GLASS AS A STRUCTURAL MATERIAL

by

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Abstract

Glass can be beautiful and strong, so why is it not used more often as a structural material? Most often the reasoning is because people fear its perceived fragile and dangerous nature. Although this is the perception, it is far from the reality. Structurally designed glass can even withstand higher loads than steel. The following report will present several advantages of using glass as a structural material. Because understanding the history of glass can foster a greater understanding of where the future of glass is headed, it is discussed early on. After this, the focus is on how to make a mixture of molten liquid into a structural member. The manufacturing process is at the root of the strength of glass, as are the material properties. The composition and properties of glass are addressed before discussing various uses of glass as a structural material. As architects begin to ask for more structural glass in their projects, structural engineers must be prepared to design the systems or to specify performance criteria to a specialty engineer. To aid in design, published guidelines and testing must be utilized and are therefore discussed. In a glass structural system, the glass is not the only aspect that needs an engineer's attention. Connections present a special challenge when designing with structural glass, but several different forms of connections have been successfully demonstrated in construction. To tie all the previous topics together, three examples of structural glass systems are presented. Europe has been using glass as a structural material for years, but the United States has been slow to follow the trend. Glass has been proven to work as a structural material that can create impressive visual impact. With the support of the glass manufacturing industry and the courage of design engineers, the United States could easily start a movement towards building with structural glass.

Table of Contents

List of Figures

List of Tables

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CHAPTER 1 - Introduction

Even though it is technically liquid, glass could be the greatest structural material known to man. It is considered a liquid because the molecules are disorganized like in a fluid, but they are rigidly bound like a solid. Architects love glass because it does not obstruct a view or visually interrupt a room. Structural engineers should love it because when theoretically compared to steel, it can carry two times the tension load (Maloney 30). Also, because glass is the most recycled material in the world, the supply is plentiful and non-detrimental to the environment (Nijsse 21). However, theory and practice are two different things. While glass would win in a theoretical competition for the best building material, it would fail in a practical contest. Both social and physical limitations must be overcome before glass can gain widespread acceptance as a structural material.

The social limitations of glass include the psychological effects of having no privacy and the stigmata that glass is fragile and weak. The Russian film director Sergei Eisenstein is famous for showing the human desperation that is caused by too much openness and lack of privacy (Nijsse 11). To an extent, this constraint can be overcome by using translucent or frosted glass. As for the perception that glass is fragile and weak, this can be overcome with education. In actuality, glass is very strong and versatile. Because most people feel glass is dangerous, building with it is very risky. This risk is what keeps many owners from asking for it and many contractors from agreeing to build with it.

Actual physical limitations do hinder the growth in the use of glass as a structural building material. The main weakness with glass is its brittle nature. Glass must meet the following criteria to be considered brittle: It will fail in tension and not shear, and will deform very little before it breaks. Finally, glass develops forked fractures due to internal stresses. When an original fissure is traveling with explosive violence, smaller splits will propagate throughout the glass (Phillips 63). To demonstrate the lack of plasticity in glass and the immense brittle nature, the velocity of crack propagation is examined. A crack travels through glass at about 5040 feet per second, which is one-third the speed of sound through glass. At that speed, a crack would travel 2.5 inches in only $^{1}/_{24,000}$ second (Phillips 70). The brittleness of glass keeps it from redistributing forces, which causes intense stress concentrations. Typically, failures in glass are due to these concentrations.

Through an understanding of the properties of glass, one could realize the many possibilities of glass in structural applications. One such example is the Berlin main train station shown in Figure 1-1. Knowing how glass is manufactured and its material properties will aide in an understanding of glass as a structural material. To design any structure, an engineer must follow codes and specifications. An added complication of designing glass is how to hold the structure together. Connections can determine the difference between stability and failure. After reviewing all of the factors that effect glass design, looking at examples will bring everything back together. In today's society, fear and economics hold glass designers back. Until that fear is overcome by a better understanding of the strengths and limitations, glass will never move into mainstream construction in the United States (Davidson Online).

Figure 1-1 Main Train Station in Berlin, Germany (Personal Picture)

CHAPTER 2 - History

Glass existed, even before humans intervened. Before humans began to artificially manufacture glass, it occurred naturally. One such glass is obsidian, a volcanic rock that is rarely transparent and more typically translucent. While some light can pass through a stone of obsidian, it cannot be seen through. It is theorized that this type of glass was used by inhabitants of the Stone Age for various purposes. For example, arrowheads, spearheads, knives, and razors were easily crafted with little skill (Phillips 3). Beads could also be easily fabricated by carving large blocks of solid glass into the desired size and shape (Maloney 50).

The first use of man-produced glass was as glazing. Glaze was a decorative coating of glass around a vessel made of another material. The item to be glazed was given a new exterior layer by dipping it in molten glass. Once the glass had set, the vessel was reheated and threads of colored class were pressed in to add designs (Maloney 51). Stone beads have been found that used glass as a decorative coating. Some beads from Egypt have been dated as early as 12,000 B.C. (Phillips 4). Glazing was also very common during the Eighteenth Dynasty in Egypt from 1500 to 1250 B.C. During this time, glass was used to adorn various pottery pieces and stones. It was typically done by coating a sand form or core with several layers of molten glass. Once the glass was thick enough to support itself, the sand core was removed leaving a shell type vessel. Many experts agree that glassmaking began in Egypt because after the discovery of the glazing method, glassmaking became a very stable and long-lasting industry (Maloney 51).

While a number of experts believe that Egypt was where artificial glass was first used and manipulated, others believe that evidence shows that it originated in Mesopotamia. Those experts who believe it started in Mesopotamia also acknowledge that the glass making process was quickly taken to Egypt soon after its discovery (Phillips 4). During the early days of glassmaking, it was rare to have transparent glass. Very little was known about the chemistry of glass and there was no way for the people to manipulate the natural occurring colors. At this stage in the history of glass, transparency was not a concern like it is today. Because glass was so rare, it was most commonly used for personal ornamentation. The rarity was a quality that made it nearly as valuable as naturally occurring gems. This was true until an industrial revolution, between 300 B.C. and 20 B.C., made glass easier to produce, thus transforming it into a necessity (Phillips 5).

In Babylon around 200 B.C., a few simple inventions revolutionized the glassmaking process. The first and most commonly known tool was the blowing iron. This hollow rod was typically made of iron. The length varied from 40 to 60 inches. One end of the blowing iron had a mouthpiece and the other had a knob. Figure 2-1 shows how the beginning of a globe is formed from a ball of molten glass using a blowing iron. The mouthpiece is where the glassmaker would blow to shape the molten glass that was attached to the knob at the other end. Because of gaps in glass history, the name of the inventor as well as the date is unknown (Maloney 51).

Figure 2-1 Blowing a Glass Globe (Personal Picture)

Similar to the blowing rod, a pontil (or punty) was an iron rod used to shape glass. The difference between the tools was that the pontil was a solid rod. Instead of blowing through this rod, the glassmaker shaped the glass by spinning, squeezing, and cutting the soft glass. With either of these rods, a marver was typically used. This tool was a polished iron slab that molten glass was rolled on. Again, because of gaps in history, the backgrounds of both of these tools are relatively unknown (Maloney 51).

Some experts believe that the Christian era was the first golden age of glass. Part of the reason for this theory was that glass was becoming more easily produced, partly due to the stability of the Roman Empire. Glassmaking techniques spread very quickly during this period because manufacturing flourished in every country Rome conquered. As the manufacture of glass spread, some glass objects became household necessities while others remained luxuries (Phillips 7).

The materials in glass most typically defined the color of a finished glass piece. Glassmakers used this to their advantage to create beautiful vases. The beauty and intricacy of these vases often made them more precious than vases crafted of silver or gold. In regions where the religion advocated cremation, glass urns became a very popular option. Items such as these were only available to the wealthy because of the cost of manufacturing them (Phillips 8).

The major advances in the glass industry were essentially lost after the collapse of the Roman Empire. For several hundred years afterwards, glass was produced in Western Europe, but the quality was nowhere near what it was during the earlier Egyptian and Roman eras. Finally, around A.D. 970, the Byzantine people developed stained glass, which derived its name from the natural tint certain glasses possessed (Philips 10). Early glassmakers found that certain metallic oxides would create colors when added to a glass mix. Even a small change in the oxide content of a mix could create dramatic changes in color. Copper was often added to create a ruby red stain, while introducing iron oxide into a glass could create a green, black, or brown color. Farther along in the history of glass there is evidence that glass was painted to change its color. The most common application was a stain made of silver chloride. When applied to an already colored piece of glass, the silver chloride would change the appearance, thus making it possible to see two colors in a single object of glass. Often the solution was applied to blue glass to turn it bright green, or even to red glass to produce orange. As glassmakers discovered more colors, the demand for decorative glass increased. It was during the Middle Ages that the first uses of stained glass in windows were recorded (Maloney 54). Although windows had been around since the end of the third century, stained glass was a new use for glass during the end of the tenth century. Typically, the colored glass was used in church and cathedral windows (Industry Online).

While it appeared to be simple, the manufacturing of flat glass presented many challenges. Because of this, windows were typically small and expensive. Until the nineteenth century, most flat glass was created by blowing and spinning. This technique is depicted in Figure 2-2. To begin the process, the glassmaker would create a globe on the end of his blowpipe. From there, the globe was opened up, reheated and spun. The spinning created a centrifugal force that caused the glass to flatten out. The problem with this process was that it rarely created quality glass. A disk would be spun until it had cooled sufficiently to hold its shape. Even after the piece hardened, it was not completely flat. It was easy to see where the centrifugal force had pushed the glass away from the center because it was thickest at the center and grew thinner towards the edges. Along with varying thickness, rings of ridges and hollows surrounded the thick bump where the disk was removed from the blowing iron. These variations caused severe distortions that caused limited illumination and little visibility (Maloney 62).

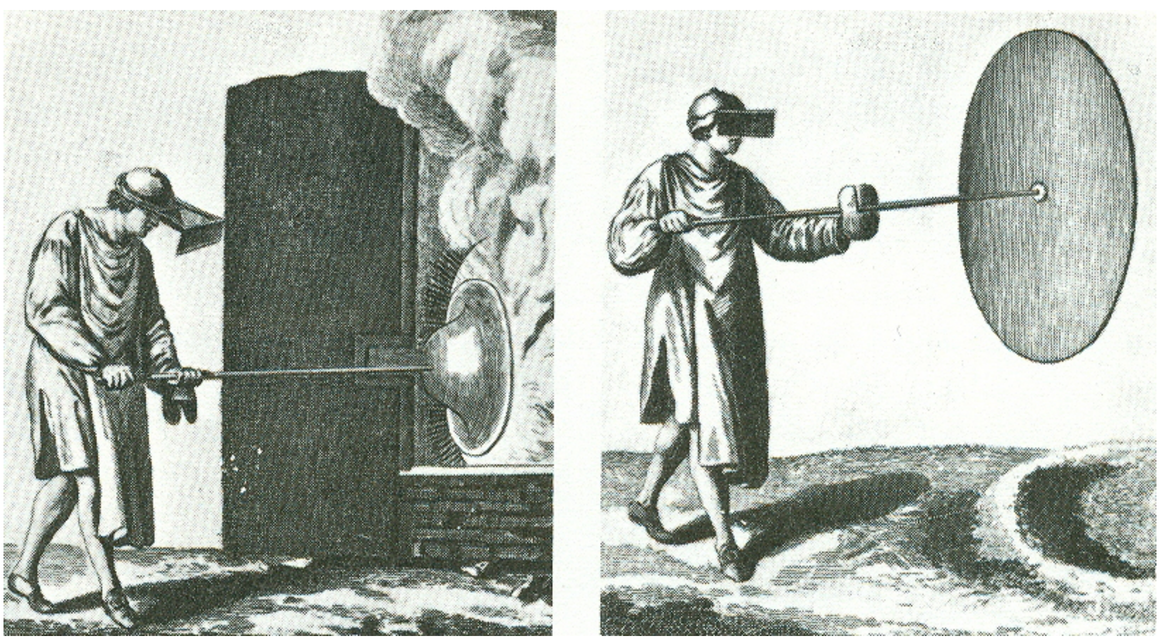

Figure 2-2 Method for Spinning Flat Glass (Maloney 63)

For nearly four centuries following the Crusades, the center of the glass world was Venice. During this time, all the advancements of the Romans were rediscovered and put into practice. In addition to employing the same glassmaking techniques, the Venetians improved upon the Roman skills. The most notable achievement of this time was the introduction of the first absolutely colorless and transparent glass. The glass was labeled “Cristallo” which is where the modern word “crystal” comes from. The properties of this glass allowed it to be blown very thin and worked into nearly any shape (Phillips 10-11).

By the fifteenth century, the use of glass was very widespread. Nearly every European country had established a glassmaking industry. As the art of glassmaking spread, it became more and more uncommon to find homes built without glass windows. Also, it was very common to have not only dishes and bowls made of glass, but also drinking glasses, bottles, and flasks (Maloney 58).

Since the late sixteenth century, glass manufacturing has become more scientific. Innovations such as changing from wood to coal furnaces revolutionized the manufacturing process. These coal furnaces were capable of reaching higher temperatures, so it took less time to melt glass. Temperatures between 950ºF and 2750ºF must be reached to achieve a viscosity acceptable for fabrication of glass pieces (Phillips 57).

In the first few decades of the seventeenth century, a process for casting glass was invented, making large polished plate glass much easier to produce. An English developer found in 1675 that using lead oxide in glass gave it brilliance and a relative softness, which made it easier to work with. This glass was called flint glass because very pure silica was introduced to the mix in the form of flint. From the discovery of flint glass, until the late eighteenth century, most glassmakers produced flint glass (Phillips 13). Another important discovery came in 1790 when a method for producing optical glass was found. Optical glass is different from the typical flint glass because it is chemically homogeneous and free from most physical imperfections. One of the biggest advancements in glass manufacturing during the last 200 years was the discovery of new elements available to create glass. Prior to 1880 only five or six different elements were used in glass production. The two most common types of glass were flint glass, which uses lead oxide as a base, and crown glass, which used lime as the main element. After years of research by many scientists, the number of elements increased by at least 25 (Phillips 14).

The historical roots of glass are firmly embedded in Europe and Asia, but it also has a strong history in America. Not long after settlers arrived in James Towne, Virginia, the first manufacturing establishment was built. The first operating factory in American was a glass factory. In 1609, glass became one of the first exports from the colonies. In the beginning of American glass manufacturing, wood furnaces were used to produce bottles, beads, and other charms. These items were then used to barter with Indians. Throughout the early years of the American colonies, many glass factories opened, but many did not remain in operation for any significant length of time. The first successful long term manufacturing plant was located on Manhattan Island from 1645 to 1767 (Phillips 15).

In 1900, many glassmakers were using the same processes as they were 500 to 1500 years prior. At this time, secrets still dominated the industry. Most often, a family kept a secret and passed it from generation to generation. Although many achievements were accomplished by Europeans during the early history of glass, American workers have also had a helping hand in making glass what it is today. It was Americans who designed the glass for Edison's light bulb in 1879, invented heat-resistant glass (Pyrex) in 1904, and invented "safety" glass in 1926. Using glass as more than windows in a building began with glass blocks in the early 1930s (Phillips 18). Knowing the history of glass gives an understanding of where it has been, but more importantly where it is going. Table A-1 in Appendix A gives a side-by-side comparison of the history of glass and the history of man in terms of major accomplishments in science and the arts.

CHAPTER 3 - Manufacturing Process

Over the centuries, glass has evolved in many ways. In the beginning, humans had no understanding of how to manipulate it, so the natural occurring glass was the only available option. Now glass can be made to perform any number of tasks in any number of shapes. The manufacturing procedure controls the possible uses of glass. From the batch contents to the forming and finishing method, each process of glassmaking produces a different product. Such products include everyday items such as windows, drinking glasses, vases, and bottles. Also, less common products are produced from glass including telescope lenses, glass masonry, or even glass floors, and glass beams.

In the glass making process, combining the right quality and proportion of materials is very important. Several elements and compounds are usually combined together to create particular types of glass. The ingredient that usually constitutes the highest percent in most glass is silica, SiO_2. Other elements are often present in the form of oxides, including soda, which is sodium oxide (Na2O), and lime which is an oxide of calcium (CaO). Slight variations in a mix can alter the properties as well as the mechanical behavior of glass when loaded (Industry Online).

The components of glass, whatever they may be, are combined in a furnace where they will be "melted" together. The temperatures that must be reached for this phase are dependant upon the individual components of the glass, but they range from 2400ºF to 2900ºF. The use of the term "melting" can be misunderstood when referring to glassmaking. While all components begin in a solid form, not all of them immediately turn into a liquid during the initial heating process. Instead, what happens is at the escalated temperatures the raw materials react and create new compounds. This process is a necessary step on the way to the high temperature fusion that creates molten glass. Once the glass is molten, chemical reactions continue to occur during the refining stage. The refining phase is very important because this is when all the gasses present in the mix are released through bubbles. This stage takes place at temperatures ranging from 2700ºF to 2900ºF. Failure to eliminate all the gas prevents the glass from becoming a homogeneous solution resulting in a weakened final product. The best way to eliminate bubbles is to melt the glass as rapidly as possible. This allows the bubbles to escape by their own buoyancy (Maloney 78).

In the modern manufacturing process, any glass that is trimmed away or broken is kept to be reused. This waste glass is added, along with the basic ingredients, into a new batch. The waste glass melts faster than any of the individual ingredients, so it aides in lowering the mixture's overall melting point. Thus, in addition to eliminating waste, recycling the glass makes the mixing process faster (Maloney 76).

To melt glass, either a pot furnace or a tank furnace can be utilized. Because the heating process takes longer, typically the only time that a pot furnace is used is for optical glass or crystal-glass. A pot furnace contains three to twelve pots made of a refractory material. The pots must be made of refractory material so that they can withstand the high temperatures created in the furnace. The main purpose of the pots is to retain the molten glass. The furnace that the pots are placed into is responsible for producing the heat required to melt the glass. The pots are preheated at a slow rate in a special furnace called a pot arch. Once the pots reach a temperature above 1000°C, the pots are transferred to another furnace that is operating near the required glass-melting temperature. The pots are preheated to prevent cracking that could occur if pots were placed directly into a furnace and heated quickly (Maloney 74). In the case of most structural glass, such as in windows, a tank furnace is employed. A tank furnace is one in which the walls serve to retain the heat as well as hold the molten glass. Tanks can range in capacity from five tons up to 1000 tons. Most tank furnaces used today are a continuous tank. They are continuous because as glass is being drawn from one end, components are added to the batch at the other end. This provides a constant output of glass, which is ideal for manufacturing purposes (Maloney 77). No matter which type of furnace is used, it is important that the interior of the melting tank be specially designed to prevent corrosion. Molten glass is very caustic so the usable life of a normal continuous tank furnace is limited to three or possibly four years (Maloney 75).

