases and smoke, as well as with thermal isolation.

Figure 1. Arrangement of internal fire resistant skylights.
Due to the designed size and layout of the horizontal and fire resistant glazing system, a custom evaluation of system performance had to be conducted.
2 Fire rated glazing
Fire rated glazing defines a glass material being resistant against fire impacts.

2.1 Range of fire rating classifications
While specifying fire resistance glazing, the range of classifications depends on the purpose and performance requirement and can be identified as follows:

**E = INTEGRITY**
E classified glass provides a barrier against fire, hot gases and smoke.

**EW = RADIATION REDUCTION**
EW classified glass provides a barrier against fire, hot gases and smoke and assures a reduced passage of thermal radiation.

**EI = INSULATION**
EI classified glass provides a barrier against fire, hot gases and smoke, by creating an additional thermal insulation.

![Figure 2. Range of fire resistance classifications.](image)

2.2 Product technologies
In order to fulfil performance requirements complying with fire rating classifications, various glass materials and product systems have been developed and constantly improved over years.

2.2.1 Integrity (E) glass
E- Classified glass provides an effective barrier against the passage of smoke, flames and hot toxic gases. By remaining transparent and fully intact, the glazing allows people to make their escape and rescue services to be fully aware of any impending danger. Products for integrity rated glazing are usually wired glass, specially tempered glass or glass ceramics.

Wired glass is annealed glass with incorporated metal wire which holds the glass in a stable state once impacted by flames and heat. Wired glass is available in fire ratings up to 45 minutes.
Where appearance in internal architecture plays a higher role, specially tempered glass will be used in lieu of wired glass. Lobbies and corporate offices often require clear glass without wire. Specially tempered glass meets this need and, unlikely ordinary safety glass, carries fire ratings up to 20min coupled with additional impact safety. Typical products are either Pyroswiss® (Vetrotech Saint-Gobain) or SuperLite® (Safti First).

The ultimate performer of clear integrity fire rated glass is glass ceramic, formerly widely known as the ‘glass cover for fire places’. Glass ceramic looks like ordinary glass, but carries the excellent mechanical properties of ceramic including low thermal expansion and the ability to withstand high temperatures. This makes it stable for durations of up to three (3) hours. Typical products are either Keralite® (Vetrotech) or FireLite® (Technical Glass Products).

2.2.2 Radiation reduction (EW) glass
EW- Classified glass provides an effective barrier against the passage of smoke, flames and hot toxic gases as well as reduces radiant heat in order to provide temporary escape corridors for evacuation within buildings and allow rescue workers to reach the heart of the fire with fire fighting equipment. Special coatings let the glass control heat radiation of <15kW per sqm at a distance of one (1) meter in front of the glass e.g. Vetroflam® (Vetrotech Saint-Gobain).

2.2.3 Insulation (EI) glass
EI- Classified glass provides an effective barrier against the passage of smoke, flames and hot toxic gases while performing as a fully insulated heat shield. When exposed to fire, special intumescent interlayer’s turn opaque and expand to form fire barriers including heat resistant foam blocking fire penetrations for periods of up to 120 minutes. EI glass systems typically include an insulated air space, like ordinary insulated glass, in order to avoid conduction of heat through the glass unit to control heat radiation at the fire unexposed face within room temperatures and vice versa, making it also an ideal product for exterior glass applications. Different product systems are e.g. Contraflam® (Vetrotech Saint-Gobain), Pyrostop® (Pilkington) or Pyronova® (Schott).

Figure 3. Performance of different fire rating classifications.
3 Project related design approach

Horizontal floor slabs separating adjacent spaces to safeguard against the spread of fire and smoke within the building as well as against the spread of fire to or from individual building blocks are designed to accommodate large crowds of people and required a fire strategy to be approved and regulated by the local Civil Defence Authority of the Emirate Abu Dhabi.

The interior spaces within and between the floors of the Universities swimming pool at basement level 0, gymnasium level 1 as well as library level 3 have been included and considered within this sophisticatedly designed fire strategy, specifying the resistance towards fire and smoke penetration through horizontal structures including their incorporated materials with a duration of two (2) hours.

Within tight project schedules, especially, if being called to a project at a late stage, the first and ultimately fastest design approach always seems to be the use of existing and available products and systems which may not necessarily require time consuming testing, benefiting the project progress and its completion date. This requires a careful comparison between project design requirements, product & system limitations as well as product fabrication and delivery times and corresponding logistics.

In order to match the panel layout of the exterior roof glass skylights at building level 6, the typical glass panel layout of internal skylights has been predefined. Average panel sizes of 1.33m x 1.75m for lens shaped side light wells, increased to a maximum of 1.33m x 2.00m within the circular shaped skylight at library level 3 have been set as design boundaries. While researching through existing systems, the only available, two hour fire tested and rated glass floor system in the market was limiting its panel sizes to a maximum of 1.21m x 1.27m.

Apparently, that the only way to comply with the architectural design intent, without cannibalizing the layout, was a custom design approach.

3.1 Custom design development

A custom design development for fire resistant glass assemblies always starts with a detail – the detail of how to fix, secure and protect the weakest element within the system, the glass. The first and most important task is to avoid any combustible and heat conducting elements and materials. What sounds like a logic undertaking requires a clear specification of materials and their ingredients.

3.1.1 Assembly

The new skylight structure is based on a double layer glass application with upper laminated glass floor and lower fire-rated laminated glass ceiling. Both glass layers are separated by a structural steel frame which functions as primary skylight substructure as well as glass support frame. The air cavity within the frame is neither ventilated nor hermetically sealed, but dehydrated by Silica desiccant gel incorporated within the frame transom members. The skylight structural support is being provided by the building slab structure.
Figure 4. Typical perimeter support detail of fire rated glass floor / ceiling [4].

An ultra slim structural steel frame based on 300mm x 60mm x 6mm provides the primary structure of the double layer floor / ceiling assembly in order to structurally support dead-loads and internal live-loads introduced through the bottom layer of fire protective glass enclosure as well as upper walking glass surface. The top layer of traffic accessible glass is laid onto the steel frame, separated by Norton glazing tape and caulked with a structural silicone sealant. The bottom layer of fire resistant glass is supported by a custom trapezoid shape folded attachment profile which is fully welded to the primary steel frame. U-shape formed 5mm thick steel pressure plates, separated by a ceramic tape and 20mm thick calcium silicate provide a secured and non-conductive support of the fire rated glass panel back to the primary steel frame. Fixing bolts and perimeter accessories have been finally protected with 8 pcf nominal dense and 25mm thick
ceramic blanket insulation, covered by an 2mm thick aluminum cover cap. The cover cap has been powder-coated in order to maintain a uniform look at the bottom of the entire assembly.

3.1.2 Glass specification
In order to eliminate any heat impact on the structural steel frame the use of EI – rated glass type Contraflam® 120 clear by Vetrotech Saint-Gobain has been used. The make-up of this custom engineered glass unit includes multiple layers of glass combined with intumescent gel interlayer’s, an integrated air-space at the upper side and a laminated heat-strengthened layer at the bottom face. The latter was required in order to comply with the overhead safety glass requirements within the building.

The top layer of walk-able glass has been designed as triple laminated glass compromising 29.04mm based on 2 x 10mm clear heat-strengthened glass, 2 x 1.52mm clear PVB interlayer with a protective layer of 6mm fully tempered and heat soaked glass at the very top.

4 Analytic evaluation
Predicting the impact of fire and heat on a glass assembly is always very difficult and depends on multiple factors. Only experience and a clear understanding of the behaviour of fire and heat during a defined period of time as well as the knowledge about the cause of system failures gives an indication about how a new custom system should be dimensioned.

The principle of theoretically evaluating the fire resistance of a glass goes through its layers respectively the number of layers and assumed duration of fire resistance of each individual layer. This sounds being an easy process; however, the time duration within individual layers burn down in a heated furnace varies and depends on panel dimensions i.e. the structural capability of burning material under increasing heat impact and the capability of its support system.

To start with an evaluation for a relatively unknown horizontal assembly, the relation between following indicators has been taken into account from vertical assemblies:

\[ dv \quad = \quad \text{thickness of tested glazing system for vertical applications} \]
\[ T \quad = \quad \text{duration of fire resistance} \]

… as well as rarely available horizontal assemblies under shorter fire resistances.

\[ dh \quad = \quad \text{thickness of tested glazing system for horizontal applications} \]
\[ T \quad = \quad \text{duration of fire resistance} \]

A horizontal assembly needs to account for vertical deflection occurred from dead-load and potential live load (if any) which accelerates the destruction of material through elongation, decrease of material density and increase of affected area. The deflection also needs to be set into a time function due to fact the total thickness and relative stiffness of a fire impacted panel decreases over time.
Simplified, the deflection of the panel can be calculated based on thin plate theories as follows:

\[
W(x,t) = c \times p \times b^4 \div \left(E \times dh^3\right)
\]  

(1)

\(W(x,t)\) = deflection of plate depending of time  
\(c\) = Stiffness constant  
\(p\) = area loading  
\(b\) = width of plate  
\(E\) = Young’s modulus  
\(dh\) = thickness of (horizontal) plate

4.1 Base data
Based on available product specific data for vertical & horizontal Contraflam® applications, the following information has been taken into account for further evaluation:

Table 1.  Vetrotech Contraflam® reference data [3].

<table>
<thead>
<tr>
<th>Duration</th>
<th>Thickness (mm)</th>
<th>Glass</th>
<th>Gel (dhgl)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vertical 120 min.</td>
<td>39</td>
<td>5-layer</td>
<td>4-layer</td>
</tr>
<tr>
<td>Horizontal 90 min.</td>
<td>41</td>
<td>4-layer</td>
<td>3-layer</td>
</tr>
<tr>
<td>Horizontal 60 min.</td>
<td>30</td>
<td>3-layer</td>
<td>2-layer</td>
</tr>
<tr>
<td>Horizontal 30 min.</td>
<td>21</td>
<td>2-layer</td>
<td>1-layer</td>
</tr>
</tbody>
</table>

The 30/90/60 min. horizontal glass specification includes a 44.2 laminated heat-strengthened bottom layer in order to comply with overhead safety requirements. Any insulating air space has not been considered for total product thicknesses shown in Table 1.

During UL-263 fire endurance testing, time-temperature curves are specified as follows:

Table 2.  UL-263 Time-Temperature curve [1].

<table>
<thead>
<tr>
<th>Temperature F</th>
<th>Temperature C</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>538</td>
<td>5</td>
</tr>
<tr>
<td>1300</td>
<td>704</td>
<td>10</td>
</tr>
<tr>
<td>1550</td>
<td>843</td>
<td>30</td>
</tr>
<tr>
<td>1700</td>
<td>927</td>
<td>60</td>
</tr>
<tr>
<td>1850</td>
<td>1010</td>
<td>120</td>
</tr>
</tbody>
</table>

4.2 Project specific evaluation
To evaluate the behaviour of a custom designed 1.33m x 2.00m panel under fire impact load of up to 120 minutes, available reference product data as well as the time-temperature curve and associated increase of heat load, especially between 90 and 120 minutes, have been taken into consideration as follows:
Temperature increase between 30 minutes and 60 minutes: 10.00%
Temperature increase between 60 minutes and 90 minutes: 4.00%
Temperature increase between 60 minutes and 120 minutes: 9.00%

The increase of temperature in time steps of 30 minutes, from 30 minutes duration to 90 minutes duration, compared with the material requirement of intumescent gel within these load steps results into an exponential increase of thickness for a 120 minute glass, compared with to 60 minute glass, converted into required layer quantities as follows:

\[ dh(120)_{gl} = dh(60)_{gl} + dh(60)_{gl}^{1.9/4} \]

Solving Eq (2), the required quantity of additional layers of intumescent gel to perform towards a continuous heat load between 60 minutes and 120 minutes would result into \( dh(120)_{gl} = 4.75 \) to be rounded to 5 additional layers of gel which should include for a 5% safety factor accounting the potential decrease of total system stiffness and higher deflection according to Eq (1).

Under consideration of a nominal gel layer thickness of 5mm as well as five (5) additional layers of 6mm glass, between the intumescent gel is being sandwiched, the total additional required unit thickness accounts to 55mm which results into:

\[ dh(120) = dh(60) + 55mm \]  

Nominal required thickness of 30mm + 55mm = 85mm fire resistant glass system without insulating air space. In order to provide adequate insulation of the primary steel frame at the fire unexposed side of the fire rated glass, one (1) additional air space of nominal 16mm has been added followed by a second air space of equal thickness, which was required due to fabrication and handling limitations of the glass panels within the glass processing factory. Finally the total nominal thickness for the new horizontal 120 minute fire resistant glass system could be specified with:

\[ dh(120)_{total} = dh(120) + (2 \times 16mm) = 85mm + 32mm = 117mm \]

5 Testing
Testing of the floor-ceiling assembly specimen has been planned and conducted in compliance to specified standards ASTME E119 & UL-263 “Fire Tests of Building Construction and Materials”, 14th Edition, dated June 21, 2011 [1]. The purpose of the investigation was to develop fire test data on the test assembly when subjected to a fire exposure test in accordance with the standards. The fire
endurance test was conducted at the Fire Engineering Department of the Underwriters laboratory - UL in Northbrook, IL, USA; being fully recognized and acceptable to local authorities having jurisdiction for fire protection ratings.

5.1 Type, size and character of test specimen
In accordance to UL-263, the area exposed to the fire shall be not less than 16.70 sqm, with neither dimension less than 3.70m [1]. The assembly has been rated as unrestrained. The actual assembly has been dimensioned with 5435 x 4318mm, resulting into a total exposed area of 18.75 sqm. The largest glass panel size was 1.33m x 2.00m and located around the centre of specimen.

![Figure 5. Test specimen plan drawing.](image)

In accordance with the project load requirements, the top layer of triple laminated heat-strengthened glass has been equipped with a superimposed live-load of 2.00kN/sqm which was to be uniformly applied to the assembly using a symmetrical array of concrete blocks. The total loading (dead-load & live-load) stressed the entire assembly to 50% of maximum allowable bending stress in the main mullion of primary steel frame.

5.2 Details of specimen installation
In accordance to system specification and method, details have been executed in full compliance with the custom design.
**Figure 6.** Test specimen panel, 1.33m x 2.00m, thickness 117mm, 570kg weight

**Figure 7.** Test specimen steel frame with installed fire rated glass
5.3 Results of fire test
Observations during the fire test showed visible space of the first IGU – air space at one of the intermediate glass panels after 63 minutes. This was matching with the assumption of theoretic failure of the first dh(60) package after 60 minutes.

Figure 8. Test specimen at fire exposed surface after 63 minutes.

After 113 minutes, the second IGU – air space has been penetrated by flames which was protected by an intermediate package of 4-glass/3-gel layers (original dh(90), leaving a final package of 3-glass/2-gel layers for the rest of the required period. As per our theoretical evaluation in accordance to Eq (2), reiterated to 113 minutes instead of the original 120 minutes, the intermediate package should have been gone after dh(113)gl = 3.31 gel layers, providing an undetermined safety factor of 10%.

The last package of fire-resistance glass system successfully passed the 120 minute mark with neither collateral failure nor temperature penetration. The furnace has been shut off - the test has been terminated after 135 minutes without failure of the system while glow was discovered in most of the panels, giving an indication for a potential flame penetration within a short time. The assembly continued to support the applied live-load until termination and beyond that time.

Obviously, the last package performed better than expected, providing a total system safety of 135/120 = 12.5%.

Temperatures at the unexposed surface within the cavity of the assembly rose to a maximum of 325 F, maintaining an average temperature of 250 F, outperforming the average limiting temperature of 322 F as well as maximum limiting temperature of 397 F, specified as per UL-263 [1] [2].
Figure 9. Test results after 123 minutes and 28 seconds.

Figure 10. Time – Temperature curve of conducted fire endurance test [2].

5.4 Post test inspection
Observations after termination of fire endurance test and cooled out furnace revealed the appearance of various hot spots the glass panels were fighting against while being attacked by the fire and heat. These hot spots were observed
at panel width centres, but not necessarily in centre of each panel length, which
gives an indication for the fact the layout and furnace itself plays a significant role
of influence. The earlier assumption that the deflection of panels works proactive
to the destruction of material has been validated with this observation.

Figure 11. Hot spot observation at cooled out specimen.

6 Conclusion
Predicting material and system behaviour during an impact of fire is a difficult
task. An attempt for an analytic approach to maximize panel dimensions in a
horizontal 2 hour fire rated glass assembly has been concluded and verified by
testing.

The concept considers historical data of available systems for lower rated fire
impacts and fire resistance durations and develops an analytic evaluation to
engineer a custom glazing system which fulfils performance requirements
outlined by codes and building standards.

The designed, evaluated and tested horizontal glazing system has been
successfully verified by fire endurance testing and certified by Underwriters
laboratories UL® for a fire rating of 120 minutes. The system provides the largest
assembly by single panel size currently being executed.

Due to material variations in glass and intumescent interlayer’s, this analytic
evaluation concept is product specific. An application to a broader range of
products shall be part of an additional study in order to develop analytic methods
for future dimensioning concepts of horizontal fire resistant glazing assemblies.
7 Fabrication and installation
While completing this study, actual installation works have been progressed in the NYU building. Strict methods for on-site assembly and installation have been developed in order to comply with the system design as well as to mirror the conditions of the tested assembly to complying with the system certification.

Figure 12. View from basement through six floors equipped with two internal fire resistant glass floors & one external skylight during installation.

Figure 13. View from gymnasium level 1 through one internal fire resistant glass floor & one external skylight with matching layouts during installation.
References

Acknowledgements
Vetrotech Saint-Gobain, Klaus Wildenhain & Sean Ross, as R&D partners
White Aluminum Enterprises LLC, Hasan Rayan & Jabr Doshan, as project JV partners
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Arlington Glass & Mirror, Chicago, IL, USA, as laboratory test installers
Framing Achievable, Stretch Goals for High Performance, Integrated Fenestration Systems

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Abstract
The building industry remains confused about the role of windows in a world threatened by climate change. Windows add ~$20B per year to the energy bills of commercial building owners, but technically windows have the potential to be net suppliers of energy in any U.S. climate. The gap between investment decisions made by the Architectural/Engineering/Contractor/Owner community in selecting windows, and the potentials for dramatically improved performance, is huge. Closing this gap is an enormous challenge involving the following perspectives: 1) innovators see tremendous technology potential in high-R, dynamic glass, daylight redirecting glazings, smart controllers, and energy storage and generating windows; 2) suppliers see little demand for high performance products at “acceptable” price levels; 3) specifiers see products that are too complex and costly; 4) facility managers don’t believe occupants can reliably operate shading/daylighting controls, yet don’t trust automated solutions; 5) code officials will not accept performance promises that are not backed by data; 6) occupants and owners are unhappy about designs that promise, but often to not deliver, comfort, views and green ratings; 7) utilities worry about peak cooling impacts; and 8) government agencies have neither the plans nor resources to address these issues comprehensively. This paper outlines some of these challenges and suggests an action framework to address these complex challenges.

*Keywords: façade, energy performance, daylighting, simulation tools, testbed*

1 Introduction
Windows account for about 10% of all energy used in buildings in the U.S. at a cost to building owners of about $50B/year. Unlike many building components and systems, e.g. lighting and HVAC, windows do not directly consume energy but rather indirectly drive the requirement for energy use to offset thermal loads in summer and winter. In addition they often are major determinants of peak heating and cooling loads which directly impacts system size, purchase cost and performance. A full consideration of window performance should examine benefits and costs, and how they might be managed to optimize performance. The conceptual problem is simple: 1) reduce thermal losses in winter and capture useful solar gain to offset heating; 2) reduce solar gain in summer to reduce cooling loads; 3) admit air when energetically favourable to displace...
ventilation need, to offset loads and to provide thermal comfort; 4) provide glare free daylight (and view) to offset electric lighting needs. We note that there are intrinsic conflicts in meeting these needs, e.g. rejecting sunlight to minimize cooling conflicts with admitting daylight to offset electric lighting. An optimized façade design that individually and collectively meets all these needs over time must be dynamic in nature, responsive to a range of internal and external needs, and intelligent to prioritize and optimize those diverse needs.

We have framed the goals above around an optimized façade solution that can achieve “net zero energy performance” over the course of a year, e.g. the energy “cost” of the façade during some hours of operation is more than offset by the energy services delivered to the building. At the macro scale we have examined façade performance in the context of the U.S. commercial building stock to explore how different technologies and strategies might impact current energy use. Results are shown in Figure 1. The high level conclusion is that the right combination of thermal management strategies e.g. highly insulating glazings with dynamic solar control, as part of an “integrated façade” e.g. using daylight controls, can not only offset all the current energy impacts of commercial facades but move to a net positive energy impact.

**Commercial Building Window Energy Use**

![Figure 1. Commercial Building Window Energy Savings Potentials](image)

Technical savings potentials by converting all Commercial windows to the Current or Future technologies shown at the left

### 2 Directional Progress Towards Goals

We believe there are four key elements required to move towards realistically capturing these performance potentials.
2.1 High Performance Components and Systems
The backbone of any high performance system is the component technology of which the system is comprised. For commercial facades this includes 1) highly insulating glazing and framing, 2) solar control and shading elements, 3) ventilative components, and 4) daylight redirection and control. While examples of each exist today there is a need to dramatically increase the number of options, and improve their performance characteristics while reducing their overall cost.

2.2 Integrated, Responsive Intelligent Fenestration Systems
As long as the earth rotates and climate remains variable then at least some aspects of fenestration performance must be dynamic in order to provide the right functionality at the right moment. This functionality goes well beyond “energy” parameters to include thermal and visual comfort, acoustics, view, privacy, etc. While in principle this dynamic control can be managed by occupants, we believe that desired outcomes will not be routinely achieved if left to the uncertainties of purely manual occupant control. Dynamic control is ideally automated, and responsive to 1) occupant needs and preferences, 2) building operator requirements, and 3) electric grid behaviour and requirements, e.g. demand response. At times the required action will be clear and unambiguous; under other conditions compromise and trade-offs will be required. Intelligent façade systems will need to be an integral element of a broader intelligent building system with its own logic for priority and control. The recent and increased availability of low cost sensors, model-based control paradigms, wireless communications and control, cloud based computing, location based sensing, etc all provide potential useful inputs to an optimized control platform for buildings. However the lack of open systems controls standards, the rapidly changing hardware/software infrastructure for buildings, the lack of a tradition of aggressive building management to meet explicit performance targets all suggest that there is much work to be done to transition to the point where these capabilities can be routinely and properly implemented.

2.3 Design --> Construct --> Operate for Guaranteed Energy Performance
Meeting a building performance goal in 2014 is a roll of the dice- predictions are made, ratings are achieved, codes are complied with, and then the industry collectively holds its breath to see what the outcome is. In most cases the energy outcomes are never even known. A new paradigm is needed to reshape expectations and then deliver on them. Some recent trends suggest that change is on the way. Many cities and some states are now implementing disclosure laws that require each building to publicly disclose its energy performance. This provides a form of peer pressure on the AECO team to work harder toward delivering on design expectations. The concept of guaranteed performance exists in many industries today and even in parts of the building industry, for example the ESCO markets. But these models must be adapted to meet the market realities of the commercial building sector. Fortunately there is much work underway that should provide models and tools that begin to move the profession toward ensuring that design expectations are met. This is a building wide challenge, but the integrated façade systems will likely never perform as expected
unless they are part of a broader building infrastructure that delivers on its promises.

2.4 Tools and Testbeds
Making the transition from a design that meets performance goals to a building that delivers on performance promises cannot happen without new tools and models, and at least for some interim period, actionable measured data from the field that validates model predictions, reduces risk and encourages investment in these new directions. With on-going support from the U.S. Department of Energy, LBNL has provided many of these tools and data sets to the window industry and is updating the current suite to better address gaps in capabilities.

Figure 2  Schematic showing simulation tools and databases supporting Fenestration design and optimization. The top two rows provide properties of glazings, windows and facades. The bottom row provides energy and performance impacts. More information about each tool and access to download the tools is available at [http://windows.lbl.gov/software](http://windows.lbl.gov/software). Over 40,000 copies of these software packages were downloaded in 2013.

The tools in Figure 2 have all been validated in laboratory test chambers to ensure that their outputs are accurate, objective and meaningful. But the overall energy impact of a façade system in a building can only be meaningfully measured either in a building, or in a suitable outdoor testbed. While building testing has value, it is expensive, and difficult to extract and evaluate data on a comparative basis. In addition to tests in occupied buildings, we have utilized several other types of “test beds”. The common feature of each of these is that they allow controlled testing under outdoor climate conditions with a range of different technical and operational challenges. These facilities include:
1) Living lab- using the occupied spaces within a building as a test laboratory to measure system performance;
2) Custom testbeds in a building – building out special test rooms within an existing building to conduct controlled tests of systems and occupant response;
3) Custom testbeds replicating specific building design near location of final building, to test systems integration and performance issues; e.g. New York Times mockup
4) Mobile Calorimetric field test facility with side by side room-size test chambers; (MoWiTT- Mobile Window Thermal Test facility)
5) Three side by side test rooms for testing dynamic façade and daylight integration, including occupant response (Façade test facility)
6) FLEXLAB – Facility for Low Energy EXperiments in Buildings- 4 outdoor reconfigurable testbeds, one and two stories high, one rotating, with reconfigurable glazing, shading, HVAC and Lighting to dynamic performance and systems interactions, including occupant response.

Figure 3: Exterior shading systems being evaluated in the Advanced Façade Testbed, LBNL. Left photo: Exterior view of 3 room test bed; two rooms at left contain experimental systems; room at right is control room. Right photo: Interior view of three-zone blind test.

As we move toward the vision of integrated, responsive, intelligent facades in the next few years we expect the Façade Test Facility and FLEXLAB to allow us explore the performance outcomes with sufficient rigor to validate simulation models that can then be widely used to optimized custom designs for all climates and building types. The facilities serve: the needs of the research community and industry in developing new high performance solutions; the needs of the AECO community in reducing risk in adopting new solutions, and the needs of the public sector in developing new outcome based codes and standards, or by
encouraging utilities to provide additional rebates for the solutions that “work” and deliver on performance expectations

Figure 4: FLEXLAB. Upper left image: site diagram showing 4 testbed modules; rotating testbed on the left;  Upper right photo: May 2014: First reconfigured testbed with facade design from a new building under construction in San Francisco; tests will verify dynamic shading, daylighting, light control performance. Lower photo: Facility nearing completion in April 2014; rotating single story unit at left; two single story testbeds with base case windows installed flank the two story testbed that can accomodate a 25 foot high glazed facade.

3 Summary
There are an increasing number of countries, states and cities that have aggressive energy efficiency and carbon reduction goals in the years ahead. Façade system performance remains a challenge in this context- building codes still argue to minimize glazing area to provide an energy efficient building. We have 30 years of test data and simulation results that shows clearly that a properly designed and operated façade can outperform highly insulating walls while delivering the light, view and amenity that people want and expect from windows. While we have demonstrated these results in the R&D world, we have not yet been able to move these perspectives and solutions into mainstream
practice. We hope over the next few years to align new partners, new savings goals, new technologies, new business interests, and new test facilities and models into a national, and potentially global, effort to reshape the vision for façade performance, and implement that vision at a scale that will help positively address global climate change challenges.

References
General references, design guides, R&D results and tools can be downloaded from project websites:  http://windows.lbl.gov
FLEXLAB   http://flexlab.lbl.gov

Guide to 60 papers for Download At: http://windows.lbl.gov/resources/LBNLresources.pdf

Commercial Windows Website  http://www.commercialwindows.org

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Thin Glass/Ionomer (TGIO) Laminates for High Performance Light Weight Glazing

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Abstract

Commercial supply of “thin” glass (< 2 mm thickness) in relatively large plate sizes (> 1 m²) has raised the possibility of new light weight glazing structures. The inherent compliance of “thin” glass, is however, expected to limit many practical applications where strength and deflection behavior determine the glazing design. One solution to this compliance limit is to combine “thin” glass with a less dense polymer interlayer to enable stiff, lightweight composite laminates. In this contribution we examine the mechanical behavior of such laminates. It is shown that optimum light weight laminates are best achieved through the use of a relatively stiff, polymer ionomer interlayer (such as DuPont™ SentryGlas®). We present results of bending experiments in which laminate deflection has been monitored as a function of load for various laminate structures. Interpretation of the laminate mechanics using effective thickness theories is demonstrated and tested against observations. We present a formulation for computing the optimum specific stiffness of a laminate and establish theoretical limits to weight reduction for a defined monolithic glass performance target.

1 Introduction

Laminated glass has been traditionally used for protecting people from hazards associated with glass breakage due to accidental human contact and hazards from natural and man-made threats, such as severe weather (e.g. hurricanes) and terrorist attacks (e.g. bombings). The tough, adhesive, polymer interlayer used in laminated glass functions by retaining glass fragments in the event of glass breakage and by providing resistance to further loading post glass breakage. Glass fragment retention reduces the risks of cutting/piercing injuries and the barrier performance protects people (and property) from any further imposed loads post glass breakage.

When substituting monolithic glass with laminated glass to enable such safety and protection performance, the overall glass thickness is often increased versus the monolith. This is especially so when using a compliant, rubbery interlayer, such as poly-vinyl butyral (PVB). In the case of most PVB interlayers, the relatively low polymer shear modulus is not sufficient to couple the glass...
components together efficiently during loading. The two glass plies slip relative to each other and the laminated glass exhibits reduced stiffness versus a monolithic glass plate of the same total thickness. However, stiff ethylene copolymer-based (ionomer) interlayers (such as DuPont™ SentryGlas®) couple the glass components together to a high degree thus imparting stiffness (and strength) behavior that is comparable to monolithic glass. It is now common in the glazing industry to design laminated glass using ionomer interlayers in which this structural efficiency is fully exploited. Designs take advantage of the increased stiffness and strength versus traditional PVB-based laminates. In many glazing applications these advantages translate into glass thickness reduction and associated weight reduction versus traditional PVB laminate solutions.

Most laminated glass in use to date consists of glass components that are typically anywhere from 2 mm to 25 mm thick. Common polymer interlayer thicknesses fall into the range of 0.38 mm to 2.5 mm; thus, the ratio of glass/polymer thickness ranges from 3 to 10. The commercial availability of relatively thin glass (0.4 mm to 1 mm) in relatively large plate sizes (> 1 m²) has increased significantly in recent years due to thin glass use in display and mobile device applications. This availability raises the possibility of fabricating laminates where the glass polymer thickness ratio can be reduced readily in a range of 0.1 to 1. Laminates consisting of thin glass and a thick ionomer interlayer have recently been shown to exhibit strengths equivalent to 3 mm to 5 mm monolithic glass. Because such laminates primarily consist of a low-density polymer (relative to glass), thin glass ionomer (TGIO) laminates demonstrate significant stiffness/weight ratio advantages over monolithic glass or laminated glass made using conventional PVB interlayers. The uncommon glass/polymer thickness ratio in these high-performance laminates calls for an investigation of the structural behavior of TGIO laminates and the development of a rational design methodology to establish optimum laminate structures. In this contribution, we investigate the mechanical behavior of thin glass ionomer laminates and demonstrate applicable physical models that enable the efficient design of thin glass ionomer laminates with high specific stiffness characteristics.

2. Theory

2.1. The effective thickness concept

Several studies of the mechanical behavior of glass/polymer laminated glass have attempted to reveal how the large modulus mismatch between the glass and the affects laminate deformation and structural behavior [1,2]. Due to the relatively low compliance of the polymer interlayer, the strain distribution in the cross section of the laminate is not continuously linear; therefore, a standard composite beam model based on linearity is not applicable - plane sections do not remain plane during bending. Among various analytical approaches that have been proposed, the concept of the laminate “effective thickness” has been proposed as a rational and practical method for treating deformation behavior and has been used in the design community for general, thicker glass-polymer
laminates. In this section, we review the simplest of the effective thickness approaches. The analysis proposes analytic equations that provide a method to calculate the thickness of a monolithic glass beam with bending properties equivalent to those of a laminated beam. This thickness can then be used in place of the actual thickness in classic analytic equations for the deformation of beams and a simplified finite element analysis.

