GLASS AS AN ENGINEERING MATERIAL

by Desi J. Kiss, M.S., P.E. ©

The application of glasses in engineering design can have many facets and innovative contributions to many industries. Besides the window-type applications, glass fibers are uses in insulation, sound deadening, as fillers in plastics, and as reinforcement in plastic laminates and structural shapes. Glasses can be used to transmit or shield radiation. Moreover photosensitive glasses for fluidic devices are used in machine controls. Glasses are widely used in the food industry because their chemical resistance and many foods are processed in glass-lined tanks. Probably the largest use of glass, yet mostly ignored by designers and engineers, is the construction industry. Glass has been used in building construction since ancient times.

Over time, the basic recipe for glass has evolved rapidly to the present composition for common soda lime glass, which is approximately 69 % silica, 17% soda, 11% lime and magnesia and 3 % alumina, iron oxide and manganese oxide. Although the main structural frame is made out of steel or concrete, most of the of the new high and medium-rise buildings are predominantly glass, which is strong enough to take wind loads and withstand the outdoor environment indefinitely with the only maintenance being an occasional wash.

Traditionally, glasses are defined as super cooled liquids. This is because glasses do not behave like metals, ceramics, or even plastics on cooling from the molten condition. Glasses are predominantly non-crystalline fusion products of inorganic materials, mostly oxides. They have good mechanical properties and a wide range of thermal, electrical, and optical properties. Other chemical compositions have been developed since the early 20th century for more specialized uses such as low-iron, water-white glass and borosilicate glass (Pyrex).

Glasses are resistant to most acids, bases and solvents, but a few things like hydrofluoric acid will rapidly attack them, and corrosion data must be consulted prior to design specifications for the various environments. Glasses are slowly attacked by water and some alkaline solutions. Even though glasses have a questionable melting point based on physical property measurements, they do melt. To be more exact, on heating, the viscosity decreases to the point where the glass can be poured into mold sand cast to shape. They have large applications in machines and the construction industry, but many more could probably found with a little consideration on the part of the designer or the design engineer.

PROPERTIES OF GLASSES

The properties of glasses vary with composition, and any novice knows that glass breaks. Chemically strengthened glasses can have tensile strengths as high as 50 ksi (345 MPa). Commercial availability of stronger glass will further increase the use of glass for structural and architectural applications. Machinable glass-ceramics are also available for use as insulators in machines and similar applications. They have continuous use temperatures as highs as 1500º F (815ºC). Design Engineers are aware that glass breaks because it is weak in tension and that common window glass typically fails in bending.

Some general statements can be made about glass in general:

- Glasses have low ductility; they are very brittle.
- Glasses have a tensile strength in the range of 4 to 10 ksi (27 to 69 MPa).
- Theoretical compressive strength of glass, based on atomic bond strength calculations is approximately 3,000 ksi.
- Glasses have a low coefficient of thermal expansion compared with many metals and plastics.
- Glasses have low thermal conductivity compared to metals.
- The amorphous glasses have a modulus of elasticity in the range from 9 to 11,000 ksi (62 to 76 x 10^3 MPa) and crystalline glasses have a modulus of elasticity of approximately 20,000 ksi (138 x 10^3 MPa).
- Glasses can be good electrical insulators (electrical resistivity can be higher than 10*15 Ω cm)
- Glass has a density of 158 PCF, slightly less that of aluminum.
- Glasses can be used at elevated temperatures, and are resistant to many acids, solvents and chemicals, and are slowly attacked by water and some alkaline solutions.
- Optical properties of glasses make them superior to clear plastics for lenses, sight glasses and windows.
- High-silica glasses have excellent thermal shock resistance and can be heated red-hot and water quenched without cracking.

Although, the compressive strength of glass is much higher than concrete for example, it never tests out at anywhere near the 3,000 ksi level, since any uniaxial test induces tensile stresses, and unpredictable surface imperfection in the glass causes stress concentrations that result in varying failure stresses, even between otherwise seemingly identical test samples, due to imperfections which are not visible to the naked eye and irregular cracks in the surface of the glass. Larger imperfections such as scratches will also severely weaken the glass, as anyone who has worked with glass can tell.

Moreover, the presence of water or other contaminants in these flaws can attack the atomic bonds, making the glass weaker. Load duration may also affect glass strength in terms of 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 un certainty, glass is often given a survival probability at a given stress level.