Chemical composition influences the properties of glass, but it is not the only feature that does. The shape of the glass product and how that shape is formed can determine the properties of each piece of glass as well. In addition to the shape, the way a member is finished will have a tremendous effect on its mechanical properties. Ultimately, the final use of a piece will dictate what finishing process will be used. For example, several ways exist to strengthen glass for use in structural applications. A few of the finishes that can alter the strength of glass are annealing, toughening, tempering and laminating.

Finishing Processes

Glass has a relatively low actual fracture strength compared to its theoretical strength. The theoretical fracture strength is determined by the amount of force that must be applied to overcome the maximum restorative force, which is a function of the distance of separation between atoms. If the distance between atoms becomes too large, the maximum force is exceeded and the glass breaks apart at the molecular level (Shelby 185). While most of the difference in fracture strengths is a result of small surface imperfections, a part of it has to do with the method of manufacture. Because of the brittle nature of glass, even small tension stresses can cause complete and immediate failure in a member. Tension is very detrimental to glass because if it is present at the tip of a flaw, it causes that flaw to propagate without boundary (Maloney 30). To alleviate this problem, different finishing processes are employed, some of which reduce stress while others induce stress.

Stresses that are inherently present in a finished piece of glass are residual stresses and are caused by strain that is induced during the cooling procedure. Annealing is the process of removing all these residual strains from a piece of glass by reheating the finished piece to a precise temperature range depending on the composition of the glass. Although this process was used in ancient times, it was not scientifically based until World War I. When scientifically analyzed, it was found that strain can be eliminated by very precise temperature control over a narrow temperature range. At the annealing point, the upper limit, internal stresses are relieved by the flowing of the glass. The other end of the range is often referred to as the strain point. Unlike the annealing point, the lower temperature limit is often a vague number because of a number of interrelated variables. When the internal temperature of a piece falls below the strain point, little or no viscous flow takes place, so no more strains are removed. The time it takes to anneal a typical commercial plate glass is around sixteen hours (Phillips 228). For most commercial annealing, there are limits on the maximum practical level of stress that remains in an object. Table 3-1 shows some of these tensile stress limits (Phillips 230).

Table 3-1 Practical Stress Limits for Commercial Annealing (Phillips 230)

Object Being Annealed	lbs/in^2
Optical glass – Course Annealing	42
Telescope reflector blanks	85
Common practice – Most ware	250
Sections flame annealed	400
Tubing – Tension, inner surface	480

While annealing removes the residual stresses induced during the production process, toughening actually induces a pre-determined amount of strain into the object. Glass is not tough because it has very little resistance to crack growth. Once a flaw forms, a crack will propagate until the glass reaches failure. The toughening process is performed after the glass is made into the final product and comes to its natural temperature. After all finishes and connections are completed, a member can undergo the toughening process. There are two ways of making toughened glass, thermally or chemically. Thermally toughened glass can also be referred to as tempered glass (Phillips 264).

Tempered glass is prepared by heating the glass to a very high temperature, near the set melting point, and then rapidly cooling the surface. Because the center cools more slowly, it creates a dense internal structure, while the surface is less dense. Also, the outer surfaces will prevent the inner area from shrinking completely. This puts the surface in compression and the center area in tension. Fracture mechanics explains that when glass fails, it is most commonly caused by a small crack or nick in the surface that is propagated by tensile stresses. With tempered glass, the tension zone is on the interior and therefore has no effect on the surface cracks which are in compression. Introducing compression stresses onto the surface of a glass element is good because that means the member can hold more tension before failure since the initial compression must be overcome first. In addition to carrying an increased tensile load, toughened glass can also withstand larger impact loads (Maloney 99).

Even with the benefits of specifying toughened glass, drawbacks do exist. For example, if a crack in the compression zone was deep enough to reach into the tension zone of the element, it could still fail quite suddenly. Another drawback is that any trimming, or hole borings need to be made prior to the finishing of the glass panel. Traditionally, glass is cut or drilled using water as a lubricant and a diamond bit. Modern techniques are slowly entering into glass manufacturing. These new techniques use lasers or high-pressure water to cut through glass (Nijsse 30). Cutting through the plate after toughening could create nicks and dings during this process, causing the glass to break immediately (Maloney 100).

Chemically toughening glass is a much different process than that of thermally toughening. The premise behind chemically toughened glass is that the surface layer has a completely different composition than the inner core. There are two different ways to chemically strengthen glass. One is by ion exchange and the other is a reverse ion exchange. In both instances, the glass member is submerged in a molten liquid that facilitates the ion exchange. During chemical toughening, lithium oxide from the glass reacts with the molten sodium chloride and leaves the sodium on the exterior of the glass member. The exchange of these ions induces compression stress into the outer layer of the member because the sodium ion is larger than the lithium ion. Therefore, tensile stresses must overcome the compressive stresses for a flaw to propagate and cause failure. The reverse ion exchange is exactly that. Instead of sodium replacing lithium, lithium replaces sodium (Maloney 173). Because of the chemicals and processes involved, chemical toughening is more expensive than thermal toughening. Although this is true, chemical treatment has two major advantages over thermal toughening, including increased strength and resistance to temperature. By using thermal glass, strength is limited. Using chemical toughening increases the strength to two or three times that of thermal toughening. Also, unlike tempered glass, heat will not destroy the intended effect (Maloney 175).

Laminating is another method of making glass stronger. The process makes two or more panels of glass into a single member by using an intermediate layer of another material. The most common interlayers include polyvinylbutyral foil (PVB or vinal), Urethane, and cast-in-place resin (Innovative Online). A few of the benefits of laminated glass are that it is not only stronger, but it also fails in a more ductile way. Standard glass gives no warning signs of failure, but with a laminated piece there is a noticeable amount of warning before failure (Designing Online).

The laminating process begins with the same mix composition and finishing as annealed glass. After the individual pieces have been annealed, they are combined with the PVB foil, which acts as a glue. Before applying the glue, it is dried to reduce the moisture content. After drying, it is applied in a sheet form to the glass. Very specific room conditions must be maintained to make the laminating process successful. When all the layers of glass and vinal are assembled, they pass through a series of heaters and rollers that form an initial adhesion. Following this, the object is placed into an autoclave where pressure and heat are added to finish the gluing process. Upon exiting, the interlayer is no more than one-hundredth of an inch thick and completely transparent. Cooling must be done slowly to prevent cracking, but once at room temperature the glass object is complete and ready for use (Maloney 100).

When using glass for structural members, such as beams, laminated glass is always used. This is due not only to its increased strengths and ductility, but also because it is a built in protector of itself. Glass beams are built of at least three glass panels that are connected together. If either of the two outer panes were to become damaged they would fail completely, but because of the redundancy the member itself does not fail. The sacrificed exterior panel may be in shattered pieces, but those bits stay connected to the glue and protect the inner panel from receiving damage (Nijsse 14). It is also possible, using laminated glass, to create greater spans. By staggering the joints between the inner and outer panels, beams can span twice as far as those without staggered joints. This method is best accomplished using a resin instead of PVB foil (Nijsse 24).

The most important consideration in designing a laminated member is that laminated glass under long term loading has less load resistance that a single, monolithic glass of the same thickness. This is due to the shear creep of the interlayer. In the case of short-term loading, this is not a contributing factor, but in sustained loads it must be considered. When loads with a longer duration are expected, it is assumed that the panes will slip past each other, thus sharing the load equally. Due to this, a laminated glass member has a lower strength than a monolithic piece of the same thickness. This is illustrated by a laminated glass consisting of two 0.625-inch panes that has an equivalent thickness of 0.875-inch, not the 1.125 inch that might be expected. As the number of laminations increase, this effect is intensified. A 0.6875-inch monolithic pane could carry the same load as a member with three 0.625-inch thick layers (Loughran 113).

CHAPTER 4 - Material Properties

Predicting the exact strength of a particular piece of glass is impossible without destroying that piece. That is why it is difficult to answer the question, "How strong is glass?" The strength is dependent upon not only the finishing process but also the ingredients of the batch. Before looking at the mechanical properties of glass, it is important to understand the differences in glass compositions.

Composition of Glass

The list of materials that can be used to make glass is quite long, but they are all used to produce just ten oxides that make up the majority of commercial glass. Typically, silica, SiO_2, makes up 60 to 80 percent of a glass batch. Sand, which is essentially quartz, is used in the manufacturing process to obtain silica (Phillips 34). While most glass only contains up to 80 percent silica, two special kinds of glass can be created that are pure silica or 96 percent silica. These two types of glass offer several advantages, but because they are so expensive, they are rarely used. Pure silica glass has a lower thermal expansion than any other type of glass, which makes it ideal for mirrors in satellite borne telescopes and laser beam reflectors. Aside from glass made of pure silica, glass made with 96 percent silica has the lowest coefficient of thermal expansion. The 96 percent silica glass is slightly less expensive to manufacture and is used for missile nose cones and windows in space vehicles (Maloney 44). Although these two types of glass are the simplest chemically and physically, they are quite difficult to manufacture. Most furnaces are unable to reach temperatures high enough to melt pure silica. Another problem is the prevention of bubbles in the pouring process. Because bubbles are nearly impossible to avoid, they must be removed by electrical melting in a vacuum while air pressure is applied (Phillips 40).

After silica, soda, Na_2O, is the most important oxide in glass making. The most common source of soda is from sodium carbonate, also known as soda ash. Other materials can be used to acquire soda and the material used is often dependent upon the desired goal. For example, salt cake, Na_2SO_4, is added to prevent silica from foaming and not mixing into the solution. Sodium nitrate is another form that is commonly used because it accelerates the melting process (Phillips

34). Some glass that contains soda is called alkali silicate glass. This glass contains only silica and soda. By adding just 25 percent soda to the silica, the melting point decreases more than 1650 degrees Fahrenheit. Because two component glass mixtures are readily soluble in water, they cannot be used to make bottles, building blocks, or insulators (Phillips 41).

The most common of all glass has a combination of soda and lime added to the silica. It is estimated that by tonnage, 90 percent of glass melted today is soda-lime-glass (Phillips 41). Soda-lime-glass contains roughly 70 percent silica, 15 percent soda, and 10 percent lime, CaO. The remaining 5 percent is typically magnesia, MgO, or alumina, Al_2O_3, which is used to adjust the chemical resistance or electrical properties. This type of glass is usually used for plates and sheets (including windows), containers and light bulbs. The lime is added into this mixture to improve the chemical resistance, alumina, Al_2O_3, can also be used for this purpose (Maloney 45). Another benefit of lime is that it further reduces the melting point of the mix. To insert lime in the mix, raw ingredients of limestone or burnt lime are added (Phillips 35).

Other oxides are used in the production of glass, but they are less common or are used for intensifying the effects of the three main compounds. Other common oxides include boron oxide, B_2O_3, potash, K_2O, lead oxide, PbO, barium oxide, BaO, and zinc oxide, ZnO (Phillips 34). Table 4-1 is shows the typical composition of various types of glass. Window and plate glass has the closest composition to glass used in structures.

Table 4-1 Composition of Common Glass Types (Phillips 42)

Types of Glass		Silica	Alumina	Lime	Magnesia	Soda	Potash	Lead Oxide
Window glass	Libbey-Owens Ford (1942)	71.7	0.7	9.7	4.3	13.0	---	---
	Fourcault (1942)	71.0-72.5	1.0-2.0	7.0-9.0	2.5-4.5	14.5-15.5	0.2-0.8	---
Plate glass	(1942)	72.2	0.14	11.2	2.0	13.7	---	---
Tableware	Heavy lead pot glass	53-56	---	---	---	---	10-13	30-36
	Lime pot glass	72-73	0-1	4-6	3-4	14-18	0-2	---
	Machine-made	72-74	0-1	4-6	3-4	15-17	0-1	---
Conventional container	(1942)	73.0	1.5	5.2	3.6	15.2	0.8	---
Electric bulb (lime)		71.5-73.5	1.0	5-6	3.5-4.5	15-17	0-1	---

During batch mixing, it is of great importance to try to eliminate certain compounds. Nickel sulfate can be a dangerous compound if it is present in a glass object that is to be tempered. During the melting of a mix, nickel and sulfide can combine to form stones that become problematic when the piece is heat-treated. While the effect is not immediate, a nickel sulfate stone in glass will cause spontaneous breakage, which can be quite catastrophic (Loughran 10). Preventing the formation of these stones can be relatively simple. A manufacturer must take care that all raw materials are inspected for contaminates. Also, limiting the contact of molten glass with nickel-bearing hardware, such as stainless steel, reduces the likelihood that a stone will form (Loughran 22).

Properties of Glass

Glass can be mixed and manufactured in many different ways. This makes it difficult evaluate numerical values of strength for glass. To further complicate the issue, it is possible that even when using the same mix and finishing process, different properties will be produced. This is typically due to imperfections in the glass or on the surface of the glass. Some organizations, such as American Society for Testing and Materials, have produced guides on the strengths of glass. These will be discussed more in Chapter 6.

The main reason that glass is often perceived as dangerous is because it shows no warning signs before failure. This is due solely to the lack of elasticity in glass. The elastic modulus, also known as Young's modulus, gives a numerical approximation of how the glass will respond when a tension stress is applied. The modulus, E, is the ratio of applied stress, σ, to the resulting strain, ε. This ratio is illustrated in the following expression.

$$E = \frac{\sigma}{\varepsilon} \qquad (4.1)$$

The relationship between tensile stress and tensile strain is also very apparent in a graph. Figure 4-1 shows the stress-strain curves for three structural materials, steel, glass, and wood. It can be observed that unlike steel, glass does not yield before failure. This is because of the brittle nature of glass (Loughran 107).

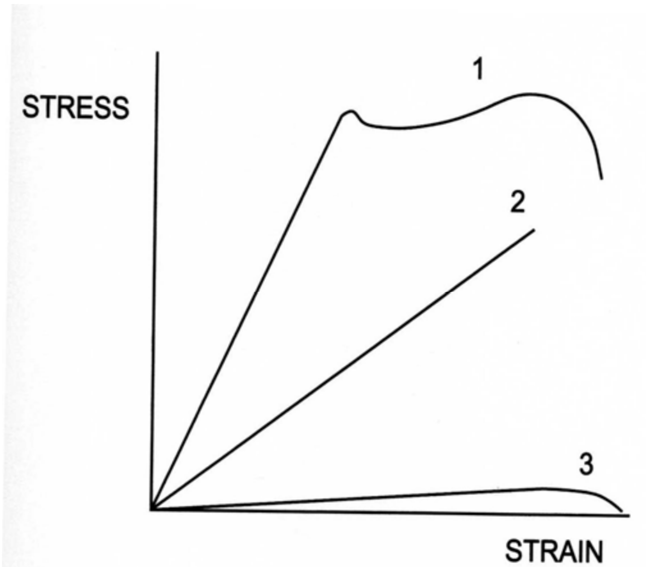

Figure 4-1 Stress-Strain Curve of Common Materials (Loughran 107)
1-Steel 2-Glass 3-Wood

For most commercial glass, *E* is approximately 10,000,000 pounds per square inch (psi). It has been found that heat-treating a glass will actually lower the modulus, but only to a limited extent. When tested, the largest difference in modulus between a non-treated and heat treated specimen was seven percent (Phillips 60). Increasing the elasticity of glass is very advantageous to using it as a structural material. One way to increase this is to increase the lime content. This was found to produce a decided increase in elasticity in soda-lime glass (Hodkin 25).

Another aspect of strain that must be considered to determine the strength of glass is Poisson's ratio, v. It can be illustrated by an example of a glass rod that is being tensioned along its longitudinal x-axis. As would be expected the rod elongates in that direction, but it also simultaneously contracts in the y and z directions. The relationship between the elongation and cross sectional shrinkage is Poisson's ratio. The ratio is that of transverse strain to axial strain. For most oxide glass, v typically ranges from 0.2 to 0.3. It is lower for pure silica glass at only 0.17 (Shelby 182).

Another stress-strain relationship is the shear modulus, *G*. Some scientists do not believe it is important to glass, while others do. It draws a correlation between shear strain, γ, and shear stress, τ. Those who believe it is unimportant in glass understand that glass is a brittle material, so it would fail in tension before it would fail in shear. The following expression shows the relationship (Shelby 183).

$$\tau = G\lambda \tag{4.2}$$

The shear modulus for the most common types of glass is about 4,300,000 psi (Loughran 110).

The use of these constants can help explain the strength of glass, but it still does not answer the question about how strong it is. Although, these relationships between stress and strain are developed in a laboratory under idealized and controlled conditions, they do not give an ideal representation of a glass objects practical strength. Through installation and use, flaws and imperfections greatly reduce the amount of stress that glass can withstand. For example, the chemical durability of glass is very important. One scientist, George W. Morey, defined chemical durability as “The resistance which glass offers to the corroding action of water, of atmospheric agencies, and of aqueous solutions of acids, bases, and salts” (Phillips 53). It is important to remember that the raw materials used in each mix will have a drastic affect on the chemical durability of glass. For example, pure silica glasses are not attacked by water and can resist most acids. One exception to this is phosphoric acid at high temperatures and hydrofluoric acid. Silica glass is, however, damaged by alkaline solutions. Because of this, most soda-lime-silica glasses contain the elements of their own demise. When water on the surface combines with sodium ions, it produces an alkali, sodium hydroxide. This solution then attacks the silica, especially at any broken glass surfaces. This eventually causes cracks that will propagate under stress until failure (Maloney 40).

Damage from water is not only a problem on the surfaces of glass. It is possible that water can penetrate certain glass to a significant depth below the surface. When the glass is then heated and dried, a large number of minute cracks will appear. While the cracks may not cause failure, they will create a dull appearance thus reducing the transparency. In either case, where water acts on the surface or the interior, the effect is intensified if an alkali or caustic soda solution is applied. If a concentrated acid is applied, it has little effect on the glass. However, a diluted acid will have a more detrimental effect, but this is largely due to the water in the mixture (Hodkin 52).

Water can also lead to an increased amount of fatigue in glass. It is known that even under normal conditions, glass loses strength over time. When all the ambient conditions and load remain constant but strength is lost, it is known as static fatigue. Another form of fatigue is observed when the load applied is varied. Studies of dynamic fatigue show that the quicker the load is applied, the higher the failure strength. Water has been attributed with causing most fatigue in silica glass due to the stress-enhanced reaction of water at the tip of a crack (Shelby 190).