2.2 Effective thickness by Wölfel and Bennison

The approach is based on analysis of composite sandwich structures originally developed by Wölfel [3] and applied by Bennison et al. [4] to the case of laminated glass. The analytic equations describe the shear coupling between two glass plies through the interlayer. The shear transfer coefficient, $\Gamma$, which is a measure of the transfer of shear stresses across the interlayer, is given by:

$$
\Gamma = \frac{1}{1 + \beta \frac{E h_{lw} \Gamma^{2}}{G h^{3} a}}
$$

(1)

where:

$$
I_s = h_1 h_{s;2}^2 + h_2 h_{s;1}^2
$$

(2a)

$$
h_{s;1} = h_5 h_1 / (h_1 + h_2)
$$

(2b)

$$
h_{s;2} = h_5 h_2 / (h_1 + h_2)
$$

(2c)

$$
h_5 = (h_1 + h_2)/2 + h_v
$$

(2d)

and $h_v$ is the interlayer thickness, $h_1$ and $h_2$ are the two glass ply thicknesses, $E$ is Young’s modulus of glass (72 GPa), $a$ is the length scale of the simply supported beam, $G$ is the interlayer shear modulus, and $\beta$ is a coefficient, which depends on the load condition. $\beta$ values are found in reference [3] for specific conditions. For example, $\beta = 9.6$ for uniformly distributed loads, $\beta = 12$ for a line load concentrated at the midspan. To calculate the laminate deflection, the laminate effective, $h_{ef;w}$, is given by:

$$
\sqrt{\frac{1}{h_1^3 + h_2^3} + 12 \Gamma I_s}
$$

(3)

Associated effective thickness formulae for the calculation the maximum glass bending stress are presented elsewhere [4].

The primary interlayer property that influences laminate deformation is the shear modulus, $G$. The greater the shear modulus, the more effectively the two glass
plies couple and resist deformation under loading. The effective laminate thickness approaches the total laminate thickness (monolithic limit) for stiff interlayers ($\Gamma \rightarrow 1$) and approaches the layered limit for compliant interlayers ($\Gamma \rightarrow 0$). Note that the polymer does not need to attain the full glass modulus level to impart efficient structural coupling. This effective thickness approach has been termed the “Wölfel-Bennison (W-B) Model” by Galuppi and Royer [5].

Defining: $h_2 = kh_1 = kh$, Eq. (3) (effective thickness for deflection) is reduced to:

$$h_{ef,w} = \sqrt[3]{a_1 k t^2 + a_2 k^2 t + a_3 k^3}$$  \hspace{1cm} (4)

where:

$$a_1 = \frac{12k}{k+1} \Gamma$$  \hspace{1cm} (5a)

$$a_2 = 12\Gamma k$$  \hspace{1cm} (5b)

$$a_3 = (1 + k^3) + 3\Gamma (1 + k)$$  \hspace{1cm} (5c)

and $t$ now specifies the interlayer thickness.

A more general effective thickness calculation approach called the “Enhanced Effective Thickness (EET) Approach” has been developed recently by Galuppi et al. [5 - 7]. It employs an energetic approach to determine the laminate effective thickness and treats the influence of the support system type and partial loading more accurately than the original effective thickness approach. The W-B model and EET model provide similar results in the four point bending test geometry described in the following sections. In addition, the upper limit of $s$ where W-B theory is applicable with SentryGlas®/glass laminates has been shown to be around 100. Therefore, in the current study we employ the W-B approach for analysis as a simpler method of modeling laminate behavior.

### 2.3 Weight reduction ratio

When examining the potential for weight reduction using laminated glass, we look for a laminate can substitute for monolithic glass where the laminate effective thickness is equal to the monolithic glass thickness. For example, a 1.1 mm glass / 1.8 mm SentryGlas® / 1.1 mm glass laminate is calculated to have an effective thickness of 3.68 mm for deflection. In this example, the weights of 3.68 mm monolithic glass and the laminated are compared (at equal stiffness). Given the density of soda-lime silica float glass is 2.5 Mg.m$^{-3}$ and that of interlayer is 0.95 Mg.m$^{-3}$, the laminate weight is 78% of the monolithic glass weight and is attained for deflection matching (equal stiffness/compliance). Here, we define weight ratio of laminated glass to equivalent monolithic glass, $W$, is given by:
\[ W = \frac{2\rho_g h + \rho_i t}{\rho_g h_{ef}} \]  \hspace{1cm} (6)

Where \( \rho_g \) and \( \rho_i \) are density for glass and interlayer, respectively and \( h_{ef} \) is effective thickness for deflection or stress. By substituting effective thickness for deflection, Eq. (6) is transformed to:

\[ W_w = \frac{3}{\sqrt{a_1 s^2 + a_2 s + a_3}} \left( a_6 + \rho_i s \right)^\frac{1}{3} \]  \hspace{1cm} (7)

Dividing both denominator and numerator by \( \rho_g \) and \( h \) the following is obtained:

\[ W_w = \frac{\frac{1}{\sqrt{a_1 s^2 + a_2 s + a_3}}}{\frac{3}{3}} \left( a_6 + \rho_i s \right)^\frac{1}{3} \]  \hspace{1cm} (8)

It is noteworthy that weight reduction ratio is determined solely by the density and thickness ratio of interlayer to glass. As the density of soda-lime silica float glass and an ionomer polymer interlayer are considered to be 2.5 Mg.m\(^{-3}\) and 0.95 Mg.m\(^{-3}\) respectively, the dominant factor for weight reduction is the ratio of interlayer to glass.

3. Experimental

The weight reduction ratio of thin glass and thick polymer laminates was investigated by means of four point bend tests. Details of the laminate structures tested are shown in Table.1. Standard “thin” soda-lime silica float glass was used for the glass plies and DuPont\textsuperscript{TM} SentryGlas\textsuperscript{®} was used for the interlayer.

The four point bend tests were conducted using a universal testing machine (Intron 5965). A loading arm speed of 1 mm/min was employed with applied load and maximum laminate deflection measured at 0.5 second intervals. A linear variable differential transformer (LVDT) (Instron 2601-093) was used for the deflection measurements.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample Thickness of the Upper Glass Ply</th>
<th>Interlayer Thickness</th>
<th>Thickness of the Lower Glass ply</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table. 1 Laminate glass structures for the four point bend experiment.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size [mm]</td>
<td>[mm]</td>
<td>[mm]</td>
<td>[mm]</td>
</tr>
<tr>
<td>-----------</td>
<td>------</td>
<td>------</td>
<td>------</td>
</tr>
<tr>
<td>1</td>
<td>250 x 100</td>
<td>1.1</td>
<td>1.8</td>
</tr>
<tr>
<td>2</td>
<td>250 x 100</td>
<td>1.1</td>
<td>3.6</td>
</tr>
<tr>
<td>3</td>
<td>250 x 100</td>
<td>1.1</td>
<td>6.2</td>
</tr>
<tr>
<td>4</td>
<td>250 x 100</td>
<td>0.55</td>
<td>0.97</td>
</tr>
<tr>
<td>5</td>
<td>250 x 100</td>
<td>0.55</td>
<td>2.5</td>
</tr>
<tr>
<td>6</td>
<td>250 x 100</td>
<td>0.55</td>
<td>4.3</td>
</tr>
</tbody>
</table>

![Fig. 1 Schematic representation of the four point bend test. Deflection is measured at the center of the bottom side of the lower glass ply. Laminate effective thickness was calculated using the slope of the initial load-deflection line and Eq. (9).](image)

Laminate effective thickness was calculated using the slope of the initial load-deflection line and Eq. (9).

\[
h_{ef;w} = \frac{\sqrt{\frac{Pls(3L_1^2 - 3L_3^2)}{4EEd}}} \]

(9)
The effective thickness (W-B approach) was calculated with Eqs. (1) - (3). The shear modulus of interlayer (DuPont™ SentryGlas®) was taken as 173 MPa at 24° C for a load duration of 1 minute [4]. Note the load ramp time scale was on the order of one minute. The shear modulus was measured via dynamic mechanical analysis (DMA) and analyzed using a time temperature superposition [2]. Weight reduction ratio was calculated by real weight of the laminated glass and density times its effective thickness.

4. Results

The weight reduction behavior as determined from the four point bend measurements are summarized in Figure 2 in addition to comparisons with calculated values. Shear transfer coefficients and theoretical maximum weight reduction ratios (shear transfer coefficient \( \gamma = 1 \)) are also plotted in these figures. The shear transfer coefficient is calculated theoretically using Eq. (1).

![Figure 2(a) Glass thickness = 0.55 mm (sample No.1~3)](image-url)
Fig 2(b) Glass thickness = 1.1 mm (sample No.4–6)

**Fig. 2** Interlayer thickness vs. weight reduction maintaining bending stiffness

Fig. 2 (a) and (b) are reorganized as a function of $s$ (thickness ratio of an interlayer to a single glass sheet) in Fig. 3.

**Fig. 3** Interlayer/ glass thickness ratio $s$ vs. weight reduction ratio

Overall, the experimental observations of weight reduction and calculated values based on the effective thickness model are consistent.
5. Discussion

5.1 Theoretical weight reduction limit

Laminates fabricated with combinations of relatively thin glass and thick polymer interlayers provide significant weight reduction potential over use of monolithic glass. The interlayer / glass ratio primarily determines the weight reduction ratio at equivalent bending stiffness. In these thin glass / thick interlayer structures, laminated glass shows high stiffness when the distant two glass plies work together with good coupling as if it were a monolithic glass ply. When interlayer is stiff enough to reach the theoretical monolithic limit \( f^* = 1 \) and the laminate structure is symmetrical \((k = 1)\), the total thickness ratio \( T_w \) of a laminated glass and equivalent monolithic glass, is given by,

\[
T_w = \frac{2h + t}{h_{ef}} = \frac{3}{\sqrt{\Theta}}
\]

(10)

where \( \Theta \) in terms of stiffness (deflection) is given by,

\[
\Theta = \frac{(s + 2)^3}{2(3s^4 + 6s^3 + 4)}
\]

(11)

At a critical value of \( s \), the weight changes from replacing glass with polymer balance. Consequently, increasing \( s \) no longer provides weight reduction advantage as seen in the maximum weight reduction in Fig. 3.

Here, further analysis is presented for the maximum weight reduction ratio. The interlayer / glass thickness ratio is obtained by calculating the differential of weight ratio \( W_w \):

\[
\frac{\partial W_w}{\partial t} = -a_1 \rho_r s^2 + 2(a_2 a_6 - a_2 \rho_r) s + a_3 a_6 - 3a_3 \rho_r
\]

(12)

Regarding weight reduction maintaining bending stiffness, \( \frac{\partial W_w}{\partial t} = 0 \) gives:

\[
s^2 + 2 \left( \frac{a_2}{a_1} - \frac{a_6}{\rho_r} \right) s + 3 \frac{a_3}{a_1} - \frac{a_2 a_6}{a_1 \rho_r} = 0
\]

(13)

For positive values of \( s \), the solution of this quadratic equation is given by:
The thickness ratio \( s \) is determined by shear transfer coefficient and thickness ratio of upper and lower glass plies. Accordingly, the maximum weight reduction ratio is provided by these two factors. When two glass plies have the same thickness \((k = 1)\) and the shear modulus of an interlayer is sufficient to reach the monolithic limit \((I = 1)\) then \( s \) and \( W_w \) for stiffness (deflection) are given by:

\[
s = \left( k + 1 \right) \left( 1 - \frac{1}{\rho_r} \right) + \frac{k+1}{4/k} \left[ 4I \left( 1 - \frac{1}{\rho_r} \right)^2 - 1 \right] k^2 + \left( 1 + \frac{4}{\rho_r^2} \right) I/k - (3I + 1) \] \tag{14}
\]

Therefore, the maximum weight reduction percentage is shown to be 36.0 % \((1 - W)\). Here, interlayer’s density is assumed to be 0.95 \(\text{Mg.m}^{-3}\). Though there are slight differences in density for various interlayers, most fall within the range of 0.95 to 1.05 \(\text{Mg.m}^{-3}\).

This theoretical limit is consistent with experimental observations presented in Fig. 3. The optimized glass laminate (with \(I = 1\) and \(s = 7.41\) or 4.55) demonstrates the highest specific stiffness among all glass laminates. Periodic structures of glass sheets and polymeric interlayers potentially provide higher specific stiffness in the case of soft interlayers. However, glass / interlayer / glass structures in which all glass components are positioned on the outer side are the most efficient in attaining the highest stiffness.

### 5.2 Design approach for light weight glass laminates

As weight reduction ratio can be calculated by the Eq. (8), the relationship among interlayer/glass thickness ratio, shear transfer coefficient and weight reduction ratio can be summarized as shown in Figure 4. The maximum weight reduction lines (minimum weight ratio line) are also plotted in the same graph. Though only the case of a symmetrical laminate \((k = 1)\) is shown in Fig.4, other cases such as \(k = 2\) or \(k = 0.5\) can be calculated in the same way. These diagrams enable rapid light weight glazing design with laminated glass. As the thickness of glass and interlayer has relatively small impact to the shear transfer coefficient in Eq.(1), the shear transfer coefficient can be roughly estimated by setting \(t\) and \(h\) to values of one, and then the diagram in Fig.4 provides optimum \(s\) for target weight reduction ratio. Once the \(s\) is fixed, the effective thickness is calculated with possible thickness combinations which satisfy \(s\) using Eq. (4) and one combinations of glass polymer structure can be specified.
Key finding here is weight reduction is achievable with higher interlayer / glass thickness ratio and a sufficiently stiff interlayer to reach a high shear transfer coefficient. For example, if we consider around 25% weight reduction with a sufficient stiffness interlayer, $s = 2$ with 0.5 mm glass thickness means 1 mm interlayer. However, $s = 2$ with 5 mm glass requires 2.5 mm interlayer which is more unrealistic solution for practical applications. Accordingly, combination of thinner glass and thicker polymer interlayer is the optimum way of achieving the weight reduction. Because larger weight reduction is expected with higher interlayer / glass thickness ratios, combinations of thin glass and a stiff polymeric interlayer demonstrates advantages that are hardly achieved with conventional thick glass and soft interlayer laminates.

**Conclusions**

The combination of relatively thin glass ($< 2$ mm) and a thick polymeric interlayer with high shear modulus can replace monolithic glass ($< 5$ mm) with significant weight reduction but no penalty in stiffness performance. The weight reduction ratio is determined by the interlayer / glass thickness ratio. The greatest weight reduction is achieved when the interlayer / glass thickness ratio is 7.41 (at constant stiffness) with an associated weight reduction ratio of 36.0 %, providing that shear coupling between two glass plies is sufficient to approach the monolithic limit. Such performance may be realized with stiff, ionomer-based interlayers such as DuPont™ SentryGlas®. Since larger weight reductions are expected with increasing interlayer / glass thickness ratio, combinations of thin glass and a stiff polymeric interlayer imparts structural performance advantages.
that are difficult to realize with conventional thick glass and compliant interlayer laminates based on standard PVB interlayers. These findings can be utilized in rational and efficient design approaches for higher specific stiffness and structurally efficient glass laminates.

References

Analysis of Curved Triple Insulated Glass Units: Rehabilitation of Hypo Vereinsbank Tower Munich

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Abstract

In terms of rehabilitation of existing buildings often a new façade is planned and build to make building more sustainable. Depending on the weather conditions and the location of the building the costs for heating of residential and commercial premises are in Germany approximately 25% to 35% of the final energy consumption. In order to reduce CO2 emissions many buildings dating from the 1960s and 1970s are being now refurbished. In more and more cases not only new windows but complete new façade and even so called double skin facades are carried out. This second skin has several advantages like sound protection, possibility of natural ventilation, contribution to energy balance and others. One recently realized task is a high rise building of more than 100m height in Munich, a listed as historic building – so additional attention to appearance was necessary. And moreover curved insolation glass units had to be used; as there do not regulations special theoretical research and calculations had to be carried out. The calculation of the glass, e.g. for the climatic loads in the inner of the IG-unit, is a “new technological territory”. Especially the boundary conditions like very narrow radii, small elements and few alternatives concerning kind of glass and thickness of glass made the calculation to a challenge.

Keywords: Rehabilitation, Curved Glass, Analysis, Facade

1 Introduction

Glass as a transparent building material allows natural lighting of rooms. This means less costs for lighting energy as well as positive effects to people. The advantage using double skin facades is not only the possibility of dividing the different tasks to two layers and giving additional thermal and sound insulation but that in fact the space between the two facades can be regarded as an additional component. And by planning the opportunity to open each facade and maybe even change the open cross section the second facade moreover acts as variable element supplementing or replacing an artificial ventilation system. So a second facade allows windows to be opened (and by this natural air) also in
comparatively loud areas and is nearly independent of weather or wind conditions even in high buildings. And in addition the use of simple sun blind instead of expensive systems protected from wind and weather is possible. This again saves energy and capital as well as it has positive effects towards the people's conscious.

The high rise building of HVB-tower of the banking company “Hypo-Vereinsbank” in Munich, erected 1981 and a landmark in Munich is at present under rehabilitation. The building is 114 m high with 27 levels above ground and 4 levels below ground. Some of the project objectives are the redesigning of the office space (Smart Working) and an improvement of the fire protection concept. To get a green building according LEED standard, amongst other topics like the installation of a rainwater utilization system and using the energy of geothermal heat, the old facade is replaced by a modern double skin facade. The building is classified as a historic monument, meaning that renovation is subject to strict conditions. The outer appearance of the building has to remain unchanged. Remarkable features of the building are the curved edges, which are only partially covered by the German regulations for glass.

Figure 1. Overview of the building

Figure 2. Samples for coating

There were some important aspects which have to be taken into account:

The glazing of the existing façade (Figure 1) is produced in 1981 with a special low-e coating for a selective filtering of the solar radiation. Until now there were made of course technical progress and improvements concerning the coatings of glass. Closely related to this the color of possible coatings changed the last 35 years. To match the former appearance of the façade an extensive sampling was
done on site, see Figure 2. Finally there was found a solution which matches the "original" color the best.

In the corner of the building special bent elements were used, according the state of the art in form of triple insolation units. This application is not covered by the German regulations. The calculation of the glass, e.g. for the climatic loads in the inner of the IG-unit, is a "new technological territory".

It was necessary to design a very slim new element with all technical characteristics of a double skin façade – with the same appearance of the old façade. Especially the necessary openings for ventilation have to be implemented into the element. This was done inter alia with very small drillings in the metal sheet.

It was necessary to fix the new elements with a higher weight to the existing concrete floors of the building.

Because of the not sufficient parapet height the element acts as anti-drop device.

Figure 3. Change of Elements
Figure 4. Change of Elements, detail
2 Curved Triple Insolation Unit

2.1 General

The corners of the building are covered with bent insolation glass units. Especially the boundary conditions like very narrow radii, small elements and few alternatives concerning kind of glass and thickness of glass made the calculation to a challenge.

The bent radius of the glass is between 400mm and 1500mm, the height of the glass is between 700mm and 2600mm. There are also different opening angles (45°, 90° und 135°).

The standard formula for IG-Units ([17], [18], [19]) cannot be used for the calculation.

In Figure 6 and Figure 7 the demounting of these elements is shown.
2.2 Calculation Formulas

The resulting pressure in the space between the panes and the mechanical stress to the edge seal is very high.

For a uniform load bent glass behaves much stiffer than flat glass panes. For the so called “climatic loads” almost isochoric conditions are given (VSZR= const.).

According the DIN 18008-1 [8] it is not allowed to consider a shear connection in the edge seal. So it was necessary to consider two cases in the calculation:

- Only radial constraint (stiff or elastic)
- Additional shear transfer in the edge seal

Aspects like elastic constraint influence of the spacer, consideration of the gluing (intact or with delamination), consideration of the kind of sealing material and many others were very important to investigate. Especially the Kind of sealing material has an important role in the calculation. E.g. a polymer has a nonlinear behavior. The Stiffness depends on the geometry, the temperature and the ageing. The question is if is necessary to implement these phenomena in the calculation. Figure 8 shows the stress-strain diagram for a gluing according [7], appendix B.
For the design of bent glass, the climatic loads have a main influence. According to the DIN standard the following formulas apply accordingly:

Summer:

$$\Delta T = T_{SZR, Summer} - T_{prod} + \Delta T_{Absorptionsgrad} + \Delta T_{sunprotection}$$

$$= 39°C - 19°C + \Delta T_{Coating} + \Delta T_{sunprotection} = \text{min. 20 K}$$  

(1)

Winter:

$$\Delta T = T_{SZR, Winter} - T_{prod} = 2°C - 27°C = -25 K$$  

(2)
Next step is the approximate calculation of the volumetric coefficient with a linear relationship between variation of volume and load:

$$\Delta V = v \cdot p \tag{3}$$

Based on [17], [18] and [7] a special procedure for the analysis was developed. For each glass pane I,II,III, each load case and each constraint situation it is necessary to determine a volumetric coefficient:

$$f_{\alpha,Zug} = \sigma_{\text{max}} / (p=1) \tag{4}$$

$$f_{\alpha,Druck} = \sigma_{\text{max}} / (p=-1) \tag{5}$$

$$f_{\alpha,Holm} = \sigma_{\text{max}} / (q=1) \tag{6}$$

To determine realistic pressure conditions in the cavity, it is necessary to calculate the isochoric pressure:

$$\Delta p_T = c_T \cdot (T_{\text{inst}} - T_{\text{pr}}) \tag{7}$$

$$\Delta p_{\text{met}} = p_{\text{met,inst}} - p_{\text{met,pr}} \tag{8}$$

$$\Delta p_H = c_H \cdot (H_{\text{inst}} - H_{\text{pr}}) \tag{9}$$

$$\Delta p_{\text{ex,1}} = p_L \cdot v_1 \cdot \frac{p_{\text{ex,1}}}{V_{\text{pr,1}}} \tag{10}$$

$$\Delta p_{\text{ex,2}} = p_L \cdot v_{\text{III}} \cdot \frac{p_{\text{ex,III}}}{V_{\text{pr,2}}} \tag{11}$$

with

- $c_T$ 0,34 kPa/K
- $c_H$ 0,012 kPa/m
- $T_{\text{inst}}$ relevant temperature in SZR at mounting location
- $T_{\text{pr}}$ relevant temperature when closing the sealing
- $p_{\text{met,inst}}$ relevant meteorological air pressure at mounting location
- $p_{\text{met,pr}}$ relevant meteorological air pressure when closing the sealing
- $H_{\text{inst}}$ Height above sea level
- $H_{\text{pr}}$ Height above sea level when closing the sealing
- $p_L$ surrounding air pressure 100 kPa
- $V_{\text{pr}}$ initial volume of SZR
The get the real pressure differences in the cavity, a system of equations must be solved, considering the equation of state for real gases.

By superposition the pressure in the cavity with the external loads it is possible to get the resultant loading.

\[
\Delta p_1 = \frac{\varphi_1 (\Delta p_{T,1} + \Delta p_{m,1} + \Delta p_{H,1} + \Delta p_{ex,1}) + \alpha_1 \varphi_2 (\Delta p_{T,2} + \Delta p_{m,2} + \Delta p_{H,2} + \Delta p_{ex,2})}{1 - \varphi_1 \alpha_1 \varphi_2 \alpha_2}
\]

(12)

\[
\Delta p_2 = \frac{\varphi_2 (\Delta p_{T,2} + \Delta p_{m,2} + \Delta p_{H,2} + \Delta p_{ex,2}) + \alpha_2 \varphi_1 \varphi_2 (\Delta p_{T,1} + \Delta p_{m,1} + \Delta p_{H,1} + \Delta p_{ex,1})}{1 - \varphi_1 \alpha_1 \varphi_2 \alpha_2}
\]

(13)

Another important point is the determination of the load on the edge seal. This is possible with the formulas according ETAG 002 [7] or with a finite element analysis.

2.3 Finite-Element Analysis

The Finite-Element Analysis was done on basis of the numerical investigations. It is important to consider the edge seal and the spacer close to reality. Figure 10 shows exemplary plots for Stress and deformation.

One result was that it is very difficult to predict location and size of stress and deformation.

Figure 10. Exemplary plots for stress and deformation
2.4 Results of the Calculation

First conservative calculations showed a clearly exceedance of stresses.

A realistic modelling of the edge seal resulted in more realistic results, but it was still not possible to fulfill the demands concerning the allowable stress according the German regulations.

To fulfil the demands it was- because of the very high pressures - necessary to adjust the pressure in the space between the panes in the production process. The optimum for the production temperature is in this case 15°C. Finally it was possible to realize the curved elements in the edges of the building.

The Relationship between production temperature and the possible stress ratio is shown in Figure 11.

![Figure 11. Case study](image)

3 Pendulum Impact Test

Not only the load carrying capacity of the intact glass elements is important.

It must be sure that a glass construction cannot collapse in case of breakage of glass, so that the safety of people, e.g. falling against a glass facade is guaranteed. Depending on the kind of application the testing of residual resistance is done with different testing methods. In case of glass-panes of facades a pendulum impact test is done. The behavior after breakage of a glass pane depends on many factors. The kind of glass (thermally toughened or heat strengthened glass), the kind of lamination between the glass panes (PVB-Foil or cast-in-place resin) and the kind of constraint have mainly influence.
To fulfil the demands of anti-drop device, pendulum impact tests were done for the project Façade of the HVB tower like shown in Figure 12.

![Figure 12. Pendulum Impact test](image)

4 Conclusion

Retrofitting existing buildings is very often even more complex than designing new ones as the remaining structure has to be included in the design concept and in many cases compromises have to be made to meet standards and requirements. Double skin façades has much potential to improve old buildings concerning the CO2 emissions and the living and working conditions. For the design many aspects a very important like monument conservation, connection to the substructure, building physics, a proper static analysis, higher loads and much more. In case of the presented building in Munich the rehabilitation was realized successful. The calculation of the curved insulation units was a challenge, but finally it was possible to fulfil the demands of the German regulations. On the one hand side a very closed to reality calculation method was developed, on the other hand side the load ability of the IGU was improved by a special production technology.

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DIN 18008 – New German design code for structural glass

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Abstract

With DIN 18008 parts 1 – 5 [1], [2] a family of codes for several applications of architectural glass does exist. They will substitute the so called “Technische Regeln” [3], [4], [5], [6] – actual design regulations based on the “old” principle of global safety factor. DIN 18008 follows the partial safety concept and by this the principle of the Eurocode [7]. Part 1 gives basic principles, following parts 2 and 3 cover regulations for linear supported or point fixed glass elements, respectively. For glazing acting as balustrade additional regulations including calculation method for impact are found in part 4. Glass floors and stairs are covered by part 5. Regarding the field of application the published parts cover most of the daily work; two last parts (6 accessible for maintenance work and 7 for structural elements) are under preparation at the moment. So regulations covering most aspects for structural design of glass structures will be available.

Keywords: German design code, DIN 18008, Eurocode, design of glass structures

1 Introduction

1.1 Design of structural elements in Europe

In Europe the establishment of a common European single market is one of the top goals, of course also in the field of structural engineering. To enable this, harmonized rules in the building sector were needed. Responsible for these are different committees or working groups of CEN. As a result European standards for products as well as for structural design were created. Harmonized product specifications are used for years, some for over a decade. The codes for structural design are well known as “Eurocode”, consisting of EN 1990 [7] (Eurocode: Basis of structural design) and EN 1991 to EN 1999 (Eurocode 1 to Eurocode 9 or EC 1 to EC 9). In Germany they have been set to power since mid of 2013. A schematic overview about the family of existing Eurocodes is given in Figure 1. EC 1 covers actions on structures and the following parts design of structures made of different materials – with the exception of EC 7 (Geotechnical Design) and EC 8 (Design of structures for earthquake resistance).
By this the design of structures made of different materials follow the same (Euro-
codes in whole Europe – except so called “nationally determined parameters”
given in a “national annex document” to the single Eurocode documents every
European country can publish; in fact not only parameters in the sense of single
numbers or values but also design formulas or equations and text paragraphs are
changed (adjusted) by these national annex documents.
Regarding glass structures for the products harmonized specifications are used –
and by this at in the EU a market without obstacles does exist theoretically. The
design of glass structures at present still follows different rules or codes in most
European countries; in the following the actual (May 2014) situation in Germany
is described.
Based on the appropriate mandate recently work on a Eurocode for design of
glass structures has started, for more detailed information see section 3.3.

1.2 Design of glass structures in Germany

1.2.1 General
Starting from applications of the craftsmen with predominately use of glass as
window the fascinating material glass was increasingly used as structural
element. Parallel to this of course also design methods had to change from
simple, mainly on experience based rules of thump to more complex methods.
The latest, actual step is the application of state of the art design concept of
partial safety factors also for material glass used as structural element.
At present design of glass is done in Germany using rules based on global safety
concept and experience, so called TRLV [4], TRAV [5], TRPV [6] (abbr. for all:
TRXV). They only cover a small field of application, for interesting structures
special knowledge is needed and a special permit has to be applied for in
Germany.
In Europe in the field of structural design the transfer from global safety concept to the concept of partial safety factors (Eurocode) is done since several years, concept of design for all structural elements of any building material except glass do follow the modern concept of Eurocode. And of course action / loads including their combination were adjusted to this concept.

Because of this (field of application only partly covered and incompatibility of modern codes for actions/loads with glass design rules TRXV) and as on European level no such code covering most of applications was expected, DIN standard working committee NA 005-09-25 AA "Bemessungs- und Konstruktionsregeln für Bauprodukte aus Glas" was established in 2002 to develop a code according the new concept. With this occasion also the field of applications covered by codes was widened to almost every form of application, see Table 1.

Table 1. Comparison of covered applications by TRXV and DIN 18008

<table>
<thead>
<tr>
<th>Application/installation</th>
<th>Bearing situation</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>linear</td>
<td>Point fixed</td>
</tr>
<tr>
<td>Vertical</td>
<td>TRLV</td>
<td>DIN 18008-2</td>
<td>TRPV</td>
</tr>
<tr>
<td>Horizontal</td>
<td>TRLV</td>
<td>DIN 18008-2</td>
<td>TRPV</td>
</tr>
<tr>
<td>Barrier glazing</td>
<td>TRAV</td>
<td>DIN 18008-4</td>
<td>TRAV</td>
</tr>
<tr>
<td>Accessible for public</td>
<td>TRLV</td>
<td>DIN 18008-5</td>
<td>-</td>
</tr>
<tr>
<td>Accessible for maintenance</td>
<td>-</td>
<td>DIN 18008-6</td>
<td>-</td>
</tr>
<tr>
<td>Special structures</td>
<td>-</td>
<td>DIN 18008-7</td>
<td>-</td>
</tr>
</tbody>
</table>

As design criteria for structural elements of glass (e.g. plate for window-panes as well as beams for stairs or girders) usually the tensile stress is used. In addition criteria of maximum deflection are sometimes introduced; the latter can be understood as service limit state or sometimes as a hidden requirement for ultimate limit state.

It is obvious that with development of design rules and regulations for wider field of applications the simplicity also had to decrease: from simple to use tables to several complex formulas. But of course still simple to use design tools not only for “traditional applications” can be made easily.

1.2.2 Safety concepts

Although the concept of partial safety factors was already used for other building materials (like e.g. DIN 18800 for design of steel structures since 1990) the actual DIN 18516-4 [1], TRLV [2], TRAV [3] and TRPV [4] (dated 1990 and 2003 and 2006!) still use the concept of global safety factors. Here in a design equation an existing stress “vorch σ” is compared with so called allowed stress “zul σ”. The “existing stress” is calculated using characteristic values of loads whereas the “allowed stress” is the material strength divided by a global safety factor which takes all uncertainties of material, geometry, load, static model and so on. In addition maximum deflections are not allowed to be exceeded; as stated above
this is not only to guarantee serviceability but acts as additional, hidden load ability prove.
The modern concept of partial safety factors — as the name lets expect — used a safety factor which is split and put to stress and resistance side, respectively. By this partial safety factors for material, geometry, loading, load combination et cetera are introduced; to make it more convenient some of these factors are chosen as 1.0. For further details see e.g. [7].
A mixture or combination of codes based on two different concepts on the short look can make faster application of “old” codes TRXV together with EC 1 (characteristic values of actions/loads) possible. For standard applications and load combinations this may work, but usually also SLS and accidental combinations with reduced partial safety factors is needed, so this proves not to be a sufficient way. In addition the use of the concept of partial safety factors for design of all structural elements made of any material has the advantage that e.g. bearing force of glass elements can be used for design of superstructure made of other materials like steel, wood, concrete without further or additional recalculation.

2 DIN 18008
2.1 Structure of DIN 18008
Based on the background of existing regulations for glass and codes for other materials used in structural design a subdivision in multiple parts was made. After definition of terms and general basics the rules for different applications are given in appropriate parts of the DIN standard. The structure of DIN 18008 is the following, [1], [2]:
Part 1: Terms and general basics
Part 2: Linearly supported glazing
Part 3: Point-fixed glazing
Part 4: Additional requirements for barrier glazing
Part 5: Additional requirements for glazing accessible for public
Part 6: Additional requirements for glazing accessible for maintenance
Part 7: Special structures
At present part 1 and 2 were published as final version in December 2010 [1], meanwhile an English version is published. For parts 3 to 5 after a first draft from October 2011 a final version was published in June 2013 [2], the English version is under preparation. Work on part 6 is finished, after final editorial work it will be published soon; and for part 7 a structure was set up.
In the following an overview about content of published parts will be given and – due to limited space – only some regulations looked at in detail. Further information can be found e.g. at [8], [9], [10], [11], [12], [13].