For a probability of breakage of 50 % the modulus of rupture can be expected to be approximately 6.0 ksi for annealed glass which means that half of the test samples would be expected to break at stresses below 6.0 ksi, and half at stresses greater that this value. Some glass producers recommend a design modulus of rupture around 2.8 ksi (non factored load) for annealed glass based on a probability of breakage of 0.008, which is accepted by 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 sec., which is commonly used for wind loadings. For some designs the above value for breakage may be considered high, and a lower design stress would be called for.

For most of the glasses used in the building industry ASTME E 1300 - Standard practice for Determining Load Resistance of Glass in Buildings provides design guidelines for design engineers for various applications. The guidelines are limited to uniformly loaded rectangular panels having continuous support on all four edges. For additional applications, hand or computer generated calculations should be sufficient when support conditions allow for simple beam assumptions. Finite element analysis (FEA) is required for non-rectangular panels and for other type of panels and for other support conditions.

MOST COMMONLY TYPES OF GLASSES USED FOR DESIGN

Design engineers are familiar with a wide range of traditional engineering materials such as: steel, aluminum, concrete, wood, masonry, plastics, ceramics, composites and many other metals and engineering materials. These traditional materials of choice for the design engineers are well known and the choice appears to begin and end with them. Although new materials have been introduced recently, a material like glass, which has a density and Young's modulus similar to aluminum, and a theoretical compressive strength approximately one thousand times that of concrete is not included in this traditional group of engineering materials?

Despite the high compressive strength of glass, it has never been used as the primary structural element in any building or structure, except perhaps for a few temporary research and demonstration projects. However, recently glass is now frequently used as secondary structure for resisting transient loads, most notably as fully tempered glass mullions for suspended glass walls and other applications.

In addition glass fibers are used for various structural and architectural applications such as: grating, structural shapes, handrails, stairs and platforms. In addition the most common reinforcement for polymer composites is glass fiber. The acronym FRP, for fibrous-glass-reinforced plastic, was established to prevent the misuse of the Fiberglass trade name, and this acronym was replaced by RTP, for reinforced thermosetting plastic.

Flat Glass Types

Sheet glass can be made by casting in flat plate-type molds. The less flat window glass is made by drawing a sheet out of a molten pool. The most commonly used type of flat glass is annealed, whish results when the glass is cooled in a controlled manner as it emerges from a float bath from a temperature of approximately 1,100º F down to approximately 200º F, such that any residual stresses near to the surfaces are close to zero. *Annealed glass* can be easily worked and cut. *Annealed glass* is brittle and breaks easily into small pieces, and for this reason shall not be used in hazardous locations, subject to human impact and where falling glass may cause harm.

The relative high coefficient of thermal expansion of soda lime glass combined with its low tensile strength gives it poor thermal shock resistance. Annealed glass may be strengthened by heat treatment or by chemical means. Fully *tempered glass* is produced by heating annealed glass to approximately 1,160º F and then rapidly cooling it. Since initially faces are cooled first they go into tension. As the interior cools latter it contracts and will pull the outer surfaces into compression, on the order of more than 10 ksi. The glass sheet becomes prestressed. Fully tempered glass is typically 4 to 5 times stronger than annealed glass. Another benefit of tempered glass is that when it breaks, it is less dangerous since it breaks into smaller cubed like pieces. Tempered glass cannot be cut or drilled after tempering, since doing 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.

Between the annealed and fully tempered glass is *heat strengthened glass,* similar to tempering with the exception that the residual compressive stress at the surfaces of the panel are kept between 3.5 and 7.5 ksi. This is done to improve thermal shock characteristics. This type of glass is about twice as strong as annealed glass. 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 designer or engineer. ASTM C 1036- Standard Specification of Flat Glass provides quality properties such as blemishes and other imperfections that affect aesthetics rather than mechanical and other properties.

Laminated Glass

Laminated glass is obtained by laminating two or more layers of flat glass with polyvinyl butyral in an autoclave. The essence of the laminated glass 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. Two annealed layers may be both broken, but he overlapping shards tend to keep the assembly intact until it can be safely replaced. This type of glass is used for overhead applications and more recently for flooring in assemblies with annealed and tempered glass layers. 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 long term loads 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. ASTM C 1172-

Standard Specification for Laminated Architectural Flat Glass provides mechanical properties and other information applicable for design.

Safety Glazing

Safety glazing requirements are provided by the 2007 California Building Code (CBC) or the 2006 International Building Code (IBC). As defined in Chapter 24 of the CBC/IBC *safety glazing* is required in all areas subject to human impact. Such glass must satisfy test requirements as specified in ANSI Z 97.1-2004 - Glazing Materials Used in Buildings, Safety Performance Specifications and Methods of Test. Typically, acceptable materials include laminated glass, fully tempered glass, wired glass, and certain plastics. To pass the test, samples must either break safely with no sharp-edged shards or not break at all. In addition to the ANSI Standard, 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.

