Structural Glass Technology: Systems and Applications

By

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ABSTRACT

Glass cannot compete with steel in terms of strength or durability, but it is the only structural material that offers the highly sought after qualities of translucency and transparency. The use of glass has evolved from purely decorative or architectural to structural, encouraging glass technologies to advance concurrently with increased demand. As a result, contemporary methods used to produce structural glass provide excellent strength characteristics, particularly after treatments including annealing, tempering, and heat-strengthening, which reduce its vulnerability to cracking and sudden brittle failure. Its modulus of elasticity is roughly equal to that of aluminum—greater than both wood and concrete—but doesn't allow any plastic deformation. Lamination dramatically improves both the strength and durability of glass by joining strengthened layers of glass using resin or a polyvinyl butyral foil. No comprehensive design code is currently available to aid in the design of structural glass members. The behavior of glass is examined through a variety of structural applications including beams, columns, walls, roofs and floors, and domes. Case studies are explored to underscore the technical principles discussed for each structural glass element utilized in place of more traditional building materials.

Thesis Supervisor: Jerome J. Connor
Title: Professor of Civil and Environmental Engineering

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Introduction

In his 1750's periodical, The Rambler, English writer Samuel Johnson penned these thoughts about the creation, glass and its profound impact on humankind:

> "...it might contribute to dispose us to a kinder regard for the labors of one another, if we were to consider from what unpromising beginnings the most useful productions of art have probably arisen. Who, when he saw the first sand or ashes, by a casual intenseness of heat, melted into a metalline form, rugged with excrescences, and clouded with impurities, would have imagined, that in this shapeless lump lay concealed so many conveniences of life, as would in time constitute a great part of the happiness of the world? Yet by some such fortuitous liquefaction was mankind taught to procure a body at once in a high degree solid and transparent, which might admit the light of the sun, and exclude the violence of the wind; which might extend the sight of the philosopher to new ranges of existence, and charm him at one time with the unbounded extent of the material creation, and at another with the endless subordination of animal life; and, what is yet of more importance, might supply the decays of nature, and succor old age with subsidiary sight. Thus was the first artificer in glass employed, though without his own knowledge or expectation. He was facilitating and prolonging the enjoyment of light, enlarging the avenues of science, and conferring the highest and most lasting pleasures; he was enabling the student to contemplate nature, and the beauty to behold herself."
>
> -Samuel Johnson, "The Rambler" (April 17, 1750)

Over 250 years ago, glass was already recognized as a unique and valuable material, but its advocates had no concept of the uses it would find in modern day building. Architecture Week stated in 2002 that, "Laminated safety glass frees architects from strict reliance on opaque structural materials." Glass also liberates us from the confinements that separate us from the environment. In ways never before seen, structures need not impose on the landscape, but can simultaneously protect us from it and enhance our relationship with it. How many other transparent materials have the load-bearing capacity of glass? To accept glass as a structural material, we must first free ourselves from the ingrained notion that glass is a delicate ornament. We feel safe viewing sharks swimming in a glass tank or watching a lightning storm from behind the windows of our homes. Why then, do we consider glass as a mere decorative element when we trust the strength of an auto windshield to protect us from rocks flying up from the road?

Chapter 1: History

1.1 Prehistoric Natural Glass

The first glass, used by early man, was created by nature. Rhyolite lava flows from volcanoes and swiftly cools, impeding the formation of crystals and creating obsidian glass. This glass has an irregular structure and, therefore, fractured into smooth curved shapes with finer edges. Around the world, many early cultures discovered these properties and utilized this glass in weapons, tools, and decoration.

1.2 Ancient Man-Made Glass

From archaeological evidence, researchers speculate that glass making spread from western Asia, Mesopotamia and Egypt, to the vast Roman Empire.

1.2.1 Mythical Origins

The origin of man-made glass is fraught with speculation. The mythical origins of glass offered by Pliny the Elder in his "Historia Naturalis," still circulates, crediting sea traders in Phoenicia. On the shores of the River Belus, the sand "does not glisten until it has been tossed about by the waves and had its impurities removed by the sea." On this expanse of sand exposed by the retreating tides, a ship of soda traders moored. "Here they spread out along the shore to make a meal. There were no stones to support their cooking-pots so they placed lumps of soda from their ship underneath them. When these lumps became hot and fused with the sand on the beach, streams of an unknown liquid flowed, and this was the origin of glass." (Pliny, 362)

1.2.2 Evidential Origins

It is possible that the Phoenicians did invent glass blowing as a way to manipulate the material, but casting, cutting, and grinding predated the advent of the technique. The earliest man-made glass objects are thought to date to 3500 BC in Egypt and Eastern Mesopotamia, [2] although Pliny alleged that the soda trader's accidental discovery occurred somewhere around 5000 BC. The ancient Romans created molten glass in wood burning furnaces, casting it in pre-made "blank" molds, very similar to the methods for making pottery. Samples from these glass furnace works and glass blowing buildings, found in archaeological sites scattered across the ancient Roman empire, abound in museum collections—their survival a testimonial to glass durability.

1.2.3 Etymological Origins

The word, glass, derives from Latin *glacies*, meaning *ice*. Many permutations of the word were adapted to each culture that embraced the use of glass, i.e. Germans *glas*, and old English *glaes*. The Germanic tribes also used the word *glaes* to describe amber, and Romans admired the clear beautiful resin as glass-like gems called *glaesum*. Anglo-Saxons used the word *glaer* for amber, proving this substance was admired by many cultures for its transparent luminosity, or, glass-like qualities. [17] It is not so difficult, then, to understand our cultural, historical, and universal fascination with glass.