2.2 DIN 18008-1: Terms and general basics
As stated by the subtitle of DIN 18008 part 1 covers terms, concept and general basics. In detail definition of used terms and symbols as well as information about safety concept and construction material glass is given. And of course design
principle for ULS (ultimate limit state) and SLS (serviceability limit state) is explained shortly. In addition general rules for construction as well as for securing sufficient residual strength are given.

The annex gives a method for calculating special problems related to insulating glass units like climatic loads or cushion effect; these are comparable to actual rules in TRLV [4].

For ULS one has to prove that the design value of stress $E_d$ is less than design value of resistance $R_d$: 

$$E_d \leq R_d$$

In this equation design value of stress $E_d$ is to be calculated according to Eurocode. For standard design situations $E_d$ is given by:

$$E_d = \sum_{j \geq 1} \gamma F G_{k,j} \oplus \gamma P P_k \oplus \gamma Q Q_{k,i} \oplus \sum_{i > 1} \left( \gamma Q_{0,i} \psi_{0,i} Q_{k,i} \right)$$

(2)

The design value of resistance $R_d$ of thermal treated glass is given by quotient of material strength $f_k$ and material safety factor $\gamma_M$ (for thermally treated glass $\gamma_M = 1,5$) multiplied by construction-factor $k_c$ (usually 1,0):

$$R_d = \frac{k_c \cdot f_k}{\gamma_M}$$

(3)

For calculation of design value of resistance of float glass ($f_k = 45$ MPa) an additional factor $k_{mod}$ for considering time dependence is introduced:

$$R_d = \frac{k_{mod} k_c f_k}{\gamma_M}$$

(4)

In this equation the factor $k_{mod} = 0,7$ for short term loading like wind or personnel load on balustrades, for mid-term loading like snow or temperature $k_{mod} = 0,40$ whereas for long term loading (dead load or change in altitude) $k_{mod} = 0,25$; in any case also the load combination without short-term loading has to be taken into consideration. That is to say only long term loads like dead weight has to be taken into account – although this might not lead to a maximum value for stress the ratio of stress by resistance might become extreme. The safety factor for material float glass without tempering is $\gamma_M = 1,8$.

In case of tensile stress along edges of float glass, resistance has to be reduced to 80%. The use of laminated safety glass is taken into account by a bonus of 10%.

The values for characteristic strength $f_k$ of the different types of glass have to be taken from the appropriate product specification code. As the formulas at a first look seem to be complicated and the values for $f_k$ have to be taken from other codes, several values for $R_d$ are calculated for different loading and situations of installation and given in Table 2.

The requirements for guaranteeing SLS are related to its application, so they are given in the appropriate parts of DIN 18008 [1], [2].
Table 2. \( R_d \) in MPa (N/mm²) for different glass types and situations of installation, [11]

<table>
<thead>
<tr>
<th>Glass product; ( f_k ) in MPa</th>
<th>Edge under tensile stress</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Monolithic</td>
<td>LSG</td>
<td>Monolithic</td>
<td>LSG</td>
</tr>
<tr>
<td>Floatglass; 45</td>
<td>( k_{mod} \cdot 20 )</td>
<td>( k_{mod} \cdot 22 )</td>
<td>( k_{mod} \cdot 25 )</td>
<td>( k_{mod} \cdot 27,5 )</td>
</tr>
<tr>
<td>Floatglass; 45; ( k_c = 1,8^* )</td>
<td>( k_{mod} \cdot 36 )</td>
<td>( k_{mod} \cdot 39,6 )</td>
<td>( k_{mod} \cdot 45 )</td>
<td>( k_{mod} \cdot 49,5 )</td>
</tr>
<tr>
<td>HSG; 70</td>
<td>46,7</td>
<td>51,3</td>
<td>46,7</td>
<td>51,3</td>
</tr>
<tr>
<td>HSG with enameling; 45</td>
<td>30</td>
<td>33</td>
<td>30</td>
<td>33</td>
</tr>
<tr>
<td>FTG; 120</td>
<td>80</td>
<td>88</td>
<td>80</td>
<td>88</td>
</tr>
<tr>
<td>FTG with enameling; 75</td>
<td>50</td>
<td>55</td>
<td>50</td>
<td>55</td>
</tr>
</tbody>
</table>

If not stated other \( k_c = 1,0. \) “enameling” is for glass with enameling or printing on tensile surface.

* For linearly supported glazing according part 2

Taking a positive effect of shear connection between single plies of laminated glass made of PVB (Polyvinylbutyral) into account is not allowed – except for calculation of impact according to part 4 or 6. This is unchanged in comparison to classic regulations – and probably also in the future shear connection can be taken into account by using special laminated safety glass with general national approval. The reason for this is the lack of an appropriate product code defining the necessary requirements for such laminated glass in a sufficient way – in detail all products for producing safety glass on the market differ at least in details of material composition or assembly.

2.3 DIN 18008-2: Linearly supported glazing


Depending on the inclination of installed glass element it is classified as vertical glazing (inclination up to 10°) or horizontal glazing (inclination bigger than 10° vs. vertical); the latter was formerly called overhead glazing – a term better describing the situation because a glass roof with a slope of e.g. 45° is more likely identified as being over-head than vertical...

For SLS the maximum deflection is limited to \( l/100 \) (where \( l \) is the span). Alternatively it is not necessary to obey this deflection criterion for vertical glazing if it is granted that sufficient edge cover of 5 mm is given under all loading...
situations; hereby also in-plane deformations due to large deflections have to be considered. The construction factor \( k_c \) may be set to 1,8 for float glass, for thermally treated glass \( k_c=1,0 \); this is valid for any installation situation (vertical and horizontal) and not only 4-sided support but also e.g. 2-sided support. Depending on the way of installation and span additional rules for construction or product properties are requested. For horizontal glazing e.g. single glazing or the lower pane of IGU have to be made of laminated safety glass made of float glass or LSG of heat-strengthened glass (HSG) or wired glass only in order to protect public areas below the glazing in case of glass breakage. Depending on span and number of supports minimum thickness of PVB as well special regulations for application of wired glass can be found. Maximum span for horizontal glazing not on all edges supported is 1,20 m for laminated safety glass and 0,70 m for wired glass, respectively. For vertical glazing e.g. monolithic single glazing with installation height of over 4 m require a four sided support in case they are made of coarsely breaking glass or laminated glass (LG) only. For an installation height of maximum 20 m above ground level as well normal production and loading situation vertical glazing made if double- or triple-pane insulating glass may be used without further considerations (in the sense of static calculation) if special conditions are met: maximum size of element is 1,6 m², thickness of single pane is not less than 4 mm, where the difference in the thickness is maximum 4 mm, the cavity is not exceeding 16 mm and characteristic value of wind loading is not exceeding 0,8 kPa.

2.4 DIN 18008-3: Point-fixed glazing

For point fixed glazing at first diversion is made to clamp fixing (bearing only by clamping, no holes in glass) and bolted disc fixing (combination of discs and a connecting bolt going through cylindrical bore holes in the glass). Flush point fixing e.g. with conical drillings are not included in actual part 3. Geometrical requirements for clamp fixings are a minimum depth of \( s=25 \) mm and a clamping area of 1000 mm²; these values can be reduced, if a minimum clamping depth of 8 mm is guaranteed under all loading situations, where again also in-plane deformations have to be considered. For bolted disc fixing a minimum diameter of 50 mm for the disc is required, minimum depth \( s=12 \) mm; minimum distance from bore hole to next bore hole or free edge is 80 mm, see Figure 2.

![Figure 2. Section cut of clamp fixture (left), bolted disk fixing (middle) and distances of bore holes (right)](image)

The rules regarding construction origin more or less from previous regulations, of course updated because of positive experience and meanwhile grown knowledge. So the ratio of thickness of single plies of laminated glass is allowed...
to be at maximum 1.7. Glazing supported by point fixings only require a minimum of 3 point fixings – not positioned on one straight line.

Depending on the way of installation (vertical glazing or horizontal glazing) and the way of fixing (linear or by different types of point fixings) a different behaviour and by this different levels of safety can be expected – especially for the scenario of glass breakage. Based on this several regulations are given in part 2 and 3, requirements regarding the glass product for different installation situation are systematically put together in Table 3.

The most interesting – and in comparison to existing regulations new – elements can be found in the annexes. In Annex A and B the user does not only find information about values for material to be used for FEA but also hints for a correct modelling. And in addition Annex C gives a simplified method for design in sense of calculation of point fixed glazing without using time and money consuming sophisticated FEA. The testing procedure described in Annex D makes it possible to get values for ULS and SLS of point fixing themselves as well as data for FEA modelling.

**Table 3.** Allowed glass type for different fixing method and way of installation

<table>
<thead>
<tr>
<th>Linear bearing L</th>
<th>Clamp fixing C</th>
<th>Bolted disc fixing P</th>
<th>Float-glas</th>
<th>HSG</th>
<th>FTG</th>
<th>FTG-heat soaked</th>
<th>LSG made of</th>
<th>FG</th>
<th>HSG</th>
<th>FTG</th>
<th>FTG-heat soaked</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single glazing (no IGU)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>C</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
<td>+</td>
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<tr>
<td>P</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>IGU one pane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
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<tr>
<td>L</td>
<td>+</td>
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<tr>
<td>C</td>
<td>+</td>
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<td>+</td>
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<tr>
<td>P</td>
<td></td>
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<td>+</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>IGU other pane</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>+</td>
<td>-</td>
<td></td>
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<tr>
<td>C</td>
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<td></td>
<td>+</td>
<td>-</td>
<td></td>
<td></td>
<td></td>
<td>+</td>
</tr>
</tbody>
</table>

- **Vertical glazing**

- **Horizontal glazing**

(1) only if all sides supported
(2) only for glazing with upper edge maximum 4 m above traffic level

**2.5 DIN 18008-4: Additional requirements for barrier glazing**

In case a glazing has to fulfil the (additional) task of a railing the appropriate rules for construction and design are put together in part 4.
The first topic in DIN 18008-4 is the division of such glazing to 3 categories: category A for elements where only the glass is responsible for function as barrier, category B is cantilevered glass balustrade with hand rail whereas category C is the lowest category with elements acting as infill of a e.g. steel railing structure, see Figure 2. The classification was done by looking at the remaining risk in case of a possible glass breakage: barrier of category A the glass is the only retraining element, so a sufficient residual load carrying capacity is needed whereas in case of a category C glazing still a classic handrail exists to take horizontal forces. Category B is somehow between: a handrail does exist, but is supported by neighbouring glass element.
Figure 3. Different categories of barrier glazing (left) and example of pendulum impact test with 50 kg twin-tyre impactor on pendulum cable (right)

In addition to proof of ULS and SLS according to part 1 in combination with parts 2 or 3 (depending on bearing situation) one has to proof safety against human impact.

According to the standard 3 methods are possible:
- by testing with pendulum impactor as shown in Figure 2
- by choosing a construction from tables with in the past positive testing results
- by numeric calculation.

This of course does not only apply for the glass but also for the fixing parts: it is still a problem if a glass element survives an impact but falls out of a façade as a whole due to weak fixation.

Prove of sufficient resistance against possible impact of human body against the glass element is done by a pendulum swing test, using a twin-tyre impactor of 50 kg. As it is an elastic collision, the 50 kg simulate the weight of standard human sufficient. Falling height depends on the category: for A 900 mm are required, for B 700 mm and for C 450 mm, respectively. Compared to realistic energy induced by fall of human body against a barrier these values seem to be far on the safe side – 200 mm would be sufficient. The higher values result from additional safety to compensate possible statistical scattering of testing sample and realized construction (e.g. testing sample is of better quality than required whereas the realized construction is on minimum strength level). For this reason the falling height used for prove by numeric calculation may be reduced to 200 mm for all categories. To meet the requirement in testing no penetration of the impactor, complete collapse or bigger gap of a broken laminated safety glass is allowed.

For calculation a maximum tensile stress not to be exceeded is given; as the impact is a short duration loading, full shear connection can be assumed and the maximum tensile stress is higher than for regular loads.

The detailed regulation can be found in Annex A (testing method for set consisting of glass element and fixing), Annex B (glass elements known to withstand impact), Annex C (fixing known to withstand impact and testing procedure for fixing only), Annex D (calculation methods for glass element only).

As a free glass edge (where free is meant in the sense of not protected by structural elements like columns) do have the risk of glass breakage also by accidental hit this has to be looked at in addition: again two ways of proofing safety are given:
- testing according Annex E including pre-damaging free edges or
- using appropriate edge protector according Annex F.

2.6 DIN 18008-5: Additional requirements for glazing accessible for public

For the case that on a glazing – usually in horizontal installation – can be walked on the appropriate regulations are given in part 5. Not covered are glazing accessible only for maintenance reason – this application is ruled in part 6.

The maximum characteristic value of uniform loading covered in this part of the code is 5 kPa, and no vehicles are allowed on the glazing. Due to risk of damage and requirement for safety of traffic also in case of a breakage glazing according
to part 5 have to consist of laminated safety glass made of at least three plies of glass.

**Figure 4.** Example of impact test for glass stair and sketch of 40 kg-impactor

For SLS the maximum deflection is limited to \( \frac{\ell}{180} \) (where \( \ell \) is the span). Analogous part 4 again additive specific requirements are formulated for resistance against impact and residual strength. The testing procedure is described in Annex A, an example can be seen in figure 3. In short: half of the traffic load has to be applied in form of 100 kg weights with contact area of 200x200 mm² and then a 40 kg impactor has to be dropped from 80 cm to the glass floor; no penetration of the impactor nor a full collapse is allowed within 30 minutes after impact. Annex B gives several combinations of glass types with positive testing results gained in the past.

### 2.7 DIN 18008-6 and DIN 18008-7

As stated above, development of part 6 dealing with glazing accessible for maintenance is finished, after final editorial work it will be published by second half of 2014. In part 7 regulations for special applications like e.g. glass fins, glazing acting as shear panels etc. will be put together, work started recently; a first draft may be expected in 2015.

### 2.8 Implementation of DIN 18008 to building legislation

After being published as DIN 18008 in a final version, so after passing through comments-resolution meeting, the DIN 18008 can be regarded as state of the art. To get a normative character in Germany two more steps have to be taken: first it has to be listed in a national so called “Musterliste der Technischen Baubestimmungen” (model list of technical building regulations) and in a second step each federal state has to take it in their federal list. The second step usually is a formal step – but also takes some time. At the moment the first step is taken, at the earliest step 2 can be done by 10\(^{\text{th}}\) of July 2014, but based on experience with the procedure in the past it can be expected that in most federal states step
2 will be made by 1st of January 2015. Until this DIN 18008 can be applied by asking for a special permit at the responsible authorities.

3 Discussion, conclusion and outlook

3.1 Discussion and conclusion

Comparing the regulations of actual used TRLV [4] and TRAV [5] on the one side and the future design code DIN 18008 [1], [2] one recognizes differences of the extent of design equations. This is predominately not due a new concept for design based on fracture mechanics or other sophisticated calculations; the reason is the application of concept of partial safety factors with numerous load combinations in accordance to Eurocode [7]. In other words, the more of work is necessary on the side of stress, the calculation of resistance is not a big effort, as shown above a single table for $R_d$ can be set up easily.

As the use of concept with partial safety factor [7] is mandatory for all other materials and design engineers are familiar to this they are looking forward to apply it also for glass. Some opposition can be seen from craftsmen: they usually do not have the necessary education as engineers but want to do their work. Here a change in thinking will be necessary, appropriate training and supporting tools can improve the situation.

For a comparison of level of safety or the necessary material examples have to be calculated. Alternatively it is possible to rearrange the design equation and by this obtain a “allowed tensile stress” which is comparable to the “old” permissible stress; here due to different partial safety factors for different loads or load combinations not one value but a certain span is received (depending on portion of load types an “average” partial safety factor between 1,35 and 1,50).

As result of this comparison it can be stated that for structures made of thermal treated glass for same loads less glass thickness is needed (or in other words for same glass thickness the ratio of stress to resistance is lower). For annealed float glass the situation is different and ambivalent: it is depending on the loading situation as well as on the way of installation – bearing (linear or point) and inclination (vertical or horizontal). To be sure that there are no changes for “classic windows” special paragraph was implemented.

With the new design code for glass DIN 18008 [1], [2] at last regulations based on partial safety concept [7] do exist also for glass. This makes design procedure of structures consisting of different materials more convenient. Predominantly the more of work is caused by design concept and code for loads itself and not by design code. By using existing reserves especially for glass elements with thermal treatment material can be used more economically. For simple applications easy to use design tables have to be supplied for bigger acceptance among all users, see [8], [11].

Comparing the situation in Europe it can be stated, that DIN 18008 with its 5 parts covers most of the daily work applications. This is not the case for all codes in all other European countries. A table giving maximum tensile stress $R_d$ for design equation following the concept of partial safety concept of Eurocode makes a comparison of different codes possible; for information also the values coming from the “old” German rules TRXV is converted to the new safety concept and put
in the table for reference. As sometimes additional requirements do exist this may not be the full story, but at least it shows, that differences do exist but are in most cases not too extreme.

**Table 4.** Maximum tensile stress $R_d$ in MPa according to different codes for thermally treated glass for vertical glazing (wind load), taken from [11]

<table>
<thead>
<tr>
<th>Code</th>
<th>Heat strengthened glass</th>
<th>Fully tempered glass</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mono</td>
<td>LSG</td>
</tr>
<tr>
<td>TRLV, $\gamma_F = 1,5$</td>
<td>43,5</td>
<td>75</td>
</tr>
<tr>
<td>DIN 18008 Teil 1, $k_c = 1,0$</td>
<td>46,67</td>
<td>51,33</td>
</tr>
<tr>
<td>ÖNorm B 3716</td>
<td>46,67</td>
<td>80</td>
</tr>
<tr>
<td>EN 13474** (EN 16612)</td>
<td>39,33</td>
<td>81</td>
</tr>
<tr>
<td>NEN 2608***</td>
<td>45,83</td>
<td>87,5</td>
</tr>
</tbody>
</table>

**$\gamma_{\text{M;A}} = 1,8$; $\gamma_{\text{m;A}} = 1,2$; $k_{\text{ABC}} = k_{\text{DEG}} = 1,0$ assumed

**$k_a, k_e, k_{\text{sp}}, k_z$ set to 1,0 and $c = 16$

**Table 5.** Maximum tensile stress $R_d$ according different codes for horizontal glazing made of float glass, combination of dead load and snow load, taken from [11]

<table>
<thead>
<tr>
<th>Code</th>
<th>Edge under tension</th>
<th>Tension in surface</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mono</td>
<td>LSG</td>
</tr>
<tr>
<td>TRLV, $\gamma_F = 1,35...1,5$</td>
<td>16,2...18</td>
<td>20,25...22,5</td>
</tr>
<tr>
<td>DIN 18008 Teil 1, $k_c = 1,0$</td>
<td>8</td>
<td>8,8</td>
</tr>
<tr>
<td>DIN 18008 Teil 2, $k_c = 1,8^*$</td>
<td>14,4</td>
<td>15,8</td>
</tr>
<tr>
<td>ÖNorm B 3716</td>
<td>14,4</td>
<td>18</td>
</tr>
<tr>
<td>EN 13474** (EN 16612)</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>NEN 2608***</td>
<td>7,92</td>
<td>9,9</td>
</tr>
</tbody>
</table>

* For linear supported according DIN 18008 Teil 2

**$\gamma_{\text{M;A}} = 1,8$; $k_{\text{ABC}} = 1,0$ assumed

*** $k_a, k_{\text{sp}}$ set to 1,0 und $c=16$

### 3.2 Outlook – Eurocode for design of glass structures

Meanwhile in CEN/TC 250 a working group 3 has been established doing the preparatory work for a planned Eurocode for Glass. As a first outcome of this a so
called “Scientific and policy report” has been published, documenting the actual situation of design of glass in European countries.

![Figure 5. European code environment for Eurocode for design of glass structures [14].](image)

In Figure 5 the European code environment for the preparation of the Eurocode for design of glass structures is shown. Interesting is the strict division between product specifications and structural design rules – execution rules are set up by more TCs. The experience gained in development of DIN 18008 and its application can be brought in the work to be done for developing Eurocode 10.

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   Part 3:Point-fixed glazing, English translation under preparation
   Part 4: Additional requirements for barrier glazing, English translation under preparation
   Part 5: Additional requirements for glazing accessible for public, English translation under preparation
[3] DIN 18516-4 (02-1990): Cladding for external walls, ventilated at rear; tempered safety glass; requirements, design, testing.

[6] TRPV (08-2006): Technische Regeln für die Bemessung und die Ausführung punktförmig gelagerter Verglasungen (TRPV) - Schlussfassung August 2006, Mittlg. DIBt, Berlin (Technical Rules for Point supported Glazing)


Active Shooter: What to expect, what to do, is there a role for protective glazing?

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Applied Research Associates, Inc., USA

Abstract

“Active Shooter” is a term that seems to permeate our media and unfortunately our dinner table conversations. What really is an active shooter, what is the profile, how often does this really happen? More importantly, what do I need to know if my family or I are in an active shooter event? Is there anything that would enhance my chances of survival? This paper and presentation concisely cover these topics and provide the audience with the basics that may save their lives or the life of a colleague or loved one. While the basics of responding include Run, Hide, Fight; are there also things that we should consider in the design and construction of public facilities like malls, schools and office buildings? In an operational security framework, we normally consider a timeline of prevention / deterrence, detection / warning, delay / access denial, active response and recovery. But offices, schools and malls will not become hardened bunkers. So, can protective glazing play a practical role in mitigating the hazard and reducing the potential losses? This paper and associated presentation address these questions.

Keywords: Active Shooter, Security, Forcible Entry, First Responders, Protective Glazing

1 Introduction

While writing this paper, notifications are streaming across my computer about another on-going active shooter event occurring in real time at Fort Hood, TX (April 3, 2014). Four people dead (three victims plus the shooter) and 16 more injured. The incident just ended with the shooter killing himself after being confronted by law enforcement. The story is all too familiar. The tragic human consequences of such events now play out through the media to which we are all continuously connected. Computers, cell phones, tablets, e-readers, cable news, social media in addition to traditional print news, broadcast television and radio bombard our daily lives with the details and images that in past we would only have been able to imagine. News outlets dwell on such events providing no escape for their audiences. The fear of being hunted, the shock of being attacked and the sense of helplessness that such events instill in all of us make
these events something that command our attention and drive our imaginations. While this is definitely a real phenomenon that shakes the foundations of our sense of security; panic and paranoia are not in order. After all, the chances of any specific individual being the victim of an active shooter are extremely small. We are orders of magnitude more likely to die in a car accident while driving home tonight. However, the horror that the active shooter instills mandates that we act. We want to feel safe yet we don’t want to surrender our liberty and freedom. We are not willing to turn our schools, malls and offices into high security, hardened facilities. So what can we prudently do to reduce our chances of being a victim? Fortunately there are some very simple and practical things to consider. Knowledge helps assuage fear. A plan and training improve reaction time and reduce the chances that we’ll make poor choices under stress. And some selective hardening can help reduce the damage and number of victims if an event does occur. Delaying an attacker by mere seconds or minutes can save lives in an active shooter attack. The focus of this paper is on open, publicly available facilities with little or no hardening and minimal security. The purpose is to provide basic education and awareness that may save lives.

2 Who is an active shooter?
How does an active shooter differ from someone just killing someone else with a gun? The Department of Homeland Security (DHS) generally defines an active shooter as “an individual actively engaged in killing or attempting to kill people in a confined and populated area; in most cases, active shooters use firearms and there is no pattern or method to their selection of victims.” To further differentiate an active shooter from just a murderer or a nut with a gun, the New York City Police Department (NYPD) has suggested that this definition be clarified to include only those cases that spill beyond an intended victim(s) to others. In other words, the victims go beyond those that may have been the initial or focused target of an attack.

2.1 The data
Much has been written about the so called active shooter phenomenon. A good summary describing the active shooter can be assembled from an analysis performed by the NYPD on a significant dataset of 202 active shooter events. The following data are drawn from that study unless otherwise noted. Not surprisingly the analysis indicated that the vast majority of active shooters are male. In fact, some 96% of the perpetrators were men. While the age of those
shooters ranged from as low as 10 to as high as 89, the median age is 35. The study also showed a strong, and probably to be expected correlation between age and the location of attacks (Figure 1). Attacks in schools are dominated by younger perpetrators with a peak concentration in the 15 to 19 year old group. Attacks outside of schools tend to be committed by older shooters with a peak centering on those in the 35 to 44 year old range.

While there are notable exceptions like the Columbine High School incident, most cases involve a single shooter. The NYPD reports that multiple shooters were only seen in about 2 percent of the cases studied. There is also a wide disparity in the preparations made in these active shooter attacks. These range from little to no preparation to extensive pre-planning. This may include surveillance, procuring and/or making bombs and booby traps, procuring and training with specialized weapons, pre-positioning weapons, cutting communications to/from the attack site, and blocking entrances and exits. In many cases (36 percent of the attacks studied), the attacker used more than one weapon ranging from assault type rifles, shotguns, pistols as well as secondary weapons such as knives and improvised weapons of mass destruction.

The targets of these attacks are somewhat random as the DHS definition of active shooter indicates. People with current or former workplace or professional relationships with the attacker (41 percent) are the largest group. Other victims include those with academic affiliations (23 percent), and family, friends or social acquaintances (14 percent). Finally, 22 percent have no current or prior relationship with the assailant. From the news coverage, one would expect that most active shooter events include very large numbers of people. While there have been mass casualty events, the majority of incidents resulted in 5 or fewer killed and 5 or fewer injured. The median numbers of people killed and injured in the dataset of 202 cases studied by the NYPD were both 2. The average numbers of people killed and injured were 3 and 3.6, respectively. Twenty-nine percent of the attacks studied occurred in schools, 23 percent in open commercial facilities, 13% in office buildings, 13% in factories/warehouses and 22% in other locations.

Finally, it is important to note that active shooter events are generally over in a matter of minutes. Most last only 10 to 15 minutes. They are often terminated with the suicide or attempted suicide of the shooter. This has been noted in 40 percent of the attacks. Very often the shooter will self-terminate even before law enforcement can arrive on the scene. In the other cases, the attacks are generally forcibly terminated by the intervention of law enforcement, private security or bystanders. Only in 14 percent of the cases was no force required (i.e., the event was ended by the perpetrator or through negotiation).

3 How can I prepare?
Preparation can reduce the risk of an active shooter incident and, if one occurs, can mitigate or reduce the number of potential victims. Operationally, security specialists consider a framework that includes prevention/deterrence, detection/warning, delay/access denial, active response and recovery. The extent of the preparations may vary greatly depending on the type of organization, the openness requirements of the facility, the actual or perceived threats, the tolerance for visible (perhaps intrusive) security measures and funding. However, even for soft
targets like schools, malls or office buildings, prudent steps can and should be considered. A facility, school or office building should conduct a security assessment. Such an assessment can be performed by a qualified security consultant or company, or local law enforcement. Requiring credentials such as PSP (Certified Physical Security Professional) or CPP (Certified Protection Professional) by the American Society of Industrial Security (ASIS) or similar credentials are a good way of ensuring a sound assessment is performed. The assessment should evaluate the threats, identify vulnerabilities to those threats, quantify the potential loses, evaluate the relative risks, and recommend measures to mitigate these risks. Such measures may be operational, technical or architectural in nature. An independent party (not a vendor seeking to sell specific systems) will generally provide a more unbiased and comprehensive assessment.

3.1 Prevention/Deterrence

Prevention starts well in advance of an attack. Many people report initial reactions like “I never would have thought he would do such a thing. What a quiet, nice young man.” But when you look past the initial façade, there are often many signs which seem obvious in retrospect. If people were more observant and felt free to report potential problems without recrimination, many troubled would-be active shooters may be stopped and get help before tragedy strikes. Often people are afraid to say anything for fear of not being politically correct or being chastised or embarrassed for making accusations. Some just don’t want to get involved. However, we must create an environment in our schools, workplaces and other public places where “if you see something, say something.” This is critical as the first line of defense. There may be observable characteristics or behaviors that can provide the clues that something just isn’t right. Some may be conflicting and it is not really possible to list or classify one set profile that would indicate this person is about to commit an atrocity. Such characteristics may include being sullen, withdrawn, openly aggressive, changes in normal behavior and appearance, odd or out of place statements, fascination with weapons, etc. People often just know or have a gut feeling that something’s not right. They need to be encouraged to say so.

The concept of CPTED (Crime Prevention through Environmental Design) is also a good place to start. It is commonly described as a multi-disciplinary approach to deterring criminal behavior through environmental design. CPTED strategies rely upon the ability to influence offender decisions that precede criminal acts. It requires application of psychology as well as sound security design. CPTED includes common sense approaches of ensuring adequate lighting, eliminating hiding places, etc. that can improve security, reduce vulnerability and help deter criminal activity.

As evidenced by the statistics, many active shooters are set on destruction, and their own mortality is not a concern. They never intend to get out of the assault alive. This can limit the value of deterrence. However, many active shooters, especially those who plan their actions carefully, want their plans to succeed. Even suicide bombers have been known to avoid certain targets because they fear they’ll be stopped or interdicted prior to completing their mission. A robust security posture and presence can certainly help in this regard. For lightly protected facilities like schools, malls and office buildings, this may be limited to such things as visible
signage, random guard patrols, adequate lighting of exterior parking and entrance areas, CCTV cameras, substantial exterior door locks, simple access control systems (turnstiles, badges, etc.), and secure locking doors to key areas or passageways. Installing and maintaining a closed circuit television (CCTV) system can function as a deterrent (prevent the attacker from attacking due to the visible presence of cameras), as a detection capability (motion activated or otherwise monitored screens will provide early detection and observation of an attack), and as part of the response capability (cameras can show law enforcement the location of the attacker and victims and their activities in the facility). In some facilities, it may also be possible to introduce the ability to control or lock down parts of the facility. This may include turning elevators off/on remotely, or locking or unlocking hallway doors from a central command station. Coupled with CCTV or other technology this may be an effective way to control or guide the movement of an assailant during an attack. Safe rooms and duress alarms can be built into new facilities or added as retrofits to existing buildings. There are, in fact, a wide range of possible design features coupled with security systems available improve the security posture of even lightly protected facilities. All of these measures can provide some level of deterrence.

3.2 Detection/Warning
Early detection of an active shooter generally relies on such measures as behavior-based surveillance (i.e., is a person acting oddly, dressed oddly, out of place, etc.). This can be accomplished by students, teachers, office workers, shoppers, in fact all of us. Aside from the professional security guards however, this requires us as a society to build that “see something, say something” mentality and for people to be generally aware of their surroundings. In addition, simple measures such as requiring visitors to sign in and get a badge, not only helps identify those people as visitors but it provides an excellent choke point to observe those entering a facility. This function can be performed by greeters at the doors of retail establishments, office staff, or formal security guards in uniform. While there is a vast array of intrusion detection systems available today, people’s eyes and ears tend to be the most reliable especially in an open, non-hardened publicly accessible facility. As a minimum, however, solid security locks and doors are essential. These may be coupled with sensors to detect motion or unauthorized access. If they are to be more than just a deterrent and delay device, these sensors should also tie back to a central reporting station for interpretation and action.

Alarms are essential and must go beyond the old style school fire alarms which we all fondly remember. Studies conducted on the evacuation of large public facilities have clearly shown that the efficiency of large scale evacuations are increased substantially when audible alarms giving simple verbal directions are provided compared to a general klaxon-type alarm. This is especially so in an active shooter situation where specific directions to staff or occupants may improve survivability. If for example the shooter is located in the cafeteria of the building, it would be beneficial to direct people away from that area. Additional measures for warning should include messages to employee computers, text messages, email, etc.

3.3 Delay/Access Denial
Having consulted with many major airport facilities throughout the United States, I have concluded that denying access to the terminals would provide the highest level of security for the
flying public. With this approach, however, there would obviously be no flying public and the airports would soon be out of business. Security professionals understand that a reasonable balance of openness and security must be achieved. This is especially difficult in open facilities like schools, malls and office buildings. Access control, high-security locks, reinforced walls, blast/ballistic resistant doors and windows, vestibules and mantraps, ballistic resistant partitions and other barriers may just not be feasible in many places. However, all of these things to some degree should be considered for the renovation of older facilities and especially in the design/construction of new facilities. The cost of implementing unobtrusive security measures in new facilities is far less than trying to retrofit an existing facility. Selectively used they may also be effective and affordable in renovations.