Glass Fibers

Glass fibers are made essentially by flowing molten glass through tiny holes in dies. Two very important types of glass are in wide use for reinforcements: E glass, which is essentially a borosilicate glass named for electrical and electronic applications, and high strength S glass which is a magnesia-alumina-silica material with higher tensile strength than E glass. Fiber diameters are in the range of 0.0002 to 0.001 in. Both are used for the same type of applications; however E glass is more cost effective, since it can be fabricated at lower temperatures. Glass reinforcements are available in every imaginable form. The most common are *chopped strand* widely used for reinforcing of thermoplastics and for bulk molding compounds. *Strands* usually consist of many individual filaments for use in filament winding or in making *weaves*. Another common form is the *mat cloth*. Math cloths are made from randomly intertwined discontinuous fibers of moderate length, not unlike a felt. Glass fiber mats require more resin for saturation than do weaves, but they produce a better surface texture after molding.

GLAZING APPLICATION AND DESIGN ASSUPTION FOR INSTALLATION

Application of glasses in engineering design are multi faceted and are used in many areas of our society. Besides the window-type applications, glass fibers are uses in insulation, sound deadening, as fillers in plastics, and as reinforcement in plastic laminates. Glasses can be used to transmit or shield radiation. Moreover photosensitive glasses for fluidic devices are used in machine controls. Glasses are widely used in the food industry because their chemical resistance and many foods are processed in glass-lined tanks.

Probably the largest use of glass, yet mostly ignored by designers and engineers, is the construction industry. Despite its high compressive strength, glass in general is never used as the primary structure. Steel, concrete masonry or timber or the most frequently used materials for construction. However, as the cost of materials increases, glass is now frequently used as a secondary structure for resisting transient loads.

Glass must be expected to carry loads such as wind or impact or blast loads and transfer such loads to four sided supporting frames that also support the self weight of the glass panel. In addition 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 expand or to deflect and to allow for enough face clearance between the glass and the frame to avoid direct contact and to accept sealant or epoxies. This clearance must be between 1/8 to ¼ in. The frame deflection is limited to span/175 or ¾ in, whichever is less, measured perpendicular to the glass pane. The Glazing Manual published by the Flat Marketing Association provides additional information with regards to installation procedures weather proofing. As water is detrimental to insulated and laminated glass lites, frames must be designed to weep or to exclude any water that may tend to accumulate. Other systems such suspended glass are possible, but many of these are proprietary.

It is in general, more cost effective to have the manufacturer specify the product and the installation, taking into account the costs related expenses with regards to research, development and testing by these companies to bring these products to market and to provide the warranty for the product and its safe installation. Glass may be also installed in structural glazing systems, in which the out of plane forces of the surface of the glass are resisted by adhesives or epoxies acting in tension and/or shear, rather than by an enclosing frame.

Recently, fiberglass structures, systems and structural shapes are widely being introduced to the construction industry especially in corrosive environments. Fiberglass solves corrosion and maintenance problems for many of the applications. Most fiberglass structural shape manufacturers provide design manuals for designers and engineers for use and reference. Architectural applications of prefabricated lightweight fiberglass structures, handrail, stairs, platforms and landings can be designed to blend into existing architecture.

One such example is a 37-foot tall, all-fiberglass, gold leaf clad Spire, installed atop of the 55 story C&S Building is the golden high point on the Atlanta skyline. The fiberglass Spire is transparent to electromagnetic waves and houses communications antennae. Architects believe the fiberglass Spire aesthetically enhances Atlanta's tallest building-making it the city's landmark skyscraper. In addition, the Spire is extremely valuable real estate – prime antennae rental space is scarce and expensive.

There are yet many other applications for which no design manual or procedure exists, such as: boats, sculptures, impact from blast explosions, etc, and the design engineer must use his/her creativity and innovative judgment and common sense, prudence and the knowledge of fundamental engineering principles to ensure safe installation. Glass is important in building construction but is hardly understood by most design engineers and building and equipment designers. While glass it is a brittle material like concrete, by its nature it cannot be engineered by traditional load factor or allowable stress assumption, due to highly unpredictable failure stresses. Instead, design stresses are given at a probability of breakage that is low enough to be considered acceptable. 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 application. By using this approach the design engineer can determine what type and thickness of flat glass to specify for a given project or application.

The advantages of using glasses and glass fibers are numerous, and they will ultimately increase the useful, life span of the structural and architectural systems.

This is an example of the new building environment pressing the construction industry to new levels of value-added performance, resulting in superior solutions.

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