1.2.4 Glass Trade

Glass technology proliferated across Western Europe and the Mediterranean largely due to the conquests, trade relations, road building, and effective political and economical administration of the Roman Empire. Glass production flourished during the reign of emperor Augustus, extending as far as China along Roman trade routes. Glass was used for both practical and decorative purposes including containment vessels, ornamental urns, mosaic tiles, and jewelry (Figure 1).

Figure 1: Roman glass vessels used for containing olive oil and fish sauce [27]

1.3 Origins of Architectural Glass

It was the Romans who began to use glass for architectural purposes, with the discovery of clear glass (through the introduction of manganese oxide) in Alexandria around AD 100. Cast glass windows, albeit with poor optical qualities, thus began to appear in the most important buildings in Rome and the most luxurious villas of Herculaneum and Pompeii [2]. The art of glass production was considered a national secret, and Venetian craftsmen were threatened with death if they disclosed trade information or emigrated to practice elsewhere. Stuart Fleming, while curating a show on Roman glass at the University of Pennsylvania, *Roman Glass: Reflections on Cultural Change* used glass to highlight the empire's sway toward materialism, and away from military expansionism. Representing decadent expense, decorative, utilitarian, and architectural glass in the homes of wealthy Romans spawned both the burgeoning glass industry, and a hungry competition in building. In A.D. 330, Emperor Constantine, created his new seat at Constantinople. This period included the building of 14 basilicas, 11 palaces, and the beautiful Church of Holy Wisdom. [14] When Roman military might waned, Europe lost access to glass production and its use was severely limited to cathedrals and some palaces. While the industry and markets stayed alive in the Middle East and Asia, it finally re-established itself as a trade in Venice and Byzantium, allowing the manufacturing techniques of glass to survive this dark period.

1.3.1 Middle Age Advancements

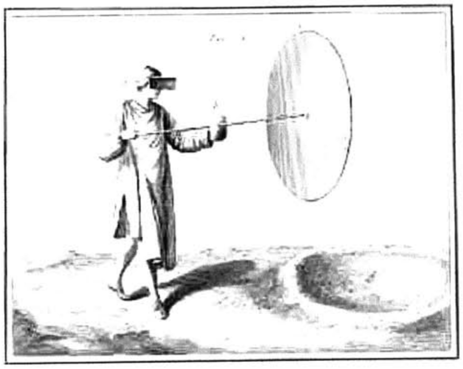

Figure 2: Man spinning a molten lump of glass into a plate [22]

In the 11th century, German craftsmen developed a technique to produce glass sheets. This method was later refined through the 13th century by Venetian glass makers. A hollow glass sphere was blown and swung vertically so that the force of gravity pulled the glass into a cylindrical capsule measuring as much as 3 m long and 45 cm wide. The ends of the capsule were truncated and a cut made down the length of the cylinder producing a flat sheet as the glass cylinder unfurled. A second technique entailed spinning a molten ball of glass on the end of a pipe such that the inertial forces flattened the mass of glass into a disk of limited diameter. In both cases, these small panels of glass could be assembled into a framework using lead strips to create windows. Glazing was considered a great luxury through the Middle Ages, and was consequently found primarily in buildings of civil importance such as royal palaces and churches. Gradually, fenestration became more common in homes of wealthy and noble families.

1.3.2 French Plate Glass Manufacturing

Figure 3: Hall of Mirror in Versailles [18]

Plate glass production was founded in France circa late 17th century. Vanity prevailed, for its principal use was for mirrors, replacing poorer substitutes such as polished metals and low-quality glass predecessors. Versailles (Figure 3) is an example of the apex of architectural glass, where its soaring windows and towering mirrors reflect the glory of 17th century France. Using a large flat table constructed to hold the molten glass, the pour was rolled until flat, then ground using a method of iron disks. Abraded with consecutively finer sands and polished with felt, the finished product was a higher quality "plate" of flat, useable glass, perfect for various applications. The addition of a liquid coating of metal resulted in excellent reflective mirrors. Although the excellent properties of plate glass resulted in great demand, its use was limited due to its costliness, and it did not see common widespread use until the mid-to late 18th century. Its desirability as an architectural element spread throughout Europe and America, literally changing the "face" of retail and business, as large panes offered new marketing opportunities to passersby, and companies trumpeted success with their gleaming windowed edifices.

1.3.3 Blown Glass in Colonial America

In colonial America, molten glass was kept in a liquid state using a wood-burning furnace. A considerable amount of wood is consumed to heat a furnace over 1000 degrees. Pam Rossmen, of the Jamestown glasshouse, estimated that in the 1600s, it would take enough wood to build a two-story house to heat the furnace for just one run of glass. The growing popularity and demand for glass in structures would quickly deplete the regional natural wood supplies. This forced the glassmakers to move to other districts once they had exhausted the wood in the surrounding forest. Given the prohibitive cost of plate glass, typically windows were constructed with small, hand-blown panes. Blown from a larger molten mass, once cut from the tube, it is swiftly rotated to stretch and flow into a flatter shape. Although it was flat enough for use in a window frame, the resulting indentation, air bubbles, wavy pattern of circles caused by rotating the molten glass may have reduced its optical qualities, yet it was weather-tight and allowed light into otherwise darkened homes. [3]

1.4 20th-Century Flat Plate Glass Advancements

Around 1905, a Belgian named Emile Fourcault modified the flat plate procedure by eliminating the need for grinding and polishing. His method entailed vertically drawing a sheet of continuous width glass from a tank. A second Belgian glassmaker modified Fourcault's scheme after the First World War. Belgian engineer Emil Bicheroux poured molten glass directly from a pot through two rollers. This modification resulted in a product with a more even thickness. These methods made glass production much more economical, but glass produced was still unacceptable for high-quality applications because the method generated some distortion.