Since most active shooter events generally last only minutes, access denial can be an effective way to mitigate potential losses. Slowing or delaying an aggressor by just a minutes or seconds may give law enforcement time to arrive before mass casualties are incurred.

For lightly secured facilities, a significant return on investment can generally be obtained by implementing reinforced doors lockable from the interior of office spaces, gathering areas or retail outlets. Secondary door blocking devices such as a simple rubber or wood triangular stop can provide additional stopping resistance. Those doors with windows should have small slit windows too small for an aggressor to crawl through. No windows would be preferred but may not be practical for other reasons. It is important however that if windows are present that they contain laminated glass that provides some resistance to ballistics attack and forced entry. If a gunman can shoot through the window it is important that he can not merely reach in and unlock the door. This is where simple door stops or floor angles can provide needed secondary protection. Analysis of footage from actual active shooter events have shown that the shooter will likely not spend significant time trying to get through a particular door if it is locked or blocked. Rather they move to their next target. They know law enforcement is on its way and that time is limited.

The technology and materials to provide blast, hurricane, forced entry and ballistic resistant doors and windows systems exist. These systems have been designed, tested and implemented in highly secure facilities like embassies, court-houses, government buildings, military facilities, sensitive data centers, and facilities housing historic or otherwise valuable assets for many years. Providing this level of protection in more lightly secured facilities like schools, malls and typical office buildings is often not practical, cost effective or even desired by the occupants given the level of threats and risks perceived. However, some level of protective glazing, especially for windows and doors near lobbies and other entrances offer a potential area where simple improvements can provide significant benefit. In the Sandy Hook School shooting for example, it was reported that the shooter failed to gain entry through locked doors and shot out adjacent windows. This is shown in Figures 2 and 3.
Figure 2. Entranceway with window broken out at Sandy Hook School (State Police Photo).

Figure 3. Close-up of window adjacent in to door in Figure 2.
Test data collected in projects supporting the DHS and the US General Services Administration have clearly demonstrated that some applications of properly installed security window films and thin laminated glass systems can provide resistance to forced entry even though they were not specifically designed for that purpose. These tests were conducted in response to the US Government’s concern that upgraded window systems in their facilities designed to resist hurricane wind and explosive blast forces might hinder first responders in gaining access to or emergency egress from protected spaces. This body of data was made freely available to firefighters resulting in over 5,000 trained first responders (Figure 4). The test program produced a window classification system to train firefighters how to enter and egress through such window systems. The classification system is shown in Table 1. The data should now be extended, analyzed and made available as a resource for facility owners and security designers for the purposes of evaluating the benefits of lightly protected glazing systems.

Figure 4. Firefighters using various objects, tools and techniques to breach protective glazing systems.

Table 1. Window classification system developed for the US General Services Administration and the US Department of Homeland Security. The system classifies window systems based on the type of tools required to breach the glazed system in a given period of time.

<table>
<thead>
<tr>
<th>Window Type</th>
<th>Description</th>
<th>Average Clearing Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type I</td>
<td>Hand Tools (HT)</td>
<td>10 seconds to 1 minute</td>
</tr>
<tr>
<td>Type II</td>
<td>Hand Tools or Power Tools (HT/PT)</td>
<td>1 to 3 minutes</td>
</tr>
<tr>
<td>Type IIA</td>
<td>Type I Window with Interior Fabric System or Interior Type II (HT/PT)</td>
<td>1 to 3 minutes</td>
</tr>
<tr>
<td>Type III</td>
<td>Power Tools Only (PT)</td>
<td>Typically 3 to 5 minutes but could be more</td>
</tr>
</tbody>
</table>
Just as potential victims must process through an OODA Loop where they Observe, Orient, Decide and Act, so must the active shooter. When an aggressor hits a window system for example, expecting it to easily break and it doesn't, this disrupts their processing of events. They have to make decisions. Do they continue to attack to break through? Do they change course and approach by a different route? If they start trying to break through such a window system that may take a minute or two to get through do they continue or do they give up? Regardless of the outcome, such systems can provide disruption and delay. Perhaps enough time for escape and for the law enforcement to arrive. Remember, seconds or minutes can make a tremendous difference in an active shooter event.

3.4 Active Response: What should I do and how should I react?
Fortunately, we do tend to learn from terrible events and effectively adapt to changing circumstances. Those reading this paper who are old enough to remember when commercial airline travel was pleasurable, can also recall the days when an airplane hijacking meant someone commandeering a plane and demanding to go to Cuba or some other exotic destination. The mindset was to cooperate, negotiate and go home safely. All of that changed on September 11, 2001. The brave passengers and crew of United Airlines Flight 93 demonstrated American resolve when confronted with such an event. If is doubtful that any hijacker could walk away unscathed by the hostages in today's environment. Even if it meant serious injury or death of a few, passengers and crew are much more likely to engage a hijacker and end the confrontation with violence. Likewise, our response to active shooter events has evolved. Back in 1999 when the Columbine High School event occurred, the standard response was to control the scene, set up a perimeter, bring in the negotiators and try to peacefully end the assault. Today law enforcement is trained to move toward the sound of gunfire and neutralize the shooter as quickly as possible with whatever force is necessary. This adaptation to the evolving threat has helped save lives. In an active shooter event, mere seconds or minutes make a huge difference.

So too has the required response of potential victims. In the past, being passive or trying to talk with the assailant may have been effective, but now a different course is recommended. This can simply be summarized as RUN, HIDE, FIGHT! Many teaching active shooter courses also refer to the 3 E's (Evacuate, Evade and Engage). There are several good training resources available on this topic including downloadable movies. The training movie at the following link is made available by the City of Houston, TX with support from the US Department of Homeland Security:

http://www.readyhoustontx.gov/videos.html

3.4.1 Run
If you’ve never been shot at or been in the close proximity of someone shooting, you may be surprised and not quickly recognize the sound of gunfire. It’s not like you’d expect from watching movies or television. You may think you hear popping or firecrackers. You may not even clearly hear the gunfire. Instead you may only hear calls for help, screams, or the sound of people running. You need to be ready and able to mentally process that something is not right and that action is required. Scientifically, we generally describe the process as Observe, Orient, Decide
and Act. The longer it takes a potential victim to do this, the higher the risk of injury or death. From personal experience, the author will admit that having been shot at (and luckily missed); the perpetrators had already escaped before the reality of the situation even registered to allow action on his part. Yes, I just stood there and got shot at. If a potential victim is in very close proximity to the initial attack this is often the case. There is not enough time to react and luck or fate if you believe in either will decide whether you walk away or not. After the initial few seconds of an attack however, there should be time to observe, orient yourself, and decide what to do and take action. Of course the best thing any potential victim can do is to EVACUATE the danger area. Do this as fast as you can if there is an accessible escape route. In other words RUN.

The Department of Homeland Security has published several helpful guides and brochures related to active shooters. Some good tips to remember:

- Be aware of your surroundings and pre-plan how you’d evacuate. Try to have at least two routes of egress in mind. People are creatures of habit. They normally leave a location by the route they entered even if it may not be the most direct path.
- Leave your stuff behind. It’s only stuff. If possible, however take your cell phone with you as it may provide needed communication capability. If you do, silence it when possible.
- Help others to escape, but don’t debate. Get out. Don’t wait for those who won’t leave.
- Help direct others away from where the active shooter may be.
- Do not attempt to move or wait for non-ambulatory wounded people.
- Keep your hands visible and your fingers spread so law enforcement can quickly assess that you are not a threat.
- Follow instructions of law enforcement.

3.4.2 Hide
If evacuation is not possible, HIDE. If you are in a hallway or other open area try to get into a room with a secure door. Barricade that door to slow down or possibly deter the shooter from entering your location. If available, lock the door or push heavy furniture or other objects against the door. Something as simple as a wedge block of wood or a rubber door stop may be enough to deter or slow entry long enough for the assailant to move on or be stopped by law enforcement. Hide under and behind heavy equipment, dividers or furniture. Stay low. Remember a typical attack lasts only minutes. Stay out of sight and stay quiet. Silence your cell phone.

3.4.3 Fight
The last resort and this is the hardest part. Many people don’t think they can do this, but if all other options fail and you are confronted by an active shooter, your chances of survival are
significantly increased if you attempt to take down (kill or incapacitate) the shooter. This is a decision that you need to make ahead of time and commit to accomplishing your actions. If you decide to go after the shooter, remember that it is likely a life or death encounter. Someone may not survive. You don’t want to be the victim. Quickly incapacitate, or kill, the attacker by any means. Fight like your life depends on it. You can’t engage the assailant with the idea that you are going to have a “fair fight.” Many everyday objects (e.g., fire extinguishers, scissors, pens, heavy objects, your belt, etc…) can be used as effective lethal weapons once the decision to use them in that manner has been made. If there are several people being threatened join in and completely overpower the attacker. If you do nothing, all may be killed or injured. If you all attack, some or all may survive.

3.5 Recovery

Recovery from an active shooter event includes both immediate and short-term measures as well as long-term sustained actions. Immediate actions must focus on employee, student or occupant accountability. In order to account for people best practices include such steps as having daily personnel status reports to include whether people are present or on leave. Access control logs are possible in some facilities. As a minimum having up to date emergency contact lists including home and cell phone numbers is essential. In the short-term, having a pre-planned marshalling area to count heads is important. People need to know where to go to be counted and for information. Dealing with the press is an issue that requires pre-planning. Who is designated as the facility spokesperson and does that person have at least some minimal training? Of course, long term recovery will likely require employee and family support and counseling. Prior experience shows that while some people recover quickly with few ill effects, others never fully recover from such events.

Once the crime scene is clear, a damage assessment is required to develop a plan for cleaning and repairing the facility prior to resumption of operations. Obtaining the services of a professional cleaning and repair business is highly recommended. During this process, it is important to remember that fixing the facility is the easy part. Mending human damage is much more difficult and important with an uncertain outcome. Preplanning the recovery from any major disaster or event can significantly improve the final outcome.

4. Conclusion

At the outset of this paper, an active shooter event was in progress. It ended quickly (8 minutes after the first shot was fired) with the suicide of the shooter, the tragic deaths of 3 victims and 16 more injured. The event was over in a shorter time than it took for the average person to read this paper. The shooter, 34 year old Army Specialist Ivan Lopez, fit many of the traits and characteristics described in this paper. The Active Shooter phenomenon is a reality and deserves attention to help prevent such tragic occurrences, to mitigate the damage and loss when they do occur, and to preserve our sense of security in a dangerous and sometimes unpredictable world. It is important to remember that we should not overplay the danger, oversell the protection offered by various products, or sow fear into our children and citizens.
However, the Active Shooter is a reality that we cannot ignore. Simple planning, awareness and training can save lives. Remember the bottom line: RUN, HIDE, FIGHT. Be ready to act.

References


[2] Raymond W. Kelly, Active Shooter Recommendations and Analysis for Risk Mitigation, NYPD.


Structural Insulated Glass
Achieving Maximum Transparency in Free Forms using Curved and Flat Glass

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Chris Stutzki / Matt Kuba  Stutzki Engineering Inc., USA

Abstract

Responding to the Architectural Design continuously pushing the limits of mullionless glazing systems, the insulated glass becomes the secondary structure itself. To achieve full transparency support systems are fully concealed and visual joints are minimized to a maximum extent. Complexity increases once curved forms join flat elevations. Stiffness and deflection properties vary significantly between flat and curved glass, setting the requirements for the structural behavior of the sealant materials. Climate loads and isochoric pressure are among others controlling factors to the final project specific design.

Properties outlined in existing material data is found too conservative to achieve the Architectural goals outlined above. In the absence of established industry methods and / or code regulations, complex engineering analysis and material and component testing are methods chosen to obtain the design confirming values.

Different approaches have been chosen to best address the performance of the façade on each individual project. On the basis of current and recently completed façade projects Roschmann Steel & Glass Construction Inc. will provide an insight to their engineering work for custom facades.

1 Introduction

Roschmann Group is a fabricator of custom designed architectural glass and steel facades headquartered in South Germany. The increasing international demand in specialty glass manufacturing and custom engineered facades has led Roschmann Group to open an US operation in April of 2010.

For this presentation we have chosen three of our North American projects containing flat and / or curved structural insulated glass units. Although the three projects distinguish themselves in their architectural language and user program, they share the desire to achieve a maximum transparency in the glazed building envelope.

- James A. Michener Art Museum, Edgar N. Putman Event Pavilion Philadelphia, PA
- Sisters of Saint Joseph, Toronto CA
- Grace Property Holdings / 365 Lukes Wood Road New Canaan, CT
While the first two projects will form an introduction, the main focus will be on the engineering and design work for the façade of the Grace Property Holdings project in New Canaan, CT, currently under construction.

1.1 Definition

1.1.1 Structural Glass
According to the McGraw-Hill Dictionary of Architecture and Construction a Structural Glass is “Glass, sometimes colored, which is cast in the form of cubes, rectangular (solid or hollow) blocks, tile, or large rectangular plates; used widely for wall surfacing”. [1]

1.1.2 Insulated Glass
“The double glazed window was invented in 1930s, and was commonly available in US in the 1950s under the Thermopane™ brand name, registered in 1941 by Libbey-Owens-Ford Glass Company.” [2]

1.1.3 Structural Insulated Glass Unit
A Structural Insulated Glass Unit (Structural IGU) became a popular term in the Façade Design of the 21st century. While the façade is still transferring loads to the building structure, the term “structural” has been introduced to account for the absence of the curtain wall framing. The glass takes over the supporting function of the framing, the glass becomes the secondary structure itself. In most cases the glass is two side supported, spanning from top to bottom.

The structural behavior of the insulated glass depends largely on the effective thickness of the glass itself, the type of interlayer chosen in case of a laminated assembly, and the distance between the individual lites separated by a sealed encapsulated or pressure controlled airspace and/or cavity.

To achieve a maximum transparency in the glazed building envelope, non-vision areas are reduced to the edge seal and spacer of the insulated glass and the joint between the lites itself. Opaque and/or translucent components stay within the plane of the glass, no longer further obstructing the angular view.

2 Grace Property Holdings / 365 Lukes Wood Road

2.1 General Project Description
The project consists of individual pavilions connected under a continuous roof meandering through the descending landscape. The pavilions are free formed shapes, fully glazed with insulated glass units, housing the foyer, the library/administration, the dining space, the gym, and the sanctuary of the new community centre.

To achieve maximum transparency in the vertical façade all glass is two side supported using uncoated low iron substrate. Top and bottom support channels are concealed within finished floor and ceiling panels.
2.1.1 Façade Design Criteria and Objective

The façade consists of a total of 203 fixed exterior lites. Approximately 80% of the insulated glass units are curved in radii varying from 2.9 to 99m, with the majority of lites being in the 3-30m range.

Glass units are based on an approximate width of 2.30m with a maximum height of 3.96m. Due to the descending roof and ground some of the lites have a rhomboid shape. Reducing the potential for visual distortion inherent to the heat treated bending process, all typical curved lites are annealed. To satisfy code in regard to safety glazing, interior and exterior lites are laminated throughout the project.

The overall width of the insulated glass unit is maintained consistent between concave, convex, and flat glass within one pavilion. The vertical joint between the glass units was set at a nominal dimension of 12mm.

To be able to accommodate the different radii a flexible silicone foam spacer has been used in conjunction with a structural silicone secondary seal. The silicone foam base incorporates a desiccant in-fill and a pre-applied primary PIB seal in conjunction with a vapour barrier seal applied to the outer face of the spacer.
While maintaining the 12mm vertical glass joint the design objective was to reduce the vertical edge seal dimension to a warranted minimum.

Figure 3. Site Plan (SANAA / Handel Architects)

Figure 4. Radii Distribution Graph
2.2 Engineering Analysis
Extensive engineering analyses were conducted in collaboration with Stutzki Engineering Inc. confirming the minimum required edge seal dimension in regard to
- Structural Loads (mainly wind loads and self-dead loads (glass handling during fabrication and installation))
- Climatic Loads (isochoric pressure)

2.2.1 Curved Glass Matrix
Since each lite is different in radius and size a glass matrix was developed containing all geometrical information and related structural properties. [3]

Figure 5. Structural Properties for Thin Circular Arcs

Figure 6. Ratio Ix (curved / flat glass) in relation to glass radius (based on an arc thickness of 18mm)
Comparing the Moment of Inertia of the curved lites (centroid of Arc) to a same size flat glass, the ratio in strong (x) axis varied between 150.57 to 1.231, while in y axis the ratio was in the range of 0.98 to 1.00.

### 2.2.2 Structural Calculations

The glass makeup was first determined by the deflection limitations of the largest flat lite under maximum wind load (uniform pressure). Calculations were based on the International Building Code with Local Amendments [4], ASTM E-1300 [5], and ASCE 7 [6]. Since the pavilions vary in height two different glass thicknesses were chosen, while the airspace thickness remained the same.

- For glass height >3327mm: Inner and outer laminated lites consisting of 2x10mm – airspace - 2x10mm
- For glass height ≤3327mm: Inner and outer laminated lites consisting of 2x8mm – airspace - 2x8mm

The interlayer chosen was a PVB with superior edge stability and increased stiffness at higher temperatures compared to a conventional PVB.

All glass was found adequate based on stress for a temperature range of 30-50°C Celsius.

**Figure 7.** Glass Deflection of Flat Insulated Glass

The occurrence of high temperature with high wind load is unlikely (Hattis, 1991) [7]. Recommended temperature for deflection calculations - determining effective thickness of the laminated glass- is 30°C (86°F).
At a mean recurrence interval of 5 years and an interlayer temperature of 30°C, the maximum deflection for 3.96m (156") tall IGUs was 17.7mm (0.696") [L/224] and for 3.33m (131") tall was 0.606" (L/216).

The use of structural silicone between adjacent curved / flat lites further reduces these deflection values. The worst case deflection happens when 3 or more flat IGUs occur in a row. A total of 16 lites did show a flat / flat vertical edge condition.

Figure 8. Edge Seal Diagram

A secondary sealant width of 6mm structural silicone was found adequate based on uniform wind load and handling during fabrication and installation.

2.2.3 Climatic Study / Surface Temperature Analysis

A climatic study was conducted to determine interspace and glass surface temperatures. The temperature in the airspace will cause the air to expand or contract which will impart a pressure or suction on the glass lites as well as the air space seals (isochoric pressure).

Figure 9. TRLV-2006 [8]

A model of a typical building created in Trimble Sketchup 8 using the Legacy Open Studio plugin was generated. Surface temperatures were applied on this modelling using EnergyPlus by inputting a Typical Meteorological Year, Version 3 (TMY3) data sets.
From the US Department of Energy: The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories.

The glass was defined within the Energy Plus program using optical data generated by the Optics 6 and Window 6 programs. The interior temperature was set at a low temperature of 68°F (20°C) and a maximum temperature of 77°F (25°C).

The maximum outside surface temperature occurs on July 4th, at 17:00 on west facing façade units. The calculated airspace temperature was 42.035°C; the difference between Inside and Outside Surface Temperatures was 1.528°C. This was also the maximum Inside Surface Temperature and the maximum Airspace Temperature.

![Diagram of temperature variations](image)

**Figure 10. Maximum Outside Surface Temperature**
The minimum outside surface temperature occurs on January 29th, at 07:00 on west facing façade units. The calculated airspace temperature is -4.925°C; the difference between Inside and Outside Surface Temperatures is 15.118°C. This is also the minimum Airspace Temperature.

The minimum inside surface temperature occurs on February 11th, at 03:00 on west facing façade units. The greatest surface temperature differential occurs on January 14th, at 11:00 on south / southeast facing façade units resulting in a difference between Inside and Outside Surface Temperatures of 19.532°C. The calculated airspace temperatures in these two cases do not exceed the ones reported above.

![Figure 11. Minimum Outside Surface Temperature](image)

As shown in the summary [Figure 12] the minimums are very similar to one another and do not vary from window to window. This is because most are occurring either during night hours or very early during sunlight hours, so the ambient air temperature is the dominant factor on the surface temperature; conversely, the maximum temperatures vary according to how much direct sunlight the surface receives during the day.
The maximum calculated airspace temperature is 47.3°C and the minimum calculated airspace temperature is -5°C. If it is assumed that the glass is manufactured at 20 °C, this results in a differential of +27.3°C / -25 °C. The inside glass surface temperature ranged between 2.5°C and 42.8°C. The outside glass surface temperature ranged between -12.5°C and 41.3°C.

<table>
<thead>
<tr>
<th>Window</th>
<th>Inside Face Temperature (°C)</th>
<th>Outside Face Temperature (°C)</th>
<th>Difference Between Inside and Outside Temperature (°C)</th>
<th>Surface Inside Face Temperature (°C)</th>
<th>Surface Outside Face Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Max</td>
<td>36.106</td>
<td>19.376</td>
<td>-16.73</td>
<td>36.106</td>
<td>19.376</td>
</tr>
<tr>
<td>1 Min</td>
<td>2.568</td>
<td>-4.912</td>
<td>-7.42</td>
<td>2.568</td>
<td>-4.912</td>
</tr>
<tr>
<td>2 Max</td>
<td>36.636</td>
<td>19.376</td>
<td>-17.27</td>
<td>36.636</td>
<td>19.376</td>
</tr>
<tr>
<td>2 Min</td>
<td>2.569</td>
<td>-4.912</td>
<td>-7.42</td>
<td>2.569</td>
<td>-4.912</td>
</tr>
<tr>
<td>3 Min</td>
<td>2.562</td>
<td>-4.916</td>
<td>-7.48</td>
<td>2.562</td>
<td>-4.916</td>
</tr>
<tr>
<td>4 Max</td>
<td>39.196</td>
<td>19.376</td>
<td>-20.82</td>
<td>39.196</td>
<td>19.376</td>
</tr>
<tr>
<td>4 Min</td>
<td>2.571</td>
<td>-4.923</td>
<td>-7.45</td>
<td>2.571</td>
<td>-4.923</td>
</tr>
<tr>
<td>5 Max</td>
<td>38.577</td>
<td>19.376</td>
<td>-20.21</td>
<td>38.577</td>
<td>19.376</td>
</tr>
<tr>
<td>5 Min</td>
<td>2.56</td>
<td>-4.902</td>
<td>-7.46</td>
<td>2.56</td>
<td>-4.902</td>
</tr>
<tr>
<td>6 Max</td>
<td>37.88</td>
<td>19.376</td>
<td>-18.51</td>
<td>37.88</td>
<td>19.376</td>
</tr>
<tr>
<td>6 Min</td>
<td>2.5411</td>
<td>-4.924</td>
<td>-7.46</td>
<td>2.5411</td>
<td>-4.924</td>
</tr>
<tr>
<td>7 Max</td>
<td>39.916</td>
<td>19.376</td>
<td>-20.54</td>
<td>39.916</td>
<td>19.376</td>
</tr>
<tr>
<td>7 Min</td>
<td>2.5415</td>
<td>-4.924</td>
<td>-7.46</td>
<td>2.5415</td>
<td>-4.924</td>
</tr>
<tr>
<td>8 Max</td>
<td>37.917</td>
<td>19.376</td>
<td>-18.54</td>
<td>37.917</td>
<td>19.376</td>
</tr>
<tr>
<td>8 Min</td>
<td>2.5522</td>
<td>-4.924</td>
<td>-7.46</td>
<td>2.5522</td>
<td>-4.924</td>
</tr>
<tr>
<td>9 Max</td>
<td>36.763</td>
<td>19.376</td>
<td>-17.39</td>
<td>36.763</td>
<td>19.376</td>
</tr>
<tr>
<td>9 Min</td>
<td>2.5523</td>
<td>-4.924</td>
<td>-7.46</td>
<td>2.5523</td>
<td>-4.924</td>
</tr>
<tr>
<td>10 Max</td>
<td>40.189</td>
<td>19.376</td>
<td>-20.81</td>
<td>40.189</td>
<td>19.376</td>
</tr>
<tr>
<td>10 Min</td>
<td>2.5538</td>
<td>-4.916</td>
<td>-7.46</td>
<td>2.5538</td>
<td>-4.916</td>
</tr>
<tr>
<td>11 Max</td>
<td>42.125</td>
<td>19.376</td>
<td>-22.75</td>
<td>42.125</td>
<td>19.376</td>
</tr>
<tr>
<td>11 Min</td>
<td>2.5536</td>
<td>-4.924</td>
<td>-7.46</td>
<td>2.5536</td>
<td>-4.924</td>
</tr>
<tr>
<td>12 Max</td>
<td>42.758</td>
<td>19.376</td>
<td>-23.39</td>
<td>42.758</td>
<td>19.376</td>
</tr>
<tr>
<td>12 Min</td>
<td>2.5143</td>
<td>-4.925</td>
<td>-7.45</td>
<td>2.5143</td>
<td>-4.925</td>
</tr>
<tr>
<td>13 Max</td>
<td>41.888</td>
<td>19.376</td>
<td>-22.51</td>
<td>41.888</td>
<td>19.376</td>
</tr>
<tr>
<td>13 Min</td>
<td>2.5322</td>
<td>-4.924</td>
<td>-7.46</td>
<td>2.5322</td>
<td>-4.924</td>
</tr>
<tr>
<td>14 Max</td>
<td>38.928</td>
<td>19.376</td>
<td>-19.55</td>
<td>38.928</td>
<td>19.376</td>
</tr>
<tr>
<td>14 Min</td>
<td>2.5561</td>
<td>-4.925</td>
<td>-7.45</td>
<td>2.5561</td>
<td>-4.925</td>
</tr>
</tbody>
</table>

Figure 12. Temperature Summary

2.2.4 Internal Pressure Analysis

Based on geometry curved glass is much stiffer than a flat lite with comparable width and thickness. This stiffness will cause a curved lite to deflect less than a comparable flat lite. This additional stiffness is especially interesting when it comes to isochoric pressure in the airspace of insulating glass units (IGUs).

All IGUs see isochoric pressure due to temperature change, variation in meteorological pressure, and elevation difference between manufacturing location and installation location.
The pressure acts to either push apart the inner and outer lites (positive pressure) or pull them together (negative pressure); both cases stress the secondary seal, though the positive pressure is of more interest. In flat IGUs this pressure causes the glass to bend, thus increasing the volume of the airspace. In curved IGUs the glass is stiff and resists the pressure. To relieve the pressure (increase the airspace volume) the secondary seal is stressed and stretches.

ASTM E 1300 addresses the misalignment of interior and exterior lites of glass in IGUs caused by this pressure by including a sealed airspace pressure (asp) factor in the glass type factor (See X2.2.6 ASTM E1300-12ae1).

The German document: "Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen (TRLV)" (roughly translated as Technical Rules for the Use of Glazing with Linear Supports) goes farther in Appendix A: Calculation Method for Insulating Glass. Here the document provides a calculation methodology to determine the isochoric pressure based on temperature difference, variation of the meteorological air pressure, and geological height difference between the manufacturing location and the location of the installation.

Appendix A of the TRLV provides a method to determine interior pressure due to change in temperature, change in meteorological pressure, and change in elevation. As described change in temperature was the object of this analysis. Due to the difficulty in translating the calculated interior pressures for a flat IGU (per the TRLV) to a curved IGU Finite Element Analysis (FEA) was used to analyze the primary and secondary seals. Abaqus 6.12 by Dassault Systemes was used for all FEA analysis.

First, the FEA was calibrated to the TRLV method for flat glass. Second, the effects of curved glass were studied by graphing the glass radius vs. internal pressure. Finally, five selected glass lites from the Grace Farms project were analyzed to determine the maximum pressure in the airspace due to temperature increase/decrease.

The analysis was based on the temperature change prescribed in EN1279-2 Glass in Building – Insulated Glass Units – Part 2: Long Term Test Method and Requirements for Moisture Penetration. [9], which is +/- 38°C. This resulted in more stringent temperature differences than what has actually been found based on the Climate Study described under 4.3.3 above. The stiffness of the structural silicone secondary seal impacts the change of the volume of the airspace and affects the internal pressure of the IGU.

A flat IGU of 1000mm x 1000mm was calibrated to the TRLV hand calculation. Different glass thicknesses were studied. The internal pressure in the FEA was compared to the TRLV hand calculation. During the design process, the FEA results diverged from the TRLV calculation as the glass thickness increased. We hypothesized that the difference was due to the silicone stretching. As the silicone deforms (even slight deformations), the volume of the airspace changes resulting in a different internal pressure. To test this theory, we supported both plies of the IGU in the FEA to prevent the silicone from stretching.
Figure 13. Finite Element Model

![Finite Element Model Diagram]

Properties of the Air Cavity applied to the Reference Node.
Quarter-Symmetry used to reduce analysis size.
Line Support in X-Direction on Vertical and Horizontal Edge of Glass.
Both Glass Plies modeled with Brick Elements.
6mm thick Silicone modeled as a hyperelastic material. Edge spacer was ignored for the analysis.

Figure 14. FEA Calibration to TRLV

<table>
<thead>
<tr>
<th>Glass</th>
<th>FEA Pressure</th>
<th>TRLV Pressure</th>
<th>FEA Pressure</th>
<th>TRLV Pressure</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>kPa</td>
<td>KPa</td>
<td>psf</td>
<td>psf</td>
<td></td>
</tr>
<tr>
<td>6x6</td>
<td>0.553</td>
<td>0.575</td>
<td>11.5</td>
<td>12.0</td>
<td>-1.1%</td>
</tr>
<tr>
<td>6x6 Line</td>
<td>0.627</td>
<td>0.575</td>
<td>13.1</td>
<td>12.0</td>
<td>8.2%</td>
</tr>
<tr>
<td>8x8</td>
<td>1.055</td>
<td>1.285</td>
<td>22.0</td>
<td>26.8</td>
<td>-21.8%</td>
</tr>
<tr>
<td>8x8 Line</td>
<td>1.375</td>
<td>1.285</td>
<td>28.7</td>
<td>26.8</td>
<td>6.6%</td>
</tr>
<tr>
<td>10x10</td>
<td>1.601</td>
<td>2.293</td>
<td>33.4</td>
<td>47.9</td>
<td>-43.2%</td>
</tr>
<tr>
<td>10x10 Line</td>
<td>2.422</td>
<td>2.293</td>
<td>50.6</td>
<td>47.9</td>
<td>5.4%</td>
</tr>
</tbody>
</table>

The silicone stretches changing the volume of the air space.
The glass above designated as “Line” have both plies of the IGU supported. This prevents the secondary silicone from stretching and changing the volume of the air space. The glass lites with the “Line” designation are within 8.2% of the TRLV calculation.

In summary, the FEA model is more accurate than the TRLV since it accounts for the change in volume of the IGU due to silicone stretching. In this context see also the study “The Influence of the Edge Sealing in Curved Insulated Glass” [10].

![Figure 15. Effects of Glass Curvature](image)

The curvature of the glass has a significant impact on the internal pressure of an IGU. The geometry of the curved glass creates extra stiffness due to its inherent shape. This causes the internal pressure to dramatically increase. The graph above [Figure 15] shows the pressure difference due to a 20°C temperature increase on a 1600 mm x 1000 mm lite of glass with 6mm thick glass on each ply.

### 2.2.5 Insulated Glass Study (Project Specific Glass Design)

Five representative glass lites on the Grace Farms project were analysed to determine the maximum internal pressure in the IGU.

1. ) Max Height – Minimum Radius (S-58)
2. ) Max Height – Flat (S-13)
3. ) Minimum Surface Area (F-16)
4. ) Minimum Height – Minimum Radius (A-32)
5. ) Minimum Height – Flat (A-11)

10mm + PVB + 10 mm + 12mm Air Space + 10mm + PVB + 10mm glass was assumed. The effective thickness of the glass was determined via ASTM E1300 [5]. For temperature increases, the glass was assumed uncoupled (t = 11.36mm). The glass was modelled as a rectangle to simplify the analysis.
The highest internal pressure was found at lite F-16 with 0.00099MPa. For the conditions listed above the stretch of the IGU secondary seal was analyzed. The largest silicone deflection was found at lite S-58 with 0.739mm.

A 6mm vertical and a 25mm horizontal secondary seal have been found sufficient to maintain the integrity of the insulated glass.

![Diagram of deflection measurements](image)

**Figure 16.** Stretch of Secondary Seal

### 2.3 Verification of Engineering Analysis

To confirm the outcome of the Engineering Analysis described under item 4.3 above several performance tests and visual mock ups were conducted.

#### 2.3.1 Insulated Glass Chamber Testing

Testing for Insulated Glass Units was conducted in accordance with EN1279-2.

The chamber testing described in the EN standards is comparable to the IGCC [11] testing which forms a basis of climate testing for insulated glass units in North America. The testing conducted consisted in the first part of cyclic testing (56 12 hour temperature cycles with a temperature delta ranging from -18°C to +53°C, relative humidity at high temperatures above 95%). The second part
consisted of a constant climate testing (+58°C holding temperature for a duration of 7 weeks, relative humidity at high temperatures above 95%).