The behavior of glass under certain loads has been extensively studied by modern glass manufacturers. From the data collected in several tests, empirical glass strength curves have been developed. These tables make it possible to predict the stress levels that a glass specimen will be able to withstand. From these tables, the breakage probability is used to select the design strength. The breakage probability is the likelihood that a glass will break under a certain loading. Most glass in enclosure systems, such as windows or façades, is designed to meet an 8 in 1000 probability of breakage. This means out of 1000 objects, only eight will break under the given load case (Loughran 110).

Probability of breakage must take into account several different types of stress in the glass. Two of the stresses most commonly considered are tensile and flexural stress. Most often tension is the limiting stress on any piece of glass. In tension, failure is caused by a separation of bonds at the atomic level. One scientist proposed that the magnitude of stress required to cause failure is determined by the energy needed to create two new surfaces. This stress, often referred to as the Orowan stress, σ_m, is given by the expression

$$\sigma_m = \sqrt{\frac{E\gamma}{r_0}} \tag{4.3}$$

where E is the elastic modulus, γ is the energy needed to create fracture, and r_0 is the strained interatomic distance (Shelby 185). Because the tensile strength is dependent upon the molecular cohesion, the composition of glass has an effect. It is assumed that each oxide has a theoretical tensile capacity and that they are additive. According to this theory, the calculated tensile capacity would be the percentage of each oxide multiplied by its designated factor. Calcium and zinc oxides contribute the most to the theoretical tensile strength (Hodkin 23).

Silicon and oxygen, when they form silica, create a very strong atomic bond, which leads to the high theoretical tensile strength of glass. Newly formed fine glass fibers will support loads of nearly 1,000,000 pounds per square inch. This number is twice as much as the theoretical value of the best steels (Maloney 30). Tempering or annealing glass increases the tensile capacity, but flaws that occur after that process cause a significant drop in the actual strength.

Due to stress-concentrating flaws, the allowable tensile strength, which is used for glass design, is typically between 5,000 and 10,000 psi (Maloney 40).

In ordinary experiments, it is actually the weakness of the surface on the specimen being tested that controls the ultimate strength rather than the tensile strength of glass. This is because failure begins at surface imperfections and propagates through the member until complete failure occurs. The surface hardness determines the amount of surface damage that is sustained both during manufacturing, installation, and in use. Hardness cannot be measured quantitatively so Moh's scale is one method used to gain a qualitative estimate of the surface's resistance to damage. Moh's scale uses ten common materials of increasing hardness. The list includes (1) talc, (2) rock salt, (3) calc-spar, (4) fluorspar, (5) apatite, (6) feldspar, (7) quartz, (8) topaz, (9) sapphire, (10) diamond. Comparisons are made by noting which of the standard materials can be scratched by the material being tested, in this case, glass (Hodkin 25). Another method used to obtain a quantitative measure for hardness, is an impact abrasion resistance test. This test blasts sand repeatedly against a specific area of glass. Standard plate glass is used as a standard and all other the hardness of all other glass is expressed as a ratio of the number of blasts required to reach the same depth of penetration on the test sample as the standard plate (Phillips 65).

Tension stresses are the controlling factor for the strength glass nearly all the time. It has been found to be nearly impossible to successfully establish the compressive strength of glass by testing. It has been theoretically calculated that newly formed glass can withstand a stress of 3,000,000 psi in compression. The tests that have been done to verify this stress have ended with the formation of tensile stresses that ultimately break the glass prior to reaching the theoretical value. The typical surface allowable compression of tempered glass is 10,000 psi or greater. For heat-treated glass, it ranges from 3,500 to 10,000 psi (Loughran 111).

The tension stress that a member can reach in flexure before failure occurs is denoted by R, which is the modulus of rupture. By loading a sample of glass for 60 seconds in flexure, the modulus of rupture can be established. The finishing that gives the least flexural resistance is simple annealing. Typically, an annealed piece of glass can only withstand 6,000 psi in flexural tension for one minute. Fully tempering will produce results four times that of annealed glass at 24,000 psi (Loughran 110). At the other end of the spectrum is chemical toughening. Unfortunately, chemical toughening can be very expensive, so is rarely used. Many types of chemical finishing will give glass a flexural strength of nearly 100,000 psi. There is even a glass known as Pyroceram that can obtain strength of nearly 242,000 psi (Maloney 173).

All of the stress values given above are calculated assuming temperature makes no difference. That is not always true because when glass is exposed to different temperatures new stresses are induced into it. Treated glass offers a greater resistance to temperature changes than regular plate glass does. It has been shown that heat-toughened glass will retain its quality within a range of temperatures from 572ºF to -94ºF (Gloag 53). These numbers were determined by slowly and evenly heating a specimen of glass. If glass is subjected to a sudden change in temperature it has a tendency to fracture. When a hot glass coffee pot is placed on a cold counter, it shatters because the surface is suddenly cooled which causes tensile stress. This rapid cooling is more detrimental than abrupt heating because heating creates a compressive force on the surface which will actually prevent fracturing (Maloney 41).

Thermal endurance is the ability that a glass has to withstand a sudden temperature change without failure. This property is dependent upon several different factors including elasticity, thermal conductivity and expansion, and tensile and compressive strengths (Hodkin 28). Temperature changes cause stress that can cause fatigue in glass. Frequent variations of temperature affects the time it takes for fatigue to cause failure in glass. At temperatures below -150 º F, fatigue is non-existent, but in a more natural temperature range fatigue increases as temperature rises. If glass is at room temperature the time to failure decreases with increasing humidity (Shelby 190).

Even if glass is heated at a slower rate, it can still create dangerous stresses. Like most other materials, glass expands when it is heated. If only a portion of a glass piece is heated, it will expand while the other portions remain unchanged. Those portions that have not been heated will attempt to resist the expansion, which creates tensile forces within the glass. When observing a failed glass member it is possible to identify what was a thermal break and what was not. Figure 4-2 shows that thermal breaks form at right angles to the surface which differs from a non-thermal break (Loughran 24).

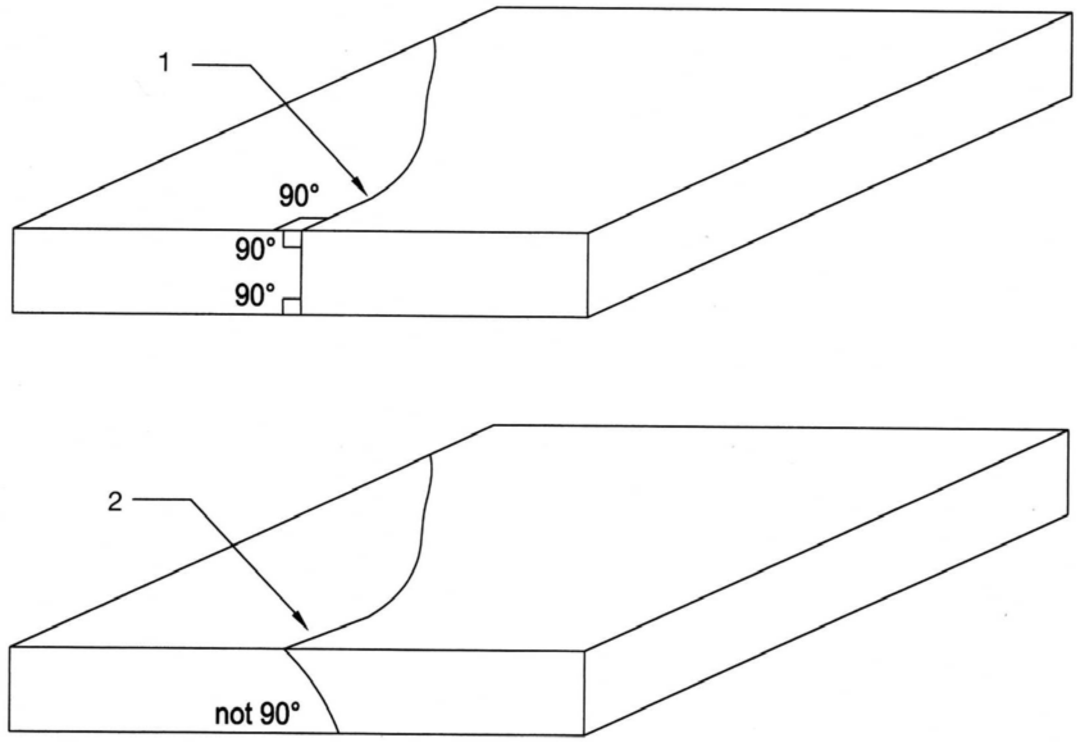

Figure 4-2 Identifying the Cause of Failures (Loughran 26)
1 – Thermal break 2 – Non-thermal break

The coefficient of expansion for glass, α, will determine how much the size will vary. This is a linear coefficient and is measured by the change in original length per 1 degree Fahrenheit rise in temperature. For most commercial glass, the value is roughly 5×10^{-6} ºF. To predict the change in length, the equation

$$\Delta L = \alpha \, \Delta T \, L \quad (4.4)$$

is used where L is the original length, ΔL is the change in length, and ΔT is the change in temperature (Loughran 27).

Special consideration must be made for temperature when laminated glass is used. When subjected to temperatures between 100ºF and 120ºF, laminated glass performs more like layered glass than as a monolithic sheet. This changes design values because it decreases strength and changes the deflection characteristics. Even more problematic is that at temperatures over 170ºF the interlayer adhesive becomes useless and the layers act completely independent of each other (Loughran 114).

Another important consideration when working with laminated glass is residual stability. Once a laminated glass member is broken, the remaining resistance it can offer to prevent complete failure is residual stability. This stability is very important for glass that will be used overhead or for walking on. Various factors can affect a member's residual stability including the kind of glass used, the type of intermediate layer, the method of mounting and loading, and the fracture pattern of the damaged glass. If too many of these factors act together unfavorably, a sufficient residual stability will not be achieved and complete failure will occur (Kaltenbach 33).

The most common method for increasing the residual stability is to make armored laminated glass. This is done by adding a layer of armor between the glass layers. Figure 4-3 shows the composition of an armored laminated glass structure. The armor is needed because of the low bending strength and load-bearing capacity of the broken glass pieces. Although a high tensile stress is required of the armored elements, it is also important that they are very thin so as not to disrupt the transparency of the object. Research has found that the best reinforcing elements are meshes made of stainless steel wire or high-strength springs. Another option is embedding glass-fiber or carbon-fiber products into the PVB layers (Kaltenbach 34).

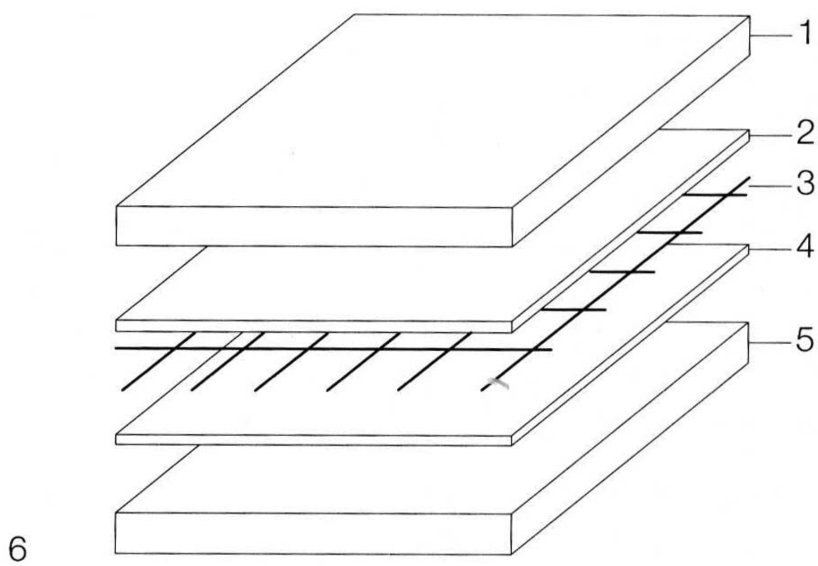

Figure 4-3 Armored Laminated Glass Structure (Kaltenbach 35)
1 - Glass Pane 2 - PVB Membrane 3 - Armor 4 - PVB Membrane 5 - Glass Pane

Armored laminated glass must be specified for overhead glazing and any glazing that will be walked or crawled on. This is to insure the safety of people below a fractured overhanging glazing and the safety of people crossing glazing if it fractures. For safety, the building inspector requires that glazing survive for at least 24 hours after any failure. This provides enough time for locating the problem and diverting any people who may be in harms way (Kaltenbach 34).

CHAPTER 5 - Glass as a Structural Material

Laboratory tests have shown the possibility of using glass as a structural material by proving its strength under various loading conditions. While most designers and contractors are hesitant to use glass as a building material, it is becoming more common. One recent example is the glass skywalk that extends over the Grand Canyon. Glass use in buildings, aside from windows, began as glass façades and claddings that were supported by steel. Innovative designers have continually tried to push the limits of glass, and are now using glass for nearly all major building components including canopies, floors, stairs, beams, and columns.

While it is not always required, safety glass is preferred for most structural members. This is to protect anyone who may be nearby if a member were to fail. Although heat strengthened glass and fully tempered glass are approximately two to four times stronger than annealed glass of equal thickness, neither is considered a safety glass. This is because they crumble when broken. Tempered glass breaks into small cubes that do not have sharp edges, but they can still be dangerous if they fall from overhead. Laminated glass is the best solution for safety glass in a building. Because of its tendency to stick together when broken, it limits the amount of debris from a member if it were to fail. To be considered safety glass, laminated glass must meet certain requirements. The American National Standards Institute and the U.S. Consumer Product Safety Commission have both published documents that outline requirements for manufacturing and testing glass that will be classified as safety glass (Innovative Specifications 12).

The first obstacle that must be overcome to build with glass is strength. Chapter 4 discussed characteristics that affect strength that included toughening, annealing, and laminating. It is also important to limit flaws during the transporting and installing phases. Once a glass member arrives on a construction site it is imperative that no field cutting be done. Doing so can create flaws that will create large stress concentrations that were not accounted for during design. Lastly, a contractor should not install any member that has edge damage or other noticeable imperfections, because those flaws can cause a member to fail (Innovative Specifications 15).

During the nineteenth century, glazed roofs and canopies began to appear in buildings. Their popularity grew because they would allow natural light into areas that previously prevented it. In areas such as these slight distortions were allowable, so vertically drawn sheet glass was used. Laminated and toughened glasses were too expensive most times, so a shatterproof wired glass was used. The glass had electrically welded wire netting inserted during manufacture. With the wire inside, the pane of glass was less likely to break and fall. Another important benefit was that a piece of wired glass would withstand fire better than a standard annealed piece of the same thickness. After World War II, it was determined that the fire-retarding properties of wired glass protected many structures from ruin by incendiary bombs (Maloney 136).

Recently glass claddings have gained popularity. When first introduced to the market, they were simply steel frames that had glass panels spanning between them. As the desire for transparency increased, the amount of steel used in these systems decreased. The latest trend is to replace the steel mullions with glass fins. These fins support and stabilize the panels, also known as main plates. Using glass is advantageous because a glass fin structure can be used on an interior, exterior, or the envelope of a building (Innovative Specifications 1). Before the use of steel mullion claddings, a type of glass brick was used to create the appearance of a glass-face. In this method, opaque, toughened glass is anchored to a lightweight concrete block using both an adhesive and a mechanical anchor. This type of brick was very attractive but also load-bearing and fire resistant, thus making it more appealing than simple stonework (Maloney 138).

Just as with any other building material, stability is a major concern when using glass. In any structure, a system that can distribute lateral loads into the foundation is imperative. Until modern history, glass would have never been used in a lateral system because of its importance. In 1986, a glass pavilion was built that used mainly glass superstructure to produce both lateral and transversal stability. To create the transversal stability, a frame was created using two glass columns that were clamped into a concrete foundation and a steel truss to transfer the load between the two. Glass panels that ran between glass columns provided enough in-plane strength to create the longitudinal stability that the pavilion required (Nijsse 19). Figure 5-1 shows this glass column and roof of this pavilion. Sometimes it is not possible to obtain the needed lateral stability by using glass alone. In these cases, steel is most often the fall back material because of its high tensile strength. In structures, steel cables have been used to create tension in the plane of beams. This gives a greater stiffness and allows the cables and glass beams to become a single horizontal member that is connected into the foundation (Nijsse 44).

Figure 5-1 Sonsbeek Art Exhibition Pavilion (Nijsse 18)

Because officials are still wary of glass, special considerations must be made when designing any member of glass that will be supported above the ground. Falling glass presents a substantial danger, so precautions must be taken. As discussed above, safety glass is one option, but that is often not enough. If glazing is installed at a slope of 15 degrees or more, fully tempered, heat-toughened, wire glass, or laminated glass must be used. Even if one of the first three is used, a protective screen must be installed below the glass. Using laminated glass is the only way to eliminate the screen requirement (Innovative Specifications 11).

Strength and stability calculations are not the only element that needs attention during the design of a glass floor. The psychological effects and need for privacy must be considered. Because people perceive glass as a fragile material, it can be difficult for them to accept that a completely transparent floor is going to carry their weight safely. Also, a completely see-through floor cannot give the people above any privacy from those people below. Because of these factors, it is suggested that at least a part of glass walkways be opaque. Even though the difference is only a thin foil that is less than 0.02-inch, a higher level of privacy is offered and people are set at ease (Nijsse 47).

Another important consideration of glass walkways is that manufactured glass has a naturally smooth surface, which can be detrimental when specified for walkways. When a smooth surface, such as glass, gets wet it becomes very slippery. This is a hazard that must be avoided in building construction. To prevent glass from becoming slick, it must be specially treated before it is installed. Making a rougher and more durable surface is a simple process. One face of the glass is melted until it is of a syrupy consistency, and then grains of sand or small pieces of broken glass are sprinkled onto it. The pieces that are dropped onto the glass will sink until the glass is no longer molten enough. After this the glass is allowed to return to a normal temperature, and the surface hardens. Aside from making a rough, non-slip surface, this process also slows the wear process of the glass because the sand grains or glass pieces are very well connected to the original glass surface (Nijsse 47).

Using glass manipulated for use specifically as floors, is a major benefit because of its durability and ease of replacement. Some designers choose to design walkways with glass instead of acrylic or a polycarbonate member because of how well it withstands wear. An acrylic covering would have to be replaced much more often (Designing Online). Although it is long-lasting, glass panels will still occasionally need replaced. Depending upon the method of installation, it is possible that replacement of broken or otherwise damaged pieces can be done in a short amount of time. Using glass planks that are supported by a grid-type frame, it is even possible to change panels in a matter of a few minutes (Innovative Online).

