THE USE OF NON-MEMBRANE STRUCTURAL GLASS
A Primer for Architects and Designers

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Keywords
Structural Glass
Facades
Glass Fins
Glass Beams
Laminated Glass

Abstract
This white paper examines the current applications of non-membrane structural glass, that is to say, structural glass elements which serve their main function more as pure structure rather than as a “membrane” or enclosure. These elements include for example: glass fins, beams, and shells. The discussion is comprised of two parts. The first part comprises an overview of what “non-membrane structural glass” actually is and how it differs from “glazing” and other types of “structural glass”, as well as the current technology used to implement its application including materials, fabrication methods, and construction techniques. The second part examines the practical applications of non-diaphragm structural glass in the recent and current work of Skidmore Owings and Merrill (SOM), as well as in certain notable examples created by other design firms. While written from the perspective of an architect and façade specialist, this paper incorporates information and data from glass and structural engineers, other façade consultants, glass fabricators, and façade contractors with the intent of creating an introductory yet informative discourse for architects and designers.

1.0 Introduction
The term “structural glass” can have a broad and sometimes misunderstood definition. Generally speaking, it can be applied to any glass element which serves an integral role in transmitting forces, either directly or indirectly, within a building or a portion thereof. This definition should not apply, for example, to a glass lite which is simply held in a frame and is not necessary to maintain the stability of the frame itself, the adjacent building element, or support any live loads such as wind, snow, or people. That might be referred to as “glazing” and is not the subject of this discourse. Glass elements that are used as primary, secondary, or tertiary structural elements (i.e. glass column, glass beam, or frameless glass panel) are all defined as “structural glass”, and as such may often be considered as either “membrane” (enclosing or barrier) or “non-membrane” (non-enclosing). While structural glass membranes naturally bear live loads and can be designed to transmit lateral loads (shear/racking), usually they do not support dead loads and simply form planes of enclosure or shelter as walls or canopies, though this is changing as planar glass elements become more accepted for structural use. In contrast, non-membrane structural glass (NMSG) commonly supports the dead loads of the enclosure, as well as transmits the tributary live loads to the main building structure in the form of glass fins, mullions, beams, and masonry walls.
2.0 Non-Membrane Structural Glass (NMSG)

2.1 History of NMSG

Experiments using glass as structural elements for buildings began in the early 20th century, and accelerated after the heat strengthening process was developed in France in the 1920’s. After Pilkington’s invention of the float process in the late 1950’s, very large, flat glass panels could then be produced much more economically and further ushered glass structures to be implemented on actual building designs. The Hahn suspended glass system which used single-ply glass fins as stiffeners to reduce deflection was used at the Maison de la Radio in 1953 and would evolve to allow even larger glass walls. Norman Foster’s Willis Faber & Dumas building, completed in 1975, is widely considered to be the first use of modern glass fins on a commercial scale.

2.2 Materials and Fabrication

There are actually two main types of glass that are used in NMSG systems, soda-lime silicate and borosilicate, as well as several other materials which are crucial to the system as a whole. These include polymers for interlayers, seals, gaskets and adhesives, and metals for connections and fasteners.
Soda-lime silica glass is the most common type used for architectural applications, and is created using silica sand, soda (Na₂O), and lime (CaO) as the primary ingredients. Most float glass is soda-lime silicate glass. An ultra-clear variety of soda-lime glass, known as low-iron glass, is created by reducing the amount of iron oxides in the glass melt during production. Low-iron glass is virtually devoid of the green tint seen in conventional glass and can be used for essentially the same applications, however there is typically a 10-20% cost premium associated with low-iron glass and not all glass suppliers can produce it in greater thicknesses. These production capabilities should be verified as accurately as possible with potential suppliers during the design process.

Borosilicate glass is made primarily from silica sand, boron-oxide (B₂O₃), and potassium-oxide (K₂O) and is less commonly used in architecture. However, borosilicate glass has much higher thermal and chemical tolerance and therefore is used to create load-bearing glass masonry and structural elements where high environmental tolerance and lower thermal expansion are required. Because of its more difficult manufacturing process, borosilicate glass is not produced by all glass manufacturers and it does typically carry a higher cost than soda-lime glass. It is generally not used for glazing purposes except for in certain fire-rated glazing products.
There are a few emerging new glass types such as “Gorilla” and “Willow” glass which are stronger and more scratch resistant than soda-lime glass. These glasses are not produced using the float and heat treating processes and so are devoid of optical distortion and blemishes. Current production methods allow for only relatively small panel sizes and so these glasses are not yet cost effective for architectural use, but research is ongoing and we may soon find these glass types as structural options in coming years.