Long term performance under UV light was not performed on the material components of the edge seal since successful historically test data is available through the manufactures.

Figure 17. Insulated Glass Chamber Testing in accordance with EN 1279-2.

The EN standard specifies the dimensional geometry (350mm +/-2mm x 500mm +/- 2mm and thickness of the glass (4mm). To account for the increased internal pressure, silicone stress, and silicone stretch predicted for the actual project lites the thickness of the glass has been increased to 6mm for the chamber tests [Figure 18].

Figure 18. Comparison of project lites to EN standard

All tested insulated glass lites passed the test. The average moisture penetration index (percentage of moisture increase) was approximately half of the allowable as per EN 1279-2.
2.3.2 Performance Mock-up Testing
Performance mock up testing was conducted. Reported deflections under maximum wind loads were in the range of the close range of the calculated values.

2.3.3 Visual Mock ups and Quality Control
To maintain a 12mm nominal joint between the glass lites and a vertical 13.3mm nominal edge seal dimension (6mm structural silicone and 7.3mm spacer width) several trial production runs and visual mock ups and took place. These are necessary to confirm the technical feasibility and quality control required to maintain these values through production.

References
Integrated Structural and Thermal Design of Façades in Hot Climates

Christian Stutzki
STUTZKI Engineering, Inc., USA

Matthew Kuba
STUTZKI Engineering, Inc., USA

Abstract
Some glazing applications require the accurate consideration of temperature effects. This paper describes a procedure to determine temperature differences and temperature changes in glass and how to use them as load data to determine stresses and deflections in the glass units.

The first part of the paper describes how to determine glass surface temperatures with the help of the energy simulation software EnergyPlus [1]. Temperatures are determined based on the local weather data, hourly sun-radiance and angle, glass make-up, glass thickness, glass color, and glass coatings. Partial shadings are taken into account.

The second part of the paper consists of a design example where the glass temperatures, critical to the structural design, are calculated.

The final part of the paper addresses structural questions about temperature load on glass façades.

1. Introduction
The objective of the method described in this paper is to review the structural integrity of insulated or laminated glass in hot climate environments. Potential problems are:
- Seal breakage due to overpressure in the air space of insulated glass units.
- Glass breakage due to thermal stresses in the glass.
- Glass breakage of laminated glass under wind load because the stiffness of the hot interlayer was underestimated in design.

The engineering response to these potential failures is a new method, consisting of the following three steps:
- Employ simulation software, which is used to simulate the energy performance of buildings, to determine the surface temperature of glass.
- Use these temperatures as loads in a structural analysis for the glass, with various load scenarios for wind, shading, and temperatures.
- Determine the required glass strength and thickness, as well as determine the thickness of structural silicone for IGU’s. If required, use heat resilient interlayers for laminated glass, based on the findings of the previous step.
These three steps are illustrated in more detail in the following paragraphs. The method can be used for:

- Design of new glass walls
- Forensic investigation of damaged glass walls and skylights

Temperature effects can be more serious in hot climate zones. The examples presented are selected from the authors’ practice, which deals with projects worldwide, the more interesting case studies are situated in hot climate zones, in particular in Saudi Arabia.

The traditional architecture reflects wisdom and thousands of years of experience still unmatched by modern engineering and building science (Figure 1). A recently designed office building uses bio-mimicry, simulating the ribs of a cactus to preserve pockets of shade and lower temperature (Fig. 2, Fig. 3 and Fig. 4)

![Figure 1. Traditional and Modern Buildings in the Desert, Ribs on Cactus Plants and as Shading Elements on Buildings](image)

Of particular interest here are the spandrel units with tinted glass:

What temperature can the glass reach under the desert sun and how does that affect its strength?
2. Determination of Glass Surface Temperatures

The method developed and discussed in the following is in essence discovering the synergy between two different fields of applied science:

- The world of planning the energy efficiency of buildings and designing solar energy devices
- The world of structural engineering for glass

Each of these realms uses its own types of software tools. The new method takes advantage of the fact that one of the by-products of energy simulation is the surface temperature of building components, in particular the surface temperature of glass. That was the missing link for engineers who tried to understand the response of glass to different temperatures.

Fortunately the US-DOE software "EnergyPlus [1]" calculates the heat transfer through building walls, including glass walls, taking into account radiant energy transfer and energy absorption of solar radiation. The energy absorption, transmittance, reflection, and radiation are carefully determined across a wide range of wavelengths, including the far infrared range that is the main contributor for temperature increase of surfaces of materials.

![Figure 2. Flow chart of the procedure to determine glass surface temperatures](image-url)
A model of a typical building will be created in Trimble Sketchup [2] using the Legacy Open Studio plugin [3]. The Legacy Open Studio plugin allows various constructions consisting of surfaces, interior zones, and exterior shading elements. Once built, a file will be generated that can be used with EnergyPlus. The EnergyPlus program will apply representative weather data to the model and generate a number of different results, including surface temperatures.

The weather data files used are supplied by the National Renewable Energy Laboratory. From the US Department of Energy:

The TMY3s are data sets of hourly values of solar radiation and meteorological elements for a 1-year period. Their intended use is for computer simulations of solar energy conversion systems and building systems to facilitate performance comparisons of different system types, configurations, and locations in the United States and its territories. Because they represent typical rather than extreme conditions, they are not suited for designing systems to meet the worst-case conditions occurring at a location. The source data are available for download from the National Renewable Energy Laboratory for download. [4]

TMY3 is the Typical Meteorological Year, Version 3. Included within the weather data file is temperature, wind speed, humidity, precipitation, and various other values for every hour of every day of a year. The values are not taken from one specific year but are intended to be representative of larger time period (in this case, 1991 – 2005). Extreme conditions will need to be analyzed separately.

For the purposes of the method described herein, EnergyPlus is only being used to study the effects of the weather conditions, i.e. the effects of temperature and solar radiation on the surface temperatures of the glass. No mechanical systems are a part of the models being used, however, an internal thermostat is typically being used to regulate the inside air temperature.

The glass is defined within the Energy Plus program to use optical data generated by Optics 6 and Window 6. The following data are characteristic for a typical glass unit:

- Thickness
- Solar transmittance
- Front side solar reflectance
- Back side solar reflectance
- Visible transmittance
- Front side visible reflectance
- Back side visible reflectance
- Infrared transmittance
- Front side infrared emissivity
- Back side infrared emissivity
- Conductivity

![Figure 3. Section of a typical Glass Makeup](image-url)
3. Design Example

A weather file for Riyadh, Saudi Arabia was retrieved from the National Renewable Energy Laboratory. Models were then constructed to simulate building performance. This case considers a test cell constructed to simulate the spandrel glass. The model includes a one module wide and one story high portion of a façade (Fig. 8). In reality the façade will be much bigger. The exterior sun control devices are part of the model. Each IGU is 1735mm high by 3000mm wide, and the cavity between the IGU and the back of the enclosed cavity is 25mm. Each IGU is split vertically into two surfaces to assess the performance of the exterior sun control devices. The cavities are modelled as unconditioned to simulate how the internal air temperature will behave. The model uses an interior zone modelled as a conditioned space with thermostat set-points of 25°C for cooling and 20°C for heating.

![Graph of solar spectrum and energy transmitted through different glass types](image)

**Figure 4. Solar spectrum and Energy transmitted through different glass types**

The results of a simulation run over an entire year, in one hour time steps, are surface temperatures of all defined materials, also in hourly time steps.

Each surface is part of the simplified building model, with its true orientation towards North and its true slope. This allows tracking of the surface over a day or over a year with its realistic exposure to the sun (in its realistic azimuth and altitude angles) and shading at other times of the day.
Figure 5. Simplified building model for simulation

Figure 6. Peak temperature history of the west side spandrel glass

A typical result is shown in Figure 9: The peak temperature of 75°C for this example of a west façade is at 5 p.m. in the afternoon.
4. Structural Issues Regarding Temperature Load

The glass engineer will have several questions related to temperature:

- Can the glass break due to partial shading?
- Can the IGU seal break due to internal air pressure?
- Can the laminated glass break due to wind gusts?

The answers are crucial to long term durability and stability of the façade.

4.1. Glass Breakage Due to Thermal Stress

For a partially shaded glass surface the temperature differential is calculated by subtracting surface temperatures from a surface in complete shade from surfaces that are in direct solar radiation on the South or West sides of the model (depending on time of day).

For a cold glass perimeter in a glass channel, surface temperature increases are examined from the time right before sunrise to two hours after sunrise. It should be noted that glass has a reasonably high thermal conductivity, comparing surface temperatures of lites in complete shade to surface temperatures of lites in complete sunlight or changes over the course of two hours will return conservative maximum surface temperature differentials. Temperature differentials will be calculated for both inside and outside faces.

A study was conducted of partial shading of a glass panel. A small all glass model is created with glass panels oriented in all directions to examine simultaneously shaded and exposed surfaces. Using temperatures taken from the glass lites on the sunny side of the pavilion, and the temperature of the shaded portions from the dark side a finite element model was created. The results of the finite element analysis of the differential shading show the magnitude of thermal stresses along
the edge of the shaded portion (Fig. 10). The Finite Element Software ABAQUS [9] is used for the stress analysis.

These stresses need to be superimposed (u combination factors) with stress from wind load to show the full impact of climate loads.

4.2. Can the IGU seal break due to internal air pressure?
The methodology of the answer to this question is presented in depth in a parallel presentation [11], and therefore will not be explained in this paper. This topic is of high interest to IGU manufacturers who are producing glazing units for hot climate countries.

4.3. Glass Breakage due to Wind Loads
The study of laminated glass typically assumes some composite action between two plies of glass. This composite action depends on the shear stiffness of the interlayer, which in turn depends on the temperature of this polymer (Figure 11). Thus the stresses in laminated glass, due to wind load, depend on the accurate estimate of the temperature.

![Figure 8. Stiffness of a typical polymer interlayer](image)

Underestimating the temperature could mean underestimating the bending stress in the glass, which may mean a reduced safety against breakage. For a temperature of 50 degrees Celsius and more there is basically no composite action for PVB interlayer, which means the stress and the deflections are similar to two separate, parallel sheets of glass. Results are much higher than with the usual assumption of composite action. The question of the probability of high temperatures and high wind loads is discussed in several papers [7]. These considerations may be used to design in a more economic way, and not use the most conservative combination of wind and temperature.
5. Conclusions
The tools for energy simulations of buildings are available and offer the ability to determine surface temperatures of building materials, depending on the orientation of the surface, the layers of the envelope, and the material properties. The simulations, running in hourly time steps through a whole typical year, offer new insights into the performance of building components.

6. Summary
It is important to know the surface temperatures of building materials that form the envelope of buildings in order to analyze the short term and long term structural performance. Software packages to simulate the energy performance of buildings, such as ENERGYPLUS, offer these surface temperatures as side results of the simulation. These simulations can be coupled with structural analysis to assure the structural integrity of the enclosure elements.

7. References:
[2] Trimble Sketchup 8
Vacuum Glazing - The Optimal Solution of Future Glass Architecture with unique Production Features for Green and Heritage Building

Abstract

The concept of energy saving buildings has promoted many green buildings, like active-houses, energy-plus houses, zero energy consumption buildings and passive houses. No matter, what kind of the green building is, it should have low energy consumption, which asks for the building envelope, especially the window, having good thermal insulation and solar shading properties. Under such demands, Vacuum Glazing could show its advantages very well like thermal insulation, sound insulation, lightweight, thin and wide application. This paper introduces the application and advantages of Vacuum Glazing used in Green Buildings. It analyses some questions, about life time, costs, projects and industrialization. Vacuum Glazing has comprehensive advantages in Green Building applications, and its industrialization need strong support from related industry and institutions, also from governmental research projects.

The industrialization of Vacuum Glazing VG after strong research in the past twenty years is now on track. A series of technical difficulties have been solved to start the first global mass production of high-quality Vacuum glazing within Company Synergy in Beijing. The Debugging of the fully-automatic Vacuum Glazing production line, recently built by Synergy Company in Beijing with support by Dr. Hohenstein Consultancy is basically finished.

High-quality means high performance and long-life which are interrelated. Finally widespread Vacuum Glazing (VG) applications are now on the horizon. A mass production line must be able to achieve these two requirements, if it is to produce Vacuum Glazing products that can be accepted by the society. With U-values between 0,3 and 0,5 W/m²K based on Low-È with an Emissivity of 0.03 till 0.06 the door is wide open for further advantages and hybrid solutions. Thinnest versions, with only 6 or 8 mm can be exchanged directly against single glazing's...
in windows and thus contribute enormously to renovation and historic heritage buildings.

Keywords: Vacuum Glazing-, energy saving, advanced window and façade systems, industrial production, Energy Plus Houses

1. Introduction

1.1 Historical Reflection
Glass companies have been searching for over 20 years for a new option for Insulating Glass, mainly due to intense competition, poor price-cost ratio and to improve the energy saving performance. Unfortunately most investigations did not result in a new generation of innovations, only small improvements in a few areas following standard technologies.

1.2 Big demand for new solutions
Many notable companies turned to Vacuum Glazing Development as an Alternative, but no one was able to discover a marketable industrial solution. The only Company was Nippon Sheet Glass starting in 1997. Their development is based on research at Sydney University under the direction of Professor R. E. Collins who worked with a partner, Professor Jianzheng Tang, a Chinese, who had been living in Australia for a number of years. NSG acquired 1995 the rights on these patents. Professor Tang left Australia in 1998 and made - unnoticed by Western states - his own research with new patents and started within a new company in 2001.

1.3 Initial production
The developing company - owned by a governmental real estate holding in Beijing - trusted the long term success and had been producing a small automated line of Vacuum Glazing for some time and sold VIG to Chinese governmental projects from 2004 onwards as shown in the report.

In the past twenty years a series of technical difficulties need to be conquered in order to mass produce high-quality Vacuum Glazing. High-quality means high performance and long-life. Due to promotion of energy saving and emission reduction, both subjective and objective conditions for industrialization of Vacuum Glazing are now ready, and a continuous automatic production line for Vacuum Glazing is soon starting in Beijing.

1.4 Requirements for Vacuum Glazing production
In regards to equipment and in general this is discussed in this report. To achieve market recognition, the most important thing is to ensure the quality of the product, and then reduce the costs.

1.5 New Advantages – market options
Glass Companies compare VG/VIG price today with triple insulating glass with 2 coatings considering similar windows and facades production. With Vacuum Glazing the door is wide open for complete new solutions and advantages in window, façade and wall construction. Architects, who come more from a holistic
approach and the performance side, balance costs for investment against utilization and operational costs.

1.6 **Missing innovation of windows and facades**
If one considers the frame development for windows, it is easy to see that there is a lack of new solutions for energy saving and it was more a development of steady growth of the cross section. Frames have taken more and more surface area on a window. We can use the former space of IG especially for triple IG as an excellent opportunity to build, for example, a new box-type or counter-sash windows replacing the triple IG, but with the option to integrate other functions. We are only at the beginning. Very few experts and companies have shared their thoughts on these aspects. But we do need less independent actions; we need more integrated vertical teams to find new solutions.

Energy Plus (+) Houses with Vacuum Glazing - the future of building
There is so much to do and so much to achieve. This industry should have a general concept to utilize Vacuum Glazing in order to satisfy the present architectural requirements and future expectations.

2. **Introduction – a historical reflection**
But in this industry there is a big demand for new solutions. Many notable companies turned to Vacuum Glazing as an alternative but no one was able to discover a marketable industrial solution. The only Company that offered VIG was Nippon Sheet Glass starting in 1997.

Their development is based mainly on the research at Sydney University under the direction of Professor R. E. Collins who worked with a partner, Professor Jianzheng Tang, a Chinese who had been living in Australia for a number of years. He shared not only all rights on patents and know-how, he was the driver. NSG acquired 1995 the rights on these patents. Sydney University enjoyed long relationship with NSG and only recently the remaining experts are free to work on new developments. Professor Jianzheng Tang left Australia in 1998 and made - unnoticed by Western states - his own research with new patents and started within a new company in 2001. What is astonishing, is the fact that NSG did not use their early advantage to develop the technology further. They remained more or less within the initial achievements and limited applications.

In the past twenty years a series of technical difficulties need to be conquered in order to mass produce high-quality Vacuum Glazing. High-quality means high performance and long-life, the two are inter-related. A mass production line must be able to achieve these two requirements if it is to produce Vacuum Glazing products that can be accepted by the building society. Gradually this has to be improved and developed by continuous reduction of cost and maximization of production capacity. Due to promotion of energy saving and emission reduction as well as technological progress, both subjective and objective conditions for industrialization of Vacuum Glazing are now ready, and a continuous full
automatic production line for Vacuum Glazing has been finished and is now under final debugging in Beijing.

Again it is a surprise that the leading glass companies were not willing to invest on a real production scale, they remained on the research level compared to Professor Tang's strategy, and lost time. Professor Tang succeeded with his first projects and sales whilst at the same time learned a lot from actual practice. This led to the eventual breakthrough.

3. Equipment requirements for Vacuum Glazing production

3.1 Key factors for Vacuum Glazing production

- High vacuum guaranteed for a minimum of 20 years. First ensure the products achieve the vacuum degree during production, and second retain vacuum for a long time – optimization of process and getter system
- Hermetic sealing system available, to ensure high vacuum and easy handling as well
- Virtually invisible micro spacers (=pillars), put in place with less than 1 % surface and not harmful to the Low E coating
- Excellent equipment to temper glass with perfect flatness to fulfill alignment requirements. There are very few machine suppliers, who can provide feasible equipment, but it is the operator finally who brings the quality to the glass.
- Top cutting equipment to cut 2 glass panes in the same size +/- 0.2mm per meter
• Perfect arris or seaming device to enable perfect condition for tempering as well as long lasting performance avoiding breakage.
• Glass drilling required for the valve and getter system has to be very smooth and has not to generate any additional weakness for the glass.

As the Vacuum Glazing is more sensitive to production process and to handling, the manufacturing equipment has to be high quality to ensure the required results. Here is room for further achievements by skilled partners Synergy would like to win as partners.

Apart from energy performance, shading, sound insulation, safety and other properties are also better than for standard insulating glass. Plus, it has relatively thin thickness, lightweight, and Low-E coating is better protected. Thus VG offers an overall advantage compared to insulating glass.

• Inclined glass in roofs has due to the lack of convection no loss of insulation (regular IG up to 50 %).
• In modern conditions, Vacuum Glazing’s service life can be 50 years in theory which is generally the life time architects want.
• After almost 20 years of technical improvement the quality of these materials and processes has greatly improved,
• Owing to the working temperature of glass solders used to seal edges of insulating glass and air extraction port in case of old techniques can be higher than 430 °C. If toughened glass or heat-strengthened glass is used due to such high temperature, they will “anneal” to become common glass.
• Temperable Low-E glass with emissivity from 0.03 is readily available with the new line. For the VG shown in Figure 2, two sheets of glazing are not common glass but regularly tempered (only on new line possible) and heat-strengthened glass (on existing line). This is only possible with lower process temperatures.
• Production of Vacuum Glazing is much more complicated than that of insulating glass. It is necessary to test the quality of each piece of glass produced.

3.2 Costs – an important issue going to market and being competitive
Vacuum Glazing is a high-tech product. To achieve market recognition, the most important thing is to ensure the quality of the product, and then reduce the cost. Good quality is usually related to higher costs, but it is not always to be like this. There are some reliable machine suppliers that can provide the required quality at a reasonable price. It is a matter of putting the right specification together to get high quality and price that's right for the market. The most important point is to have a full and clear understanding of the process itself as well as to have the specification of the final products in quantity and quality fixed. This is a must to have at the very beginning to avoid any misunderstanding within a project that could lead to additional costs. There are many improvements possible starting with the first automatic line and the process itself– the Story just begins.
4. Application of Vacuum Glazing in Green Building

For high-level energy conversation buildings, the main products of advanced glass are vacuum and triple insulating glasses. Insulating glass has been used for many years, and its technology is relatively mature. High-level products reduce its U-value by adopting high quality Low-E coatings, adding the coating layer, increasing insulating layer thickness, filling with argon and so on. For Vacuum Glazing, the basic structure, two panes only, can get a lower U-value.

Now, VG has been designed in initial sample buildings by a number of domestic and international designers. For example, Werner Sobek, Professor at Stuttgart University Germany, Director of Architectural Design and Structure Research Institute, world famous glass engineering office, has adopted Vacuum Glazing products made by Beijing Synergy Company in one of his active houses. The structure of Vacuum Glazing is shown in Table 1, the building is shown in Figure 2.

Table 1: Vacuum Glazing product data for Professor Sobek’s Active House

<table>
<thead>
<tr>
<th>Glass type outside inside</th>
<th>Thickness mm</th>
<th>Visible light transmitance τvis in %</th>
<th>Selectivity S</th>
<th>Total solar energy transmitance g-value</th>
<th>Emissivity of Low-E glass</th>
<th>U-value W/m² K</th>
<th>Sound reduction index dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Laminated + insulating + heat strengthened VG T5+0.76P+TL5+9A+TL5+V+T5</td>
<td>29</td>
<td>61.13</td>
<td>1.6</td>
<td>0.382</td>
<td>0.17</td>
<td>0.059</td>
<td>0.463</td>
</tr>
</tbody>
</table>

Remark:
1. All data is calculated by Window 7 software according to NFRC 100-2010.
2. T - tempered glass or heat strengthened glass, TL - tempered coated glass or heat strengthened coated glass, V - vacuum layer
3. Definition of glazing selectivity coefficient [S] (other name: light-to-solar gain coefficient [LSG]): the ratio of transmitted visible light and total transmitted solar light energy. LSG(S) = τvis/g-value. At the same solar heat gain, the higher the index, the more visible light can one get into the room.

The building is located in the center of the Weissenhof Siedlung building group in Stuttgart, which is completed in 1920s, and memorable as “Weissenhof Siedlung” Building Exposition in the history of modern European architecture. Many famous European designers have been involved in the building design of this area. They designed modern urban living facilities with new building materials, new construction methods.

Werner Sobek has raised nearly € 3.9 million to support this project, with the help of government research grants and sponsors. The energy conversation house is fully recyclable, and can generate electricity through photovoltaic panels. It not only provides electricity for the surrounding residential communities, but also for the electricity grid. This energy model building is a unit with 85 square meters; it
can save energy by large hybrid Vacuum Glazing which is $2.5 \times 1.7$ m$^2$, and retractable balcony, which is fixed in wooden front wall. It’s the most energy-efficient method at present [1].

Vacuum Glazing has also been applied in the “Water Front” passive low-energy consumption demonstration project, which is located in Qinhuangdao city. The project is one of first batch national level technology joint program, which is implemented by China Construction Ministry and German Energy Agency DENA. And it may become the new generation standard in the field of building energy conversation in China.

“Water Front” project consists of four residential buildings which are designed according to the German passive and low energy consumption building standard, which is part of integrated project with 1.5 million m$^2$. Project picture is shown in figure 3. Each building has 18th floor, 45 suites, and a total of 6500 m$^2$. The building energy saving index is much higher than the current China energy conservation standards, such as door and window heat transfer coefficient $U$-value is less than 1 W/m$^2$K [2]. Table 2 lists two kinds of glazing adopted by the project, one is hybrid Vacuum Glazing (VIG) and the other is triple glazing with Argon. The solar transmission ratio and selectivity of glazing could be adjusted by Low-E glass and it’s Emissivity.

5. The advantages and disadvantages of Vacuum Glazing applied in Green Buildings

- Insulation property is superior to insulating glass, much thinner
- Coefficient of Sun-prevention is same as insulating glass;
- Excellent sound insulation properties, particularly at low-frequency, weighted sound reduction index of tempered Vacuum Glazing is up to 37dB and compound Vacuum Glazing is up to 42dB; Vacuum layer is
sound insulated. Sound insulation performance of Vacuum Glazing is lowered due to support inside forming “sound bridge”, but still better than sound insulation performance of common glass [3].

- Long-life;
- Better utilization and protection of Low-E coating;
- Superior anti-frost and anti-condensation performance;
- No breaking or crack problem of VIG when used in areas with low air pressure (like Tibet);
- U-value invariable - when used horizontally or inclined.
- New window and façade construction technologies possible
- Weight reduction
- No atmospherically change
- Increase of visible area per window

Table 2 shows that VG has obvious comprehensive performance advantages:

<table>
<thead>
<tr>
<th>Building No</th>
<th>Structure outside inside</th>
<th>Thickness mm</th>
<th>Visible light transmittance $\tau_{vis}$ (%)</th>
<th>Selectivity coefficient S</th>
<th>Total solar energy transmittance g-value</th>
<th>Emisivity of Low-E glass</th>
<th>U-value W/m²K</th>
<th>Sound reduction index dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>13#</td>
<td>IG + Heat strengthened VG</td>
<td>31</td>
<td>63.7</td>
<td>1.16</td>
<td>0.55</td>
<td>0.17</td>
<td>0.5</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td>T5+16A+TL5+V+TL5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>15#</td>
<td>Tempered triple IG</td>
<td>43</td>
<td>46.2</td>
<td>1.54</td>
<td>0.30</td>
<td>0.05</td>
<td>0.146</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td>TL5+16Ar+TL5 +12Ar+TL5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Remark:
1. IG + heat strengthened VG in the table is provided by Beijing Synergy Vacuum Glazing Co., Ltd
2. The data’s in the table are calculated by the Window7, the boundary conditions are chosen according to the JGJ151-2008 standard.
3. T - tempered glass or heat strengthened glass, TL - tempered coated glass or heat strength coated glass, V - vacuum layer, N - float glass, L - coated glass.

5.1 Low U value, even lower in the future.
Synergy's hybrid Vacuum Glazing VIG has the lowest U value in “Water Front” project in China. Actually, if we use lower emissivity Low-E glass or use two (VG) or three Low-E glasses (VIG), the U value of Vacuum Glazing could be even down to 0.3.
As shown in Table 3, taking an example of “IG + heat strengthened Vacuum Glazing” in “Water Front” project, if using single Low-E glass with the emissivity of 0.06 and 0.03, the U value can reach 0.50 and 0.41 W/m²K; if using double Low-E glass with the same emissivity, the U value can reach 0.41 and 0.35 W/m²K. At the same time, if one choose VG with such low U values, one could reduce the frame - window ratio, which could still keep the U value of the whole window the same or lower, also could increase the whole light transmittance, and make living environment brighter. Usually the visible light transmittance, the selectivity and total solar energy transmittance need to be adjusted according to the region and climate zones.

Table 3: Properties of hybrid Vacuum Glazing VIG with different Low-E glass

<table>
<thead>
<tr>
<th>No</th>
<th>Glass structure</th>
<th>Thickness mm</th>
<th>$\tau_{vis}$ %</th>
<th>Selectivity $\sigma$</th>
<th>Total Solar Energy Transmittance g</th>
<th>Low-E Emissivity</th>
<th>U W/m²K</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>IG+single Low-E heat strengthened Vacuum Glazing T5+6A+TL5+V+T5</td>
<td>21</td>
<td>42.46</td>
<td>1.41</td>
<td>0.302</td>
<td>0.06</td>
<td>0.50</td>
</tr>
<tr>
<td>2</td>
<td>IG+single Low-E heat strengthened Vacuum Glazing T5+6A+TL5+V+T5</td>
<td>21</td>
<td>56.54</td>
<td>2.21</td>
<td>0.256</td>
<td>0.03</td>
<td>0.41</td>
</tr>
<tr>
<td>3</td>
<td>IG+double Low-E heat strengthened Vacuum Glazing T5+6A+TL5+V+TL5</td>
<td>21</td>
<td>24.33</td>
<td>0.92</td>
<td>0.265</td>
<td>0.06</td>
<td>0.41</td>
</tr>
<tr>
<td>4</td>
<td>IG+double Low-E heat strengthened Vacuum Glazing T5+6A+TL5+V+TL5</td>
<td>21</td>
<td>43.12</td>
<td>1.82</td>
<td>0.237</td>
<td>0.03</td>
<td>0.35</td>
</tr>
<tr>
<td>5</td>
<td>Lamination+ single Low-E heat strengthened Vacuum Glazing TL5+V+T5+1.14P+T5</td>
<td>16</td>
<td>59.91</td>
<td>2.24</td>
<td>0.267</td>
<td>0.03</td>
<td>0.43</td>
</tr>
</tbody>
</table>

Note: 1. The data in the table are calculated by Window7 program, the boundary conditions are chosen according to the JGJ151-2008 standard.

5.2. Thin, even thinner in the future

With similar U value, the thickness of the Vacuum Glazing is far less than triple insulating glass. As soon as 3 mm temperable Low E with Emissivity of 0.03 is supplied on the Chinese market VG of total thickness of 6 mm can be supplied (actual 8 mm and more)., Not only one can reduce the thickness of the frame of respecting windows and facades and thus reduce building load for façade construction, but also one can increase the used space, and the floor area of buildings could be increased and offers more value.
5.3 Long life time
VG is sealed with inorganic material, in our case with a glass frit. Besides, in the process of production, it has been strictly exhausted at high temperature. Under extreme environment like high temperature, low temperature, high humidity, ultraviolet light and so on, Vacuum Glazing will keep the good performance and the problems such as attenuation of vacuum degree, aging performance failure will not appear. There is a so-called patented getter used to keep high vacuum in spite of outgassing effects. The lifetime is predicted to more than 50 years by theoretical calculation, but also by tests. Actually, after nearly 3000 days (9 years) tests in actual environment outside and in Beijing, thermal conductivity of VG samples changed very small, no more than 5% maximum, nearly within failure range, as shown in Figure 4. For hybrid IG+VG-structure (=VIG), U value will not change much, even if IG-sealant of IG fails.

![Figure 4: The variation of thermal conductivity of Vacuum Glazing over 8 years](image)

5.4 Good performance of sound insulation
It can be seen from Table 4 that the sound insulation of VG is much better than for triple IG, Especially at middle and low frequencies. Better property of sound insulation grants us a comfortable life. We can improve the sound insulation property of VG by laminating or insulating. VIG Rw value can reach 39 dB to 42 dB. In fact the total effect is not only influenced by the glass, but also the frame, so SYNERGY has cooperated with well-known sound insulation windows companies and done lots of tests. Finally we got a good result of 42dB as shown for No. 7 in Figure 6. New partners are well come again.

5.5 Wide application
Vacuum Glazing could be used in any building in cold climates, because of its excellent thermal insulation property. But with adding in future solar control coatings and other means for shading and smart glasses, it can provide extreme
savings for hot and summer climates considering cooling energy. This is the next development sector.

### Table 4: Rw value of hybrid Vacuum Glazing

<table>
<thead>
<tr>
<th>NO.</th>
<th>Type</th>
<th>Structure</th>
<th>Testing Organization</th>
<th>Rw/dB</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Hybrid structure VIG</td>
<td>T5+V+T4+1.14PA+T5</td>
<td>Tsinghua</td>
<td>39</td>
</tr>
<tr>
<td>2</td>
<td>Hybrid structure VIG</td>
<td>N6+V+N4+0.38+N4+12A+N6</td>
<td>CABR</td>
<td>42</td>
</tr>
<tr>
<td>3</td>
<td>Hybrid structure VIG with 86PVC frame</td>
<td>T5+26A+T5+V+T4+1.14PA+T4</td>
<td>Greentec</td>
<td>40</td>
</tr>
<tr>
<td>4</td>
<td>Hybrid structure VIG with 86PVC frame</td>
<td>T8+26A+T5+V+T6</td>
<td>Greentec</td>
<td>40</td>
</tr>
<tr>
<td>5</td>
<td>Hybrid structure VG with 86PVC frame</td>
<td>T8+26A+T5+V+T6</td>
<td>CABR</td>
<td>40</td>
</tr>
<tr>
<td>6</td>
<td>Hybrid structure VG with 60 thermal broken frame</td>
<td>T6+12A+T5+V+T4+1.14PA+T5</td>
<td>Tsinghua</td>
<td>41</td>
</tr>
<tr>
<td>7</td>
<td>Hybrid structure VG with 86PVC frame</td>
<td>T6+25A+T5+V+T6+0.76 PVB+T4</td>
<td>Tsinghua</td>
<td>42</td>
</tr>
</tbody>
</table>

VG can be transported from low altitude area to high altitude area, because the vacuum layer could avoid cavity expanding and breakage - lacking any convection and gas expansion by atmospheric conditions - resulting with any altitude application and transport, lower stress and more safety. When one installs IG in building roofs and for overhead glazing, the gas convection and thus conduction would increase, but VG wouldn’t. Whereas for IG the U-value rises more than 30 % it remains constant for VG.