Much like glass floors, glass stairs are becoming more common. Some staircases are a combination of glass treads with steel support and others are all glass that only use steel for connections. Glass treads are usually made of laminated glass. One example of a tread is a laminated glass that has three layers of toughened glass that are each 0.59-inch thick and a top layer of annealed glass that is 0.39-inch thick. The thickness for stair treads must be designed for the dynamic load of people who would be fleeing during an emergency. In this case, the stairs were over 2 inches thick to accommodate the load (Nijsse 58).

To completely remove any visual obstructions, designers need to eliminate the use of steel as a supporting member. This is done by removing steel beams and replacing them with glass beams. Like other structural glass members, beams are made of laminated glass. Typically, they are designed so that the inner pane can support the entire load without the help of the outer-most panes. This is a safety factor that allows damage to some of the panes without complete failure of the beam. Because the outer layers are just for protection, they are typically thinner than the interior layer. When an insulated glass roof is being designed, it is possible to connect it directly to the glass beams. This connection is designed to withstand gravity loads as well as wind uplift forces (Nijsse 24).

Laminated glass beams can be manufactured to meet nearly any size required. Because the use of such beams is rare, there are no standard sizes that designers must use. The limiting factor on size of a beam is the limitations of the manufacturer's equipment, such as their autoclave, which is used in the laminating process. Typically, beams are made no longer than 14 feet, but if the owner is willing to pay more, lengths up to 23 feet are possible. If longer spans are required for a glass beam, it is possible to create a beam using staggered joints. When this type of beam is made, a resin interlayer is used instead of PVB foil. To gain the extra length, two panels must be uninterrupted at the location where another panel stops. By alternating the joints, a continuous beam is created (Nijsse 22).

In addition to the length, the designer can also specify whatever depth and lamination thicknesses they choose. For example, a beam spanning roughly 14 feet and 9 inches was designed to be 15.75 inches deep with three layers laminated together. The total thickness was just over an inch thick. In this case, the exterior panels were solely for protection, so they were 0.16-inch thinner than the interior panel (Nijsse 24). Another example spanned only about 11 feet and 6 inches, but had three equal layers of approximately 0.4-inch. Along with a shorter beam came a decreased depth, which was just less than 12 inches (Nijsse 28).

Even when glass beams were being used in buildings, most columns were still made of steel or concrete. A column can fail in three ways, which are illustrated in Figure 5-2. The least likely method of failure is crumbling, which is where the column can no longer withstand the compression force and yields to failure. The next form of collapse is a shear failure, where the shear force is too large and two pieces of the member slide along each other. Most commonly the type of failure in a column is buckling. In this case, the member bows out until it finally breaks in the middle.

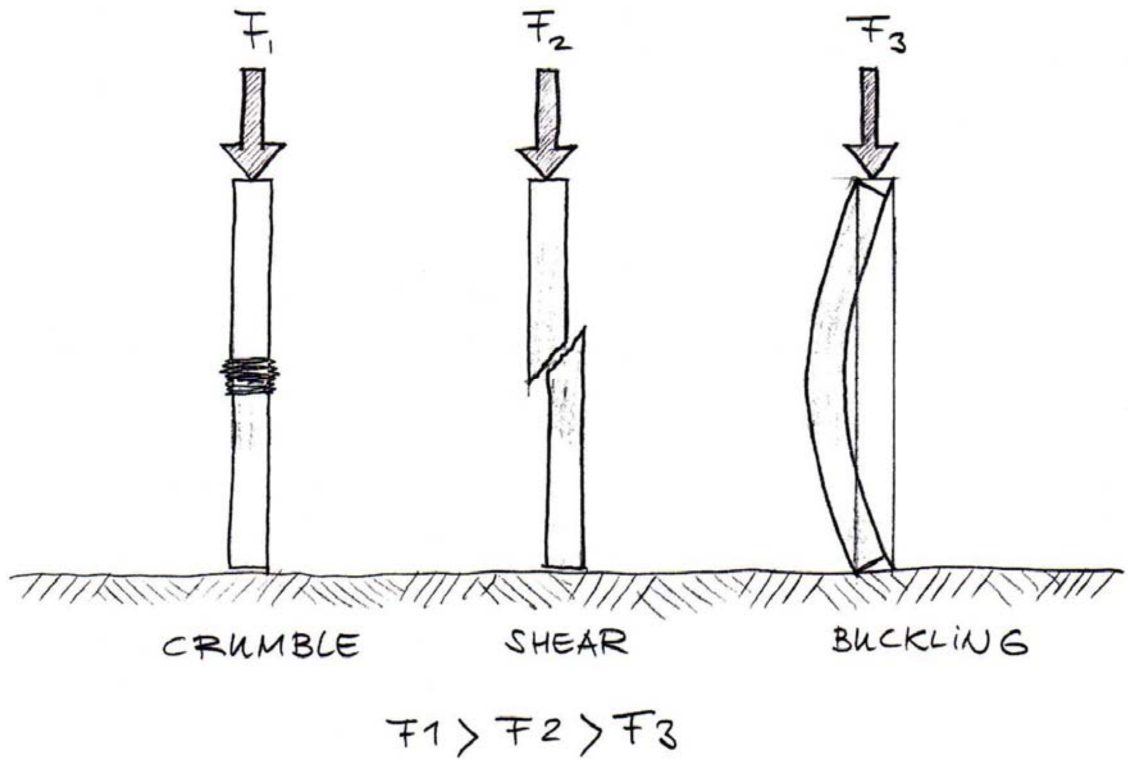

Figure 5-2 Failure Modes of Columns (Nijsse 60)

Although glass works well under compression, it is difficult to prevent a glass column from buckling. When a column buckles, tension forces are introduced into the glass, which eventually breaks. Laminated glass principles can be used to reduce the likelihood of buckling in columns. In laminated columns, each layer acts as a lateral support for the others and the slenderness ratio is decreased. Designers have come up with three different methods for creating safe laminated glass columns. Figure 5-3 shows these three approaches (Nijsse 69).

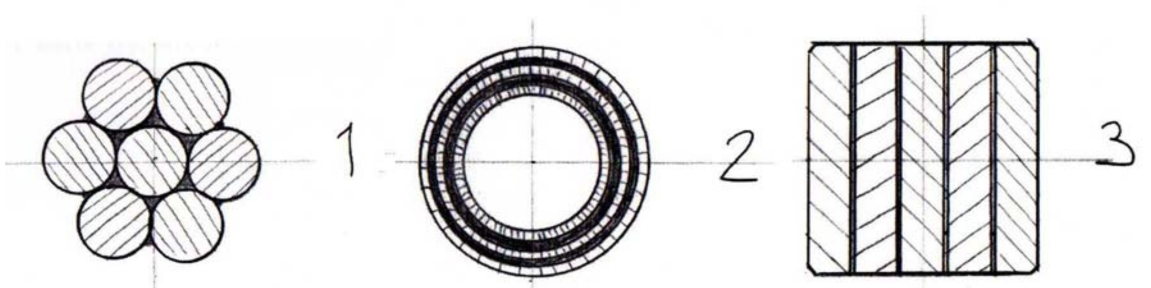

Figure 5-3 Laminated Glass Column Configurations (Nijsse 69)

1. Bundle of massive glass bars, glued together.
2. Cylinders glued together.
3. Rectangular glass panels, laminated.

Each of the illustrated methods could be used as a 9.5-foot column that could carry a load of nearly 7,870 pounds, including a safety factor of 1.5. If a bundle of bars, known as the "Holten concept," was used, it would take seven bars of about 1.2 inches diameter each. The bars would be adhered together by UV-activated glue creating a single column with a diameter of about 3.5 inches. Another option was using two laminated cylinders. This method, known as the "Corea concept," would require the outer cylinder to be just less than four inches in diameter and 0.3-inch thick. The inner cylinder's diameter would be 3 inches with a thickness of 0.4-inch. The reaming gap of 0.18-inch would be filled partially with epoxy glue. The final option for this load-bearing column would be laminated glass panels. Seven annealed glass strips could be glued together using a resin, and the resulting column would be around 2.75 inches thick. All of these options were structurally sound, but none were used in this particular case because of the financial restraints of the project (Nijsse 70).

Another example that was never carried out used the laminated cylinders style. The column was to support an all-glass spiral staircase. The column was actually made of three cylinders laminated together. The diameters of the cylinders were roughly 9.84 inches, 8.86 inches, and 7.87 inches. All of them were 0.3-inch thick, and the lamination was completed with transparent glue. To eliminate the occurrence of any tension, a single tension cable was run through the center of the hollow column to induce a compression force. Another interesting feature of this design was the length of each column section. To minimize the length, each column section sat on the stair below and had a stair resting on its top. This created a stair, column, stair, column pattern all the way from floor to floor (Nijsse 67). A major benefit of using multiple cylinders is that perfect positioning of the cylinders is not necessary. As long as the cylinders are firmly held together by the epoxy glue, the column will be safe (Nijsse 71).

One column form that has been practically used is a cross-shaped column. For a town hall in the small French town of Saint-Germain-en-Laye, this type of column, shown in Figure 5-4 was utilized. The column has one laminated panel that is continuous and a second that is in two pieces. The two panels that abut the continuous panel act as a brace to withstand buckling. The height of this column is 10.5 feet, and its maximum loading is over 15,500 pounds of force. Each section of the column is made of three layers. The outer two laminations are each 0.4-inch thick and the middle layer is 0.6-inch. Because the ends of the glass panels are just as susceptible to damage as the rest, the middle panels of the laminated sheets are recessed a small amount (Nijsse 72).

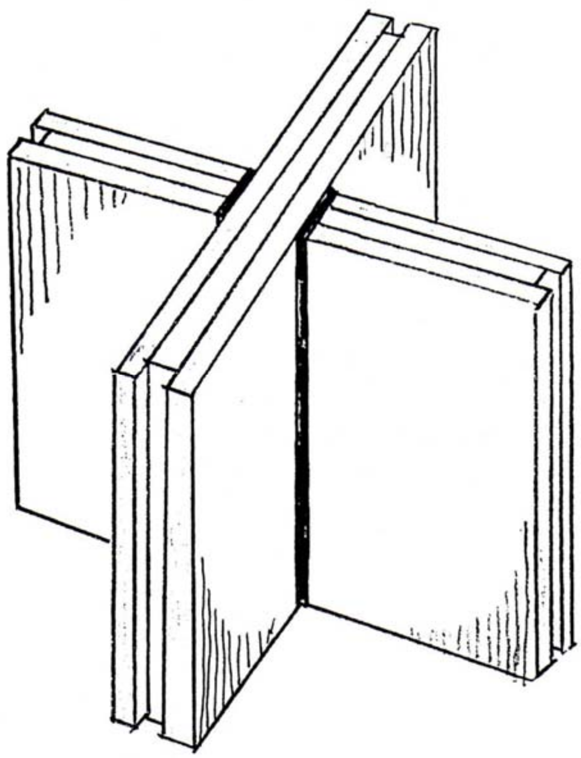

Figure 5-4 Cross-Shaped Column (Nijsse 72)

CHAPTER 6 - Design Guidelines and Testing

Most engineering design is based on standards that are published by material-specific agencies. For example, the American Institute of Steel Construction publishes *Specification for Structural Steel Buildings*. This type of specification does not currently exist for structural design using glass. While glass specific organizations exist, they have not published any specifications or standards about how to build with structural glass members. Because such a publication does not exist, it is often necessary to test glass members and their connections to determine their structural adequacy.

Design Guidelines

When it comes to structural glass design typically two paths can be taken. A structural engineer can do all the design for a project and assume all liability by placing his seal on the drawings. The other option is to have a specialty engineer prepare the structural glass design and assume the liability for his portion of the design. Some manufacturers will act as the specialty engineer to provide the design of their systems to the engineer of record.

Without a specific standard or specification, structural engineers are often left to do their own research on how to design with glass. Even the model building codes used in the United States do not directly address the issue of structural glass design. Except for the standard use of glazing in buildings, the International Building Code (IBC) does not direct engineers in the design process. Coincidentally, Section 104.11 of the IBC does provide a way for engineers to design “outside of the box”. It states that the code is not absolutely encompassing, and that alternate methods and materials may be used, so long as it is approved by the building official having jurisdiction. The building official must find that the proposed design complies with the intent of the code. This means that the design must be equal to the code requirements regarding quality, strength, effectiveness, fire resistance, durability and safety. To make the decision to accept a specific design, the building official requires that supporting data be submitted. This data should include calculations and research reports from proven and trusted sources such as the American Society for Testing and Materials (International 3).

Manufacturers of glass often produce sample specifications that may be included in the construction documents by the architect or structural engineer. Specifications of this type must be abided by during the design and construction phase if included in the construction documents. One company even lists in the specifications the documents that are required to be submitted to the manufacturer and fabricator. The first required submittal is the structural calculations. Just as with any design process, all appropriate loads and load combinations should be evaluated and documented. Additionally, in each axis, the support reactions and maximum glass deflections must be computed. Finally, the panel thickness shall be designed by either the design engineer or the specialty engineer. All of the calculations and other supporting information must be supplied at the completion of this step. Prior to construction, submittals for shop drawings, installation drawings, and product data are required. It is necessary that the shop drawings include details of all the supports as well as data that shows building movements from lateral loads have been considered. The vertical and horizontal expansion and contraction must also be taken into account during the detailing process. After the structural or specialty engineer accepts the shop drawings, installation instructions and drawings are prepared. This set of drawings identifies each part by size and number. Finally, product data and samples are often required to be provided. The data must give specific descriptions of all the materials that will be used and samples of each of the materials to be supplied (Glass Online).

Aside from the glass manufacturer’s guidelines, other organizations and groups offer guidance to engineers. One such organization is the American National Standards Institute (ANSI). This group sets standards for many different materials, and they published the ANSI Z97.1, which defines a standard for safety glazing materials that can be used in buildings. The document establishes specifications and methods for testing the safety properties of glass. It defines safety glazing as “glazing materials designed to promote safety and to reduce or minimize the likelihood of cutting and piercing injuries when the glazing materials are broken by human contact” (ANSI Online). While the ANSI standard does not give structural design specifics in its standard, it serves two purposes. It provides a base for safety standards for adoption by federal, state, and local regulatory bodies and it gives building officials and engineers a reference standard (ANSI Online).

Another agency that works to further the use of glass in buildings is the Glazing Industry Code Committee (GICC). This group is a forum for developing consensus-based industry positions and it advocates the industry position to the building code developers. Since the 1980s, this group has been the voice of the glass and glazing industries. The GICC works closely with the International Code Council and offers answers to glass related questions from engineers and architects. In the frequently asked questions section on the GICC website, glazingcodes.org, various questions are answered including requirements for the allowable deflections of adjacent glass panels and the proposed IBC requirements for laminated glass floors. As of the 2006 IBC, the GICC proposed section for laminated glass floors has not been added. Many other questions regarding architectural features and possibilities are also addressed on the GICC's homepage (Glazingcodes Online).

All of these resources are available to engineers and helps them prove the acceptability of their design. Because the final approval for a project's construction comes from the building official, it is important that all the important information be supplied and supported. According to section 104.11.2 of the IBC 2006, building officials have the authority to ask that tests be performed to prove compliance with all applicable rules and regulations. These tests must be done by an approved agency and that agency must supply all required reports within the time period required for retention of public records. If the building official requests additional testing be done, it is to be done at no expense to the official's jurisdiction (International 3).

If the second design option is utilized and a specialty engineer is used, the role of the structural engineer is quite different. To complete the design, the specialty designer needs all loads and pertinent information from the structural engineer. Any required information is typically listed in a performance specification, which is most commonly acquired from a manufacturer. A sample of such a specification is located in Appendix B.

Material Testing

The German philosopher Friedrich Nietzsche once said, "You have to destroy something you love in order to understand it" (Nijsse 15). This is precisely the truth when speaking of glass. The only way to test glass is to destroy it completely. Because each piece of glass is different, it is impossible to determine the exact strength of a particular structural member. It is possible that two seemingly identical pieces of glass, tested under identical conditions can have a variation in strength by a factor of three (Loughran 110). Due to this variation, it is important that large factors of safety be applied to all glass designs.

Because glass used as a structure is a relatively unknown material, it is often considered dangerous. To lessen the fears of engineers, officials, contractors, and owners, tests are often conducted to prove the large capacities of glass before failure. Sometimes, when tests are not specifically defined, it is up to the designer to establish a suitable test method. When attempting to defend a design for a glass stair, an engineer performed a test like those used during medieval times. Calculations that showed the strength of the design were done, but the results of the tests still surprised many of the spectators. For the test, a weight of over 175 pounds was dropped on an area of 1.55 square inches and a sandbag weighing roughly 155 pounds was slung against the railing at high speeds. The structure withstood several test of this magnitude and within the first five years sustained no damage with the exception of a few superficial surface scratches (Nijsse 50).

Although glass is designed to not fail, people's fear of glass has caused the implementation of extra safety precautions. One such case is falling glass, which poses a potential threat to a person's wellbeing. When glass is used in overhead applications, it is of utmost importance that a strong laminated glass be used. The glue that holds all the laminated layers together acts as a safety net by holding any fractured glass pieces in place. In some places, when overhead glazing is used, the fallout resistance must be demonstrated. This resistance is shown by breaking a test specimen and observing how much glass is released from the system (Loughran 22).

One major benefit of laminated glass is that it can still support a load even after the outer layers have broken. In the case of overhead glazing, it is important that a broken member be able to withstand any loading while preventing any shattered glass from falling. It is not required that a member be designed to carry its total load indefinitely once it is fractured. The requirement for most members is that it be able to support itself and its normal loads for a period of at least 24 hours. This residual stability gives an owner time to adjust for the possibility of complete failure. As much load as possible should be removed from the member as quickly as possible to reduce the likelihood of human injury. Also, the 24 hours of stability allows time to clear occupants out of the way of potentially falling glass. Because residual stability is only required up to 24 hours, it is important that the owner replace the compromised member as quickly as possible to prevent further failure (Kaltenbach 34).

It is not only the glass itself that must be proven to possess adequate strength to owners, architects, contractors, engineers and the building official. The connections used to support glass construction must also be capable of supporting the required loads. Because of the brittle nature of glass, special considerations must be made to the distribution and transfer of forces through the connections. When testing a single bolt connection through a single sheet of glass, it was found that the glass could support up to 38 kips before failure. Because this was under ideal conditions, the allowable load for this particular bolted connection was considered to be less, between 12 and 20 kips, due to possible material flaws (Davidson Online).

To design a glass member loaded in bending, one valuable resource is the ASTM E1300-02. This publication by the American Society for Testing and Materials includes many figures that can be used to determine the non-factored load, which is the ultimate allowable load, on various sizes, shapes and types of glass. Following is an example that uses section 6.8 of the ASTM E1300-02 to determine the required thickness of a glass floor (ASTM 1396).

