Structural Use of Glass

By David L. Kufferman, P.E.

Glass has been used in building construction for well over 2000 years – ever since the Romans ruled. Over time, the basic recipe for glass has evolved, mostly by trial and error, to the present composition for common soda lime glass, which is 69% silica, 17% soda, 11% lime and magnesia, and 3% alumina, iron oxide, and manganese oxide. Other chemical compositions also have been developed since the early 20th century for more specialized uses, such as borosilicate glass ('Pyrex') and low-iron, 'water-white' glass. Meanwhile, techniques for creating ever larger flat sheets of glass have evolved, beginning with Roman cast glass, followed by spun crown glass by the Syrians in the eighth century, blown cylinder glass in the 12th century, improved plate casting and polishing techniques by the French in the 17th century, and drawn glass in the late 19th century.

Today, most flat glass is produced by floating melted glass over a pool of molten tin, a process developed in the 1950s by Pilkington, a major glass producer in England. Various processes for strengthening glass have also been developed, most notably the production of tempered glass beginning in France in the 1920s, which resulted in a product up to four times as strong as common annealed float glass. Techniques for laminating glass with an interlayer of polyvinyl butyral (PVB) have also been perfected, which address potential dangers of breakage.

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Thermal efficiency of glazing installations has been greatly improved with the development of insulated glass (IG) units and glass with reflective and low emissivity coatings. Many of these developments in flat glass technology went hand-in-glove with advances in construction that began in the late 19th century, notably with the widespread use of structural steel and reinforced concrete building frames, which ultimately led to the perfection of glazed curtain wall systems that are in such prevalent use today.

Given its ubiquitous use in construction in load resisting functions, it seems curious how unfamiliar most structural engineers are with the design and specification of glass in their projects. Steel, concrete, masonry, and timber are the traditional materials of choice for building structures, and sometimes it seems as if the knowledge base of many structural engineers begins and ends with these four materials. Why then is a material like glass, which has a density and modulus similar to aluminum, yet with a theoretical crushing strength about one thousand times that of concrete, not included in this repertoire?

Mechanical Characteristics of Glass

Any person on the street knows that glass breaks. The structural engineer knows that it breaks because it is weak in tension. But then again, so are concrete and masonry, but no structural engineer shies from these materials because he or she understands how to design and specify them correctly. Common window glass typically fails at flexural stress levels less than 15 kips per square inch (ksi), which is far in excess of concrete compressive strengths. So why not apply a safety factor and design accordingly, as in any other structural material?

The reason is because glass breakage is statistically unpredictable. The theoretical compressive strength of glass, based on atomic bond strength calculations, is on the order of 3,000 ksi. That is not a misprint. It is predicted to be approximately one thousand times as strong as concrete, but it never tests out at anywhere near this level. The reason for this is that any uniaxial test induces tensile stresses, and unpredictable surface imperfections in the glass cause stress concentrations that result in wildly varying failure stresses, even between otherwise seemingly identical test samples. These imperfections can be 'Griffith flaws,' which are invisibly small and irregular cracks in the surface of the glass, the formation of which is still not fully understood. Larger flaws such as scratches will also severely weaken the glass, as anyone who has cut glass at the local hardware store has witnessed. Furthermore, the presence of water or contaminants in these flaws can attack the atomic bonds, making the glass weaker. Glass strengths are also affected by the duration of the applied load, in that a glass element can sustain a short term load that may be more than double a long term load that would cause failure.

To deal with such statistical uncertainty, glass is often given a survival probability at a given stress level. For a probability of breakage (Pb) of 50%, the modulus of rupture might be expected to be 6.0 ksi for annealed glass, which means that half of test samples would be expected to break at stresses lower than 6.0 ksi, and half at stresses greater than this value. The American glass producer Libbey Owens Ford has recommended a design modulus of rupture under a 'non

Figure 1: Solar Light Pipe, Washington, DC.

factored load' (NFL) of 2.8 ksi for annealed glass, which assumes a probability of breakage of 8 per 1000, or 0.008, which is accepted in most applicable codes as the standard value of probability of breakage for design purposes. A non factored load corresponds to a load duration of 60 seconds, which is appropriate to use directly for wind loadings. In other words, for a piece of annealed glass subject to a wind load, the maximum bending moment divided by the section modulus must not exceed 2.8 ksi. For a longer duration load, a reduction factor is applied; for fully tempered and heat strengthened glass, an increase factor is applied.

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For some designs, the commonly assumed probability of breakage of 0.008 may be considered too high, and a lower design stress would be called for. It is implicit that the probability of breakage will always be greater than zero.

Glass has a modulus of elasticity of about 10,400 ksi, nearly identical to that of aluminum. It has a density of 158 pounds per cubic foot (lb/ft^3), slightly less than that of aluminum.

For most typical glass uses in buildings, the guideline for design is found in ASTM E 1300, *Standard Practice for Determining Load Resistance of Glass in Buildings*. This is limited to uniformly loaded rectangular panels having continuous support on all four edges. For other applications, hand calculations should normally be sufficient when support conditions allow for simple beam assumptions, as previously and briefly described. Finite element analysis may be required for non-rectangular panels and for other support conditions.