1.4.1 Lamination

An off-shoot of evolution in flat glass production was the strengthening of glass by means of lamination (inserting a celluloid material layer between two sheets of glass). The process was invented and developed by the French scientist Edouard Benedictus, who patented his new safety glass under the name "Triplex" in 1910.

1.4.2 Float Glass

Pilkington Brothers Ltd. Improved the aesthetic and optical quality of glass by introducing the float glass process in 1959. Molten glass, when poured across the surface of a bath of molten tin, spreads and flattens before being drawn horizontally in a continuous ribbon into the annealing oven, or lehr.

1.5 From Aesthetics to Structures

Over the next several decades, advances in glass strengthening technology and structural adhesives have permitted fascinating aesthetic concepts, but have given glass designers the responsibility of not only providing a unique identity for the building, but also protecting its occupants, controlling the interior climate of the building through thermal transmission, reflectivity, illumination, ventilation, and other climatic conditions that were previously unrelated to the glass elements of construction. Today, engineers and architects are pushing the limits of glass strength by specifying the material in novel applications including floors, beams, walls, columns, and roofs.

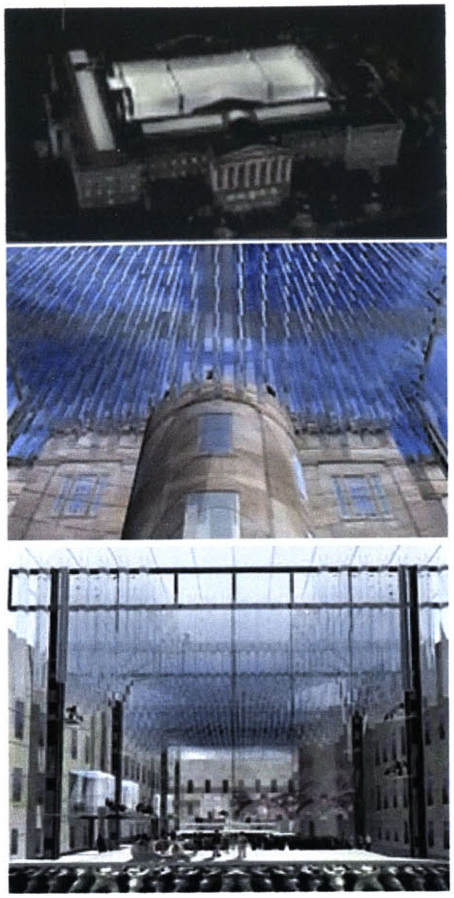

Figure 4: Washington Patent Office Building [12]

Architect Eric Owen Moss, in an article entitled "Exploring the poetry of laminated glass," reviewed the usage and impact of glass in his design of the Washington Patent Office Building (Figure 4). "The large laminated glass tubes both create the main visual shape of the roof and also form and compression struts for the trusses. The use of glass as a strut is a novel application but one that uses laminated glass in its most efficient manner—in compression. The tubular shape, apart from its aesthetic, is also a very efficient strut shape. The large number of fins, the use of laminated glass and the requirement for the tubes to be split all contribute to a multi-redundant structure that will remain in place and have a significant load-bearing capacity, even in the unlikely event of a breakage. In addition, the glass tubes are designed to give spectacular lighting—both down into the courtyard and up into the sky at night—and acoustic effects. This is a dialectic that interests me a lot: a volume of points of light so as to give a surface that is also a dense volume, a solid. It's a thick structure on the ceiling that is also so transparent that in a sense it's not there at all - because it's made of glass. Only laminated glass could be used here because of safety and also because to carry the compressive load it had to be laminated." [12]

1.6 Current Industry Standards for Structural Glass

Currently, there is little industry standardization, and consequently no comprehensive design code or independent regulating body for glass comparable to the American Concrete Institute or the American Institute of Steel Construction. National governments or local municipalities may have loose guidelines or rules of thumb that each follows, but there is a distinct need to provide a more comprehensive glass design code if architects and engineers plan to gain acceptance for their load-bearing glass structures. European nations are at the forefront of structural glass technology. The Netherlands is home to many of the notable examples of structural glass and the United Kingdom's Institute of Structural Engineers has published the most thorough design guidelines to date. The existing body of research comes mainly from the product manufactures themselves, like Pilkington and Dupont, because they must conduct extensive testing and quality assurance assessments before marketing a product. Proprietary information has made it difficult to standardize methods and material information at this level. In order to produce a definitive text for the design of glass, much more research must be conducted and an overarching authoritative body must be formed.

Chapter 2: Material Glass

2.1 Glass Substrate

2.1.1 Definition

Glass is classified as a uniform amorphous solid material, indicating it is a solid in which there is no long-range order of the positions of the atoms. This type of atomic structure occurs when a somewhat viscous molten material cools to a rigid form without allowing crystallization to form a regular network. Although liquids are characterized by a disordered structure (Figure 5), glass is different from a liquid because its inherent rigidity prevents it from flowing. It is this disordered crystal structure lacking a periodic geometry that makes glass behavior so difficult to study.