Example:

Problem:

Determine the thickness required of PVB laminated, heat strengthened glass to carry a service load of 50psf. The glass is supported by two parallel supports 5 feet apart. See Figure 6-1 for a sketch of the problem.

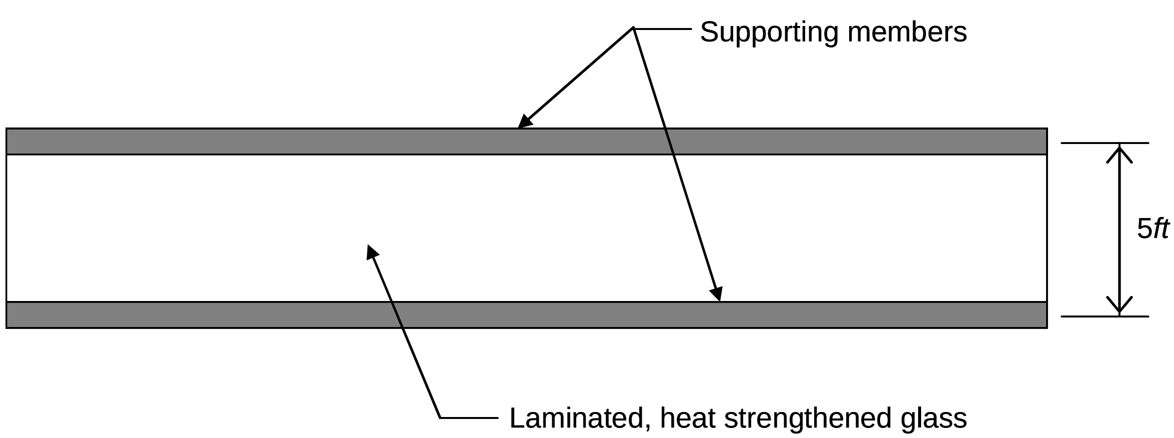

Figure 6-1 Sketch of Floor for Example Problem (Personal Picture)

Solution:

Step 1: Determine the glass type factor (GTF) for a long duration load on heat-treated glass. Use ASTM E1300-02 Table 1, which is shown in Table 6-1.

$GTF = 1.3$

Table 6-1 ASTM E1300-02 Table 1 (ASTM 1394)

TABLE 1 Glass Type Factors (GTF) for a Single Lite of Monolithic or Laminated Glass

	GTF	
Glass Type	Short Duration Load	Long Duration Load
AN	1.0	0.5
HS	2.0	1.3
FT	4.0	3.0

Step 2: Determine the needed non-factored, service, load (NFL) using section 6.8.3. Use the equation NFL*GTF=LR to find the load resistance (LR).

$$NFL = \frac{LF}{GTF} = \frac{50psf}{1.3} = 38.5psf$$

Step 3: Determine the required thickness. Use required NFL and length of unsupported edge in the upper chart of ASTM E1300-02 Figure A1.41, which is shown in Figure 6-2.

$t = ¾”$

Step 4: Check deflection. Max deflection from section 5.2.4 of ASTM E1300-02 is $^{l}/_{175}$.

$$\Delta_{max} = \frac{l}{175} = \frac{(5ft)12\frac{in}{ft}}{175} = 0.34in$$

Check the actual deflection using load (l^4) in the bottom chart of Figure A1.41, shown in Figure 6-2.

$$load * l^4 = 50psf(5ft)^4 = 31.25k * ft^2$$

Deflection = 0.3*in* < 0.34*in* OK

Solution:

For a floor spanning 5feet between supports, ¾” thick laminated, heat strengthened glass should be used.

E 1300 – 02

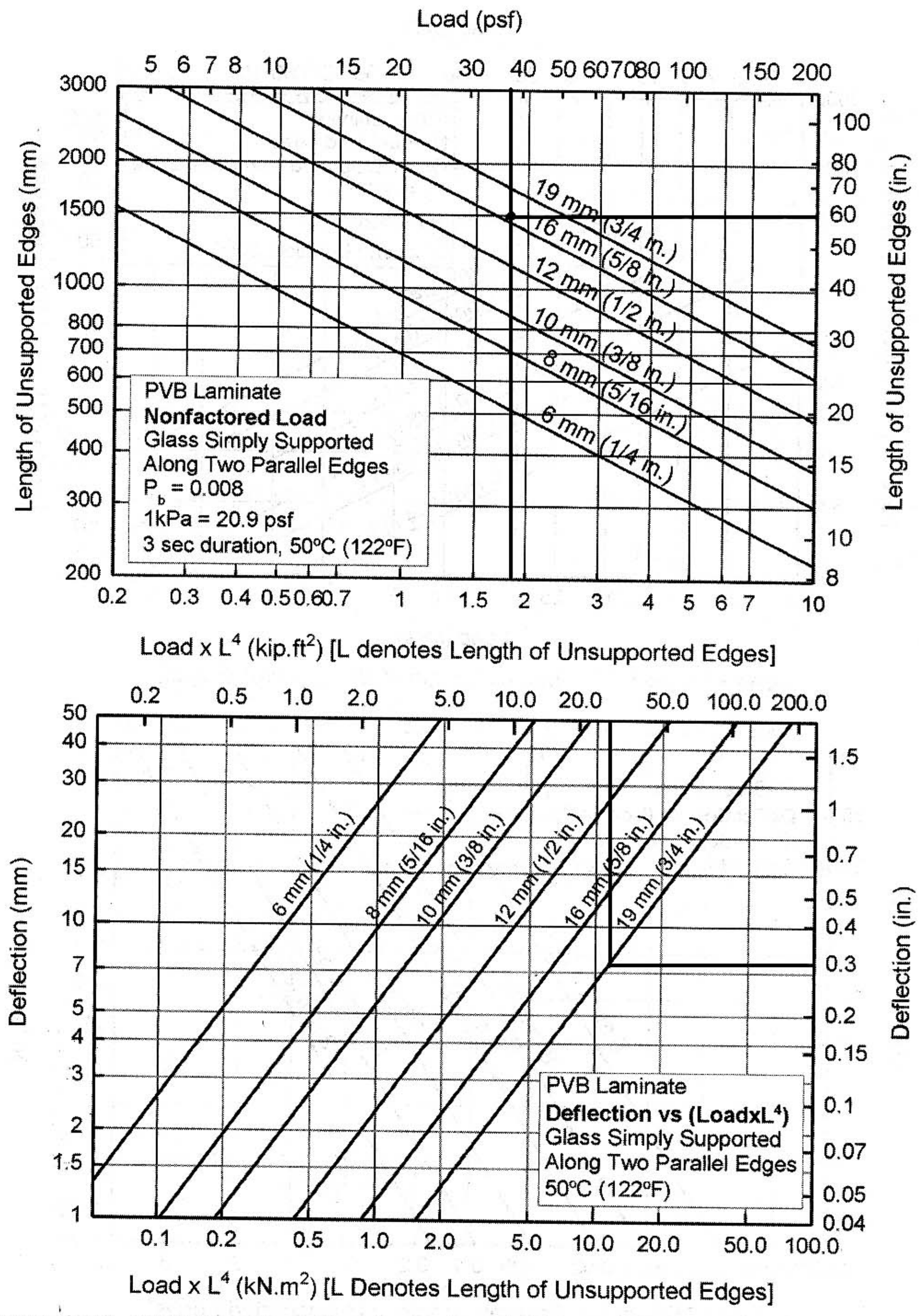

FIG. A1.41 (upper chart) Nonfactored Load Chart for Laminated Glass Simply Supported Along Two Parallel Edges
(lower chart) Deflection Chart for Laminated Glass Simply Supported Along Two Parallel Edges

Figure 6-2 ASTM E1300-02 Figure A1.41 (ASTM 1439)

CHAPTER 7 - Connections

When building with glass, it is rarely the glass flexure strength that limits design. More often than not, the limiting factor is the connections and the materials used in those connections. Any material that comes into contact with glass should be relatively soft, and should have the capability of distributing forces to and from the glass. Avoiding direct contact between glass and metal is common practice, which is why rubber gaskets are frequently used (Loughran 115).

Connecting steel and glass directly is a problem due to the way forces are transferred from the former to the latter. Because glass is a brittle material, it cannot redistribute forces. Therefore, a bolt acting in shear and bearing directly on the glass will create very large localized stresses. Where the bolt bears against the glass, a crack will form. The solution to this problem comes by making a more elastic connection between the steel and glass. An example of such a connection is a point supported connection shown below in Figure 7-1 (Novum Online).

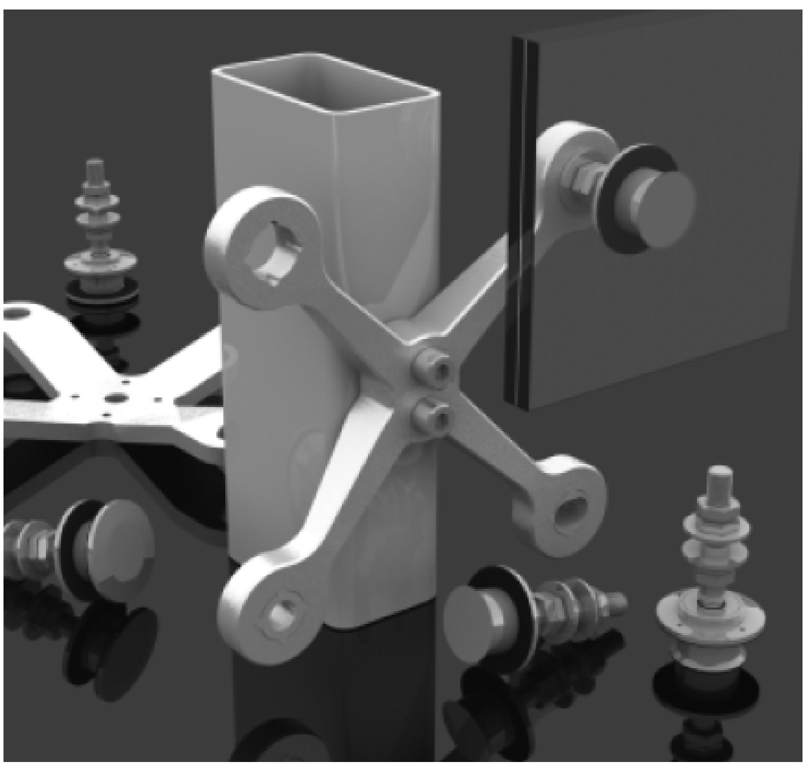

Figure 7-1 Connection for Point Supported Glass System (Novum Online)

One detail for using a bolted connection that has proved successful requires four steps. First, while in the shop, a hole should be drilled in the glass piece. The hole diameter will be five times that of the bolt. Next, the edges of the hole must be thoroughly polished. This eliminates any little cracks or damage caused while drilling. Such flaws could cause stress-concentrations that would severely weaken the connection. The third step is to insert a plug that is the same size as the drilled hole. The plug is made of either polyacetate (nylon) or polyoxymethylate (POM) and is held in place by a very thin layer of glue. At this point, the glass member is ready to be sent to its final site for construction. Once onsite, the connection should not be altered, with the exception of drilling a hole into the nylon that is large enough for the bolt. After this, steel plates can be attached with nylon pads between the glass and plate. The bolt is then tightened to the required torque (Nijsse 33).

Using a bolt through a nylon plug distributes bearing forces, however, connections can also be designed that use clamping forces. In the design of a glass frame for a particular project, forces were transferred by the clamping of bolts on either side of a glass piece and steel angles. Because there was contact between the glass and steel all along the connection, and not just at the bolts, it was important to protect the entire length of glass. This was done by inserting a neoprene sheet between the supporting steel angles and the glass column (Nijsse 18). Another example of the use of neoprene was in a glass truss. Glass rods were connected to a hollow steel section to form the truss, so to make the connection each end of the rod was covered by a stainless steel cap. To assure even transfer of forces, neoprene rings were wrapped around the rod and a pad was inserted onto the end of the glass. This connection is detailed in Figure 7-2 (Nijsse 64).

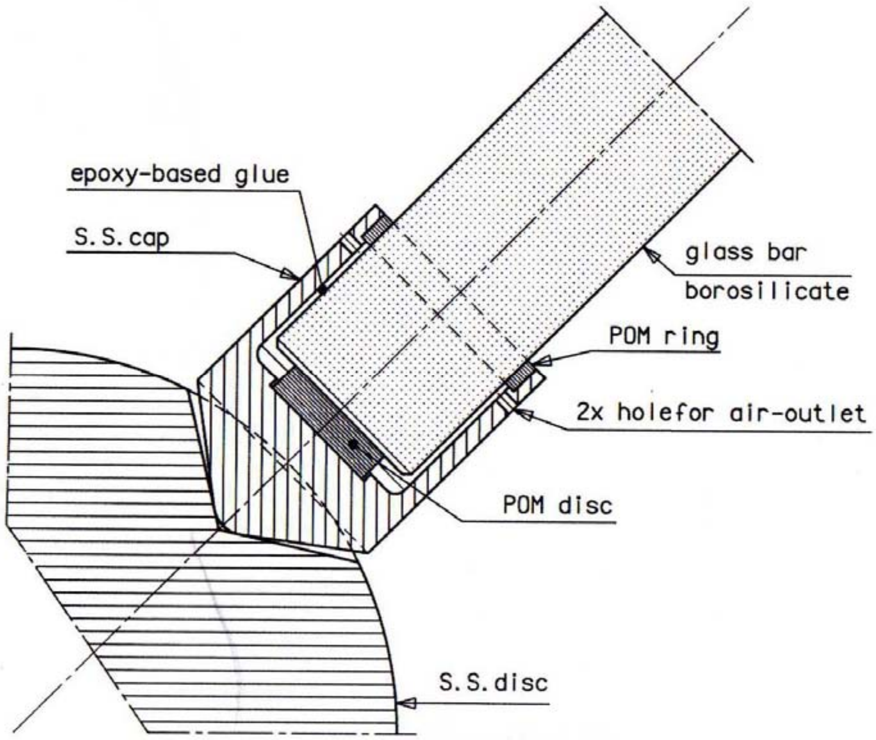

Figure 7-2 Glass Truss Connection (Nijsse 64)

Any flaws present in a piece of glass can cause failure, but those located in close proximity to connections are the most detrimental to the glass member. If a flaw is located near where forces are being transferred, it will cause a stress concentration that the glass cannot correct by redistribution. The only way to limit these flaws is to perform all drilling and cutting for connection prior to tempering the glass. When holes are present during tempering, they too, along with the normal glass surfaces are strengthened. It is often required by manufacturer's suggested specifications that no modifications should be made to glass panels following the tempering process (Innovative Specifications 13).

In one construction project in the Netherlands, it was found out just how important hole preparation is. A roof panel and an entire beam failed within a half an hour of erection because one hole for a connection was not properly cut and polished. With only dead load being supported, it was determined that the bending stress on the glass panel at the connection of the panel to a steel frame should have only been about 580 psi. This was about 8% of the calculated stress needed to cause failure. Upon investigation, it was found that a single hole had been drilled and not polished. The rough edges of the unpolished drilled hole resulted in a stress concentration that increased the localized stress in the glass by a factor of three. In addition to the flaws at the hole, there was a large scratch and a smaller scratch adjacent to the hole that had been created during the drilling process. Each of these flaws caused another stress concentration of roughly 3 times what was expected. When the connection was made, it was forced to support a load of 3 (hole) x 3 (big scratch) x 3 (small scratch) x 580psi, which resulted in a load of nearly 15,700 psi. This was much larger than the 7,250 psi, which was assumed the maximum allowable tensile stress on the connection (Nijsse 40).

Although a soft separator is present in a fitting between metal and glass, there are still strict requirements for the type of steel that is used. In their product's specifications, manufacturers list the type of metals that are allowed in their fittings. In most cases, stainless steel is specified by the manufacturer. Grade 316 stainless steel, that meets the requirements of ASTM A276, is most commonly used for plates and hardware in glass connections (Innovative Specifications 13). Although grade 316 steel is typically specified for all the hardware and fittings, it is acceptable to use grade 304 stainless steel for the plates that are being attached to the glass (Novum Online). The finish on connection hardware can be altered since not all glass systems are best accented by the shining silver finish of stainless steel. Custom fabrication of fittings allows the designer to specify the type of finish. Available finishes include brass or gold plated, as well as powder-coated or polished surfaces (Innovative Online).

To complete a connection installation, it is often important to seal any gaps, to prevent moisture penetration. Typically, silicon is used for this purpose. More often than not, silicon is used in addition to a metal, as shown in Figure 7-3 (Nijsse 24), but it is possible to eliminate metal all together and use only a silicon joint. A short bridge that was built between two buildings in the Netherlands used only an adhesive silicone strip to connect the glass floor panels to the glass beams. This bridge was built for the Arnhem Zoo and will be discussed in greater detail in chapter 9 (Nijsse 29).

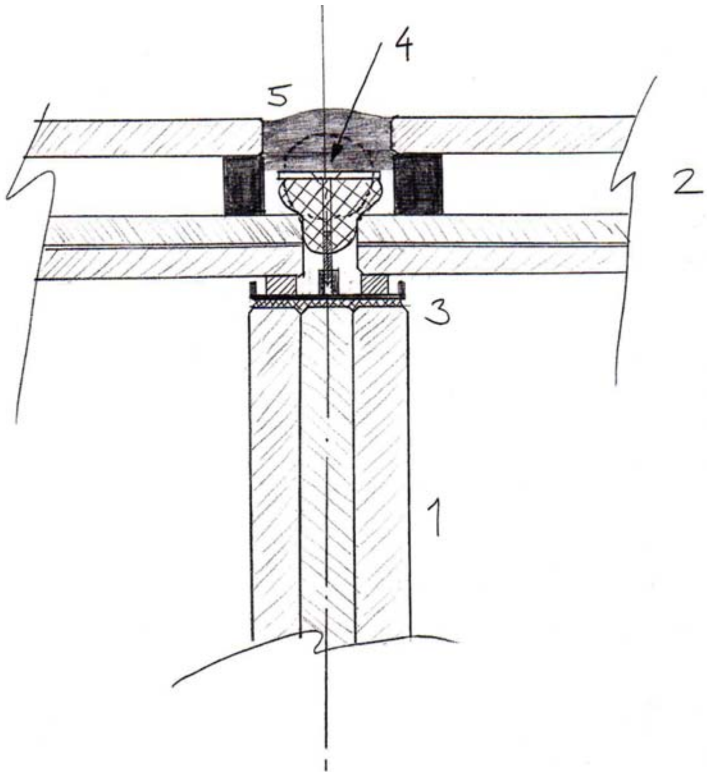

Figure 7-3 Connection Detail for Glass Beam to Insulated Glass Panel (Nijsse 24)

1. Glass Beam.
2. Insulated glass panel.
3. Aluminum strip glued to top of glass beam (little gutter).
4. Soft neoprene bar; compressed during assembling (second line of defense).
5. Silicone joint (first line of defense).