Most modern NMSG is created using the float glass process. The float process produces glass sheets in a range of thicknesses that can then be either used monolithically or laminated together to form thicker and/or higher performing elements. Float glass can also be rolled into channel shapes, and while these are inherently structural due to their shape, they are typically used as part of an enclosure system instead of as structural elements.

NMSG elements may be heat-treated to create heat-strengthened or fully tempered glass where higher structural strength or thermal resistance is required, but also are often left annealed in order to prevent any geometric or optical distortion (warping, anisotropic quenchmarks, etc) resulting from the heat-treatment process. Heat strengthened glass is approximately twice as strong as annealed glass, and fully tempered glass is approximately 2-2.5 times as strong as heat strengthened glass. Chemical strengthening is also increasingly used to achieve higher structural performance without the distortions caused by heat treatment, and also allows cutting and drilling for connections after the fact. This must be carefully considered however as the material is weakened around post-strengthened cut edges, and failure may occur if the connection design does not take this into account. The chemical strengthening process is also currently limited to lites no larger than 2.7x5m (SunGlass srl).

Like many materials, glass has certain unique but obscure characteristics that must be considered to help ensure high quality installations. For example, when laminating glass into thicker elements, it is important for a fabricator to consider that float glass has two sides, an “air” side and a “tin” side which are very slightly different on a molecular level. This is due to the fact that the glass was created by floating it on a bed of molten tin when forming the sheet and some those molecules form a extremely thin layer of tin-oxides on that face of the glass. For some laminate films this is less important, but for others (i.e. SentryGlas) it is crucial that tin-to-tin faces are adjacent. In multi-layer laminations, effective air-to-air or air-tin laminations can be simply achieved by applying a chemical adhesion promoter. Enclosure specialists, façade consultants, and fabricators are excellent resources for helping to ensure that developing designs account for these sorts of issues.
Polymers, or plastics, also play an important role in NMSG systems, most commonly in the form of laminate interlayers and seals. For both strength and redundancy purposes, NMSG elements are often laminated. The interlayers for the laminated elements are typically made from either polyvinyl butyral (PVB) or ionoplast, such as SentryGlas (SG). Ionoplast interlayers are generally stiffer and have much higher thermal and moisture resistance, allowing exposed edges with low risk of delamination, but PVB is still very commonly used for both interior and exterior applications.

Seals at the joints of glass membranes and glass structural elements can be made using either gaskets or wet seals, or both. Silicones are commonly used as both types of seals, but neoprene and EPDM are also used for gaskets. Structural silicones are also frequently used to adhere glass membrane panels to structural elements. While these can be used for both horizontal and vertical enclosures, it is not advised to support panels with structural silicone under constant shear or tension loading, and so it must be considered that vertical panels will also require a means to support their dead-load, and similarly in the case of horizontal panels being suspended from the structure above; varying solutions for this should be discussed with an enclosure specialist. One other precaution to be aware of when using laminated glass and silicone seals or adhesives is that many silicones negatively react with PVB and can cause fogging and delamination. To prevent this, a protective tape should be applied to the interlayer edges before applying the structural silicone or sealant.

Metals are widely used as connectors, splices, and other hardware in NMSG systems. Stainless steel is the most commonly used, as it combines strength, corrosion resistance, and a range of aesthetic options though aluminum, titanium, brass, and mild steel are also utilized in different applications for their varying qualities (strength, finish, cost, etc). Typically, metal connections are required to support glass membrane panels from structural glass elements, or as splice and connector plates for glass fins and beams. Normally, splice plates and connector plates are placed on the outer face of the glass member, but when using laminated elements, there is the opportunity for replacing a portion of the inner plies with the metal plate or connector, allowing for a cleaner aesthetic. In certain applications, the metal fitting can even laminated along with the glass structural element, further minimizing visible connectors. Titanium is ideal for this, since its thermal expansion rate is very close to that of glass; steel and aluminum do not share this attribute which make integrated lamination using those metals less feasible for most applications. These fittings options should be discussed with an enclosure specialist or façade engineer as there are structural and fabrication considerations to be factored into the design.
2.3 Structural Properties

Glass is a non-crystalline, brittle material with no plastic yield, which means that unlike steel or polymers which will plastically deform (e.g., permanently change shape) prior to failure, glass will fail once it surpasses its elastic deformation and reaches its maximum yield stress. Glass is also much stronger in compression than in tension. Because of this, tensile strength and buckling govern the structural design of glass elements (at least in the case of fins and beams) since failure will occur from the opening of microscopic surface flaws due to tension, long before the maximum compression yield stress is reached. Heat treating or chemical strengthening increases the overall tensile strength of glass essentially by resisting further “tearing” of the surface flaws which leads to failure. Lateral buckling must also be checked as this will partially drive the cross-sectional aspect ratio of the glass element.