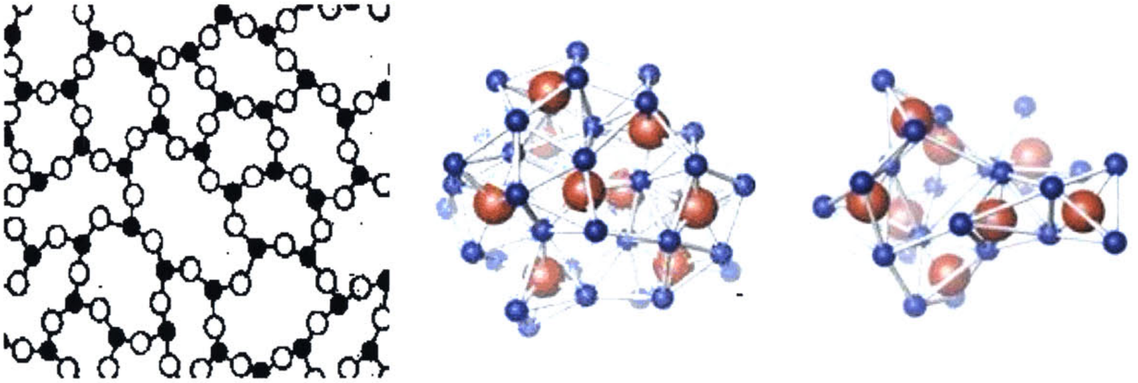

Figure 5: a) Schematic of glass atomic structure, b) and c) illustrate glass behavior under pressure [16]

Glass primarily consists of silica bonded at high temperatures with borates or phosphates. Glass can be found in nature as the volcanic obsidian and as meteoric silica glass known as tektites. Despite its disordered arrangement that places the material somewhere between a solid and liquid state, there is sufficient cohesion of the molecular structure to produce mechanical rigidity. The molten state cools to a solid form without crystallization, and reheating the solid can convert it back to a liquid form. Mineral and physical impurities change the translucency and color of the natural specimen.

2.1.2 Types of Glass

The basic ingredient of glass compositions is silica, derived from sand, flint, or quartz. Glass is a poor conductor of both heat and electricity and therefore useful for electrical and thermal insulation. For most glass, silica is combined with other raw materials in various proportions. These additives are chosen for the special assets they give to glass or because they assist with manufacturing by lowering the softening temperature, for example. Alkali fluxes, commonly the carbonates of sodium or potassium, lower the fusion temperature and viscosity of silica. Limestone or dolomite (calcium and magnesium carbonates) act as stabilizers for the batch. Other ingredients such as lead and borax bestow certain physical properties to glass. Typical commercial glasses are most commonly made from three natural materials: silica, lime and sodium carbonate. [13]

Silica Glass

Silica can be melted at very high temperatures to form silica glass, which has roughly 96-99.5% SiO_2 content. Because this glass has a high melting point and does not shrink or expand significantly with changing temperatures, it is suitable for laboratory apparatus and for such objects subject to heat shock as telescope mirrors. The fabrication of silica glass is very difficult and, thus, silica glass is not used in the construction industry.

Water Glass and Soda-Lime Glass

Soda or potash, Na_2CO_3 and K_2CO_3 respectively, are common additives in glass. Each of these compounds lowers the melting point of glass to roughly 1000 C. Soda, however, makes glass water soluble, so when in the presence of water, the glass can become a syrupy fluid. This property earns the name "water glass." In this form, the glass is used commercially for fireproofing and as a sealant. However, for most applications solubility is obviously unacceptable. Another component, lime (CaO), is added to restore insolubility. Commercial glass is predominately soda-lime based and is commonly used to produce bottles, tableware, light bulbs, window glass, and load-bearing structural glass.

Lead Glass

Lead glass is highly desirable to replicate gems for jewelry or for high-quality tableware due to its luster. The high refractive index that produces the lustrous trait is a result from the impregnation of potassium silicate glass with a small amount of lead oxide. Approximately 12% to 28% is added by weight during fabrication. Lead glass is heavy and has an enhanced capacity to refract light, which makes it suitable for lenses and prisms, as well as for imitation jewels. Because lead absorbs high-energy radiation, lead glasses are used in shields to protect personnel in nuclear installations. Current applications of lead glass include televisions and computer monitors. [26]

Borosilicate Glass

German glassmaker Otto Schott developed Borosilicate glass during the 19th century. As the name suggests, the glass contains boron as a chief ingredient, along with silica and alkali. Its benefits include durability, resistance to chemical attack, and ability to withstand and high temperatures. As a result, borosilicate glass is widely employed for cooking utensils, laboratory glassware, and chemical process equipment in a form commonly known as Pyrex. Borosilicate glass also has a very low thermal expansion coefficient, which lends itself to applications like telescope mirrors. It is also common in the processing of nuclear waste through a process called vitrification.

2.2 Manufacturing of Glass:

The fundamental composition of structural glass includes high quality sand, soda ash, limestone, saltcake, dolomite, and melt heated until the mixture reaches a highly viscous consistency. The glass used in structural applications may begin as either float glass or rolled glass, however, float glass is much more prevalent. Float glass requires extremely high quality ingredients, unlike other generically formed glass. The silica must be over 90% pure or the glass will take on a green hue and be more susceptible to imperfections.