Although silicon is often used to fill gaps in glass fittings, it can also be used as a spacer instead of nylon or neoprene. Some manufacturers choose to make stiff silicone pads to insert between metal and glass. This connection is shown below in Figure 7-4. Completely metal free joints are comprised of extruded silicone gaskets along with wet silicone (Novum Online).

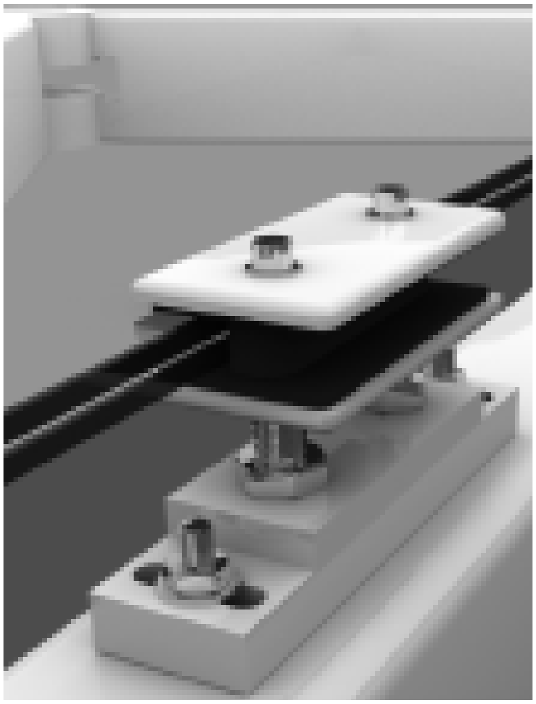

Figure 7-4 Edge Clamped Glass With Stiff Silicone Pads (Novum Online)

In most glass construction, steel bolts are used to make the connections between glass pieces or between glass and steel, although, other metals have been used. Titanium was used in a staircase located in the Apple Computer store in SoHo, New York. What makes this application unique was that the titanium was laminated between the glass. The interlayer is structural, but also formed the needed separation between metal and glass. Using metal inserts in laminated glass is very uncommon because most interlayers cannot form a proper seal around the metal, while still bonding the glass together (Stairs Online).

As mentioned in Chapter 4, temperature variation can cause substantial damage to glass systems. The systems that are affected most are exterior systems, such as façades, because they are exposed to outside temperature variations. These systems most commonly use a combination of glass and aluminum. The best way to avoid problems caused by temperature changes is to insert thermal breaks into connections. A thermal break interrupts the thermal pathway by creating a separation between any interior and exterior metals. Taking advantage of a thermal break will conserve energy as well as cut the probability of condensation forming on the inside surface of the glass enclosure. The most common method for creating a thermal break is to pour a polyurethane barrier into a cavity of an aluminum extrusion. Once the urethane has hardened, it contributes structurally just as the aluminum would, but the thermal performance is greatly improved. It is important in this method that the bond between the urethane and the aluminum remain strong. As long as the bond remains tight, the thermal break will remain intact and the polyurethane will expand and contract much more than aluminum will; therefore, initial mixture and installation of the urethane is very important because if the bond breaks, not only are the thermal benefits lost, but the member also loses structural stability (Loughran 116).

In addition to thermal considerations in façades, the transfer of lateral forces must also be considered. It is not uncommon for glass façades to require an additional member to aide in transfer of out-of-plane forces. A point-fixing connection can be used to attach steel cables to glass panels, which resist these forces. This solution first appeared in the 1980's and since then there has been an increase in the use of steel tensioning cables as wind braces (Dutton Online). In one use of a point-fixed glazing system, the glass is 0.375-inch thick laminated, tempered glass. Figure 7-5 shows the details of this system as it is used in the Hotel Kempinski at the Munich Airport. Each stainless steel connector node meets at the corner of these panels. Because the fastener passes through the joint between these pieces, it does not actually penetrate any of the glass members. The closure works as a clasp that holds two cables. These cables are tensioned by adjusting threaded stainless steel fittings at the floor and walls. To prevent the stainless steel connector from coming into contact with the glass, a silicone pad is located on both surfaces of the glass (Loughran 20).

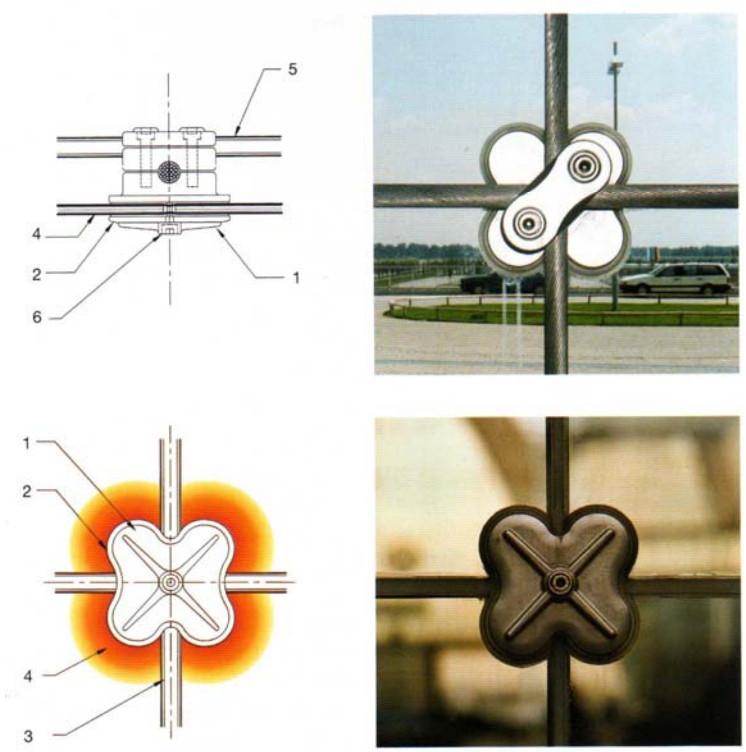

Figure 7-5 Point-Fixing Glazing Connection (Loughran 20)

Left Section and plan of connection:

1. Cast stainless steel node
2. Silicone pads separate the metal from the glass
3. Silicone sealant separates individual panels
4. High stress levels on glass occurs at the connection
5. ⅞ inch stainless steel cable
6. Joint between glass allows for a through fastener

Right The point-fixing glazing system requires tempered glass in order to sustain the design wind loads at the connections.

Research from the Division of Structural Mechanics at Lund University in Sweden has tested bolted connections in laminated strengthened glass. A 1-¼ inch cylindrical bolt was tested in a piece of laminated glass with two 0.3-inch thick layers. The bolt was tested with a compression load and a bending load applied. A method of loading for each test is shown below in Figures 7-6 and 7-7. In the compression loading test, a load of 1.3 kip was applied before failure occurred. At failure, there was a tensile stress of 25.7 kips per square inch (ksi) present in the glass. When loaded in bending, as shown in Figure 7-7, the cylindrical bolt was subjected to a moment of 154.9 pound-feet. A moment of this size created a localized tensile stress of 7.25 ksi in the glass at the time of failure (Persson Online).

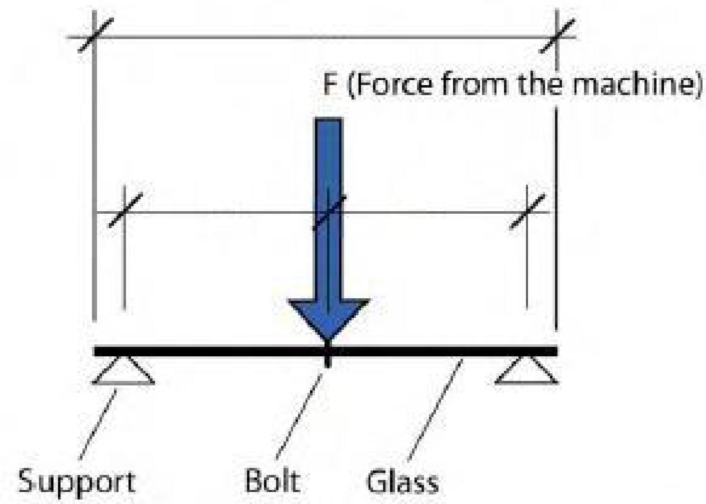

Figure 7-6 Bolt Loaded in Compression (Persson Online)

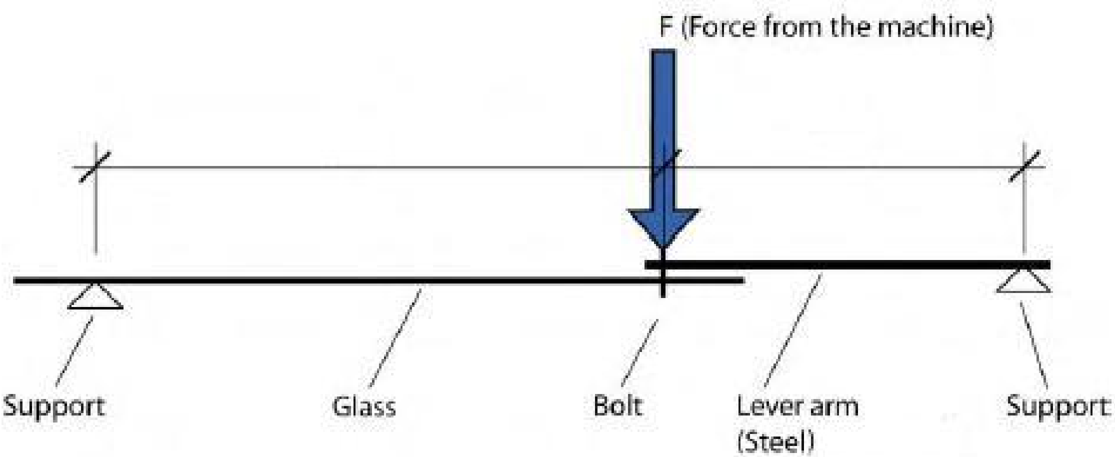

Figure 7-7 Bolt Loaded in Bending (Persson Online)

CHAPTER 8 - Examples of Glass Structures

Like many architectural styles, the trend of designing with glass first became prevalent in Europe. In the late 1990s, architectural firms and engineering firms were designing and constructing creative structures that used glass as beams, columns, floors, and even stairs. Two of the following examples are structures from the Netherlands and the final one is a more recent one from the United States.

R.O.A.M Glass House

In 1996, in Leerdam, Holland, an architectural design competition was held to design a glass house near the town center. Leerdam and the surrounding area is well known for its glass industry, so the competition was meant to emphasize the town's connection with glass. Two young architects submitted a proposal that used glass as the building's main structural component (Nijsse 108).

The design revolved around the idea of creating layers of space. From the outside, the first layer was a half-climate zone that served several purposes. This area served as a buffer for the hot or cold weather, for traffic noise, and it allowed for a visual block to afford the inhabitants some privacy. The visual blocks were mostly cupboards and screens located between the glass façade and the first interior glass wall. Inside the first interior wall, which was not structural, was the living area. Within the living area, a translucent core provided further privacy for the bathroom area. All of these walls were non-structural and served only to divide the space into livable areas (Nijsse 108).

Four glass walls, located inside the shell of the house, provided all the structural stability that was needed. Figure 8-1 shows the location of these four walls, and how they fit with the rest of the building materials. The glass walls rested directly on the concrete slab which was supported by a pier foundation. Steel beams and a wood framed roof were supported at the top of glass walls. Each wall was roughly 8 foot 3 inches square and 3.5 inches thick. The thickness of the glass was created by using six 0.6-inch layers of toughened glass (Nijsse 108).

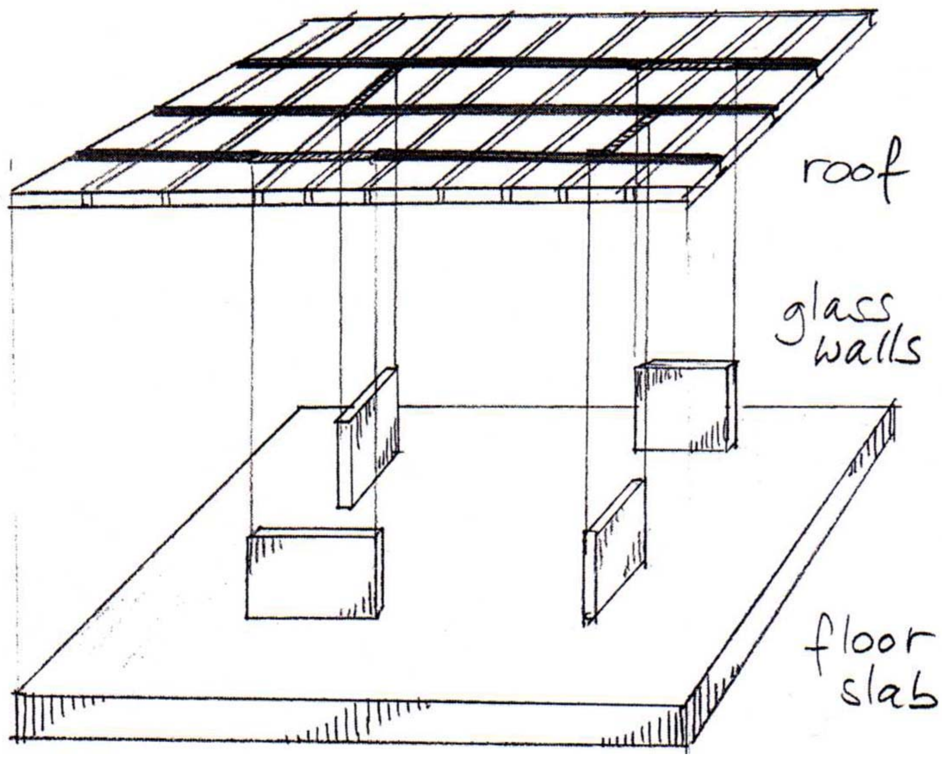

Figure 8-1 Sketch of Structural Glass Wall and Roof Structure (Nijsse 108)

Although this design would have been structurally sound, it was never constructed because it did not win the competition. What makes this project noteworthy is that it was both functional and met the goals of the community. The sponsoring group wanted to emphasize the glass connection, and this design did just that by using glass as the main structural system (Nijsse 109).

The Arnhem Zoo Bridges

Unlike the previous example, the Arnhem Zoo bridges were not only designed, but also constructed. In 1996, the owners of the Arnhem Zoo located in Arnhem, Netherlands, decided they would like to connect two buildings that were located roughly 12.5 feet apart. The owners wanted a glass bridge to span between the newer and older buildings and they desired a minimal visual impact. To achieve this goal, the architect designed a glass bridge that contained no steel. All connections were made using silicone joints. Even the connection of the glass bridge to the existing buildings did not require steel. A solution known as the “Postman Solution” was used, which allowed the glass wall panels to slip into a slit on the building (Nijsse 30).

All of the glass pieces used, which are shown in Figure 8-2, were made of toughened laminated glass. The walls were thicker than the roof because they acted essentially as very deep beams. Because damage from the interior of the bridge was unlikely, only two layers of glass were used for the walls and roof. For the walls, the outer protective layer was about 0.5-inch thick with an inner structural layer that was roughly 0.25-inch thick. To complete the lamination, PVB foil was utilized. The roof also utilized two layers, with the exterior layer about 0.31-inch thick and the inner layer about 0.45-inch thick. To allow rainwater to flow off the roof, the architect decided to make a rounded roof (Nijsse 30).

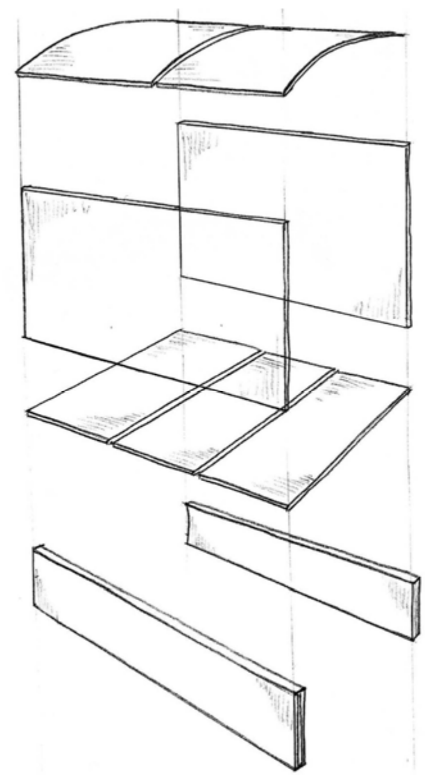

Figure 8-2 Exploded View of the First Arnhem Zoo Glass Bridge (Nijsse 30)

Following completion of the first bridge in 1999, the zoo owners decided to add another bridge to connect the opposite side of the building to an adjacent building. The first bridge was a huge success so the owners wanted the second bridge to be as similar to the first as possible. One challenge with the second bridge was that the two buildings had a considerable change in elevation. Because of this height difference, stairs had to be incorporated into the design. Using the modern glass techniques of laser cutting and high water-pressure cutting, it was relatively simple to fabricate the different wall shape (Nijsse 30).

Like the first bridge, the second Arnhem Zoo glass bridge did not use steel connections. This was very advantageous because it eliminated the need to drill holes in the glass panels. Eliminating the holes lessened the likelihood that cracks would form. With the exception of the shape of the walls and the thickness of glass that was used, the detailing for the two bridges was identical. For this bridge, each structural element was composed of laminated pieces of glass with the same thickness. The walls and roof each had two panels with the walls being 0.4-inch thick, and the roof 0.3-inch thick. The beams spanning between the two buildings and supporting the floor on each side were three laminations each 0.5-inch thick. Again, for rainwater runoff the roof was rounded. Figure 8-3 shows the completed bridge (Nijsse 31).

Figure 8-3 The Completed Second Arnhem Zoo Bridge (Nijsse 31)

Apple SoHo Staircase

The final example is a glass structure constructed in the United States. In July 2002, Apple Computer Inc. opened a new store in SoHo, New York that featured a glass staircase. The staircase used an interlayer produced by DuPont that does more than simply bond together two layers of glass. SentryGlas® Plus is a patented chemical structural interlayer, so it adds strength to the already toughened glass. Because the interlayer is of such high quality, it was possible to create stair treads that appeared to be one solid glass member (Stairs Online).