2.4 Design and Construction

NMSG elements are most often secondary-structural members. This means that while they transmit structural loads from a portion of the building (i.e. the façade), they are usually not employed as main building columns or girders, which are considered primary-structural members. This is frequently prevented by building code restrictions on the use of glass as a structural material. Because of this, NMSG systems must be designed and installed in close coordination with the main building structure to ensure both that the connections between the systems are integrated properly and also so that the primary structure can be designed to account for the secondary loads.
The particular material nature of glass elements greatly influences how the system is designed and built. Glass fin systems, for example, are usually hung from the primary structure above (i.e. slab or beam) rather than “stood” on the floor structure. This may seem counter-intuitive given the low tensile strength of glass, but by hanging the fins, the risk of vertical buckling under compression is eliminated and therefore allows the effective thickness of the glass fin to be minimized by accounting for horizontal bending forces and vertical dead-load only. Hung systems will have a fixed connection—typically through-bolt—at the top and either a shoe or slotted bolt connection at the base to allow for vertical movement and resist horizontal loads. Both hanging and standing glass fin system must be checked for buckling. To counteract buckling tendencies, fins are either increased in width (which reduces the cross sectional aspect ratio) or a means of bracing the rear edge of the fins is introduced, often in the form of tension rods or cables running horizontally between them.

Fig 7: Structural concept for glass beam roof, Apple Cube (original), engineering by Eckersley O’Callaghan; image courtesy of DETAIL.
While linear structural glass systems (fins, beams, etc) have been built with unsupported spans up to 30m, fins longer than 6m have typically been composed of multiple pieces spliced end-to-end. This is because until recently, most float glass was produced with standard max lengths of 3.6-6m depending on the manufacturer. However, a growing number of glass producers in Europe and China have begun manufacturing sheets up to 10m in length, with some specialized factories creating sheets up to 15m for one-off, high-end applications, allowing the potential for longer fins or beams. For member depth, a basic rule of thumb for preliminary glass fin sizing is to use a depth-to-height ratio of 1:12 (for laminated fins/beams), subject to live load variation. This takes into account the structural capabilities of glass elements, as well as fabrication limitations since the allowable size is affected by how the material behaves geometrically when being heat treated as tempering can cause warping of narrow elements and other issues such as weight and handling also play a role. In theory however, the size of a NMSG element is only limited by the production capabilities of the fabricator. If an element is laminated, it must be able to fit into an autoclave chamber for the lamination process, but the element itself can be composed of several pieces of glass by staggering the joints in the plies - a process known as offset lamination - much like the method used to create large wood glu-lams. Generally, this method is used when the length of a glass fin or beam exceeds 6m and the designer wants to eliminate metal splice connections. Generally, the overall member size made using this method is only limited by the factory capabilities and transportation logistics. However, a caveat to this technique it that the butt joints of the glass plies will be visible.
Primary structural glass elements such as columns and beams may built-up, laminated members (see pictured below). These elements rely on metal connectors at the end to accommodate dimensional, thermal, and seismic tolerances. To simulate the behavior of steel, built-up shapes are sometimes created using adhesives at web/flange joints, though shape profiles are far less common than simple rectangular sections. Current research is also being done to explore pre-tensioned laminated glass beams using glass and carbon fiber tendons. The behavior of these experimental beams begins to more closely mimic steel wide flange members and also provide post-failure redundancy.

Fig 10: Built-up structural glass sections and glass tube post; images courtesy of DETAIL

While short spans and/or low loads can technically allow a glass fin or beam to be monolithic (single-ply), this is highly discouraged and there are serious caveats when doing this. Laminating fins or beams can make the element much stronger and can help to keep the depth minimized, but more than that, it provides redundancy in the case of breakage. If a monolithic element is broken, either by impact, thermal stress, or spontaneous breakage of tempered glass, there is a very high likelihood that the glass panels it supports will subsequently collapse. If a laminated element experiences the breakage of one or all of its plies due to any of those causes, the element and its supported panels can often remain in place (if not fully capable of serviceability) until the area can be cleared of occupants. Also, as the laminate will retain broken glass pieces upon failure, the amount of airborne glass projectiles is minimized during blast or wind events, in contrast to the shrapnel effect of non-laminated broken glass. Furthermore, laminated elements allow for opportunities to embed hardware and connections for potentially cleaner aesthetics and assembly. It should be noted however, that while this practice is becoming more common, this technique requires a high level of craft and precision and may not be available in all regions or by all fabricators.