#### 5.6. High wind pressure resistance strength

In application, the most common pressure is wind pressure. VG has high strength under wind pressure. That is because the two panes of VG are connected rigidly by soldered glass. Non-deformability is better than single glass. For example, under the same wind pressure, the deformation and tensile stress in the center of VG with 10 mm thickness (5+5) is equal to a single glass of 8.5 mm thickness. A wider experience under different conditions shall be gained with several sample projects.

#### 5.7. Vacuum Glazing is a relatively young product. There seem to be some disadvantages

- There are support pillars in VG with size of 0.15-0.20 mm and a distance of 35-45 mm. Even, if they are very tiny, if you are very close to the glass, you can see the little dots. But normally people do not see them at all.
- The support pillars transfer heat and sound, whey they are called “heat bridge” and “sound bridge”. As stated above the good values are reached inclusive these effects. Without “heat bridge” and “sound bridge”, the heat insulation and sound insulation of VG would be even
better. There is a realistic chance, to increase the distance of such pillars in future and thus get an even better U- and sound-value.

- Because of the support pillars, when VG is impacted, there is stress concentration around the pillars which will cause that the impact strength of VG is somewhat reduced. That is why the pillars have to be set in smaller distance for annealed glass

5.8 Several issues about Vacuum Glazing

As a new product, VG has arose wide discussions, after some non-kept public announcements. We introduce several common concerned issues.

5.8.1 Vacuum Life time of VG

The life time of VG consists of two aspects, one is vacuum life, and the other is mechanical life. As introduced above, the process ensures the vacuum life. It should be noted that regular manufacturers have to check each piece of VG strictly, before it leaves factory, in order to prevent the inferior-product quality flowing into the market. Relevant departments must keep strict supervision on shoddy VG products, such as without high temperature exhaust - no getter - even fake getter; one has to completely eradicate these cases, to assure the VG public acceptance.

5.8.2 Mechanical Life Time

In order to increase mechanical lifetime, on one side we should design and produce VG products scientifically and strictly. It means that one needs the capability to manufacture heat strengthened and tempered VG to improve its mechanical strength. On the other hand, one shall use hybrid VIG like insulating or laminating combinations to improve its safety and performances. To what extend VG can be used for safety requirements should be carefully followed up.

5.9 Global Supply

Synergy basically offers license to interested partners of this technology. The actual supply problem only out of China, will be solved with the development of VG industrialization. The automatic production line of Synergy has entered into final debugging stage, once completed and launched, the design capacity will allow 500,000 m² per year. The factory is shown in Figure 5 and 6. The next generation of a medium sized capacity line of about 200,000 m² is in design, which is probably more suitable for initial producers. Synergy is willing to grant license and rights to interested parties. The Co-author of this paper, Helmut Hohenstein is the representative for international projects and any requirements, also for sample projects and technology exchange.

Please contact: helmut.hohenstein@hohenstein.biz

6. Cost reduction advantages

Cost is always an issue, VG has a much better performance compared with triple IG, but also higher price and investment is higher. The price of VG will decline by improving yield and capacity as well as using new materials and technology, but probably never to the same level. Besides this one has to consider the costs of windows and facades, which includes glass, frame, hardware and metal joint
connectors. Vacuum Glazing is light and thin, the frame could also be light and thin and metal joint connectors also could be less expensive, even more façade construction saving additional weight. There are more cost advantages considering the whole benefit for new designed houses with VG.

Figure 5: Office building and workshop of Synergy

Drying oven  Edge sealing oven
Material costs of VG might be lower than triple IG, but process costs has a potential for further improvement.

- Machines are mainly developed under quality aspects and considered less cost aspects.
- Cost reduction opportunities for the next development phase:
  - Window frames and/or facade construction
  - Much less or zero HVAC equipment, natural ventilation
  - Much less or zero Shading Devices
  - More space in rooms for sale
  - Reduced total building costs
- Savings:
  - Heat and cooling energy
  - Lowest CO₂ emissions

7. Applications in Practice - existing Projects

Application is the best way to test a certain product in practice. VG/VIG of Beijing Synergy has been used since 2005 in many buildings. Some of them are the “firsts” of domestic, even international market. For example, Beijing Sky Plaza is the first project of which all the glass units are VIG. And also it is the first time that

<table>
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<th>No.</th>
<th>Project Names</th>
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<td>Glass wall; Sunny roof</td>
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<td>2008</td>
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<td>Glass wall ( active building )</td>
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Exhibition Centre of Zhongguancun in Beijing

Great glory century building in Shandong

Zhengzhou Library, Henan
Sky Plaza building
Low energy consumption building
Tsinghua University
Figure 7: Beijing Synergy Vacuum Glazing Projects

large area glass curtain wall of VG is used in actual project. By now, Beijing Synergy has provided the most Vacuum Glazing units and actual projects all over the world. The main applications of Vacuum Glazing of Beijing Synergy are listed in Table 5 and shown in Figure 7.

8. Summary

In the extending and application area of “Green Buildings”, Vacuum Glazing has more general performance options than classic and any advanced Insulating Glass. Chinese Vacuum Glazing industry is on top of the world, the most patents, the highest industrialization level, and the most applications, which is worth of enough attention. We hope that the governmental bodies and the relevant authorities give more support on VG industrialization worldwide, as it contributes
dramatically to energy saving in hot and cold climates and also to environmental savings of carbon emissions and last but not least offers many advantages for comfort and building options.

After nearly 2 decades of no real innovation within the glass industry, Vacuum Glazing can offer all involved parties and the users a better benefit and at the same time better earnings in a wider application field, first in new generations of green buildings, but also in conventional sectors for direct exchange in refurbishment projects.

There is so much to do and so much to achieve. This industry should have a general concept to utilize Vacuum Glazing in order to satisfy the present architectural requirements and future expectations. The architecture and glass engineering world is asked to develop innovative solutions. In Germany there is a new movement towards so-called Active Plus Houses, where just recently an alliance with leading architects and institutes was founded. Also the government is focusing in future on it.

At the beginning, Vacuum Glazing will be introduced as an alternative to insulating glass for the high-end market or market that has higher demand and requirements for energy saving glass. However, as regulatory requirements on building energy conservation become more and more tight, and the limits of insulating glass become so obvious, it is not hard to imagine that Vacuum Glazing will be the ultimate choice to replace insulating glass together with given window and façade solutions and thus contribute in a high extend to a better performance for buildings and save a lot of costs at the same time. The discussions about window/wall-ratios can be stopped and all glass facades can be developed finally in a proper way for hot and humid climates with similar effectiveness than for cold climates.

Therefore, Vacuum Glazing with excellent thermal insulation performance, whether for new buildings or for the existing buildings, can bring great economic and social benefit.

Synergy eagerly looks forward to cooperate with others in the glass and building industry, in the energy conservation and environment protection industry of the world to encourage the individual application and utilization of Vacuum Glazing. Professor Tang and his company welcome those who are interested in co-operation to further develop VIG.

References:
Thermally Curved Glass
for the Building Envelope

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Skidmore, Owings & Merrill LLP
Joseph Chase
Skidmore, Owings & Merrill LLP

Abstract
Our paper discusses recent technological and practical advances in the use of thermally curved glass, a former niche product specified for an increasing number of large scale projects. At first glance, its use promises extraordinary freedom in generating modern sinuous building shapes, but there remains a series of limitations when it comes to its fabrication, use, performance, and economy. When specifying thermally curved glass, designers should understand how the manufacturing process limits geometry, size, coatings, optics, tolerances, and glass strengthening to ensure the best quality execution for the project.

Keywords: Curved Glass, Slumping, Online Bending, Glass Coatings, Chemical Strengthening

1 Introduction

Architecture’s current fascination with curvilinear forms creates a new demand for architecturally curved glass. Two basic approaches were developed to meet this demand: cold bent glass and thermally curved glass. Cold bent glass, takes advantage of glass’s inherent malleability. It relies on force and restraint to mechanically bend glass either in situ or in an autoclave during the lamination process. It requires careful coordination between the designer and manufacturer to ensure no panel exceeds the glass’s inherent stress limits. Thermally curved glass differs from cold formed glass in that it takes advantage of glass’s ability for reversible phase transitions. By introducing heat, glass benders can reverse the solid phase transition of float glass, creating a semi-liquid material that can be formed into almost any shape. This paper outlines the technical and aesthetic considerations of thermally curved glass.

Until recently, the complexity of manufacturing thermally curved glass precluded its use on large scale projects. New automated manufacturing technologies make thermally curved glass a more viable option by reducing the time and labor required to form the panels. However, depending on the requirements of the project, a manual process may still be the preferred option. In order to utilize both manual and automated glass bending technologies, the designer needs to understand the inherent limits to shape, strength, size, and surface treatments imposed by the different manufacturing processes.
Figure 1: Examples of Thermally Curved Glass
1. The Nordpark Rail Station by Zaha Hadid Architects
2. The Uptown Munich by Ingenhoven Architects
3. 8 Canada Square by Foster + Partners
4. Al Hamra Tower by Skidmore, Owings and Merrill
2 Glass Manufacturing

2.1 Overview

Today, most architectural glass is manufactured as float glass. The basic components of float glass include sand (72.6%), Soda Ash (13%), limestone (8.4%) and other minor additives. [10] The raw materials are heated in a furnace where they liquidize at 1600°C [2900°F]. The liquid then flows from the furnace to a bath of molten tin. The glass, which has greater buoyancy than the tin, floats to the top creating a perfectly flat sheet. The semi-solid sheet is then lifted onto rollers and passed through an annealing lehr where it slowly cools to its final solid state temperature. The glass emerges at room temperature from the lehr as annealed float glass. Thermally curved glass reverses the float process by reintroducing heat to the flat formed sheets. The curving process reheats the glass to a temperature of approximately 600°C [1100°F] where it regains its formable semi-liquid viscosity.

2.2 Slumping

The basic principles of bending glass have not changed since the 19th century when it was first used in exterior architectural applications. The traditional process, known as slumping, involves laying flat float glass over a mould which is then heated to between 550°C[1000°F] and 620°C [1150°F]. Once softened, the force of gravity pushes the glass over (and sometimes into) the mould below. Since the glass takes on the shape of the mould, slumping provides an enormous range of possibilities. Cylinders, cones, spheres, paraboloids, and hyperbolic paraboloids can all be formed through the slumping process.

The slumping process remains today largely a manual process. It typically requires individual custom moulds built by experienced artisans. The Nordpark Rail Station, as indicated in Figure 1, exemplifies the range of forms available in slumped glass. Designed by Zaha Hadid Architects, the project comprises 850 unique 12mm thick laminated glass panels. The architect worked with the manufacturer Pagitz Metalltechnik of Klagenfurt and the structural engineer Bollinger & Grohmann of Frankfurt to optimize the forms such that all the moulds could be fabricated using the latest CNC technology in tolerances up to +/- 3mm. [9] Nordpark’s bespoke approach will not be possible in all projects.

Increasing the number of moulds will increase both the overall cost and lead time. Large scale buildings will need greater standardization and performance. When utilizing thermally curved glass in architectural applications, heat treatments are often specified to provide strength and safety. Since both slumping and heat-treating introduce heat, they need to occur concurrently to prevent one process from undoing the other. Heat-treatments are typically unavailable with slumped glass because the custom nature of the mould prevents the use of standardized quenching equipment. If a design requires slumping, laminating and chemical-strengthening remain the only options to achieve added safety and strength.
Figure 2: Slumping requires costly moulds built by experienced artisans. The following image indicates a concave mould.

2.3 Online Bending

The economics of large scale high-rise towers impose a greater level of standardization on the design process than available with traditional slumping methods. Recent technological developments in automated glass bending make curved glass a viable more cost effective option if the design can accommodate the inherent constraints. The process, known as online bending, uses a robotic press to rapidly form and heat-treat glass within minutes along a production line. The online bender, as pictured in figure 5, consists of a furnace and a programmable press. The press, which is segmented into individual chords with integral quench jets, allows the manufacturer to specify the angle between each chord thus increasing or decreasing the overall radius of the glass sheets. Online bending overcomes the difficulties of heat-treating slumped glass discussed earlier by simultaneously forming and heat-treating the curved glass. The online bender includes integral quench jets located on each link of the programmable press. Figure 6 indicates the typical quench of an online bender.
Figure 3: Online Bending vs. Slumping

The image illustrates the different equipment used in online bending and slumping. The online bender is an automated process that bends glass within minutes whereas the slumping furnace requires time and labor.
Many architectural applications require heat treatments to strengthen the glass for size, durability and safety. Both tempering and heat-strengthening rely on the same equipment to heat the glass to approximately 650°C [1,200°F] and then rapidly cools the heated surface to increase surface and edge compression. Known as quenching, the cooling process cools the surface of the glass more quickly than the center. As the center cools it pulls back from the outer surface resulting in the center going into tension and the outer surface going into compression. Tempered glass is cooled the fastest, resulting in a compressive strength 4 to 5 times greater than annealed glass. Heat strengthening is cooled at a slower rate, which creates a compressive strength two times greater than annealed glass. Many codes and installers require the use of heat treated glass. When specifying curved glass, ensure that the approach accommodates all required strengthening requirements.

Numerous bending machines currently exist on the market. The machines are tooled to create either single axis or double axis curved sheets. However, the construction industry at this point only utilizes single axis machines. Double axis machines, like traditional slumping, still require individually built custom moulds. As a result, double axis bending machines remain a niche technology used primarily in the automotive and product design industry, where the cost of the mould can be offset by the economy of scale.

3 Technical Considerations
Designing with thermally curved glass requires a series of technical considerations. These considerations include constraints to size, shape, strength, and coating.

Figure 4: Shape Typologies

ASTM 1464 defines the above shapes to be manufactured in thermally curved glass: Online bending machines can produce all shapes except compound bends. Compound bend are for the most part still bend through traditional slumping. [1]

3.1 Shape

ASTM 1464 classifies bent glass into the following shapes: compound bends, cylindrical bends, elliptical bends, serpentine bends, multiple bends and single bends. Figure 7 illustrates common examples of each type. In all cases, the shapes are either single axis or double axis shapes. An online bender can form
most single axis shapes. If a design requires double axis shapes, the designer
should anticipate a slumping process. To avoid slumping, some geometries can
be rationalized and subdivided into small parts. If the parts can be optimizing into
cylinders, the design will ensure the economy necessary for large scale projects.
ASTM1464 and the German Bundesverband Flachglas Publication “Guidelines
for Thermally Curved Glass in the Building Industry.” specify a range of different
manufacturing tolerances for shapes illustrated in figure 7 above. The two
standards provide maximum tolerances for height, girth, shape accuracy,
maximum cross-bend deviation, and maximum twist deviation. In addition, the
Bundesverband Flachglas notes that single bends and multiple bends are prone
to inaccurate tangency. Any straight extension not tangent to a curve will appear
creased. Individual manufactures often also publish their own standard
specification. Be sure to ask the manufacture for all test results and tables
indicating the tolerances.

As an automated process, the online bending machine creates economy by
standardizing the mould into a programmable mechanized cylinder. When
designing a building that requires both economy and curvature, it is important to
consider the curve’s magnitude of scale. Often in large projects like airports or
high-rise towers, curvature can extend over large distances. What appears as
three dimensional curvature at the scale of the building may be optimizable into
cylinders at the scale of the units. In SOM’s on-going design for the Manhattan
West Towers, the building’s three-dimensional shape was optimized into simple
trapezoidal cylinders. The overall conical shape could by achieved with panel to
panel curvature of less than 1/256” out-of-tangency. (A figure, less than the
curtain wall manufacturing tolerance.) In addition, to accepting slight adjustments
to the unit geometry, the project mixes, cold-formed and thermally curved units to
reduce the over all cost by placing the curvature where it is visually needed.

3.2 Size

Manufacturers describe single axis curved glass according to the following
criteria: outer arc (girth), radius, rise, chord, angle, thickness, and length. Figure 8
describes the values as they appear in the Bundesverband Flachglas publication.
Any discussion of tolerance and size limitation will require an understanding of
the geometric language used to describe the glass. When considering slumping
or online bending it is important to note the different size limitations. Since online
bending moves along a production line, the size and radius of the glass will be
limited by the online bending machine. Typical online bending equipment
corresponds to standard glass sizes. Oversized and jumbo sizes, as a result,
ceed the capabilities of most machines. In the case of traditional slumping, the
furnace limits size. Jumbo sizes may be achievable by customizing the furnace
which can be a relatively simple task. Depending on the size and complexity of
the design, manufacturers may be willing to expand their typical capabilities.
Figure 5: Geometric Definitions

Single axis curved glass is defined by above dimensional criteria. ASTM 1464 and Bundesverband Flachglas publications differ slightly in the terms they use to define the shape. [4]

As mentioned in section 2.1, traditional slumping only allows for annealed glass. When designing large curved glass units the inability to heat-strengthen the glass may require greater glass thicknesses. The added thickness will help to strengthen the glass during installation and prevent breakage. However, thickness will not alleviate the tendency for annealed glass to crack under increased thermal loads. Known as thermal shock, monolithic or laminated annealed glass panels have a potential to crack in conditions with differential temperatures across the glass's surface. Polished glass edges will help reduce the thermal shock phenomena, but glass manufactures should always be consulted in this regards. Furthermore annealed glass cannot be used in shadow box conditions where ventilation will not alleviate heat build-up. Any design needs to consider location, climate, coatings and edge treatment before pursuing a laminated annealed approach.
3.3 Strength

Architects and designers typically use thermally curved glass for aesthetic reasons. However, the bending process creates a shell like form more resistant to bending moment. Figure 9, indicates both the deflections and stresses inherent within a 3350mm x 1920mm [6'-4” x 11'-0”] curved insulated glass unit. The diagram shows overall glass deflection and stress under typical wind loading. Compared to flat glass, curved glass deflects less. With smaller deflections, curved panels ensure surface smoothness with thinner glass make-ups.

The inherent strength of curved geometries suggests using glass in shell structure applications. By forming glass into a catenary shape, the designer will maximize the glass’s strength. The shell structure, taking advantage of glass’s excellent compressive strength, evenly distributes the directional loads entirely as compressive forces across the surface. Further research in catenary glass structures will continue to expand the use of glass in structural applications.

3.4 Coatings

Most exterior architectural applications today require low-e coatings to comply with local energy codes and high performance design initiatives. Glass coatings, however, create an added level of complexity to thermally curved glass. The design must consider the type of coating (soft or hard), coating thickness (single, double or triple silver), radius, and concave vs. convex application. [7]

Glass coatings can be classified as either "soft" sputter coats, or "hard" pyrolytic coats. Sputter coated glass, which is manufactured after the float process, is more commonly used today because they offer more neutral colors and greater energy performance. As a more sensitivity material, sputter coats are more prone to damage, requiring special handling. As a result, sputter coated glass will require greater consideration in the bending process.

When using a sputter coating, consider the location of the concave face. All sputter coats must be placed on the compressive concave face away from the rollers. As shown in figure 10, all insulated glass units comprise both concave and convex lites which limits the available coating locations. If an IGU is convex from the exterior, the number 2 surface will be concave during online manufacturing and can therefore accept the sputter coating. Likewise, a concave IGU would preclude the low-e coating on the number 2 surface but would accept the coating on the number 3 surface.

In addition to soft coating, Pyrolytic coating can be specified for thermally curved glass. Glass manufactures apply Pyrolytic coatings during the float glass production process. The chemical coating bonds to the glass in a semi-molten state. As a result, Pyrolytic coatings provide greater durability, giving the glass greater flexibility in locating the low-e coating. It is important to note that Pyrolytic glass will not perform like soft coats and will most likely not meet the High Performance Design initiatives at Skidmore, Owings and Merrill.
Figure 6: Structural Evaluation

The image indicates the deflection and stresses of a 3350mm x 1920mm (6'-4" x 11'-0") glass unit curved with a 4000mm (13'-0") radius in inward and outward pressures. The insulated glass unit was made from 6mm+6mm laminated annealed lites separated by a 12mm spacer. [5]
When designing a curved glass panel with a low-e coating it is highly recommended to conduct a full scale mock up prior to finalizing the glass specification. The glass should feature all the desired characteristics of the glass later to be specified, e.g. coatings, laminations, frits, strength treatments, spacers etc. This mock-up will protect the design team and the owner from unwelcome surprises later in the design or construction process and will ensure the suitability of the coating for the intended use.

In today’s construction industry with globally sourced products it is also important to note that glass substrates and coatings vary at times from country to country even though they are manufactured by the same company and marketed under the same name.

![Coating Location](image)

**Figure 7: Coating Location**

All insulated glass units are comprised of concave and convex lites. Glass bender as well as coating manufacturer should be consulted with early on in the design process to ensure desired coating locations care achievable.

## 4 AESTHETIC CONSIDERATIONS

When considering the use of thermally curved glass, the designer must consider certain aesthetic traits fundamental to the final product. Considerations include: Amplified quench marks, mirror distortion and light reflection and amplification.
Figure 8: Quench Marks on Heat Treated Glass

The image indicated the vertical striations in heat treated glass. These striations are more apparent with curved glass.

4.1 Amplified Quench Marks

All heat-treated glass contains quench marks. As previously described, heat-treated glass strengthens glass by inducing higher surface compression through the rapid cooling of heated float glass. The jet nozzles that heat-treat the glass do not uniformly compress the surface. Instead, the highest compression occurs directly opposite the air quench. The high compression areas exhibit a darker appearance under some viewing conditions. ASTM C1048-04 defines the strain pattern as: "In heat strengthened and fully tempered glass, a strain pattern, which is not normally visible, may become visible under certain lighting conditions. It is a characteristic of these kinds of glass and should not be mistaken as discoloration or non-uniform tint or color." [3] Such a definition indicates that quench marks should not be considered a defect since they cannot be removed from the heat-treating process.

Thermally curved glass accentuates the inherent quench marks of heat-treated glass. The curved surface creates multiple view angles catching different angles of light across the glass. The resultant play of light on the surface amplifies the appearance of stain marks.
Figure 9: Online Bending Press

The image indicates the integral quench jet built into the forming surface of the bender. The online bender both forms and heat treats the final product in a single process.

4.2 Mirror Distortions

All curved glass reflects light. As a smooth material, glass exhibits specular reflection because all light rays reflect off of the surface in a single outgoing direction such that the angle of the outgoing ray equals the angle of the incoming ray. In the case of concave and convex glass, the geometry creates a focal point which either converges (concave) or diverges (convex) the light reflecting off the surface. Convex glass diminishes the reflected objects as they move away from the surface making the reflected object seem small. Concave glass reflects different image types depending on the distance between the object and the mirror. The resultant fun-house effect will be integral to the design aesthetic. In addition, the converging geometry of concave glass tends to collect light focusing the reflection and its corresponding energy onto a single point. The tendency for light to converge makes concave shapes a potential hazard in architectural applications.
Figure 10: Girl's Make-up Room, Dan Graham

The work of the artist Dan Graham makes use of the mirror distortions of shaped glass to address issues of perception.

4.3 Spacer Color
All insulated glass units are held together by a spacer and a primary and secondary seal. In flat glass IGUs, the spacer is typically of a rigid make-up, while in curved glass units it is common to use a structural foam soft spacer. Although foam spacers may be offered in varying colors it is advisable to verify that primary and secondary seals also are available in the desired color. As of today, we are only aware of black seals, which may not be preferred particularly in structural silicone applications.

4.4 Ceramic Frit
The use of frits can be challenging with curved glass and has to be verified at the beginning of the design process. This is particular important when the frit contributes to the desired building energy performance. When available, the frit is typically applied prior to the bending process and fired on in the furnace. When slumped, the glass subsequently gets re-annealed.
Recommended Reading


References

Rotational stiffness of linear adhesive connections between cold-formed steel members and glass panels

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Abstract
In façade engineering frame-supported glass structures usually consist of glass plates mounted onto a framework of metallic elements. As the shear transfer capacity at the interface of glass and metal is often rather limited, these units are structurally not fully efficient. To obtain a structural glass unit, a cold-formed steel (CFS) frame is stabilised by glass panels which are adhesively bonded to the individual CFS members. As such, the joint-glass system restrains the CFS members vertically and horizontally. However, also a rotational restraint is introduced. In this research, the rotational stiffness of linear adhesive connections of cold-formed steel C-sections and monolithic glass panels is determined by means of experimental testing and numerical modelling. A conventional structural silicone is considered for these load-bearing CFS-glass connections. This paper reports about the experimentally obtained data by means of so-called Peköz-tests, which are compared to results obtained from a numerical model. Subsequently, the latter is also used to investigate the influence of different parameters on the translational and rotational stiffness of the adhesive CFS-glass connections. The experimentally determined rotational constraint for the adhesive CFS-glass connection considered in this paper was higher than the rotational constraint for a comparable traditional screwed CFS-OSB or CFS-gypsum connection. Therefore the study revealed the potential of this connection to provide a sufficient rotational stiffness of a cold-formed steel frame braced with circumferentially adhesive bonded glass panels.

Keywords: cold-formed steel, glass panel, rotational restraint, linear adhesive connection, adhesives

1 Introduction
In the building industry, the largest area of use of cold-formed steel (CFS) is in conventional steel structures as secondary load-bearing elements (e.g. sheeting, purlins, etc.) on a steel or (reinforced) concrete primary structure. However, CFS elements are also more and more used in residential housing as primary load-bearing structure as there are several structural, economic and environmental
advantages, such as a high strength-to-weight ratio, good serviceability performance, and recyclability or reusability. Also in commercial and office buildings cold-formed steel is nowadays used for members of a frame onto which structural sheeting (e.g. oriented strand board (OSB), plywood, etc.) is screwed. By doing so, load-bearing walls are created which are acting as primary lateral load-resisting components to maintain stability and integrity of the structural system or the (whole) structure.

The construction concept of these so-called shear wall panels consists of studs, spaced at 300 mm to 600 mm, which are fastened to tracks at their ends. The studs are the gravitational load-bearing members, while the tracks function as lateral support for the studs, simultaneously distributing the loads among them. The ability of shear wall panels to resist lateral in-plane forces can be achieved by applying one- or two-sided structural sheeting, screwed onto the frame. Although cold-formed steel members were already used for the construction of buildings in the 1850’s in the United States and England, the research on the stabilising properties of sheeting only began in the 1940’s [1]. Since then, a lot of studies were conducted on the influence of the structural sheeting, the framing, the fasteners, the wall properties, the type of loading and construction techniques and anchorage details, on the behaviour of cold-formed steel shear wall panels [2] – [8]. The axial and bending behaviour of cold-formed steel members braced with structural sheeting was thoroughly investigated at Johns Hopkins University [9] – [12]. This research led to an analytical characterisation of the stiffness of sheeting-bracing, proposals for testing components or full-scale elements, and a proposal for a new design method [13].

Despite the rather unique structural performance of cold-formed steel structures, the transparency is rather limited due to the closed spaced vertically aligned studs creating only small openings. As there exists a tendency of creating more transparency in contemporary architecture by creating large glazing areas, the possibility of cold-formed steel frames sheeted with circumferentially adhesively bonded glass panels is investigated. The use of glass panels as structural bracing element cannot only improve aesthetical performance, but also the structural and material efficiency as the load-bearing potential of glass is utilised. To obtain a good structural performance of the hybrid CFS-glass shear wall panel, it is important that the development of the adhesive connection between the materials is done carefully as this joint glass system introduces a translational and rotational restraint of the cold-formed steel members.

Different researchers studied the load-bearing potential and behaviour of glass panels subjected to in-plane compression (e.g. self-weight), in-plane shear and the combination of in-plane shear and out-of-plane distributed loads (e.g. wind load). Linear adhesive connections on two sides of a glass panel was studied in [14]. Circumferentially adhesive bonded glass panes in a steel frame was studied in [15] – [16]. Other load transfer systems, such as blocks made of grout [15], thermoplastics near the corners [17] or prestressing an elastomer over the whole circumference [18] were also studied. Composite behaviour between the glass panel and the steel frame was not observed. However, the load-bearing capacity of the glazing was activated and the results demonstrated the large potential of the use of glass panels as structural elements.
As there is a wide variety of industrial adhesives currently available on the market, a proper selection for the considered application can be difficult, in particular because each adhesive product has specific advantages and disadvantages. For the application considered in this paper, the adhesive has to ensure a durable and reliable transfer of the occurring loads on the one hand and has to absorb constraining forces on the other. Based on former research on the selection of durable adhesives to bond glass to metal [19], the structural silicone Sikasil SG-500 was selected as suitable adhesive for a structural efficient frame-supported glass structure.

The aim of this research is to determine the rotational stiffness of linear adhesive connections of cold-formed steel C-sections and monolithic glass panels by means of experimental testing and numerical modelling using Abaqus®. Experimental data is obtained by conducting so-called Peköz-tests, which allows to determine the lateral stiffness of the connection from which the rotational restraint can be calculated. The influence of the section thickness, the adhesive thickness, the glass sheet thickness, the type of section and the load direction is studied using a numerical model. The experimental results are compared with both the results obtained from the numerical model, and with the results of experimental research on traditional screwed CFS-sheeting connections.

2 Experimental research

2.1 Determination of the rotational restraint for purlin-sheeting systems according to EC3

A specific standard to determine the rotational restraint of an adhesive CFS-glass hybrid system is not available. However, in CFS it is common to determine the rotational restraint of a purlin-sheeting system by means of a so-called Peköz-test, described in Eurocode 3 [20]. Consequently, it seems natural to use the Peköz-test also for the determination of the rotational restraint in a glass-CFS configuration. Therefore, this test will be briefly explained in this section. A principle test setup according to Eurocode 3 is depicted in Fig. 1.

![Figure 1. Experimental test setup recommended in Eurocode 3 for the determination of the rotational restraint (alternative b) [20]](image-url)
In such a conventional system with a thin-walled metal sheeting, a CFS purlin is symmetrically fastened to the former with screws. On the free flange of the purlin, a load is applied which is transformed to nearly a line load by using a framework. The displacement at the junction of the web and free flange of the purlin is measured by means of a linear variable differential transformer (LVDT), which is installed mid-span of the cold-formed steel member. The relationship between the displacement \( v \) of the free flange and the applied load \( F \) is determined, a linear approximation to the \( F-v \)-curve is made and the slope of that line is defined as the lateral spring stiffness \( K \) (N/mm/mm). The total lateral spring stiffness \( K \) per unit length can be determined from:

\[
\frac{1}{K} = \frac{1}{K_A} + \frac{1}{K_B} + \frac{1}{K_C} = \frac{v}{F} \tag{1}
\]

in which

- \( K_A \): the lateral stiffness corresponding to the connection between the sheeting and the purlin
- \( K_B \): the lateral stiffness due to distortion of the cross-section of the purlin
- \( K_C \): the lateral stiffness due to the flexural stiffness of the sheeting
- \( v \): the lateral deflection measured at the free flange of the purlin
- \( F \): the lateral force applied at the free flange of the purlin per unit length

As the flexural stiffness of the sheeting is normally very large, the term \( 1/K_C \) is neglected and the total lateral stiffness \( K \) can be simplified as follows:

\[
\frac{1}{K} = \frac{1}{K_A} + \frac{1}{K_B} + \frac{1}{K_C} = \frac{v}{F} \tag{2}
\]

The total rotational restraint \( C_D \) provided by the sheeting to the purlin consists of the contribution of the sheeting and purlin connection \( C_{D,A} \) and the contribution of the flexural stiffness of the sheeting \( C_{D,C} \). \( C_D \) can be determined from:

\[
C_D = \frac{1}{\frac{1}{C_{D,A}} + \frac{1}{C_{D,C}}} \tag{3}
\]
A relationship between the lateral stiffness \( K \) and the rotational restraint \( C_D \) is adopted in Eurocode 3. Hence, from the Peköz-test the total lateral stiffness \( K \) is determined and subsequently, the total rotational restraint \( C_D \) per unit length of cold-formed steel member (Nmm/mm/rad) is calculated from:

\[
C_D = \frac{h^2}{K \cdot \frac{1}{4} \cdot (1-\nu^2) \cdot \frac{h^2}{E_t^3} \cdot \left( h_d + b_{\text{mod}} \right)}
\]  

where

- \( b_{\text{mod}} \) = \( a \) in case the purlin comes into contact with the sheeting at the web of the purlin
  = \( 2a + b \) in case the purlin comes into contact with the sheeting at the edge stiffener of the purlin flange
- \( h \) the overall height of the web of the purlin
- \( h_d \) the developed height of the web of the purlin
- \( a \) the distance between the screw fastener and the purlin web
- \( b \) the width of the top flange of the purlin

### 2.2 Test specimens

Three specimens (Fig. 2) were assembled using a 1200 mm by 750 mm monolithic annealed float glass sheet with a nominal thickness of 12 mm to which a cold-formed steel C-member was adhesively bonded along the median. The C100x2 section was characterised by a web height equal to 100 mm, a flange width of 50 mm, a lip length of 12 mm and a thickness equal to 2 mm. The quality of the steel was S390+Z275, hence the section was galvanised using 275 kg of zinc per square meter. Sikasil® SG-500, a two-component high performance structural silicone, was applied to bond one flange of the section to the glass, while the other flange remained free. Before the production of the samples the bonding surface of the steel was thoroughly cleaned with Sika® Cleaner P and then primed with Sika® 205. The surface of the glass was cleaned with acetone. 6 mm thick aluminium strips wrapped in a PE-foil were placed between both ends of the C-section and the glass panel to create a 6 mm thick cavity which was to be filled with adhesive. A 6 mm flexible packing was applied at the back of the section, near the web, to create a one-sided open cavity which was later filled with the structural silicone using an automated adhesive dispensing gun. The assembled specimens were cured and stored at ambient temperature and relative humidity for 7 days before testing.
2.3 Test setup

The rotational restraint of the considered hybrid CFS-glass system was estimated by using a test setup depicted in Fig. 3. This test setup was in accordance with the guidelines given in Eurocode 3 to estimate the rotational restraint of purlin-sheeting systems. The test specimens were assembled in a rigid framework that was composed of two vertical HEA240 columns and two horizontal UPN 100 beams. Columns and beams were connected with two M10 bolts on each end. On both beams custom-made clamps were welded to immobilise the specimens.
during testing. At the back of the glass panels, a LVDT recorded the horizontal displacements of the sheet.