As can be seen in Figure 8-4, the stairs seemed to be free floating, because they are connected to glass walls. Every stair tread was connected on each side to a vertical glass side wall by small titanium inserts. Typically it is difficult to laminate metal into a glass system, but because the SentryGlas® Plus flows so well, it completely enveloped the metal and made it act as part of the glass once it hardened. Another benefit of the new DuPont technology was that it greatly reduced the required thickness of the glass panels. Because PVB is not as strong, the stair treads would have been 50 percent thicker than they were if it had been used. As constructed, the treads were six feet long and less than two inches total thickness. They were laminated glass made of layers with thicknesses of 0.31, 0.59, 0.59, and 0.31 inches. All the layers were connected using a 0.06-inch interlayer of SentryGlas® (Stairs Online).

Figure 8-4 Apple SoHo Staircase (Stairs Online)

All the testing and calculations for the glass in this project was done by DuPont Central Research and Development in Wilmington, Delaware. When comparing SentryGlas® Plus to standard PVB foil, the structural layer proved that it could make a glass panel twenty times stronger in bending. Since the Apple SoHo store opened, SentryGlas® Plus has been used in other projects and its strength has continued to be proven. Another staircase was built using the same techniques as the Apple staircase for Bystronic's North American headquarters in Hauppauge, New York. It was found that SentryGlas® Plus increased the tensile strength by five times and the rigidity 100 times in comparison to PVB. Using DuPont's patented interlayer it was possible to eliminate the need for tempered glass in subsequent staircases (Stairs Online).

CHAPTER 9 - Conclusion

Glass can have endless possibilities in structural applications. It is very advantageous from an architectural standpoint because it is transparent and causes very minimal visual interruption. Although, just because glass possesses these properties does not mean that it is ideal in all instances that require transparency. For example, many aquariums all over the world use polyacrylic or polycarbonate panes. Even though glass is stronger and more durable than these acrylics, it is also much more expensive and challenging to supply in the shapes required (Nijsse 113).

There are various reasons why glass is not as prolific in the United States as it is in Europe. One is the reluctance of manufacturers to expand production to include specialty and structural glass. Because of the precision required to make structural glass, it cannot be produced as quickly or cheaply as nonstructural glass. This would require costly equipment investments that the manufacturer may not be able to recover due to small demand for structural glass. Another reason for the reluctance to produce and use structural glass is that in recent years research and development budgets have been dramatically reduced. What money is left for research is used to find more economical processes for creating plate glass. It is also speculated that some glass producing companies avoid structural glass because of a fear of liability. If manufacturers begin to promote applications for structural glass, they would open themselves to additional liability (Davidson Online).

Although designers of structural glass are still fighting a battle to prove the possibilities of glass, there are signs of progress. Five keys to assure the success of glass in load bearing applications have been presented in this report and explained. First, it is important that the forces have a clear load path through the glass into some sort of support. Next, because glass cannot redistribute loads like a ductile material, it is important to minimize concentrated loads. To avoid concentrated loads at connections, designers must separate glass from metal with a more forgiving material such as silicon or neoprene. Because glass typically fails in tension, the key to good structural design is to keep it in compression at all times. Finally, like in any project, it is of utmost importance to have an accurate load prediction. Unlike structural steel, glass is brittle and does not possess the ductility necessary to redistribute loads to other members of the structure if an unpredicted overload occurs (Loughran 125).

There are many challenges to overcome before glass becomes widely accepted by designers, contractors, and code officials. Even though glass members rarely fail, the perception that glass is brittle, sharp and dangerous keeps people from pursuing structural uses of it. Also, when glass fails it does so suddenly without any sign of warning, preventing even experienced designers from taking the chance. What most people fail to realize is that glass is considerably stronger than steel when carefully produced. If the glass industry could agree to work together and fund research on structural glass applications, and would create an industry wide standard for structural design, it could provide the backing needed to move this wondrous art form into mainstream construction in the United States. No other structural material can provide the transparency, strength, and beauty that is provided in the architectural use of glass.

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Appendix A - Timetable of Glass History

Table A-1 shows the relationship between glass history and the history of man in regards to outstanding achievements in art and science.

Table A-1 History of Glass and Mankind

Year (B.C.)	History, Art, Science	Glass History
75,000	Third Interglacial Period; chipped stone implements	Nature's glass – obsidian
50,000	Post-glacial Period	Earliest colored glazes
10,000	Neolithic or polished Stone Age men; domestication of plants and animals	First man-made glass
4,241	The calendar devised	
4,000	Age of Metals	
3,000	Great pyramids of Egypt	
2,500	Hittite Empire begun	
2,100	Hammurabi in Babylon	Oldest glass bearing definite date
1,500		Egypt the center of glass manufacture
1,200		Glass pressed into open molds
1,100	Alphabet, navigation; the Homeric epics	
539	Cyrus founds Persian Empire; Pythagoras; Old Testament organized	
490	Battle of Marathon	
384	Aristotle	
334	Alexander the Great	Invention of the blowpipe (?)
4	Jesus of Nazareth born	Rome the center of glass manufacture

Year (A.D.)	History, Art, Science	Glass History
54	Nero	
313	Constantine makes Rome Christian	Partial destruction of glass industry
425	Teutons overrun the Roman Empire	
476	End of the Western Roman Empire	Stained glass windows in Constantinople
570	Mohammed born	
800	Charlemagne crowned	
1071	Turks revive Islam	
1099	Crusaders in Jerusalem	
1202	Arabic numerals enter Europe	Venice the center of glass manufacture
1215	Magna Carta signed	
1348	The Great Plague	Enameled glass of the Saracens and Silvered mirrors in Venice
1446	First printed books	
1453	Ottoman Turks take Constantinople	
1492	Columbus discovers America	
1498	Vasco da Gama reaches India	Venetian "Cristallo"
1564	Galileo born	
1609	Virginia settled	First American glass
1615		Glass revolutionized by coal
1642	Newton born	
1643	Louis XIV	
1674	Velocity of light measured; Spermatozoa discovered	Flint glass in England
1688		Cast glass in France
1739		Wistarberg and Stiegel glass
1765	Steam engine invented	
1774	American Revolution	

Year (A.D.)	History, Art, Science	Glass History
1809	Dalton's atomic theory	
1819	Electromagnetism	Boston and Sandwich Glass Company
1837	Queen Victoria; the telegraph invented	
1839	Photography	
1861	Darwin	
1876	The telephone invented	
1879	Incandescent lamp; the automobile	First glass light "bulb"
1893	Motion pictures	
1895	Radio	The Owens bottle machine
1903	Airplane invented	
1904	Russo-Japanese War	Pyrex brand glasses developed
1914	World War I begins	
1918	End of World War I	
1926	Locarno treaty; North Pole flight	Laminated "safety" glass
1930	Beginning of long American depression	
1931		Fiber glass; glass building blocks
1936	Spanish Civil War	
1937	Sino-Japanese War	
1939	World War II begins	96 per cent silica glass
1940		Foam Glass
1941		Metallized glassware
1942	World War II ends	

Table A-1 is adapted from:

Phillips, C.J. Glass: The Miracle Maker. New York: Pitman Publishing Corporation, 1948.

Appendix B - ISG Standard Glass Fin Wall Specifications

The following is a sample specification for a glass fin wall from Innovative Structural Glass.

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SECTION [08 44 27] [08971]

GLASS FIN STRUCTURES

******* Unique, custom designed, glass facades, entrances, storefronts, curtain walls, skylights, canopies, and other structures can add distinction, exceptional beauty, and expansive visibility to a construction project. However, these glass structures require meticulous engineering, extensive knowledge of materials and codes, broad experience, quality materials, and expert craftsmanship. Each design will have unique parameters and requirements which must be accurately addressed in order to provide a safe, functional, durable, weather-resistant glass structure which can withstand wind and seismic loads and thermal expansion and contraction. It is critical that unique glass structures be both designed and fabricated by a single, knowledgeable entity assuming complete responsibility. Piece-meal assembly of products from numerous manufacturers and fabricators without a comprehensive design and engineered solution is not a method for achieving a functional, safe, glass structure.**

Innovative Structural Glass, Inc. can provide this essential sole source design and fabrication responsibility. They are a domestic company focused on the United States market. They provide glass luxury at affordable prices in a timely manner. Innovative Structural Glass, Inc. designs and fabricates a wide variety of glass structures including facades, entrances, storefronts, skylights, canopies, glass fin systems, and tension truss structures.

This specification guide can be used to specify a custom designed and engineered glass structure using Innovative Structural Glass's glass fin technology. With this method glass mainplates (panels) form the plane of the wall and are stabilized with vertical glass fins eliminating the need for metal mullions. The result is a total vision wall. Glass fin technology can be used for many types of structures such as entrances, storefronts, curtain walls, monuments, sculptures, decorative features, balconies, elevated floors, roofs, skylights, and canopies. Glass fin assemblies can be used on the interior, exterior, or the envelope of a building.

In contrast to more typical descriptive specifications, this section is a performance type emphasizing the critical factor of design and engineering. It provides a convenient format that can be edited to reflect the unique glass structure envisioned by an architect and ensure that it is correctly engineered, carefully detailed, accurately fabricated, and properly installed.

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Glass facades with entry doors, skylights, and canopies are specific uses of glass fin technology which can be specified using the following Innovative Structural Glass specifications. These sections also include other technologies for the construction of facades, skylights, and canopies.

SECTION 08 41 26 (08450) - GLASS FACADES
SECTION 08 63 10 (08631) - GLASS SKYLIGHTS
SECTION 08 44 29 (08973) - GLASS CANOPIES

This specification section is organized by placing information in three standard parts:

PART 1 - GENERAL	**Describes the design and performance criteria for the glass fin structure and other administrative and procedural requirements.**
PART 2 - PRODUCTS	**Describes materials, products, accessories, and fabrication methods to be used for the glass fin structure.**
PART 3 - EXECUTION	**Describes how the components will be assembled and installed at the construction site.**

Throughout this product guide specification, references are made to other specification sections that might be contained in the project manual. These references are presented as examples and coordination reminders. For each project, these references will need to be revised to reflect actual sections being used.

The six-digit specification section numbers in this guide are based on classifications and numbers contained the 2004 Edition of MasterFormat published by the Construction Specifications Institute (CSI) and Construction Specifications Canada (CSC). This is the industry standard for organizing construction specifications. Previous five-digit numbers from the 1995 Edition of MasterFormat have also been included in this guide and are listed in brackets following the 2004 Edition numbers.

Within the specification text, Imperial dimensions are presented first in brackets followed by System International Metric (SI) equivalents also in brackets. Depending on project requirements, either the Imperial or the SI metric equivalents will need to be deleted.

The specifier will need to edit this product specification for a specific project to reflect the options and applications being used. The guide section has been written so that much editing can be accomplished by deleting unnecessary requirements and options. Additional information describing the desired characteristics of the glass structure will need to be added by the specifier. Options are indicated by [ ]. Notes to assist the specifier in selecting options and editing the specification guide are printed in bold and indicated with ***. For final editing, all brackets and notes will need to be deleted from the guide.**

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****

PART 1 - GENERAL

1.1 SUMMARY

******* Edit the following paragraph to reflect project requirements. *******

A. Section includes: Functional design, structural engineering, custom fabrication, and site erection required for glass [walls] [curtain walls] [monuments] [sculptures] [decorative features] [balconies] [elevated floors] [roofs] constructed using glass fin technology.

******* List other specification sections dealing with work directly related to this section such as the following. *******

B. Related sections:

1. Section [03 30 00] [03300] - Cast-in-Place Concrete: [Foundations and slabs] [concrete structural frame] to receive glass fin structure.

2. Section [04 05 10] [04800] - Masonry Assemblies: Masonry framing to support glass fin structure.

3. Section [05 12 00] [05120] - Structural Steel: Steel structural frame to receive glass fin structure.

******* Glass may be specified in this section or in a separate section covering glass for all project glazing. If color tinted or reflective glass is required for various entrance, storefront, window, door, and curtain wall systems, it is important that glass be provided from a single glass manufacturer to ensure uniformity of appearance. However, supply and installation of glass must be part of this section to ensure sole source responsibility. Include the following paragraph if glass is specified in a separate section. *******

4. Section [08 80 00] [08800] - Glazing: Glass to be supplied and installed as part of this Section.

1.2 REFERENCES

****** List by number and full title reference standards referred to in remainder of specification section. Delete non-applicable references. *******

A. American National Standards Institute (ANSI): ANSI Z97.1 - Safety Performance Specifications and Methods of Test for Safety Glazing Material Used in Buildings.

B. American Society of Civil Engineers (ASCE): ASCE 7 - Minimum Design Loads for Buildings and Other Structures.

C. American Society for Testing and Materials (ASTM):

1. ASTM A276 - Stainless and Heat-Resisting Steel Bars and Shapes.

2. ASTM C509 - Elastomeric Cellular Preformed Gasket and Sealing Material.

3. ASTM C864 - Dense Elastomeric Compression Seal Gaskets, Setting Blocks, and Spacers.

4. ASTM C920 - Elastomeric Joint Sealants.

5. ASTM C1036 - Flat Glass.

6. ASTM C1048 - Heat Treated Flat Glass, Kind HS, Kind FT, Coated and Uncoated.

7. ASTM C1115 - Dense Elastomeric Silicone Rubber Gaskets and Accessories.

8. ASTM C1172 - Laminated Architectural Flat Glass.

9. ASTM C1281 - Preformed Tape Sealants for Glazing Applications.

10. ASTM E283 - Rate of Air Leakage Through Exterior Windows, Curtain Walls, and Doors under specified Pressure difference Across Specimen.

11. ASTM E330 - Structural Performance of Exterior Windows, Curtain Walls, and Doors by Uniform Static Air Pressure Difference.

12. ASTM E331 - Water Penetration of Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform Static Air Pressure Difference.

13. ASTM E546 - Frost Point of Sealed Insulating Glass Units.

14. ASTM E576 - Frost Point of Sealed Insulating Glass Units in Vertical Position.

15. ASTM E773 - Accelerated Weathering of Sealed Insulating Glass Units.

16. ASTM E774 - Classification of the Durability of Sealed Insulating Glass Units.

17. ASTM E1300 - Determining Load Resistance of Glass in Buildings.

D. Consumer Product Safety Commission (CPSC): CPSC 16 CFR 1201 - Safety Standard for Architectural Glazing Materials.

E. Glass Association of North America (GANA): GANA - Glazing Manual.

F. International Code Council (ICC): ICC IBC - International Building Code.

1.3 GLASS FIN STRUCTURE DESCRIPTION

A. Glass fin structure to be custom designed, engineered, detailed, factory fabricated, and site assembled and erected.

B. Type of glass structure: Glass mainplate [vertical] [horizontal] [sloping] panels stabilized and supported with perpendicular glass fins attached with metal connector fittings. Glass fins shall [extend full height of mainplate panels.] [be cantilevered from [floor] [ceiling] [both floor and ceiling].

******* Many interesting and unique glass fin structures can be created by Innovative Structural Glass, Inc. Contact them for available options and assistance in planning and specifying. Edit the following paragraph to reflect basic configuration of glass structure. ******

C. Basic configuration: [Straight] [curved] [multi-angled] [articulated] [_____] layout with [vertical] [sloped] [horizontal] glass surface stabilized and supported by glass fins to provide architectural appearance and configuration shown on Drawings.

D. Dimensions: Glass fin structure shall be nominal dimensions shown on Drawings. Minor variations to accommodate manufacturer's design and components are acceptable provided overall concept is maintained.

1.4 DESIGN AND PERFORMANCE CRITERIA

******* Innovative Structural Glass, Inc. will provide structural engineering and design for support system, connections, anchors, seals, and other elements of glass fin structure. Edit this article to reflect project conditions and applicable codes. *******

A. Design Requirements:

1. Design Wind Load: [_____] pounds/square foot] [_____] kilograms/square meter]

2. Snow Load (if applicable): [_____] pounds/square foot] [_____] kilograms/square meter]

3. Seismic Zone: [_____]

4. Live load deflection of supporting structure (if any): [_____]

B. Design, size components, and install glass fin structure in accordance with ASTM E1300 to withstand these loads without breakage, loss, failure of seals, product deterioration, and other defects.

1. Dead and live loads: Determined by ASCE 7 and calculated in accordance with applicable codes.

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PHONE: 559-561-7000; FAX: 559-561-7007; website: www.structuralglass.com

2. Seismic loads: System shall be designed and installed to comply with applicable seismic requirements for Project location and Seismic Zone [0] [1] [2A] [2B] [3] [4] as defined by of ICC/IBC.

3. Movement and deflection of structural support framing.

4. Effects of applicable wind load acting inward and outward normal to plane of wall in accordance with ASTM E330.

5. Thermal loads and movement:

   a. Ambient temperature range: [[120] [_____] degrees F.] [[48] [_____] degrees C.]

   b. Material surfaces range: [[180] [_____] degrees F.] [[82] [_____] degrees C.]

C. Provide and install exterior gaskets, sealants, and other glazing accessories to resist water and air penetration.

1. Air infiltration: Less than [[0.06] [_____] cubic feet/minute/square foot] [[1699] [_____] cubic centimeters/second] of fixed area tested in accordance with ASTM E283.

2. Water infiltration: No penetration at [15] [_____] pounds/square foot] [[73] [_____] kilograms/square meter] test pressure and [[5] [_____] gallons/hour/square foot] [[18] [_____] liters/hour/square meter] water rate tested in accordance ASTM E331.

1.5 SUBMITTALS

A. Submit in accordance with Section [01 33 00] [01330] - Submittal Procedures:

1. Product data for all proposed components, materials, products, and accessories.

   a. For each type glass, provide maximum allowable stress in both horizontal and vertical directions.

   b. Provide photographs or drawings for fittings and hardware.

2. Shop drawings:

******* Edit the following list to reflect components required for glass fin structure. *******

   a. Plans, elevations, and sections illustrating shape, configuration, and dimensions. For complex structures provide perspectives, renderings, or models.

Innovative Structural Glass, Inc., 40220 Pierce Drive, Three Rivers, California 93271
PHONE: 559-561-7000; FAX: 559-561-7007; website: www.structuralglass.com

b. Illustrate method of assembly, installation, and glazing.

c. Provide details for support framing, reinforcement, connections, joints, anchors, and other fabrication and installation conditions.

d. Indicate required tolerances and coordination with adjacent elements and work of other trades.

3. Calculations: Show compliance with performance criteria and applicable loads with stamp of Licensed Professional Engineer registered in the State of [_____].

4. Samples:

a. [12 by 12 inches] [304 by 304 mm] minimum size for each type glass.

b. Glass fitting.

c. Metal finishes.

d. Sealant colors.

5. Manufacturer's installation and maintenance instructions.

6. Certificates or test reports demonstrating components and methods have been successfully tested by an independent laboratory in the United States certifying that the proposed system has been tested and as defined by Paragraph [1.4] [_____].