Flat Glass Types

The most commonly used type of flat glass is annealed (AN), which results as the glass is cooled in a controlled manner as it emerges from a float bath from a temperature of approximately 1,100 degrees Fahrenheit down to approximately 200 degrees, such that any residual stresses near the surfaces are nearly zero. Annealed glass can be easily cut and worked. The danger with annealed glass is that it is brittle and breaks easily into dangerous shards. For this reason, common annealed glass must never be used in hazardous locations, where it may be subject to human impact and where falling glass may cause harm, such as for skylights. The relatively high coefficient of thermal expansion of soda lime glass combined with its low tensile strength gives it poor thermal shock resistance, as can be witnessed when boiling water is poured into a non-Pyrex glass.

Annealed glass may be strengthened by heat treatment or by chemical means. Fully tempered (FT) glass is produced by heating annealed glass to approximately 1,160 degrees Fahrenheit, and then rapidly cooling it. Since the faces are cooled first, they initially go into tension. As the interior cools later, however, it contracts and pulls the outer surfaces into compression, on the order of more than 10 ksi. In effect, the glass sheet becomes prestressed. Fully tempered glass is typically four or five times as strong as annealed glass. Another benefit of tempered glass is that when it breaks, the pieces are small cubes as opposed to large shards, and therefore far less dangerous. The downside is that tempered glass cannot be cut or drilled after tempering, since doing so would immediately cause a stress disruption that results in the complete destruction of the panel. All such operations must be done in the annealed state. Another sometimes unwanted by-product of the tempering process is a loss of flatness as compared to annealed glass.

Figure 2: Solar Light Pipe, Washington, DC.

Between annealed and fully tempered glass is heat strengthened (HS) glass, similar to tempering except that residual compressive stresses at the surfaces of the panel are kept between 3.5 ksi and 7.5 ksi. This is often done to improve thermal shock characteristics. Heat strengthened glass is about twice as strong as annealed.

"…glass is now frequently used as a secondary structure for resisting transient loads…"

ASTM C 1036, *Standard Specification of Flat Glass*, generally provides production quality properties such as blemishes and other imperfections that affect appearance, rather than mechanical properties. ASTM C 1048, *Standard Specification for Heat-Treated Flat Glass – Kind HS, Kind FT Coated and Uncoated Glass* is of more practical use to the structural engineer in specifying flat glass for load resisting applications.

Laminated Glass

When flat glass is used in certain hazardous locations, the possibility of falling pieces of broken glass can be effectively eliminated by laminating two or more layers of flat glass with polyvinyl butyral (PVB) in an autoclave. The essential principal is that of redundancy, that is, a structurally intact layer of glass carries a broken layer via the adhesion of the highly ductile plastic interlayer. Indeed, two annealed layers may both be broken, but the overlapping shards tend to keep the entire assembly intact until it can be safely replaced. Laminated glass is commonly used for overhead applications such as skylights, and has more recently been successfully used for glass floors. Laminated glass floors may generally use two equally thick layers of annealed glass, sized for the span and load, topped with a thin fully tempered glass layer for improved impact resistance. For short term loads, a laminated glass panel is usually analyzed as a monolithic piece of glass having a thickness equal to the total thickness of the panel. For longer term loads, however, the plasticity of the interlayer affects the overall performance of the panel. This is accounted for by analyzing the panel as if the glass layers were unadhered, with no shear transfer between them. The applicable standard is ASTM C 1172, *Standard Specification for Laminated Architectural Flat Glass*.

Safety Glazing

In areas subject to human impact, as defined in Chapter 24 of the International Building Code (IBC), so-called 'safety glazing' is required. Such glass must satisfy test requirements as specified in ANSI Z97.1-2004 *Glazing Materials Used in Buildings, Safety Performance Specifications and Methods of Test*. The test simulates the impact of a 100 pound boy running at full speed (22 feet/second). To pass the test, samples must either not break, or break safely, that is, with no sharp-edged shards. Typically, acceptable materials include laminated glass, fully tempered glass, wired glass, and certain plastics. The Consumer Product Safety Commission document *16 CFR Part 1201 - Safety Standard for Architectural Glazing Materials* assigns to safety glazing a rating of either category I or II, with II being the higher rating.

Design Assumptions for Glazing Installations

Despite the high compressive strength of glass, it has generally never been used as the primary structure, except for a few temporary demonstration projects. However, glass is now frequently used as a secondary structure for resisting transient loads, most notably as fully tempered glass mullions for suspended glass walls, as developed by Pilkington in the 1960s.