Each of the three CFS-glass hybrid systems were non-destructively tested once with a gravity load and once with uplift (Fig. 3.). The force was applied by means of a loading system with a turnbuckle. At 8 points of the free flange of the C-member this force was introduced, simulating a fairly uniformly distributed load rotating the C-section. Perpendicular to the panel, the displacement of the line of action of the load was permitted by a sliding system in order to ensure the verticality of the load during the entire test. At mid-span of the cold-formed steel member and near the middle of the free flange, a little hole in the section received a small bar that was bolted to the vertical displacement recorder. During the test, this bar remained horizontal, hence registration of the vertical movement of this bars yielded the vertical displacement of the free flange of the C-section, which was the main interest in this test.

Figure 3. Experimental setup with the position of the displacement measuring instruments and load direction (gravitational (a) and uplift (b))

During the test, the load was gradually increased and the corresponding displacements were measured (Fig. 4). Both the displacement and the load were digitally recorded every 0.1 seconds. When the deflections at the flange-web junction of the section reached a value of about 10% of the web height of the section (= 100 mm / 10 = 10 mm), the system was unloaded. No failure of the glass panel, adhesive or C-section was recorded as the system was unloaded before stresses could reach critical levels.
Figure 4. Displacement of the C-section in case of an increasing gravitational load (0 mm, 3.1 mm, 6.8 mm and 10 mm)

2.4 Results

The interpretation and presentation of the results are in conformity with Eurocode 3. The symbols used are $F$, the force registered with the dynamometer per unit of length of the section ($= 1000$ mm) which does not include the self-weight of the section, and $v$, the vertical displacement of the free flange, of which the measurement was started after the section and the loading system had been installed. Consequently $v$ does not include the displacement due to self-weight.

The load $F$ corresponding to a displacement $v$ of 10 mm ($= \text{height of section} / 10$) could be determined using the $F$-$v$ graphs (Fig. 5). To find this load, only the part of the graph up to $v = 10$ mm was used. Next, the straight line which fitted the results in the interval $v = 0 – 10$ mm best, was determined. The theoretic relation between the force and the displacement was then used to determine the value of the load $F$, corresponding to the displacement $v$ equal to 10 mm. In analogy to the traditional Peköz-test, the lateral spring stiffness $K$ (Eq. (1)) was determined. From Eq. (4), $C_D$ could be calculated with the developed height $h_d$ equal to the height of the C-section ($= 100$ mm) and $b_{mod}$ equal to half the width of the C-section ($= 50$ mm / 2 = 25 mm).
Table 1 contains the values of the rotational restraint $C_D$ per unit length of the cold-formed steel section in case of a gravitational load and in case of uplift for the three specimens. When considering a gravitational load, the mean force where the specimens showed a displacement of 10 mm was $2197 \pm 8$ N/mm. This resulted in a mean rotational restraint of $5453 \pm 46$ Nmm/mm/rad. In case of uplift the mean rotational restraint of the specimens was $7233 \pm 111$ Nmm/mm/rad, which was 24.6% higher than in case of a gravitational load, whilst the average load was only 10.1% higher ($2443 \pm 46$ N/mm).

Table 1. Total lateral stiffness $K$ and total rotational restraint $C_D$ of the three tested specimens in case of uplift and gravitational loading

<table>
<thead>
<tr>
<th>Gravitational</th>
<th>$F_{v=10mm}$ (N)</th>
<th>$1/K$ (mm²/N)</th>
<th>$K$ (N/mm²)</th>
<th>$C_D$ (Nmm/mm/rad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>2197</td>
<td>4.551</td>
<td>0.220</td>
<td>5428</td>
</tr>
<tr>
<td>S2</td>
<td>2210</td>
<td>4.524</td>
<td>0.221</td>
<td>5506</td>
</tr>
<tr>
<td>S3</td>
<td>2197</td>
<td>4.552</td>
<td>0.220</td>
<td>5425</td>
</tr>
<tr>
<td>$\mu$</td>
<td>2202</td>
<td>4.542</td>
<td>0.220</td>
<td>5453</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>8</td>
<td>0.016</td>
<td>0.001</td>
<td>46</td>
</tr>
<tr>
<td>Uplift</td>
<td>$F_{(v=10\text{mm})}$ (N)</td>
<td>$1/K$ (mm²/N)</td>
<td>K (N/mm²)</td>
<td>$C_0$ (Nmm/mm/rad)</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------</td>
<td>--------------</td>
<td>----------</td>
<td>-----------------</td>
</tr>
<tr>
<td>S1</td>
<td>2494</td>
<td>4.010</td>
<td>0.249</td>
<td>7685</td>
</tr>
<tr>
<td>S2</td>
<td>2433</td>
<td>4.111</td>
<td>0.243</td>
<td>7131</td>
</tr>
<tr>
<td>S3</td>
<td>2403</td>
<td>4.161</td>
<td>0.240</td>
<td>6882</td>
</tr>
<tr>
<td>μ</td>
<td>2443</td>
<td>4.094</td>
<td>0.244</td>
<td>7233</td>
</tr>
<tr>
<td>σ</td>
<td>46</td>
<td>0.077</td>
<td>0.005</td>
<td>411</td>
</tr>
</tbody>
</table>

3 Numerical research

3.1 Finite element model

The finite element analysis software Abaqus® was used to develop a three-dimensional numerical model of a commercially available cold-formed steel C-section which is linear adhesively bonded to a glass panel with the structural silicone Sikasil SG-500 (Fig. 6) and subjected to gravitational load or uplift. The basic model represented a Pekőz-test on a specimen as described in Section 2.2.

A linear elastic material model was adopted for the cold-formed steel C-section. Young's modulus and Poisson's ratio were assumed as 210 GPa and 0.3, respectively. Also the glass was assumed to behave linear elastically with Young's modulus equal to 70 GPa and Poisson's ratio equal to 0.23. For the adhesive, hyperelastic material properties were modelled with the Neo-Hooke material law of which the coefficients were determined based on uniaxial and planar test data provided by the manufacturer.

The monolithic glass sheet was modelled as a three-dimensional shell consisting out of four-node three-dimensional quadrilateral shell elements with six degrees-of-freedom at each node (S4R). Also the cold-formed steel member was modelled using these elements. The structural silicone Sikasil SG-500 was modelled as a three dimensional solid with eight-node hybrid linear brick with constant pressure elements (C3D8H).
The cold-formed steel member was subjected to an increasing uniformly distributed load and the corresponding vertical displacements of the free flange were recorded. Based on the relationship between this force and the displacement, the rotational restraint was determined in a similar way as described in Section 2.4.

Using this model, the influence of the section thickness, the adhesive thickness, the glass sheet thickness, the type of C-section and the load direction was studied.

Cold-formed steel C-sections are commercially available in all kind of dimensions, although most manufacturers can produce custom-made sections. In this study, a specific product range of different types of C-sections with different web heights, flange widths and thicknesses, was implemented in the finite element software. Glass thickness as parameter varied according to commercially available nominal thicknesses.

3.2 Results

3.2.1 Comparison between experimental and numerical results

When comparing the results of a numerical simulation in Abaqus® of the identical configuration as used in the experiments, good agreement was obtained (Fig. 7). In case of a gravitational load the difference between the experimentally determined mean load and the numerically determined load corresponding to a displacement of 10 mm was 2.6 %. However, this error resulted in difference of 6.1 % for the rotational stiffness. When considering uplift, the errors were respectively 3.2 % and 8.9 %. Importantly, the numerical model underestimated the rotational stiffness of the linear adhesive CFS-glass connection.
3.2.2 Influence of C-section thickness

Analyses of the numerical model with varying thickness of the section (1, 1.25, 1.5, 1.75, 2, 2.5 mm) showed an increase in total translational stiffness $K$ if the section thickness increased. Taking into account the expression for $C_D$ (Eq. (4)), this increase of translational stiffness resulted in an increase of the rotational restraint (Fig. 8). However, the magnitude of the increase decreased with increasing thickness.

![Figure 8. Rotational restraint in function of the C-section thickness](image)
3.2.3 Influence of adhesive thickness
An increase of the adhesive thickness from 2 to 10 mm, with an increment of 2 mm, resulted in a decrease of the translational stiffness $K$ from 0.300 N/mm² to 0.111 N/mm² and a decrease of the corresponding rotational restraint of the connection from 16022 Nmm/mm/rad to 1595 Nmm/mm/rad (Fig. 9). The magnitude of the decrease in stiffness between two consecutive thicknesses decreased with increasing thickness.

![Rotational restraint in function of adhesive thickness](image)

**Figure 9.** Rotational restraint in function of adhesive thickness

3.2.4 Influence of glass thickness
If only the glass thickness varied as parameter (4, 5, 6, 8, 10, 12, 15, 25 in the model of the hybrid CFS-glass system, an increase of the total translational stiffness $K$ and the rotational restraint $C_D$ with an increase of this glass thickness was observed (Fig. 10.). However, the difference in stiffnesses did not vary much between a glass thickness of 8 and 25 mm. The influence of this parameter on the rotational restraint was less than the influence of the C-section thickness and certainly the adhesive thickness.

3.2.5 Influence of type of C-section
Generally, both translational and rotational stiffness increased with increasing flange width, because of an increased width of the adhesive joint (compare C80x2, C100x2 and C170x2 in Fig. 11). The influence of the web height was less profound (comparison between C100x2 and C150x2 in Fig. 11). An increase in rotational restraint was detected, although the difference was only 6.5% in case of a gravitational load.

3.2.6 Influence of the load direction
The rotational restraint of the linear adhesive CFS-glass connection is higher in case of uplift than in case of a gravitational load (Fig. 11). The difference in
magnitude increased for an increasing width of the adhesive joint. Considering a C80x2 section, the difference in rotational restraint between uplift and gravitational load was 7.3 %, while in case of a C170x2 section this difference reached a value of 43.6 %.

**Figure 10.** Rotational restraint in function of glass thickness

**Figure 11.** Rotational restraint for different types of C-sections in case of uplift or a gravitational load (C80x2 = web height of 80 mm and section thickness of 2 mm)
4 Comparison with conventional CFS-sheeting

The experimental determined mean rotational restraints of the considered CFS-glass connection was 5453±46 Nmm/mm/rad in case of a gravitational load and 7233±411 Nmm/mm/rad in case of uplift. To allow a better understanding of these values, a comparison is made with values available in literature for comparable CFS sections attached to more conventional sheeting materials, such as OSB or gypsum board.

For instance, in a study by Schafer et al. on braced cold-formed steel studs, a value of the rotational restraint of a screwed CFS-OSB and a screwed CFS-gypsum connection was determined [9]. In detail (Table 2), a cold-formed steel C-section with a web height of 92 mm, a flange width of 41 mm, a thickness of 1.73 mm and a length of 2.4 m was screwed every 305 mm to a 11.1 mm thick OSB-sheet with #6 screws (with diameter 0.138” or 3.5 mm). An identical section was identically screwed with #8 screws (with diameter 0.164” or 4.2 mm) to a 12.7 mm thick gypsum sheet. For a gravitational load, a rotational restraint of 313 Nmm/mm/rad was determined in case of OSB, whereas for gypsum this value was 315 Nmm/mm/rad. Hence, the linear adhesive CFS-glass connection considered in this paper has great potential to provide a sufficient rotational stiffness of a cold-formed steel frame braced with glass panels. Important to notice is that the C-sections used by Schafer et al. [9] do not completely match the C-sections used in this study. Furthermore, experimental tests by Van Impe et al. [21] demonstrated that it is possible to obtain a significant rotational stiffness with conventional CFS-sheeting connections as well (Table 2).

Table 2. Comparison between a linear adhesive CFS-glass connection and a conventional screwed CFS-OSB and CFS-gypsum connection (hw = web height, bf = flange width, t = thickness, s = spacing)

<table>
<thead>
<tr>
<th>CFS section</th>
<th>Schafer et al. [9]</th>
<th>Van Impe et al. [21]</th>
</tr>
</thead>
<tbody>
<tr>
<td>hw (mm)</td>
<td>92</td>
<td>200</td>
</tr>
<tr>
<td>bf (mm)</td>
<td>41</td>
<td>80</td>
</tr>
<tr>
<td>t (mm)</td>
<td>1.73</td>
<td>2</td>
</tr>
<tr>
<td>Sheetin</td>
<td>type t (mm)</td>
<td></td>
</tr>
<tr>
<td>OSB</td>
<td>11.1</td>
<td>OSB</td>
</tr>
<tr>
<td>gypsum</td>
<td>12.7</td>
<td>glass</td>
</tr>
<tr>
<td>Connection</td>
<td>type S (mm)</td>
<td></td>
</tr>
<tr>
<td>#6 screws</td>
<td>305</td>
<td>4 self-drilling</td>
</tr>
<tr>
<td>#8 screws</td>
<td>305</td>
<td>screws</td>
</tr>
<tr>
<td>500-100-500</td>
<td>Sikasil SG-500</td>
<td></td>
</tr>
<tr>
<td>Cd (Nmm/mm/rad)</td>
<td>313</td>
<td>3019</td>
</tr>
<tr>
<td></td>
<td>315</td>
<td>5453</td>
</tr>
</tbody>
</table>
As the rotational restraint of the screwed and adhesive CFS-glass connection is influenced by a number of factors, it could be possible to create an equally stiff connection. An increase of the section thickness, for example, results in a higher resistance against distortion of the cold-formed steel section, hence an increase in the translational stiffness $K_B$, and therefore the total translational stiffness, can be expected.

As glass thickness, or more generally sheeting thickness, increases, also the flexural stiffness of the panel increases, hence the lateral stiffness due to the flexural stiffness of the sheeting $K_C$ increases. Thus, an increase in rotational restraint is expected. When the sheeting reaches a certain thickness, the influence of $K_C$ becomes negligible and therefore a further increase in thickness will have no effect, which is represented by the plateau in Fig. 10. It is also possible to change the translational and rotational stiffness of the linear adhesive CFS-glass connection by adapting the thickness or the width of the adhesive joint. Analogously, the stiffness of the screwed CFS-OSB or CFS-gypsum connection is influenced by the types of screws and screw spacing [13].

An important remark about the conducted tests to determine the rotational restraint of the linear adhesive CFS-glass connection has to be made. This rotational restraint is determined based on a linear approximation of the load-displacement relationship in the range $0 - h/10$ for the displacements. When considering a linear adhesive CFS-glass connection, it might be possible, because of the hyperelastic properties of the adhesive for example, that no linear relationship between the applied load and the corresponding displacement for the considered range of displacements exists. In this study, however, this kind of behaviour was not observed, hence the determined values for the rotational restraint of the connection are valid. When this behaviour is observed, a possible solution to this problem is either narrowing down the range of displacements to determine the rotational restraint or defining two different restraints, which might be more appropriate. All the same, further research on this type of connections will give more insight in the matter.

5 Conclusions

The experimental study on the cold-formed steel-glass connections considered in this paper demonstrates the potential to provide significant rotational restraint for CFS frames braced with glass panels which are circumferentially adhesively bonded. However, every configuration has to be studied individually as the numerical study shows the influence of section thickness, adhesive thickness, glass thickness, type of section and load direction on the value of the rotational restraint. An increase of section thickness, glass thickness and adhesive width leads to an increase in translational and rotational stiffness, whereas an increase of the adhesive thickness leads to a decrease of these stiffnesses. The influence of the web height on the stiffness is rather limited. The rotational restraint of the linear adhesive cold-formed steel-glass connection is higher in case of uplift. The developed numerical model yields good agreement with the tests and slightly underestimates the stiffness of the connection.
The study presented in this paper forms the basis for future work where more and improved experimental tests will be conducted with other types of adhesives and where the numerical model will be improved and extended.

Acknowledgements

The authors would like to acknowledge the support and help of Henk De Bleecker, Dieter Callewaert and Jerrelee Wener of Permachelisa group, with the production of the samples at Scheldebo. Also the support of the company Sadef nv who donated the cold-formed steel C-sections is gratefully acknowledged.

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Performance Testing of Glazed Cavities to Prevent Condensation and Eventual Glass Corrosion

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Abstract
Architectural designs increasingly are utilizing glass cladding assemblies where regular cleaning and maintenance of the interior surface of the glass is difficult if not impossible without disassembly of the cladding system. Glass shadow boxes, multiple layers of vision glass within double wall assemblies, or transparent and translucent rainscreen applications are a few examples. These designs are susceptible to premature degradation of their appearance when water condenses on the inaccessible surfaces, increasing the accumulation of dust and other air contaminants, and if allowed to persist, causing unrepairable glass corrosion. As such, it is critical during system design to consider the behavior of vapor within the system to prevent condensation on inaccessible glass surfaces, and to confirm system performance during execution. Accordingly, a test method that can be employed during performance mockup testing on a wide range of cladding system types has been developed to confirm vapor equalization rates are sufficient so as to prevent condensation on the critical surfaces of the system.

Keywords: glass facades, condensation, glass corrosion, shadowbox, performance testing

1 Introduction
1.1 Historical Overview of Glass Cladding
With the development of float glass production in the 1950’s by Sir Alastair Pilkington and its subsequent commercialization in 1959, architects gained a high quality cost-effective material that allowed the use of glass beyond its historic utility as an isolated window in a larger masonry or infill façade [1]. Combined with advances in aluminum fabrication, glass could thereafter be reasonably specified for floor to ceiling walls of vision glass. The logical continuation was the realization of the all glass building, where glass would be employed as a durable cladding material for the entire building [fig. 1].
Figure 1. Vision of an all glass façade by Mies van de Rohe, Friedrichstrasse Skyscraper Project (1921).

Architects very quickly realized that these cladding areas held particular potential for aesthetic play as the resolution of the glass cladding detail was equally important for the overall impression of the facade as the resolution of the vision glass detailing [fig. 2].
However, cladding a building with a transparent material revealed that, particularly in cold climates, building moisture was able to condense on the inaccessible interior surfaces of the facade due to poor insulation, thermal bridging, and an insufficient attention to the control of water vapor. With the new transparent glass cladding, this often led to premature degradation of the facade appearance, including the development of Stage I and Stage II glass corrosion [fig. 3].
Figure 3. Façade built in 1964 with transparent glass spandrels (reflective solar film was added later to vision areas). The irregular white patches are indicative of glass corrosion.

More recently and as a logical result of the unitization of curtain wall design, an insulated shadowbox is often integrated behind the spandrel glass. This raised new challenges, as now condensation appeared on the inside of the glass cladding not only in cold conditions but in warm humid conditions as well, where degradation of the appearance of the glass was much more rapid due to the quick onset of glass corrosion, often before the expiration of facade warranties [fig. 4].
Figure 4. Glass spandrels on a recent building showing signs of water accumulation and glass corrosion.

To avoid these issues, architects and other building designers need an understanding of the water vapor physics occurring at the building envelope, and a test method to verify proposed design solutions before they are implemented. This will be especially beneficial as further design typologies where there is limited access to clean the glass are developed, such as double walls and transparent or translucent glass rain screen claddings.

2 Condensation and Glass Corrosion
2.1 Condensation
Evaporation of liquid water occurs when sufficient heat is present to change the state of the water from liquid to vapor, thereby increasing the amount of water vapor in the air until it is saturated. Condensation is the reverse process that occurs when saturated air is cooled, and heat is released as the water vapor changes state from vapor to liquid. The temperature at which the water will condense is termed the dew point temperature. It is important to note that the dew point temperature depends only on the amount of water present in the air (the absolute humidity, also termed the humidity ratio or vapor pressure) and does not depend upon the air temperature. For this reason, when discussing condensation for building envelopes, we prefer to refer to dew point temperatures rather than describe conditions based on relative humidity, which is temperature dependent.
For non-absorptive materials such as glass, condensation occurs at the thin air film boundary layer between the air mass and the object’s surface when the object’s temperature is at or below the dew point. The rate of condensation will depend on how far the temperature of the surface is below the dew point of the air. The total volume of water that can accumulate will depend on the rate of air movement bringing new saturated air into contact with the cooling surface, the length of time considered, and whether the amount of water vapor is limited or unlimited.

2.2 Glass Corrosion

Should condensation occur on the inaccessible surface of the glass, glass corrosion processes will begin as soon as liquid water is present on the surface of the glass. If the glass surface is exposed for an extended period of time and the corrosion by-products are not cleaned from its surface, the glass corrosion processes will continue and may ultimately affect the façade appearance. However, even the most severe glass corrosion remains at the outermost surface of the glass, and does not affect its structural performance [2].

Stage I glass corrosion is visible as iridescence and/or a hazy white deposit on the glass surface. Since the glass surface has not yet been damaged in Stage I corrosion, the glass can be cleaned and returned to its original appearance, and the dealkalization of the surface will actually improve its resistance to further corrosion. However, if the conditions that caused the condensation and Stage I corrosion are not changed, recurrence of the glass corrosion would be expected [3].

Stage II glass corrosion is visible as a distinct white haze of the glass surface [fig. 5]. Unlike with Stage I glass corrosion, with Stage II corrosion the glass surface is permanently damaged, and only glass replacement can restore the façade to its original condition [fig. 6]. Again, if the conditions that caused condensation and the Stage II corrosion are not changed, the recurrence of the glass corrosion on the replacement glass would be expected.
3 Specific Condensation Conditions and Solutions
3.1 Cold Climate Condensation Conditions
In cold climatic conditions, the main risk of condensation on the interior of inaccessible glass surfaces is due to water vapor from within the building migrating outwards and making contact with the relatively cool glass surface of the building envelope. Design solutions to mitigate the risk of condensation generally work to provide a vapor barrier at the interior of the system, and vent the interstitial cavity to the exterior air, which is relatively cold and dry. In this case, the interstitial cavity should vapor equalize to the exterior.

3.2 Warm Climate Condensation Conditions
In hot and humid climatic conditions, the main risk of condensation on the interior of the inaccessible glass is due to humid air from the exterior being trapped in the interstitial cavity, and then the glass being cooled by either rain or by radiating heat to the cold night sky. Assuming the building is air conditioned, design solutions to mitigate the risk of condensation generally work to provide a vapor barrier at the exterior of the system, and vent the interstitial cavity to the interior relatively cold and dry air. In this case, the interstitial cavity should vapor equalize to the interior. Using an insulating glass unit as the exterior glass can also limit the heat loss of the critical inner surface of the glass, further limiting the risk of condensation.

3.3 Temperate Climate Condensation Conditions
For temperate locations where both of the above climatic conditions can be expected on a regular basis, a climate analysis is needed to determine which of the two conditions is most likely to cause degradation of the glass appearance.

If as in cooler temperate climates, the cold climatic condition is more likely to occur but there is still significant risk that the hot and humid climatic condition will occur as well, a combination of venting to the exterior but also using an insulating glass unit may provide sufficient performance.

However, if both conditions occur enough to be of concern as may be the case in warmer temperate climates, further measures may be required to mitigate risk of condensation, such as forcing filtered and dehumidified air into the interstitial cavity; providing a small amount of heat in the interstitial cavity to raise the glass surfaces above the dew point at critical temperature conditions; pressurizing and depressurizing the building such that the relatively cold and dry air from the exterior (winter condition) or interior (summer condition) is forced into the interstitial cavity.

4 Towards a Testing Protocol
4.1 Methodology
At the time of this paper, there is no agreed to industry standard for the testing of condensation resistance in interstitial glass cavities. Through field investigations of completed projects where condensation caused degradation of inaccessible glass surfaces, methodologies for measuring and monitoring the humidity and temperature conditions have been practiced. The following is a proposal to apply these same methodologies during performance mockup testing, allowing for verification of the glazing cavity performance before fabrication of the project façade.
The mockup should be located in the same climatic region as the project, so that ambient temperature and humidity conditions during testing will simulate the actual project conditions. Using a testing chamber to simulate the exterior conditions is not recommended, since it will eliminate the effects of the cold radiating night sky and the natural variability of weather events.

The performance mockup will not fully simulate building conditions. Many forces can affect the conditions in and around the façade cavities, including wind induced pressures, stack pressures, mechanical system pressures, driving rain, solar heating, and night time cooling. However by continuing monitoring during performance testing, the effects of the conditions similar to those that the building will experience can be observed and considered.

4.2 Example Specification

The monitoring program can be specified as follows:

1. *Monitor condensation performance of at least three shadow box assemblies of the Performance Mockup during the duration of Performance Mockup Testing or for a minimum of three weeks, whichever is greater. Contractor to submit proposed procedures and monitoring locations for review by the architect. The procedure shall include:*  
   a. Monitoring of surface temperatures, air temperature and dew point temperature (humidity) inside the shadow box.  
   b. Monitoring of air temperature and dew point temperature (humidity) for exterior conditions.  
   c. Monitoring of air temperature and dew point temperature (humidity) for interior mock-up conditions. The interior chamber shall be conditioned per the expected project conditions.  
   d. Pass/Fail Criteria: No condensation should occur (confirmed by visual observation at critical timepoints), and surface temperatures should remain above the measured dew point within the shadowbox at all time points.

2. *If no water has accumulated in the shadow box cavity at the completion of the above, perform confirmation of condensation dissipation test:*  
   a. Induce condensation within the cavity by a combination of raising the humidity in the cavity and cooling the glass surface. Monitor to determine length of time for water to dissipate by drainage or evaporation.  
   b. Pass/Fail Criteria: Water shall dissipate (no residual liquid water or water vapor) within 8 hours on a “dry” day for the given climate where the average ambient relative humidity for the day is below 60% (Note to Specifier: the definition of a “dry” day will vary by climate).

Particular care is required when placing surface temperature sensors [fig. 7]. If the thermocouples are not placed at the coldest locations on the glass and/or metal, the quantitative results will not be accurate. It is recommended to
undertake a thermal analysis with either a computer simulation or infrared imagery to confirm sensor locations prior to testing.

![Figure 7. An example of installed thermocouple sensors and hygrometer placed within a shadowbox cavity to allow for continuous monitoring.](image)

### 4.3 Presentation and Analysis of Results

Testing results of the sensor data should be presented in graphic form, supplemented by photographic images. By plotting the measured air temperature and dew point with the surface temperatures, one can quickly confirm if the surface temperatures fell below the dew point within the glazing cavity, indicating a condensation event [fig. 8]. Comparison of the lines representing the exterior, interior and cavity dew points will confirm if the cavity is vapor equalizing to the interior or to the exterior.
Alternatively, by subtracting the dew point temperature of the air cavity from the surface temperature at the same time point, one can plot a line that indicates “probable” and “potential” condensation events [fig. 9]. A probable condensation event would be any time point where the line is zero or less. A potential condensation event would be any time point where the difference between the dew point and the surface temperatures is less than the measurement tolerance.

Figure 8. Temperature plot of results from a warm climate.
Photos of detailed areas are necessary to confirm the presence of condensation for the probable and potential condensation events. The detailed photos and data can also be supplemented by overall time-lapse images of the façade, which will show the variation in appearance of the façade should condensation occur.

While monitoring throughout the year during all the seasons of a particular location would be ideal, it is not generally realistic given project schedules and testing costs. Careful interpretation of the results is therefore required, comparing the measured weather conditions during testing with typical weather conditions for the various seasons that can be expected for the project. Where possible, testing conditions should be compared to actual monitored site conditions.

5 Conclusion
When designing glass cladding systems, careful management of water vapor is required to avoid condensation, and the subsequent degradation uncontrolled water can cause for the glass and the building. The proposed testing procedure provides a methodology to confirm the façade system’s vapor equalization performance, and analyze the potential risk for condensation to occur. While the building industry’s knowledge on this issue is increasing, there is currently insufficient knowledge even to corroborate these testing results except for very limited cases. However, as more systems are tested, and those same systems are installed and their system performance can be confirmed, more confidence can be placed in the testing results to help prevent condensation in new designs.
References
Performance of insulating glass units – field correlation study over 25 years, 1980-2005

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Keywords:

1 = insulating glass units  
2 = field performance  
3 = laboratory testing  
4 = long term durability

Abstract

The correlation of insulating glass units (IGU) relating to the actual field performance as compared to laboratory testing was a project undertaken by SIGMA (Sealed Insulating Glass Manufacturers Association) starting in 1980. The study was undertaken to establish the correlation between the various levels of testing as outlined in the ASTM E 774 standard for weather and high humidity/high temperature testing classifications C, CB, and CBA with CBA being the most stringent testing criteria. The study was intended to obtain data on IGU's having visual obstructions in the airspace or seal failures as determined by frost points or visual inspections of 140 buildings, in various climates in the United States, and compare the results with the classifications of the ASTM standard. The buildings selected had distribution of the units over the three classifications for the standard. The field inspections were conducted various intervals of five year periods to obtain the data. This paper will present an overview of the study and illustrate the results of the twenty five year Field Correlation Study completed in 2006, included is data on various conditions that were observed in glazing systems, sealant types in the study, location of the projects evaluated and data to demonstrate field failure rates for the classifications of laboratory testing. A second study that conducted on over 14,000 insulating glass units with the CA classification that began in 1990 and completed in 2005 will be included. In addition information will be presented that is important to the continued use of IGU’s for energy savings and long term durability for future considerations in North America.

The study was originally sponsored by SIGMA and the Department of Housing and Urban Development (HUD) and was continued to completion by the support of the Insulating Glass Manufacturers Alliance (IGMA)
2 Introduction

The Sealed Insulating Glass Manufacturers Association (SIGMA), now the Insulating Glass Manufacturers Alliance (IGMA) along with the U.S. Department of Housing and Urban Development (HUD), initiated a research project to field evaluate certified insulating glass units (IGU). SIGMA and HUD began this research study in 1980 with joint sponsorship. HUD along with SIGMA was charged with encouraging and promoting the acceptance of advance construction methods and materials. One of the efforts in this regard was a field performance evaluation of certified IGU’s relating the ASTM standard E 774 “Standard Specification for the Classification of the Durability of Sealed Insulating Glass Units”. The units certified to Class C, Class CB, and Class CBA of the Standard. This report is intended to provide a brief overview of the results of the study over the 25-year period (1980-2005). The report will be comprised of many major topics, the first being a description of the ASTM E 773 Test Method and the E774 Specification, a section describing the seal systems, areas and climates in study, followed by a summary of the 10-year study, a glazing system study, a second study of CBA units only, the 15-year data, the 25 year data, summary of the 1980 and 1990 study, comments and lessons learned from the study, future studies recommended, and conclusions from the research and evaluation. Acknowledgments are presented at the end of the report.

3 Description of ASTM E 773 and E 774 Standards and the Inspection Method

The purpose of the study relating to the IGMA Field Correlation project was to determine the correlation of actual in-service insulating glass unit failures to the ASTM E 773 Test Method and ASTM E 774 specification for classification C, CB, and CBA. The ASTM Standard E 773 describes the test method for accelerated weathering of sealed insulating glass units. The units are subject to a high humidity condition of 60 ± 3°C (140 ± 5°F) and 95 ± 5% relative humidity. The same units are subjected to an accelerated weather cycle test apparatus which incorporates a six-hour cycling that lowers the temperature during the first hour from room temperature to -30 ± 3°C (-20 ± 5°F). This temperature is maintained for one-hour ± five minutes. The temperature is then allowed to rise from the low temperature to room temperature over a period of one hour ± 5 minutes and then rises over a time period of one hour ± 5 minutes. A water spray and ultraviolet lamps are also incorporated, as the temperature risen from room temperature to 57 ± 3°C (137 ± 5°F). During this time the water spray is turned off after 30 minutes to allow the temperature to continue to rise to the high temperature level. The temperature is maintained at the high temperature with continued ultraviolet exposure for a period of one-hour ± 5 minutes. The two test methods are alternated, as shown in the following summary below, for the various high humidity and accelerated weather cycles.
Table 1, Summary of High Humidity and Accelerated Weathering Test Specification.