Material	Glass Composition	Reason for Adding
Sand	72.6	
Soda Ash	13.0	Easier melting
Limestone	8.4	Durability
Dolomite	4.0	Working & weathering properties
Alumina	1.0	
Others	1.0	

[23]

2.2.1 Float Glass

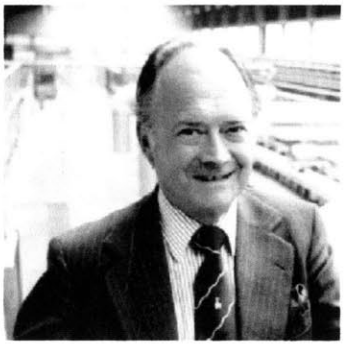

Figure 6: Alastair Pilkington [36]

Sir Alastair Pilkington (1920-1995), honored with a knighthood in 1970 for his ingenuity, invented the "float" method of glass making which revolutionized the industry in the 1960s. Supposedly, he conceived the idea in the early 1950s while washing the dishes. Watching a plate float in a sink of water made him think that the principle could be used to manufacture large plates of glass. During this period, higher quality glass was extremely expensive, and was subject to additional costly waste however, his employer, (non-related) Pilkington Brothers had also been the leader in this manufacturing process. Using markers on a mass of glass, rollers were utilized to physically grind and polish the opposing surfaces until a perfect, unblemished plate was produced.

Figure 7: Float batch in furnace [15]

Attempting to create lower cost, higher quality glass for building, auto manufacture, and personal use items such as vanity pieces and mirrors--where existed a higher imperative for non-distorted glass—Pilkington worked on the process throughout the 1950s. The seven years of research and development behind the realization of Pilkington's float glass technique nearly bankrupted his employers at Pilkington Brothers. It took 3-4 years after its implementation for it to become highly profitable.

He developed a process whereby narrow flow of glass is fed continually from a melting furnace onto a tank of molten tin in nitrogen-fed atmosphere to prevent tin oxidizing. (Figure 8) As with the plate in the dishpan of water, the molten glass stays afloat on this surface of tin, remaining at a consistently high temperature to allow the molten glass to spread out evenly. During this process any irregularities dissipate and both surfaces become equally smooth and level, since it is compelled to equalize to the flat surface of the tin. The glass is drawn off the tin bath when the desired thickness is achieved. If the glass is allowed to cool down while still spread on the surface of the molten tin, it will remain solid enough to remove, yet malleable enough to avoid damage by the rollers, particularly the vulnerable bottom plane. The end product is a perfectly clear, non-blemished plate of highly polished, uniformly thick glass. To add to its superior physical properties, it could now be produced at huge cost savings since the procedure precluded the need to physically grind and polish the surfaces.

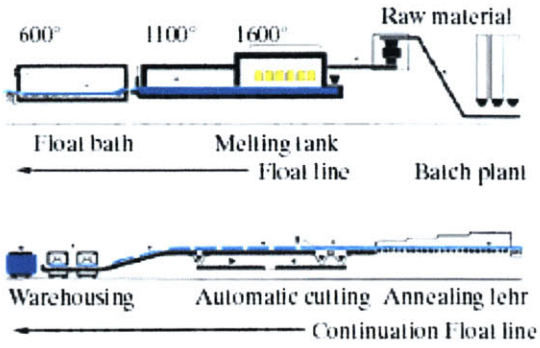

Figure 8: Float glass manufacture process [15]

Hindered by numerous setbacks, unsuccessful trial and error, it was a laborious and, often discouraging, seven years of hard labor. Pilkington recalls that people kept asking him: 'When will you succeed?', and his only response: 'We will know the answer to that only when we have succeeded.' With the expenses of the experimentation and development spiraling out of sight, it is difficult to believe the directors and board of the company allowed the research to continue. When he finally achieved success, in lieu of a restrictive patent, the company instead licensed the process, generating income and reducing the potential for rival companies to develop a rival process.

Process:

Glass is a visco-elastic material whose mechanical properties change very rapidly over a small temperature range. Between 500-600 °C, its viscosity falls by a factor of 10,000 as it transforms from a brittle solid to a plastic substance. The science of glass bending aims to use this plastic phase to produce shapes which are complex, yet free from wrinkles and other optical aberrations while starting from flat float glass. Optical distortion sets the limit for most shaping capability.

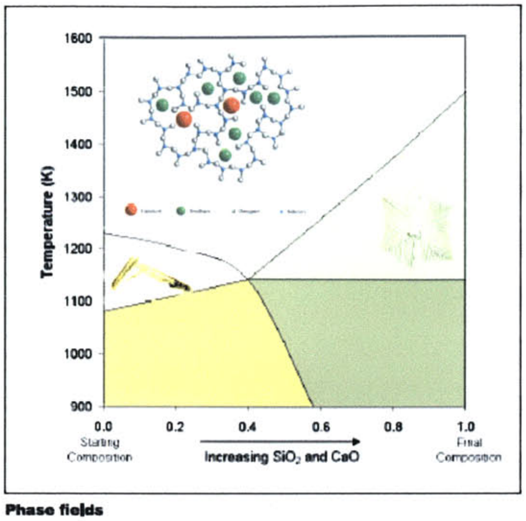

Figure 9: Phase fields of glass [15]

Figure 9 illustrates how thermodynamic modeling assists in the optimization of glass composition and affords control over devitrification characteristics through the prediction of the primary phase fields. The diagram shows how the temperature at which solids can form in the liquefied glass mixture varies as a function of glass composition. Currently, these diagrams can only be generated for simple systems like SiO_2-Na_2O.

Microscopy is an important tool used for the identification of the types of solid inclusions that may be found in float glass. High magnification images of substrate crystals provide insight into the microstructures of the solids that form in the different compositional regions. Thermodynamic predictions can be deduced from the classification of the regions. As well as solid inclusions, bubbles may also form in the float glass. The formation of bubbles is a concern since faults may form in the glass plate at bubble and inclusion boundaries. If care isn't taken to control these imperfections, large production losses can be expected. Computer modeling has served to reduce the formation of these imperfections.