More typically, glass must be expected to directly pick up applied loads such as wind or impact loads and transfer such loads to four sided supporting frames, which also support the self weight of the glass panel. Such frames must be detailed so that loads from elsewhere in the building are not transferred into the glass. This means that edge clearances must be large enough to ensure that direct contact between the glass edge and the frame is avoided, no matter how the frame is expected to deflect. Furthermore, there must be enough purchase, or 'bite,' so that the glass panel cannot pop out of its frame. There must also be enough face clearance between the glass and the frame to avoid direct contact and to accept sealant, typically between ⅛-inch and ¼-inch. Supporting frame elements should be designed to limit the maximum deflection to span/175 or ¾-inch, whichever is less, measured perpendicular to the glass pane. The weight of the glass panel itself is generally supported by two setting blocks of a resilient and rotproof material such as PVC or nylon, typically located at the eighth or quarter points. Sometimes blocks are also installed on side edges to prevent the glass panel from 'walking.' When laminated or

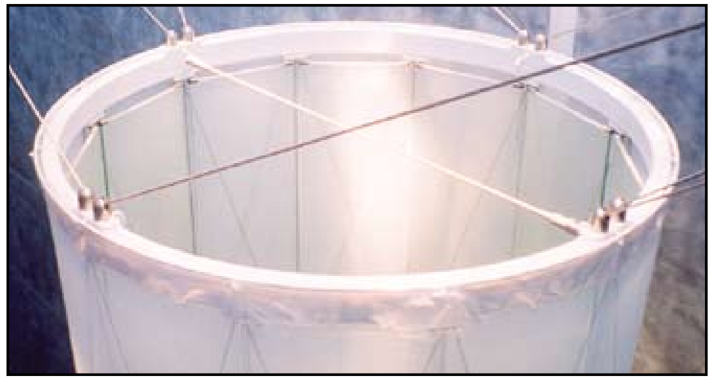

Figure 3: Solar Light Pipe - Top Supporting Ring.

insulated lites are used, the setting block material must be compatible with other materials. As water is detrimental to laminated and insulated glass lites, the frames must be designed to weep or otherwise exclude any water that may tend to accumulate. Much of this information is documented in the *Glazing Manual* published by the Flat Glass Marketing Association.

Glass may also be installed in so-called 'structural glazing' systems, in which out of plane forces on the surface of the glass are resisted by adhesives acting in tension and/or shear, rather than by an enclosing frame. Typical adhesives are wet-applied silicone or pressure sensitive foam tapes, such as the 'VHB' adhesive tapes manufactured by 3M.

Other more sophisticated suspended glass systems are possible, but many of these are proprietary, such as the Pilkington 'Planar' bolted glass system. It is generally far more prudent to have the manufacturer specify the product and its installation, especially considering the great expense in research and testing expended by such companies to bring such products to market, and the need to secure a solid warranty for the product and its installation.

There are yet other applications for which no design manual exists, such as sculptures, and the engineer has to use his or her creativity tempered with common sense, prudence and the knowledge of basic engineering principles to ensure a safe installation. One such example is the 'Solar Light Pipe' for an office building in Washington, DC (*Figure 1 - page 53* and *Figure 2 - page 54*). Nearly four tons of laminated ribbed glass is used to form a refractive cone about 120 feet high, used to bring daylight into the 14 story atrium of an office building. Sunlight is directed down the vertical axis of the cone by a roof mounted 'heliostat,' a large motor driven mirror which tracks the sun.

Figure 4: Solar Light Pipe - Bottom Support Ring.

Each of the 276 glass panels that make up the cone is fully supported by a prestressed tensile frame of stainless steel rods and cables, and machined aluminum fittings. The top of the glass cone has a diameter of 6 feet, and is held by a tubular steel ring suspended from above by high strength stainless steel rods (*Figure 3, page 55*). The cone tapers over its height to a diameter of 18 inches at the bottom (*Figure 4*). At this location, another 6-foot diameter steel ring gathers the stressed outer net of cables, which, in turn, is stressed against the building frame using a set of stainless steel tie rods. The stressed outer net acts as a three dimensional 'cable-beam,' stabilizing the glass cone laterally with radial stainless steel rods which are connected to twelve-sided machined aluminum rings which also support the weight of the glass panels. The weight is then carried up to the top ring of the structure with high strength stainless steel rods which are connected to the aluminum rings. The glass panels themselves are unstressed, merely held in place by aluminum fittings which allow a degree of movement, similar to a typical glazing installation as described previously (*Figure 5*). Though the visual impact is obviously very unusual, the underlying principles are the same.

Figure 5: Solar Light Pipe - Typical Glass Connection Detail.

Conclusion

Glass is ubiquitous in building construction but is hardly understood by most structural engineers. While it is a brittle material like concrete, by its nature it cannot be engineered by traditional load factor or allowable stress assumptions, due to highly unpredictable failure stresses. Instead, design stresses are given at a probability of breakage that is low enough to be considered acceptable, commonly 0.008. Such stresses are modified for load duration and type of glass, which can be annealed, fully tempered, heat strengthened, or a laminate of any of these, depending on what is most appropriate to use for the particular installation. By this approach, the structural engineer can determine what type and thickness of flat glass to specify for a given application.▪

David Kufferman, P.E., owner of the Connecticut firm of David Kufferman PE since 1994, was trained as both a structural engineering and as an architect. David holds a Bachelor and Master of Civil Engineering from Georgia Tech and a Master of Architecture from Columbia University.

References

Aside from those mentioned above, excellent general references for the design engineer include the Handbook of Glass in Construction by Joseph S. Amstock; Glass in Building by David Button and Brian Pye; and Glass in Architecture by Michael Wigginton.