It may be noted that some architects and fabricators argue that a better quality end-product can be had by using a monolithic structural element, due to the potential for quality loss during the lamination process of a built-up member. However the design opportunities and life safety benefits of laminated structural glass as discussed above, when coupled with a well-managed laminated fabrication process, far outweigh the risks of using monolithic glass elements.
3.0 Recent SOM Examples

3.1 Xintong Financial Tower (Schenzhen Rural Commercial Bank – Shenzhen, 2014)

Xintong Financial Tower is due to begin construction in 2014 in Shenzhen. NMSG is utilized most prominently as a 5-story glass fin system in the low-rise pavilion structure, but also as glass beams for entry canopies and skylights. The glass fins are 3-ply fully tempered, low-iron fins that are hung from the roof structure. Stainless steel splice plates are slotted into the ends of each fin segment where the center ply has been held short. Horizontal struts tie the fins back to the primary building structure at each splice in order to reduce the effective maximum span and keep the fin size minimal. The enclosure glass panels are held to the fins by small patch fitting at the horizontal joint and are structurally adhered to the fins along the vertical joint for full support.

The entry canopy to the VIP pavilion next to the tower utilizes glass beams to support a simple laminated glass plane. The beams are supported by the glass fins and are connected with stainless steel plates.
Glass beams are also employed in the cafe garden area (see image below), where the glass ceiling forms the base of a reflecting pool outside. These elements provide maximum transparency for daylight and add to the lightness and architectural refinement of the space.
3.2 Barccarat Hotel and Residences – New York, 2014

Baccarat Hotel and Residences is a hotel and condominium tower for the Baccarat crystal glass company. While the tower is enclosed by a unitized curtain wall, the podium levels feature modular external glass fin panels to support prismatic glass lites. As these fins are supported at each glass panel level, they might be more accurately described as glass mullions rather than a fin, which is typically a multi-story structural element. The glass mullions are 3-ply fully tempered laminations with SentryGlas interlayers.
3.3 Park Hotel – Hyderabad, India, 2010

The glass connector corridor is a recently built example of simple glass fin and beam joinery. The corridor consists of a series of parallel frames which vary in width and axis as they cross the courtyard, resulting in subtly curving concave plan on either side. The frames consist wholly of laminated glass fins and beams with the glass walls and roof panels providing lateral and horizontal stability for the overall system. The fin-beam connection is created using a “glass mortise-and-tenon” joint, where the inner two plies of the vertical fins extend above the outer plies and are inserted into a void in the glass beam where those inner plies have been held back. The joint is fixed with a single countersunk stainless steel bolt. The glass roof and wall panels are held against the frame using structural silicone.

4.0 Conclusions

Compared to the vast knowledge base of other structural materials such as steel and concrete, we are still relatively early in the process of fully understanding the detailed structural behavior of glass. Building codes are not fully developed for structural glass and calculation methodologies are still being refined. However as we learn more about glass as a material, fabrication and construction methods will also advance. This progress is equally advanced by design innovation, and creates one instance where design and engineering are actually pushing each other reciprocally. While there is always room for innovation, below are a few key guidelines to assist designers based on current industry standards and capabilities:

- For general design purposes of fins and beams, assume initial 1:12 depth-to-span ratio
- Reducing span (either horizontally or vertically with lateral bracing or posts) will reduce depth of glass element
- Laminated fins/beams can be stronger and safer (in terms of redundancy) than monolithic elements and are considered preferable as a best practice.
- Length of individual elements is generally limited to 6m before a splice is required (either using hardware or offset lamination), but some manufacturers (in China and Europe) can produce 10m long elements.
- Annealed glass elements are easier to work with (can be cut and drilled throughout process) and are devoid of visual distortion (warping from non-flatness and quenchmarks) but are weaker than heat-treated elements and may require larger sizes and/or more laminations. Annealed elements must be laminated.
- It is advised to work with a structural engineer or façade consultant who has experience in NMSG to take full advantage of glass as structure, and to account for all applicable building forces for detailing purposes.
- It is strongly recommended to consult with potential/regional fabricators at an early stage in the project in order to understand their capabilities before proposing complex or innovative NMSG designs to clients.
Acknowledgements
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