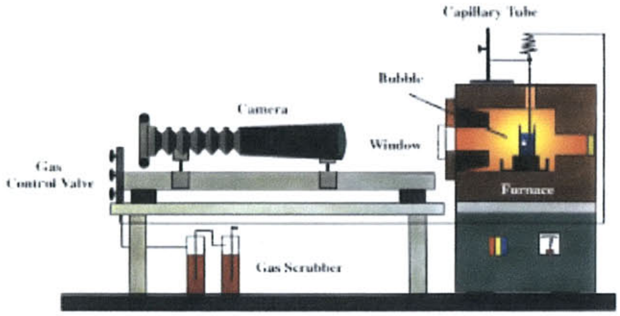

Figure 10: High temperature photography of bubbles in molten glass [15]

During the float glass process, the glass is melted with the heat supplied from the combustion of fossil fuels. Research and monitoring are necessary to minimize adverse environmental impacts. For example, by ensuring that the flames generated by the burner have the maximum luminosity and impinge on the glass at the correct angle, fuel consumption is reduced and glass quality is of the highest order. Similarly, monitoring the fuel to combustion air ratio allows optimization of heat generation while simultaneously minimizing NO_x emissions.

Float glass technology has continually evolved since its inception in 1959 to manufacture commercial flat glass. Most recent improvements have enabled float glass to be made as thin as 0.3 mm or as thick as 25 mm. Pilkington has used this technology to manufacture float glass with the lowest defect rates in the world. Currently the Pilkington's float furnaces produce less than 1 pinhead-sized bubble in every 40 m^2 of glass produced. [15]

2.2.2 Rolled Glass

Rolled glass has reduced light transmission, around 50-80% transmission of float glass, depending on its thickness and surface texture. It is used for applications where transparency is not the primary objective, for example, in a cabinet or front door. To produce rolled glass, molten glass pours from the melting tank over a refractory barrier, or weir, and continues onto the machine slab, where it flows under a refractory gate called the tweel. The tweel regulates the volume of glass before sending the glass between two water-cooled rollers. The distance between the rollers determines the thickness of the glass. [2] Finally, the glass may be annealed (see "Strengthing of Glass") and cut to size.

The two basic types of rolled glass are patterned glass and wired glass.

Patterned glass has a textured surface opposed to the typically smooth glass seen in most windows. The selected pattern has a specific depth, size and shape the affects the magnitude and direction of light reflection. For most applications, most of which are decorative, patterned glass has only a slightly lower light transmissibility. It is produced by pushing semi-molten glass between two metal rollers. The bottom roller is engraved with the negative of the desired pattern. Thickness is varied by adjusting the size of the gap between the top and bottom rollers. It should be noted that some of the patterns, because of their depth, make tempering (see "Strengthing of Glass") the glass impossible.

Wired glass is created by feeding a welded wire net into the molten glass shortly before it enters the rollers. The wire mesh is not intended to increase the strength, but rather to secure the glass pane in the sash if it shatters. The mesh pattern varies depending on the manufacturer; however, there are several common ones. For example, a diamond shaped mesh is called a misco pattern, and a square mesh is referred to as a baroque pattern. Wired glass can be patterned on one or both sides. In the latter case, the glass product is usually called rough glass. Wired glass is mostly used in fire-rated windows and doors because it is a cheap alternative to meeting most stringent fire codes for wall penetrations. This glass is not a safety-glazing and should not be used for such purposes. It also must be protected from rusting in applications where the edge of the glass panel would be exposed. As with patterned glass, rolled wire glass cannot be tempered.

2.3 Strength of Glass

If one were to ask any individual to describe glass and its strength, they would probably choose words like "transparent," "fragile," "brittle," "light," "sharp," and "shatter." Given the historic fragility of glass in any of its uses, this would be appropriate terminology for its description. Currently, there exist several processes that vastly improve the strength, failure behavior, and safety of glass. Therefore, it is possible to take advantage of the inherent strength and aesthetic value of glass as a structural material without jeopardizing safety.

Young's Modulus	Yield Strength	Hardness (MoH)	Coefficient of Thermal Expansion	Remarks
70	3600/5000	4.5-6.5	7.7-8.8	Fracture governs, not yield or tensile strength

On paper, however, glass should seem fairly strong with a strength calculation of approximately 21000 N/mm^2 based on atomic bond strength. However, failure usually occurs at tensile stress levels less than 100 N/mm^2 for flat glass, long before the theoretical value is achieved. Similarly, compressive strength of glass should fall around 21000 N/mm^2; however, any attempt to measure compressive stress generates tensile stresses, so an accurate representation of actual allowable compressive stress is difficult to obtain. In theory, given its commonly accepted chemical bonds and the energy it would take to break them, the values for the tensile strength of manufactured glass is much lower than expected.

Since strong atomic bonds make it highly unlikely for glass fractures to originate within the glass, obviously, there must be other factors at work, creating such stresses that allow for cracking to occur.

A theory put forth in 1921, described glass as inherently flawed by miniscule surface defects, which, when any force is applied allow the interatomic bonds to break, generating cracks which lead to failure. Called *Griffith flaws* after the theory originator, A.A. Griffith, these minute defects result from particles of dust and moisture contaminating the surface. The more Griffith flaws, the more likely the failure of the glass. [7] The variability of Griffith flaws in each sheet of glass makes it nearly impossible to determine the exact strength of any single piece. By performing stress and breakage tests on an established size of glass, the results produced by the samples will set the value, which can be used as a measurement level for the failure point. However, this is not foolproof, since it is impossible to achieve 100% survival rate for every piece of glass. At best, one can achieve a level of low risk and a high percent of confidence in the survival rate.