<table>
<thead>
<tr>
<th>Class</th>
<th>High Humidity (days)</th>
<th>Accelerated Weather (cycles)</th>
<th>Frost Point</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>14</td>
<td>140</td>
<td>-34°C (-30°F)</td>
</tr>
<tr>
<td>CB</td>
<td>14</td>
<td>56</td>
<td>29°C (-20°F)</td>
</tr>
<tr>
<td>CBA</td>
<td>14</td>
<td>56</td>
<td>29°C (-20°F)</td>
</tr>
</tbody>
</table>

The study began in 1980 and in the first seven years, frost points were taken on almost all of the comprised units. The original study consisted of approximately 2,400 units representing over 140 buildings in 14 cities. The study continued with visual inspection for obstruction of vision or seal failures in the remaining years of each study. This inspection was completed eight times in the first 10 years and again at the 15-year point. Almost all of the 2,400 units studied faced south or southwest. The principal investigator throughout the 25-year projects was Mr. James L. Spetz, P.E. formerly of Jim Spetz Consulting Company in Wickliffe, Ohio.

It should be noted that in the overall study, a number of buildings were not accessible, certain buildings were replaced, security issues prevented inspection, and building occupants were not accessible to achieve an inspection during the 25-year inspection conducted in year 2005. Approximately 75% of the original populations was captured in the final inspection.

4 Other important information

4.1 Seal Systems in the Original Study

The majority of the sealant systems available in 1980 were studied with the insulating glass units offered for the study by various manufacturers. The sealant technology available consisted of a single seal and dual seal units and is summarized as follows:

Table 2, Seal Systems

<table>
<thead>
<tr>
<th>Single Seal</th>
<th>Dual Seal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Polysulfide</td>
<td>Polyisobutylene / polysulfide</td>
</tr>
<tr>
<td>Permapol</td>
<td>Polyisobutylene / silicone</td>
</tr>
<tr>
<td>Hot Melt Butyl</td>
<td>Polyisobutylene / hot melt butyl</td>
</tr>
<tr>
<td></td>
<td>Hot Melt Butyl / silicone</td>
</tr>
</tbody>
</table>
4.2 Areas and Climates Included in the Field Correlation Study

The intent of the Field Correlation study was to evaluate IG use in various parts of the United States. The study included various climate conditions throughout the United States including cold climates in Minnesota and Wisconsin, more moderate climates in Ohio and Massachusetts, warm areas in Atlanta and Dallas, very warm and humid in Florida, and hot and dry in Arizona, which represents a wide range of climates in the United States. The following is a list of the 1980 original study of the 2,400 units that were included with 140 buildings in the following 14 areas.

Table 3, List of Cities

<table>
<thead>
<tr>
<th>Boston</th>
<th>Atlanta</th>
<th>Tampa</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cleveland</td>
<td>Minneapolis</td>
<td>Dallas</td>
</tr>
<tr>
<td>Montana</td>
<td>Denver</td>
<td>Phoenix</td>
</tr>
<tr>
<td>Sacramento</td>
<td>Lake Tahoe</td>
<td>Seattle</td>
</tr>
<tr>
<td>Portland</td>
<td>San Francisco</td>
<td></td>
</tr>
</tbody>
</table>

It should be also be noted that approximately 40 manufacturing plants were represented in the initial study conducted with insulating glass units provided for the various projects those manufacturers participating and supplying insulating glass units meeting classifications of C, CB, and CBA.

4.3 Glazing System Types in Study

The original 1980’s study consisted of approximately 40% of the study being residential units with the remaining 60% of the units being commercial glazed units. The following is a summary of the types of systems that were incorporated in each of the basic types:

Table 4, Glazing Systems

<table>
<thead>
<tr>
<th>Residential</th>
<th>Commercial Glazing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum-marine gasket</td>
<td>Aluminum / lock strip gasket</td>
</tr>
<tr>
<td>Aluminum-dry interior and wet interior</td>
<td>Aluminum-dry exterior and wet interior</td>
</tr>
<tr>
<td>Aluminum – both wet seals</td>
<td>Aluminum tape exterior and dry interior</td>
</tr>
<tr>
<td>Wood marine gasket</td>
<td>Wood – both wet seals</td>
</tr>
<tr>
<td>Wood both wet seals</td>
<td></td>
</tr>
</tbody>
</table>

Notes:
1. Wet seal exterior had 10% of the number of failures as dry seal on the exterior in the 1990 survey.
2. Aluminum with marine gaskets and onsite glazed units with lock strip gaskets demonstrated much higher failure rates due to trapping water against the edge seal unit at the sill.
5 Results

5.1 Field Study at 10 Years – 1980-1990

The first major tally of results from the original 1980 study was accumulated with the 2,100 units that were accessible for evaluation at ten years. The following table represents the results of the study with the total fogged units and percentage of fogged units.

<table>
<thead>
<tr>
<th>CLASS</th>
<th>CLASS CB</th>
<th>CLASS CBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL FOGGED UNITS</td>
<td>69 of 809</td>
<td>8 of 242</td>
</tr>
<tr>
<td>% FOGGED</td>
<td>8.5%</td>
<td>3.3%</td>
</tr>
<tr>
<td>Total Failure Rate</td>
<td>= 103 of 2100 = 4.9%</td>
<td></td>
</tr>
</tbody>
</table>

The summary included all jobs. Two jobs were found to have inadequate weep systems accounting for approximately one-half of the CBA failures. Without those two jobs the CBA rate was 1.2%.

5.2 1990 Study Containing CBA Units Only

In 1990, an additional study was undertaken to study the CBA units only. This included newer seal and edge technologies that were added from the original study and were incorporated in the new study. The new study which included on CBA units consisted of using a visual inspection for fogged units and was performed every two or three years with major inspections conducted in 1995 and again in 2005.

The 15-year failure rate of 10,944 units was one percent. Units were inspected in 102 buildings in Ohio, Arizona, Georgia, the Carolinas, Florida, Wisconsin, and Minneapolis. Over 50 SIGMA manufacturing plants certifying to Class CBA of ASTM E 774 had units in this 1990 study. Many of the plants had units in two or more areas. Several companies with multiple plants were represented in supplying units for this study. There were six dual seal systems and six single seal systems in the 1990 study. Several plants had installed semi-automatic production lines increasing production capabilities and quality to the manufactured units.

5.3 Field Study at 15 Years – 1980-1995

During this survey there were 2,043 units accessible for evaluation. The following table represents the results of the study at the 15-year period.
Table 5, Failures at the 15-Year Point

<table>
<thead>
<tr>
<th></th>
<th>CLASS C</th>
<th>CLASS CB</th>
<th>CLASS CBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL FOGGED UNITS</td>
<td>77 of 807</td>
<td>35 of 218</td>
<td>42 of 1,018</td>
</tr>
<tr>
<td>% FOGGED</td>
<td>9.5%</td>
<td>12.1%</td>
<td>4.1%</td>
</tr>
<tr>
<td>TOTAL FAILURE RATE</td>
<td>= 153 of 2,043</td>
<td>= 7.5%</td>
<td></td>
</tr>
</tbody>
</table>

Summary included all jobs. Eliminating the two projects with known problem glazing systems brought the CBA to 2.9%

5.4 Field Study at 25 Years – 1980-2005

During this survey there were 1,714 units accessible of the original 2,400 units or over 71%.

Table 6, Failures at the 25-Year Point

<table>
<thead>
<tr>
<th></th>
<th>CLASS C</th>
<th>CLASS CB</th>
<th>CLASS CBA</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTAL FOGGED UNITS</td>
<td>85 of 791</td>
<td>43 of 126</td>
<td>29 of 797</td>
</tr>
<tr>
<td>% FOGGED</td>
<td>10.7%</td>
<td>34.1%</td>
<td>3.6%</td>
</tr>
<tr>
<td>Total Failure Rate</td>
<td>= 157 of 1714</td>
<td>= 9.2%</td>
<td></td>
</tr>
</tbody>
</table>

The Summary did not include the two previous projects with known glazing systems problems (projects had been re-glazed), thus the 3.6% for CBA is ok.

6 Summary Comments and Lessons Learned From Study

The Field Correlation Study offered many insights into areas providing basic information for improving the glazing systems utilized, manufacturing techniques and overall performance criteria of insulating glass. It was found that systems with Marine gaskets and lock strip gaskets demonstrated high failure rates due to poor or lacking weep systems.

The 1990 study examined over 10,000 CBA units in 102 buildings from units constructed in over 50 manufacturing plants with a failure rate of approximately one-percent at 15 years. These were units that were in building throughout the United States and in the various climate zones previously referenced, and offer a representation of insulating glass units provided by over 50 manufacturers in the U.S.

Based on the information obtained from the 25-year data, it is estimated that the failure rate of C and CB units is in excess of 20% due to the number of buildings re-glazed and known systems that were not properly performing to keep water away from the insulating glass edge.
The number of C and CB units demonstrating failure in the 25-year study (14%) had approximately three to four times the number of failures of the CBA units (3.6%). This would clearly demonstrate that those units achieving the CBA level of certification outperformed the units that had only achieved the C or CB level of certification that were observed from the Field Correlation Study of 1980.

7 Considerations for Future Study

IGMA is now considering commencing a new field correlation study to the latest ASTM standard and specification, ASTM E 2190. This study will include insulating glass units with inert gas content focusing on long-term durability and thermal performance of insulating glass units certified to the current ASTM standard.

Future field correlation studies will include the United States and Canada with consideration to using the U.S. and Canadian Energy Star climate zones.

8 Conclusions from Research and Evaluation

Certification to class CBA of the ASTM Standard E 774 demonstrated a much higher level of field performance than Class C and CB. This is represented in the table illustrating the SIGMA 15 year and IGMA 25 year correlation studies summary as illustrated below.

Table 7, Summary Survey Failure Rates

<table>
<thead>
<tr>
<th></th>
<th>Phase I</th>
<th></th>
<th>Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25-Year</td>
<td>15-Year</td>
<td>15-Year</td>
</tr>
<tr>
<td>Failure</td>
<td>C+CB</td>
<td>CBA</td>
<td>C+CB</td>
</tr>
<tr>
<td>Rate</td>
<td>14.0%</td>
<td>3.6%</td>
<td>10.8%</td>
</tr>
<tr>
<td>Units</td>
<td>917</td>
<td>797</td>
<td>1,025</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The superiority of Class CBA over C and CB was, in part, justification for the one level of testing developed for the ASTM E 2190 Standard. The E 2190 Standard has been adopted by all testing agencies in the United States and Canada for the certification of insulating glass units.

The insulating glass industry must encourage those using insulating glass in both residential and commercial applications to follow the publish glazing guidelines provide in the publication TM-3000-90(04): «North American Glazing Guidelines for Sealed Insulating Glass Units for Commercial and Residential Use», follow the minimum sealant dimensions for insulating glass assembly as references in the IGMA Technical Bulletin TB-1201-89(05): Sealant Manufacturers Minimum Sealant Dimensions and Placement Survey as well as implementing a quality assurance program ensuring long-term durability of insulating glass performance.
Insulating glass units shall be certified to ASTM Standard E 2190 (replacing ASTM Standard E774 and CGSB 12.8) for assurances of long term durability against fogging (seal failure) and be glazed in accordance to IGMA standards.

9 References

ASTM E546 - 08 Standard Test Method for Frost/Dew Point of Sealed Insulating Glass
ASTM E773-01 Standard Test Method for Accelerated Weathering of Sealed Insulating Glass Units (Withdrawn 2010)
ASTM E2190 - 10 Standard Specification for Insulating Glass Unit Performance and Evaluation

Acknowledgements

Special acknowledgement and appreciation given to the US Department of Housing and Urban Development, SIGMA (currently IGMA), the Board of Directors of IGMA for continuing the study into the 25th year, Margaret Webb, Executive Director of IGMA for support in advancing the study and Mr. James L. Spetz P.E. for his 25 years of service and commitment to the Field Correlation Study.
All-glass enclosures: Spaces for working and living

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Abstract
This paper will review our experience in the design and construction of glass enclosures – of different shapes and sizes – used for social, commercial as well as residential spaces. This ranges from an 8m glass cube built in 1998 for the Arab Urban Development Institute (AUDI) in Riyadh that functions as a reading room to a 7.6m long x 5.5m wide x 2.6m high glass extension to a house then an all-glass box 24m long x 7.5m wide x 13.3m high complete this year for the Buildings by Daman in Dubai the paper ends with the presentation of a prototype glass clad house in France currently on site. Each house measures approximately 12m x 10m x 6m high with a glazed envelope of approximately 420m² made up of a double façade of translucent insulated glass units that permits up to 40% light transmission. In conclusion, the paper will compare and contrast the different design solutions and consider a possible future for glass enclosures as spaces for working and living.

Keywords: glass enclosure, Dubai, daylighting, translucent glazing

1 Introduction
1.1 Glass enclosures
In the last 5 years, we have recorded a trend where structural glass elements replace traditional materials. This dramatic increase is due to increasing interest from architects as well as the transparent yet durable material, resistant to weathering. By using supporting glass structures and frames, like beams and fins, this increases the transparency even further to form all-glass enclosures.

1.2 Daylighting
Study after study has quantified the benefit of daylight exposure. Daylight exposure has been linked to improved employee productivity, student performance, and even the regulation of a person’s circadian rhythm, which drives the all-important wake/sleep cycle. Beyond improving the human experience, effectively incorporating daylight in the interior, or daylighting, can dramatically improve the operational performance of the building and create energy savings.

2 8m Glass cube – friction grip connections
2.1 Shape and size
The cube is 8m x 8m x 8m and has no internal structure. Toughened glass beams 2.67m in length formed of two 15mm thick leaves were joined using friction grip connectors to create portal frames which carry the glazing loads and provide stability. Because of the high forces that arise when the bolts are tightened, an
aluminium spacer of low temper yet creep-resistant was inserted between the glass leaves at the connection.

2.2 Construction
For the Glass Reading Room of the Arab Urban Development Institute in Riyadh, Saudi Arabia (1998) a solution was found to friction-grip laminated glass and overcome the problem of inter-layer creep relaxing the bolt tension and hence losing the friction in the long term.
We have found that for these connections attention to detail at manufacturing stage is vital. Key things to watch for are: the steel surfaces at the friction connection must be milled perfectly flat; the fibre gaskets must be used only once and should be made of semi-flex vulcanised fibre; the thickness of aluminium must be carefully matched to the edge tape thickness to provide 5-10% compression to the tape; the joint must be clamped during UV curing of the resin.

Figure 1. Glass cube, AUDI, Riyadh with detail of roof construction

3 External glass frames
3.1 Shape and size
External 6.9m long glass beams link two parts of a Grade II listed domestic dwelling. Internal volume is 7.6m long, 5.5m wide and 2.6m high. External glass frames give a clear, unrestricted internal space where the roof level has to align with the existing low-level buildings as a planning condition. The moment-resisting glass frames required analysis of compression flange buckling of the glass beams and led to an innovative fin-to-beam connection detail that visually corresponds with the original architecture. Load transfer is achieved through bearing in holes with development in design and fabrication method.

3.2 Construction
The fact that the glass conservatory would be the subject to extensive solar gains in the summer, would make the space very hot and uncomfortable. Air conditioning was ruled out as it would require some sort of ductwork which would be unacceptable, having in mind tight headroom, and would interfere with the ‘universal space’ concept of an undivided room. Use of solar control coating solves this problem, by reflecting some of the solar energy back to the outside and therefore the room is not overheated.
Table 1. Typical performance values of the double-glazed units

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ug-value</td>
<td>1.4 W/m²K EN 673</td>
</tr>
<tr>
<td>LT</td>
<td>65% (Total light transmission)</td>
</tr>
<tr>
<td>Solar gain</td>
<td>36%</td>
</tr>
<tr>
<td>Reflectance</td>
<td>10%</td>
</tr>
</tbody>
</table>

Figure 2. Glass cube, AUDI, Riyadh with detail of roof construction

4 24m glass box – bearing connection

4.1 Shape and size
The entrance hall takes the form of a rectangular box 24m long, 13.3m high and 7.5m wide with six automatic doors and three canopies. It serves as the principal means of access to The Buildings by Daman a mixed-use office & residence complex of high-rise buildings at the Dubai International Financial Centre. The approved concept comprised 13.3m high spliced fins, 7.5m long spliced beams, roof panels either 4m x 2.5m or 2m x 2.5m and façade panels up to 4m x 3.19m whereby joints in the façade matched the jointing in the stone cladding to portal frames.

4.2 Construction
Vertical load distribution starts at the roof level where a grillage of glass beams support rectangular roof panels and span onto vertical glass fins. These glass fins are then supported in steel shoe fixings at P2 and P5 slab level. The glass façade panels are restrained by the vertical fins in the horizontal direction only, no vertical loadings from the façade panels are transferred into the fins. The façade panels are stacked one on top of the other from roof to ground level where they are restrained in a steel channel. Above the door openings the façade panels span horizontally to transfer the vertical dead load to the adjacent panels. Lateral stability is provided to the structure by using the roof and façade panels as a stiff membrane. Horizontal forces are transferred from the façade panels into the vertical fins and the roof beam grillage. The load is then transferred to the glass roof panels which act as a stiff diaphragm to transfer the forces to the façade panels.
All glass elements were designed with redundancy based on a failsafe condition. A failsafe condition is achieved through redundancy within the individual laminated glass sheets. Evaluation of the failsafe condition is made where one laminate is assumed to have failed with full live loading in accordance with Code requirements. Each element has been checked individually for this condition. The façade and roof panels are triple laminated and the glass fins and beams have 5 No. ply laminated together.

Laminated glass elements have been analysed as solid plates in the main model using actual thicknesses of glass. The interlayers have not been included in this model. Separate design checks were carried out on all the main glass elements using SJ Mepla analysis programme. In this analysis the properties of PVB and SGP laminates for short/long term and temperatures of 25°C and 50°C were included in the models and their effect on stresses and deflections therefore taken into account.

The façade and roof panel connections were simplified in the global Strand7 model to simple pinned connections. In reality stainless steel patch plates top and bottom will restrain the glass in rotation. The local rotations of the plates around these connections are therefore higher in the Strand7 model than they will be in reality. The connections have been checked using the process of submodeling. This involves exporting a small portion of the larger model including its directional and rotational displacements and refining this model to get more accurate and realistic results. When the rotational restraints representing the patch plates are added to this sub-model it effectively makes this model incompatible with the main model. i.e. additional glass stresses will be imposed on the glass when it is clamped due to the difference in plate rotation in the clamped connection compared to the pinned connection. So for vertical load combinations the glass stresses in the sub-model will be higher than in reality. Therefore for analysis the sub-model has been used to analyse only the worst case horizontal shear forces.
through the connections and the patch plates have been omitted. For the vertical load combinations an entire panel has been analysed separately with the patch fittings.

Figure 4. Images of the Glazed Entrance Hall taken April 2014

5 Construction of 3 prototype glass houses
5.1 Shape and size
The 3 houses are characterized by their simple volume 12m x 10m x 6m high and architectural respect for each other. Each house is a variation on the same theme: a parallelepiped intersected by a longitudinal volume that contains the services function of the house. A floor surface area of 170m² compares to a glazed envelope of 420m² made up of a double façade of translucent double glazed units and solar control PVB film that cuts out 40% solar heat (IR) energy, giving an exceptional thermal performance. The calculated overall U-value for the façade and roof was 1.09 W/m²K and solar gain of the façade of 0.31 and roof of 0.21.
5.2 Construction
The French building regulation RT 2005 that came into force in September 2006 require an Energy Consumption (CEP) lower that the reference (CEP ref). The maximum summer temperature Tic must be lower than a reference value Tic ref. Despite the above values being greater than the specific requirements for U-values of walls of 0.45 W/m²K and roofs of 0.34 W/m²K, the provision of a ground source heat pump resulted in a C value of 159 kWh/m² cf. C ref of 163 kWh/m² and a Tic of 64 °C cf. Tic ref of 68 °C.

Table 2. Typical performance values of the double-glazed units

<table>
<thead>
<tr>
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</tr>
</thead>
<tbody>
<tr>
<td>Uw-value</td>
<td>1.09 W/m²K EN 673</td>
</tr>
<tr>
<td>LT</td>
<td>40% (Total light transmission)</td>
</tr>
<tr>
<td>Solar gain</td>
<td>31% façade and 21% roof</td>
</tr>
</tbody>
</table>
Figure 7. Perspective of steelwork structure supporting glazed façade & roof units

Figure 8. Site images taken August 2013

6 Building accreditation
In the US The Leadership in Energy and Environmental Design (LEED) relates to environmental standards for sustainability, efficiency, and indoor environmental quality. Of the 57 available credits, one involves daylighting. Specifically, one credit can be obtained by ensuring a minimum of 2 percent daylight factor over 75 percent of the floorspace. LEED is similar in spirit, though different in detail, to the Building Research Establishment Environmental Assessment Method (BREAM). In the UK, the British Council for Offices has published a guide to “Best Practice in the Specification for Offices”. It requires a minimum daylight factor of 0.5% with an average of 2-5%. Part L (2002) of the UK Building Regulations allows an ex-emption from lighting power density requirements for spaces which are “daylit”, i.e. which have a daylight factor of 2 percent over 80 percent of the floor area.

7 Conclusions
In the US As structural consultants we have seen an increase in size and complexity of glass structures related to domestic properties. The mechanics and safety of these structures have been proven and environmental standards have been respected. At Malishev Wilson Engineers we combine consultancy on structural analysis with energy performance to give an integrated design service. National standards will become a lot more demanding: in the UK 2013 and 2016 Building Regulations will require a 44% and 150% emissions reduction, respectively, and in France the RT 2012 envisage a maximum consumption of 50 kWh/m²/year. Glazing coat-ings & films will need to continually improve to satisfy these future standards.
The SolarLeaf bio-responsive façade: 
the first pilot project “BIQ” in Hamburg, 
Germany

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Abstract

The BIQ house completed in April 2013 is the world’s first pilot project to showcase a bioreactive façade at the International Building Exhibition (IBA) in Hamburg on 23 March. With 200m² of integrated photo-bioreactors, this passive-energy house generates biomass and heat as renewable energy resources. At the same time, the system integrates additional functionalities such as dynamic shading and thermal insulation, highlighting the full potential of this technology.

The microalgae used in the facades are cultivated in flat panel glass bioreactors measuring 2,5m x 0,7m. In total, 129 bioreactors have been installed on the south west and south east faces of the four-storey residential building. The heart of the system is the fully automated energy management centre where solar thermal heat and algae are harvested in a closed loop to be stored and used to generate hot water.

The innovative façade system is the result of three years of research and development by Colt International based on a bio-reactor concept developed by SSC Ltd and design work led by the international design consultant and engineering firm, Arup. Funding support came from the German Government’s “ZukunftBau” research initiative.

A two year inter-disciplinary monitoring project investigating the technical and energy performance as well as the users’ acceptance will be completed in December 2014.

The bio-responsive facade aims to create synergies by linking different systems, i.e. building services, energy and heat distribution, diverse water systems and the mitigation of emissions. The key to a successful implementation of photobioreactors on a wider scale will be the cooperation between stakeholders and designers. It is a technology that benefits from strong interdisciplinary collaboration. What is most needed is a holistic understanding and view of the systems’ benefits for the user, the building and the environment.

Keywords: photo-bioreactor, micro-algae, biomass generation, solar thermal heat, adaptive shading, glass louver
1 Introduction

With sustainability ever more sought after, and net-zero carbon emissions an increasingly common target for building designers, the design community is looking for ways to create highly responsive façades that are adaptive and change in response to their environment. The biological cycles of nature are a great source for inspiration. The foliage canopy, for instance (Fig 1), provides best protection from the sun during hot summer months, while simultaneously being permeable to light, and cleaning and moistening the air — and yielding fruits and firewood.

Figure 1. The foliage canopy’s responsiveness is a great inspiration in developing adaptive building envelopes.

The architect Mike Davies’ concept of the “polyvalent wall” from 1981 [1] is still a stimulating reference for all who are researching technical systems for smart skins: multiple coated glass panes integrate electrically and chemically active layers, allowing the transparency to adjust to internal requirements and external conditions. At around the same time the tremendous potential of structural glass to not only promote transparency but to use the liveliness of reflecting surfaces with the presence of colourful absorbent building fabric in innovatory artwork was being explored (Fig 2).

This paper describes the evolution of the concept of a bio-responsive façade. It combines both biological and technical systems, in which micro-algae are cultivated in transparent glass containers known as flat panel photobioreactors
(PBRs) to facilitate the biochemical process of photosynthesis in a controlled environment.

![Figure 2. Glass cell structures using the tetrahedron as a structural module hold the potential to use the enclosed volumes as containers for gas or fluids to enhance environmental control.](image)

### 2 The concept

In 2009, Arup established its materials consulting practice in mainland Europe, and shortly afterwards the new consultancy was approached by the Austrian architectural practice SPLITTERWERK to join its design team for a competition on a smart materials house for the International Building Exhibition (IBA), to take place in Hamburg in 2013. This competition proved to be the perfect occasion to combine and develop the previous experience in this field of both firms.

The design featured what the architects referred to as “supernature” — a second skin enclosing stacked residential units so as to create a “mezzo-climate” between the inside and outside. At that time Peter Head, a Director of Arup and leader of the global planning practice, had published his vision of the “ecological age”; in his 2008 Brunel International Lecture [2] he described the approach towards a new green urban infrastructure, a key element of which vision was façade-applied microalgae systems.

Microalgae perform photosynthesis up to 10 times faster than higher plants, thus allowing the implementation of short carbon cycles. This idea was also adopted by the UK Institution of Mechanical Engineers, and some architects had started to show algae systems in visual renderings. These first concepts, however, were all based on glass tubular bioreactors, in which water and algae circulate through a meandering transparent tube to absorb light and carbon — a costly and maintenance-intensive type of system, and not supported by a holistic building concept.

Working on the “supernature” skin, the Arup competition support team identified a small hydrobiology specialist company called Strategic Science Consult GmbH (SSC) in Hamburg, which was researching processes for cultivating microalgae. On an open field test site SSC had developed and tested a flat panel bioreactor
that could turn daylight into biomass with an efficiency of close to 10%. This was achieved through air uplift technology, where pressurised air is injected at the bottom of the panel and the turbulences created by rising air bubbles stimulate the absorption of carbon and light, while also “washing” the panel clean from the inside.

Figure 3. Early sketches of the building integration of the bioreactors on BIQ building

As well as the increased efficiency of this system for cultivating biomass as a renewable energy resource, two further points made the major difference with respect to building integration:

- The bioreactors produce heat, similar to solar thermal collectors, that can be used for heating the building.
- The panelised geometry allows control of the algae density in the medium and consequently the transparency and total energy transmission of the façade.

In March 2010 the IBA announced that the project had won a first prize. The bio-responsive façade was highlighted by the jury as the key component of innovation.

3 External collaborative research and product development
With the opening of the IBA only three years away, the team had to push ahead with the design of the system so as to attract private investors to buy into the
scheme. Arup’s Berlin office was instrumental in pulling together an industry consortium for developing and testing the system that now also involved Colt International, a global player in façade and climate engineering components.

Further funding for the product development was secured through the “Zukunft Bau” (future building) initiative of the German Federal Ministry of Transport, Building and Urban Development. Within the overall team Arup undertook the coordination, design management and engineering roles; SSC was responsible for the process technology, and Colt for the detail and system design as well as for the procurement.

The façade component as finally developed was a storey-high glass louver: a dynamic shading device that integrates a photobioreactor for the generation of biomass and solar thermal heat. The louver is supported on its central vertical axis, allowing it to track the path of the sun. All services such as supply of pressurised air, and inlet and outlet of the medium are integrated in the perimeter framing.

The build-up of the glass units comprises four panes of monolithic glass. The inner pair forms a central cavity of 18mm for the circulation of the medium and the outer pair enclose on either side 12mm wide insulating spaces. The front panel is a laminated extra-clear micro-textured safety glass to maximise solar gain. The framing is designed in such a way that different glass build-ups can be integrated to suit project-specific requirements.
The first fully operational prototypes were installed on SCC’s test site in January 2011, and a second generation followed in December 2012. The tests demonstrated that the flat panel glass bioreactor:

- has considerably higher production rates than tubular reactors under the climatic conditions of Northern Europe throughout the year
- has 8%-10% efficiency in transforming solar energy into biomass
- experiences no deposition of algae and successive bio-fouling, due to the high flow velocity on the inside surfaces
- does not require cleaning of the inside, and
- can be operated by a fully automated control system (eg when adding nutrient to the medium), thus keeping maintenance costs down.
4 The BIQ building — the first pilot project

On the basis of this product design, the IBA in Hamburg made funding available to SSC for the construction of a pilot project featuring 200m² of the façade system, including all mechanical components to operate a closed loop system on site. The contractor Otto Wulff Bauunternehmung GmbH, also an investor in the scheme, was asked to implement the technology on a four-storey residential building on the IBA site in the Wilhelmsburg quarter of Hamburg by 2013.

Figure 7. Southwest facade with SolarLeaf Panels of BIQ Building in Hamburg, 2013

Arup was commissioned to develop the energy concept as well as the design of the energy control center and the mechanical systems. By pulling together specialists from the fields of sustainability and environmental consulting, ICT (information communication technology), and building physics, as well as the more traditional mechanical, electrical and public health engineering disciplines, Arup was able to supply the unique set of skills required to design, in collaboration with SSC and Colt, the world’s first bio-responsive façade.

Dubbed the BIQ (Bio Intelligent Quotient) House, the building was successfully unveiled on March 23, 2013, and this global debut of an operating algae-based bio-responsive façade system immediately triggered great interest from national and international media [4-8] and other stakeholders. Alongside the formal BIQ House opening, Arup’s partner Colt rolled out the jointly developed façade system under the brand name SolarLeaf. This is now commercially available and will be marketed through Colt, generating successive planning commissions.
The facade is fitted as a secondary structure on the southwest and southeast elevations. Clusters of three to five panels, each 2.5m tall and 0.7m wide, are linked by a closed loop to the plantroom. The inputs and outputs of the loop system are monitored by the building energy management system, which controls the supply of nutrition and the harvesting of the algae at the interface with the building services system. At this interface the algae content and the temperature level of the medium are monitored.

The heat generated through the solar thermal effect needs to be dissipated to prevent the system overheating; for a stable production rate the temperature is kept below 40°C. The excess heat is harvested by a heat exchanger and either used directly for the provision of hot water or stored in geothermal boreholes. The algae biomass is continuously harvested, stored and in regular intervals transported to a nearby biogas plant where it is transformed into methane.

For this small-scale pilot plant, the biomass potential of the algae represents approximately 30kWh/m²a and the net solar heat again is around 150kWh/m²a. In comparison to fossil fuels, about 6 tonnes of CO₂ is saved and an additional 2.5 tonnes of CO₂ is absorbed by the biomass every year.

Because it relies on complex, optimised systems, this technology is ideal for use on a larger scale. If it is fully integrated into the heat and emission flows of a site, it can play an important part in establishing surplus energy and zero carbon building clusters, and its implementation in newly built or retrofitted industry sites and local energy distribution networks is particularly promising.
With the possibilities of local and decentralised energy generation, new perspectives arise for planning on the urban scale. As the product is aiming to create synergies by linking different systems, the key to implementing PBRs on a wider scale will be co-operation between stakeholders and designers; it’s a technology that benefits from strong interdisciplinary collaboration, combing a range of skills from the fields of environmental design, façades, materials, simulations, services, structural engineering, and control systems.

5 Conclusions

It is important to emphasize that this is a pilot project, and that the team is still optimising processes and hardware components. The key outcome so far is that the BIQ House, which contains 15 apartments, clearly demonstrates that integrating algae systems into building services is perfectly feasible. Currently the system is being fine-tuned so that it runs at high efficiency.

This technical monitoring is progressing well and the same time the team is monitoring user acceptance — critical to marketing the project successfully. The building is almost fully occupied and the inhabitants are really positive about the façade and living in the BIQ House. This is a great relief, as none of the team had any real knowledge of how people would perceive and interact with a green bubbling façade! The next step will be the energy monitoring, to commence at the beginning of 2014.

The team believes this to be just the beginning of using the biochemical processes of fast-growing and highly responsive micro-organisms in smart and adaptable building envelopes; a first step towards the vision of the external skin of buildings becoming fully synergetic with the otherwise disparate natural and technical cycles of human environments [3].

Figure 9. Detail of „Itt's Alive – the urban building of the future”; the SolarLeaf facade as part of a building organism