7. Data showing compliance with manufacturer's and installer's qualifications specified in Paragraphs [1.6.A and 1.6.B] [_____]. Provide descriptions, locations, photographs, references, and completion dates for previous projects.

8. Copies of warranties required by Paragraph [1.11] [_____] for review by Architect. Included with warranty shall be a letter certifying the proposed system will be manufactured from one source. Glass cannot be supplied by one manufacturer and hardware from another manufacturer to comply with this warranty. Letters signed by the subcontractors or installers for this section are not acceptable.

1.6 QUALITY ASSURANCE

******* To ensure that completed glass fin structure is structurally sound, weathertight, functional, durable, and safe; specify that design, engineering, fabrication, and supply of all components, materials, and products be the sole responsibility of an experienced single entity such as Innovative Structural Glass, Inc. It is critical that unique glass structures be both designed and fabricated by a single, knowledgeable entity assuming complete responsibility. Piece-meal assemblies of products from numerous**

manufacturers and fabricators without a comprehensive design and engineered solution is not a method for achieving a functional, safe, glass structure.

A. Single source responsibility: Design, structural engineering, and custom fabrication for glass fin structure and supply of all components, materials, and products shall be sole responsibility of single manufacturer. Provision of products from numerous sources for site assembly without complete single source design and supply responsibility is not acceptable. Components to be fabricated or supplied by single source are:

******* Edit the following list to reflect components required for glass skylight. *******

1. Support framing.
2. Glass [as specified in Section [08 80 00] [08800] - Glazing].
3. Connectors, fittings, anchors, and installation accessories.
4. Gaskets and sealants.
5. All other components, products, and materials required for complete, functional glass fin structure.

B. Single installation responsibility: All components listed in Paragraph [1.6.A] [_____] shall be installed by a single installer.

C. Manufacturer qualifications: Company specializing in designing, engineering, and fabricating unique, custom designed, glass fin structures, entrances, storefronts, and other glazed structures. Glass cannot be supplied by one manufacturer and hardware from another manufacturer to comply with this warranty. Letters signed by the subcontractors or installers for this section are not acceptable.

1. Experience: 7 years minimum successful experience providing glass structures.
2. Previous projects: Successfully completed 10 minimum glass structures of scope, type, and size as proposed Project.

D. Installer qualifications: Company experienced in erecting custom designed, glass fin structures, entrances, storefronts, and other glazed structures and acceptable to manufacturer for installing proposed structure.

1. Experience: 3 years minimum successful experience erecting glass structures.
2. Previous projects: Successfully completed 3 minimum glass structures of scope, type, and size as proposed Project.

E. Design structural components and develop shop drawings under direct supervision of professional structural engineer experienced in design of glass structures. Calculations and shop drawings shall bear engineer's seal.

F. Safety glazing: Comply with Consumer Product Safety Commission 16 CFR 1201, ANSI Z97.1, and other applicable safety requirements. Each piece of safety glazing shall be permanently labeled with appropriate marking.

******* For large, more complicated structures it is appropriate that Innovative Structural Glass, Inc. send a field representative to oversee installation. Use the following paragraph to require manufacturer's field representative. *******

G. Manufacturer's field representative:

1. During installation, provide services of manufacturer's field representative knowledgeable of erection process for proposed glass fin structure.

2. Manufacturer's representative shall observe installation, quality control, and certify work meets specified requirements.

3. Manufacturer's representative shall submit report covering observations, procedures, noted deficiencies, corrective measures, and certification of proper installation.

1.7 MOCK-UP

******* For larger projects or complicated conditions a mock-up may be important to establish workability and performance of proposed glass fin structure. Include this article to request mock-up constructed on site separate from actual construction. *******

A. In accordance with Section [01 40 00] [01400] - Quality Control, prepare separate mock-up illustrating construction method for glass fin structure. Mock-up shall demonstrate performance and establish workmanship quality standard.

B. Provide concrete slab as mock-up base.

C. Mock-up shall be segment of structure with two minimum glass fins. Construct with all anchors, fasteners, sealants, and other components proposed for actual installation.

D. Approximate size: [8 by 8 feet] [2.4 by 2.3 m] [_____].

E. Test mock-up with [water hose to verify weathertightness] [[__other test__] to verify [__type of performance__].

F. Submit report describing tests, results, and any modifications made to correct deficiencies or to improve performance.

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PHONE: 559-561-7000; FAX: 559-561-7007; website: www.structuralglass.com

G. Do not proceed with installation until mock-up has been inspected and accepted by Architect.

H. Retain approved mock-up during construction as quality standard. Completely remove when work is accepted.

1.8 PRE-INSTALLATION CONFERENCE

******* Depending on project size, complexity of glass structure, and number of coordination items, a pre-installation conference maybe important. Include this article to specify pre-installation conference. *******

A. In accordance with Section [01 31 00] [01310] - Project Management and Coordination, convene a pre-installation conference at site prior to commencing work of this Section.

B. Require attendance of entities directly concerned with glass fin structure [including manufacturer's field representative].

C. Review at meeting:

******* Add to and edit the following list to reflect project conditions. *******

1. Construction of foundation and preparation of rough opening to receive glass fin structure.

2. Schedule, sequence, and method for installing glass fin structure and coordination with other work.

3. Safety procedures.

4. Availability of system materials.

5. Chemical compatibility of glass panels, sealants, adjacent construction materials, and other glazing materials.

6. Protection of adjacent items and finishes.

7. Approved mock-up to be used a measure of acceptance.

8. Other items related to successful execution of work.

1.9 PRODUCT HANDLING

A. Protect glass and other components during delivery, storage, and handling in accordance with manufacturer's instructions. Prevent edging chipping and other damage.

B. Insulating glass units: Comply with fabricator's instructions for venting and sealing units exposed to substantial altitude changes.

C. Do not store glass panels on site for extended time.

1.10 ENVIRONMENTAL REQUIREMENTS

A. Do not install solvent curing sealants in enclosed building spaces without proper ventilation.

B. During glazing, maintain [40 degrees F] [4 degrees C] minimum temperature.

1.11 WARRANTIES

A. Provide under provisions of Section [01 77 00] [01770] - Closeout Procedures:

1. Manufacturer's 2 years warranty to cover design, fabrication, and materials against defects and failure to perform and remain weathertight. Warranty to provide for replacement of defective components.

2. Glass warranties:

   a. 10 years warranty to cover replacement of insulating sealed glass units: in event of seal failure and interpane dusting, misting, and filming.

   b. 5 years warranty to cover replacement of laminated glass units in event of delamination, edge separation, and blemishes.

3. Installer's 5 years warranty to cover installation against defects and failure to perform and remain weathertight. Warranty to provide for required repairs.

PART 2 - PRODUCTS

2.1 ACCEPTABLE DESIGNER-MANUFACTURER

A. Glass fin structure shall be designed and fabricated by Innovative Structural Glass, Inc.

1. Address: 40220 Pierce Drive, Three Rivers, California 93271.

2. Phone: 559-561-7000 / Fax: 559-561-7007

3. Website: www.structuralglass.com

B. Requests to use design services and products of another manufacturer must be submitted in accordance with Section [01 63 00] [01630] - Product Substitution Procedures.

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2.2 GLASS PRODUCTS

******* Various glass types can be used for glass fin structures. Selection will be influenced by structural criteria, functional requirements, codes, aesthetics, and cost. Attributes such as visible and ultra violet light transmittance, U-value, shading coefficient, and solar heat gain coefficient will also influence glass types used for a specific project. Information and values for these attributes can be found in literature published by glass manufacturers.**

Note for glass floors, roofs, and other applications where glass is installed at a slope of 15 degrees or more from vertical, glazing must be either fully tempered, heat-strengthened, wire glass, or laminated glass in accordance with most codes. Except for laminated glass, a protective screen must be installed below glass in these type applications.

As previously noted, glass products can be specified in this section or in Section 08 80 00 (08800) - Glazing with a reference in this section. Edit the following to indicate where glass is specified. *****

A. Glass type and thickness shall be determined by glass fin structure manufacturer to accommodate Project design and performance requirements specified in Paragraph [1.4] [_____]. Types of glass shall [be as specified in Section [08 80 00] [08800] - Glazing.] [include the following.]

******* If glass is being specified in this section, select types from the following paragraphs:**

B. Primary glass products:

******* Clear, color tinted, reflective, and low-E glass products can be used to fabricate the tempered, laminated, and insulating glass panels typically used for glass fin structures. Select required primary glass products from the following, *******

1. Clear glass: Clear, transparent, flat, annealed, float glass, conforming to ASTM C1036, Type I, Class 1, Quality q3.

2. Color tinted glass: [Blue] [Light green] [Dark green] [Light gray] [Medium gray] [Dark gray] [Bronze] [_____] color tinted, annealed, float glass conforming to ASTM C1036, Type I, Class 2, Quality q3.

******* Metallic oxide coatings can be deposited onto color tinted glass during production provide a reflective appearance and increase solar control. *******

3. Reflective coated tinted glass: [_____] color tinted float glass with metallic oxide coating deposited during production and conforming to ASTM C1036, Type I, Class 2, Quality q3.

******* Low emissivity (low-E) glass products are produced by applying a neutral coating which blocks a significant percentage of solar energy and greatly improves energy efficiency. *******

4. Low emissivity (low-E) glass: Clear glass with neutral coating pyrolytically applied to improve thermal performance and reduce solar heat gain.

C. Fabricated glass panels:

****** Primary glass products can be heat treated to increase strength and resistance to thermal stress. There are two types of heat treatment - heat strengthened and fully tempered. Heat strengthened glass is approximately twice as strong as annealed glass of equal thickness. However, it does not qualify as safety glass. *******

1. Heat strengthened glass: Heat strengthened, annealed glass conforming to ASTM C1048, Kind HS.

******* Fully tempered glass is approximately four times as strong as annealed glass of equal thickness. Tempered glass does qualify as safety glass and tends to break into small cubical pieces. Fully tempered glass is used for most glass structures fabricated by Innovative Structural Glass, Inc. *******

2. Fully tempered glass: Heat strengthened safety glass complying with ASTM C1048, Kind FT and ANSI Z97.1 and CPSC 16 CFR.

******* Laminated glass is fabricated by bonding two or more glass panes with a transparent, flexible interlayment material. Laminated glass does qualify as safety glass. When broken, laminated glass tends to remain in place with glass particles adhered to interlayment. *******

3. Laminated glass: Fabricated by bonding two or more glass panes with transparent, flexible interlayment material in accordance with ASTM C1172. Laminated glass shall meet requirements of ANSI Z97.1 and CPSC 16 CFR to qualify as safety glass.

******* Insulating glass is fabricated using two glass panes, referred to as lites, separated by an air space with the interpane space purged with dry hermetic air and sealed. The air space provides insulation and reduces heat transfer as well as limiting condensation and sound transmission. *******

4. Insulating glass units: Fabricate insulating glass units with two lites separated by air space. Seal edge and purge interpane space with dry hermetic air. Comply with ASTM E546, ASTM E576, ASTM E773, and ASTM E774.

******* For glass fin structures glass is mechanical installed with stainless steel connectors and fittings. Mechanical attachment with fittings can also be used for installing glass panels directly to support substrate. These devices require accurately drilled holes in**

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glass to receive fitting pins. Holes must be drilled prior to tempering glass panels. Include this paragraph if mechanically installed glass panels are required. ***

D. For glass panels to be installed with mechanical connectors and fittings, provide holes to receive bolts and fitting pins. Holes shall be drilled prior to tempering glass.

2.3 FITTINGS

******* Innovative Structural Glass, Inc. designs and fabricates a broad range of stainless steel fittings for connecting glass panels together, to glass fins, and to other support systems and substrates. It is important that fittings be designed for specific project conditions and loadings and be provided by entity responsible for glass fin structure design. Stresses induced in glass panels by fittings must be compatible with glass strength. Innovative Structural Glass fittings have been independently tested to ensure quality and structural performance. *****

A. Provide structurally engineered and independently tested fittings by an independent laboratory in the United States for connecting glass panels and fins together and for attachment to supporting substrates.

B. Material: Stainless steel complying with ASTM A276, Type 316 with [brushed satin finish] [reflective polished finish].]

C. Types: Configuration, number of points, size, and spacing shall be determined by manufacturer and scheduled on shop drawings to accommodate project design and meet performance criteria specified in Paragraph [1.4] [_____]. Ensure that fitting-induced stresses do not exceed glass strength.

D. Providing fittings with countersunk stainless steel bolts, Delrin bushings, and resilient gaskets.

2.4 ACCESSORIES

A. Provide glazing accessories, anchors, and fasteners of type recommended by glass fin structure manufacturer and as required for complete, functional, weathertight installation.

B. Anchorage devices: Clips, anchors, fasteners, and shims required for secure installation of glass fin structure. Type, size, and spacing as recommended by glass fin structure manufacturer.

C. Cleaners and primers: Recommended by manufacturer to be compatible with substrate and glazing materials.

D. Setting blocks: Neoprene or EPDM complying with ASTM C864.

E. Edge blocks: Elastomeric material of hardness required to limit lateral movement of glass.

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PHONE: 559-561-7000; FAX: 559-561-7007; website: www.structuralglass.com

F. Gaskets: Molded or extruded elastomeric type of profile and hardness required to maintain weathertight seal and complying with ASTM C509, ASTM C864, or ASTM C1115.

G. Glazing tape: Preformed butyl compound, non-staining, non-migrating in contact with non-porous surfaces, coiled on release paper, complying with ASTM C1281.

H. Glazing sealant: Chemically curing type complying with ASTM C920, compatible with materials and conditions, and capable of anticipated joint movement without watertight seal failure.

I. Contact structural sealant: High performance, two component, non-sag, neutral cure, ultraviolet resistant, silicone sealant designed for structural glazing and complying with ASTM C920.

PART 3 - EXECUTION

******* Edit this article to reflect type of glass fin structure and components being installed. Delete non-applicable items and requirements. *******

3.1 COORDINATION

A. Coordinate provision of glass fin structure with casting of concrete [footings] [floor slabs] [walls] [structural framing] specified in Section [03 30 00] [03300] - Cast-in-Place Concrete. Ensure that [sleeves,] [inserts,] [anchor bolts,] [reglets,] [_____] and other embedded items are provided in sufficient time for embedment in cast concrete. Ensure that blockouts and pockets for glass fin structure components are provided, accurately placed, and properly sized.

B. Coordinate provision of glass fin structure with structural framing specified in [Section [03 40 00] [03400] - Precast Concrete] [Section [04 05 10] [04800] - Masonry Assemblies.] [Section [05 12 00] [05120] - Structural Steel.] Ensure that provision is made for attachments and transfer of calculated loads.

C. Field verify dimensions prior to fabricating glass fin structure components.

3.2 INSPECTION

A. Prior to delivery of glass panels to site, verify that wall openings, support framing, and substrates are ready to receive glass fin structure. Verify alignment, support dimensions, and tolerances are correct.

B. Report unacceptable conditions and deficiencies. Do not proceed with installation until corrective action has been performed.

C. Inspect glass panels for chipped edges, scratches, abrasions, and other damage. Remove damaged panels from site and replace.

3.3 GENERAL INSTALLATION

A. Site assemble and erect glass fin structure in accordance with approved shop drawings, manufacturer's installation instructions, and GANA Glazing Manual.

B. Damaged glass: Do not install glass with edge damage or other imperfections.

C. Allow for settling, expanding, and contracting to occur without breaking glass.

D. Do not field cut or alter structural framing without written approval from manufacturer and Architect.

3.4 GLAZING

******* If several types and thicknesses of glass are required for glass fin structure, a glazing schedule either in this section or on drawings may be required. *******

A. Glazing schedule: Install types and thickness of glass in locations scheduled [below] [on Drawings] [on approved shop drawings].

1. Type 1: [__thickness__], [__glass type__], [__color tint__] glass installed in [__location__].

2. Type 2: [__thickness__], [__glass type__], [__color tint__] glass installed in [__location__].

B. Protect adjacent surfaces sealants and glazing materials with masking tape or other means.

C. Install setting blocks and spacers as recommended by glass fin structure manufacturer and indicated on approved shop drawings.

1. Place setting blocks at quarter points. Maintain [6 inches] [152 mm] space from corners.

2. Set blocks in sealant.

D. Provide edge blocking as required to prevent sideway movement of glass in glazing channel.

E. Ensure glazing channels and stops provide required bite on glass, minimum edge and face clearances, and adequate sealant thickness.

******* Various glazing methods can be used depending on type of glass fin structure. Typically butt glazed joints using structural silicone sealant are used for glass fin structures. Other methods such as tape glazing, gasket glazing, and wet sealant glazing**

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may also be required depending on project conditions. Consult with Innovative Structural Glass to determine required glazing methods. ***

F. Glazing methods: [Type as determined by manufacturer and indicated on approved shop drawings.] [Use the following methods for applications indicated on Drawings.]

1. Structural silicone glazing: Use for butt glass joints.

   a. Cleaning: Thoroughly clean all joints and glazing areas immediately prior to sealant application. Remove oil, dust, grease, water, surface dirt, contaminants, and other foreign matter. Vacuum or blow out dust and loose particles from joints. Do not use water cleaning treatments.

   b. Use primers only as recommended by sealant manufacturer. Field test with and without primer before actual application.

   c. Mask areas adjacent to joints to insure neat sealant line. Do not allow tape to touch surfaces to which sealant will be applied.

   d. Install sealant back-up spacers as indicated on Drawings and approved shop drawings.

   e. Apply silicone structural sealant in continuous operation. Tool sealant immediate before skin forms. Tool concave to ensure complete contact.

   f. Post application test: After structural sealant has cured 14 to 21 days, conduct field test as prescribed by manufacturer to test sealant adhesion. Replace sealant not passing test.

2. Tape glazing.

3. Gasket glazing.

4. Wet sealant glazing.

3.5 MECHANICAL ASSEMBLED GLASS UNITS

******* Glass fins and panels are typically mechanically attached to each other and to supporting structure with stainless steel fittings. *****

A. Mechanically install glass fin structure panels with stainless steel fittings as designed by manufacturer and indicated on approved shop drawings.

B. Glass fins: Mechanically join glass fins to mainplate panels with connector fittings to provide stabilization and support.

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C. Secure glass panels to fittings with bolts. Torque bolt to amount specified on approved shop drawings using calibrated tool. Lock torqued bolt into position to prevent backoff. Reset calibrations regularly to ensure accurate torquing.

3.6 CLEANING

A. Clean excess sealant from glass and other surfaces immediately after application. Use solvents or other cleaners recommended by manufacturer.

B. Remove protective material from prefinished surfaces.

C. Wash exposed surfaces using a solution of mild detergent in warm water, applied with soft, clean cloths. Do not use abrasives. Take care to remove dirt from corners. Wipe surfaces clean.

END OF SECTION