Larger flaws on the surface of glass will also destabilize glass, since it reduces its ability to handle localized, concentrated stresses. Scratches and chipping creates raw edges, and edges of glass are usually weaker than the surface, since its inherent brittle properties allow shearing into razor-thin shards. Once an edge is exposed, glass is much more vulnerable to accidental damage and environmental wear. Even the processes of cutting and finishing glass will result in defects on the edge surfaces.

Glass is also subject to static fatigue. Glass may be strong enough to endure stress for a brief period; however, failure will definitely occur if the stress is applied for a longer period of time. This pressure would build up around any of the glass's defects, perhaps a single crack or multiple Griffith flaws that weakened the interatomic bond, until the strain causes the glass to fail. It is interesting to note that glass can actually withstand applied loads, at twice the rate of long-term loads it would take to cause failure.

The larger the sheet of glass, the higher the potential for surface flaws, and the more likely the glass will fail. Resistance to stress corresponds to the integrity of the surface, and the presence of microflaws will dramatically lower its theoretical strength. As a result, glass is tested by various stress levels, rather than simply measuring its strength. Given these variables, glass strength can be determined for engineering structures by using Weibull analyses—45 MPa annealed glass; 120 MPa tempered glass; 70 MPa heat-strengthened glass. For example, an annealed glass sample designated 45 MPa for a short-term load of 10 seconds, will decrease to 25 MPa if the load is applied for 50 days. [20]

Although glass appears "fragile," its resistance can be mighty enough to withstand loads such as gusty winds, driving rain, and pedestrian traffic. Historically, the inherent flaws governed its limited use as a structural element. Today, however, several processes compensate for the negative impacts of surface integrity, and produce glass that is as strong as conventional building materials.

2.4 Strengthening of Glass

Panels of glass are not strong enough to withstand typical loading and, as a result, would not create safe structures. Glass has a relatively high modulus of elasticity for common building materials, dwarfed only by steel. This indicates that it can withstand substantial stress without experiencing large deformations until it reaches a point of brittle failure. As with concrete, brittle failure is explosive and unpredictable. Similarly, the goal is then to induce a more ductile failure mechanism that will have some serviceability indicators. Cracking accompanied by noise are criterion that could warn of imminent failure of the glass material. A float glass panel will instantly crack when its capacity is exceeded or an impact undermines its integrity. The inability to carry load following failure is only one of the failure concerns. When glass shatters, sharp fragments may fall and cause injury to those below.

To improve the safety and strength performance of structural glass, there are four primary processes that can be conducted following basic manufacturing: annealing, tempering, heat-treating, and laminating. Although each of these processes has contributed to the advancement of structural glass, lamination is the most significant. Lamination builds upon the other processes by layering sheets of treated (annealed, tempered, or heat-treated) glass using an adhesive foil to achieve unparalleled strength and safety.

2.4.1 Annealed Glass:

Annealing glass is intended to relieve stresses that develop in glass as it cools. The glass is manufactured as float glass heated to about 1500 degrees C, and then cooled slowly under controlled conditions that avoid the introduction of new stresses. It behaves perfectly, elastically until brittle fracture. Fracture can result from impact, bending stress, thermal stress, and imposed strains. When and where it fractures also depends on the flaws in the glass that could be inherent, or resulted from cutting, grinding or drilling. The cut edges of annealed glass are often more vulnerable to weather than its primary surface. Environmental conditions may contribute to the failure of annealed glass. Humidity promotes crack propagation. A condition called fast fracture, occurs when there exist cracks of a minimum critical size, a, subject to a critical stress, σ.

$$\sigma\sqrt{(\pi a)} = \sqrt{(EG_c)}$$

; where a is the half-length, E is Young's Modulus, and G_c is the toughness. [38]

If annealed glass breaks, the shards can be extremely dangerous. It is possible that the fragments remain in the frame, and continue to support a significantly reduced load through alternative load paths.

2.4.2 Toughened (Tempered) Glass

One method of strengthening glass is to enforce compression in the outside "skin" of a glass panel. This compression serves to close small existing cracks inevitably present from the manufacturing process, and to compensate tensile forces. The glass is then more resistant to impact loads since the induced peak tensile stress at the point of impact is compensated by the compression of the skin.

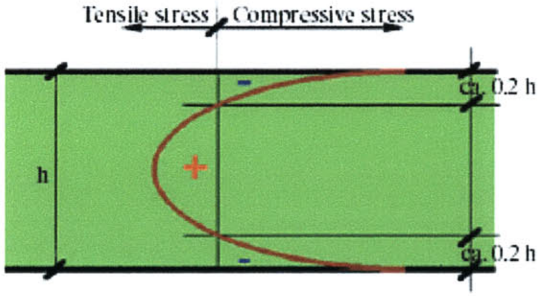

Figure 11: Stress distribution in tempered glass [20]

A sheet of annealed float glass, complete with all mounting holes and polished edges is heated to roughly 650 degrees in a furnace. The panel is removed from the heat, and then the outside of the glass is quenched with air jets so that the surfaces are cooled quickly and the core more slowly. At ambient temperature the core continues to cool and compression stresses develop in the surfaces, balanced by tension in the core (Figure 11). The tension results from the core material pulling at the already cooled and hardened exterior surface as it begins to cool and shrink. This balance of forces slows the propagation of new and existing cracks in the panel. Without this artificial compression, a crack in glass will grow by tensile action until it reaches a free edge, which will ultimately lead to failure of the panel. Since a scratch can weaken the surface compressive forces induced by tempering, it may seem intuitive that bolt holes would also undermine the effects of the strengthening treatment. To the contrary, bolt holes created prior to the tempering process do not cause large changes in surface stress if the diameter is at least the thickness of the panel of glass. This permits the cooling air to pass through the hole and cool it at a rate similar to the rest of the panel.

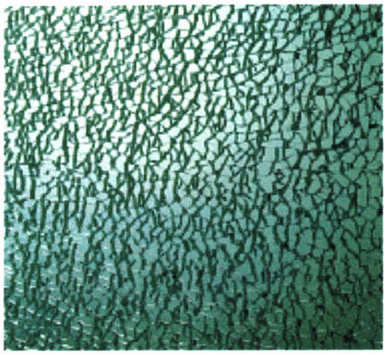
Figure 12: Fracture pattern of tempered glass [20]

An important effect of glass toughening is a change in the fracture pattern. When the stresses exceed the allowable stress, the balance between the compressive skin and the tensile core of the panel is destabilized. The result is an explosive release of the stresses that causes the panel to break into hundreds of small fragments (Figure 12), called dice that are less dangerous than the large sharp fragments that result from the shattering of non-toughened glass. Toughened glass will, on occasion, shatter for no apparent reason due to tiny nickel sulfide inclusions that expand during a phase change. Toughened glass will also shatter if a scratch is deep enough to penetrate the outer compressive layer.

It is imperative to precisely control the stress levels in panel of glass for tempering to be effective. Several optical techniques exist to measure the surface and internal stresses. In some cases, strain gauge technology is used to verify that the product was made with sufficient capacity to withstand the thermal or mechanical stresses imposed by the glazing system.

2.4.3 Heat-Strengthened Glass

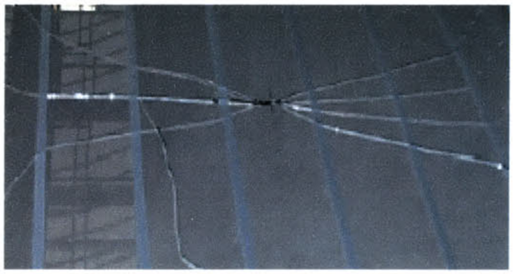
Figure 13: Typical crack pattern of heat-strengthened glass [20]

Heat strengthening is very similar to toughening, but the levels of prestress that are produced are lower. Surface compressive stress will fall within a range of 24 and 69 N/mm^2. When heat-strengthened glass breaks, the fracture pattern is similar to annealed glass and tends to remain in the opening when broken (Figure 13). Although heat-strengthened glass appears to fracture like annealed glass, it is approximately twice as strong to a comparable thickness and configuration of annealed glass. It is most appropriate for glazing applications that require additional strength and/or resistance to mechanical and/or thermal stress. Heat-strengthened glass does not perform as a "safety-glazing" and, therefore, should not be used where safety glazing is required. [25]

2.4.4 Laminated Glass

To make glass safer, a thin layer of adhesive permanently bonds together two or more sheets of annealed, heat-strengthened, or fully-tempered glass. When the sheets are joined under 250-degree heat and compression, they create a single panel that has significantly greater strength and ductility than its single laminate counterpart. A common adhesive, polyvinyl butyrate, or PVB, is invisible if applied evenly. If one layer of glass is shattered, the fragments adhere to the interlayer, which protects people from dangerous shards of falling glass as long as the remaining lites of glass are strong enough to support the total dead weight of the glass assembly. Subsequently, the internal layers of glass are protected from damage by the exterior lites of glass, which are often referred to as the "sacrificial" panels. Adhesive bonded glass panels are limited by the size of the furnace, so a second resin-bonded approach is available for applications requiring larger sizes. Laminated glass often consists of only two lites, however over 25 layers have been successfully bonded in an assembly over 100 mm thick.

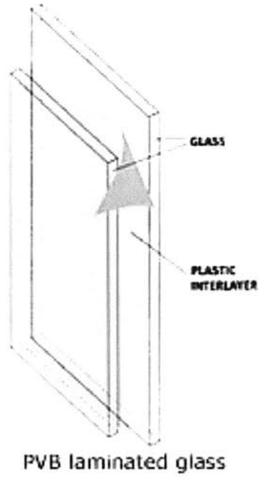

Figure 14: Laminated Glass schematic [25]

- Polyvinyl butyral (PVB) laminated glass is two or more sheets glass, which are bonded together with one or more layers (PVB) under heat and pressure to form a single piece.

- The rollers over which the glass passes during heat-strengthening and tempering processes induce small amplitude waves. When lites of these glass varieties are joined, there is a slightly larger gap between sheets due to these waves that makes a PVB interlayer less effective or impractical. Resin may be employed for these applications to attain a better bond between lites with no visible impact on transparency. Resin laminated glass is manufactured by pouring liquid resin into the cavity between two sheets of glass that are held together by double-sided tape until the resin cures by chemical reaction or UV light. The two most common resins are acrylic and polyester.

Short-term, out-of-plane loads are resisted compositely by the lites of glass and the interlayer. Long-term, out-of-plane loads are resisted by the layers of glass depending on their relative stiffness. Temperature reduces the load-bearing capacity of the interlayer, so the assembly acts less like a composite material.

The advantages of laminated glass are numerous and extend beyond the obvious safety benefits that multiple lites of bonded glass provide. Laminated glass resists penetration and impact, which is beneficial in security applications. The additional environmental benefits make its use as an architectural and engineering structural material extremely desirable. Tinted and translucent interlayers can absorb and refract light so as to minimize solar gains within the interior of a building. These spectrum-specific adhesives can be designed to block high altitude summer sun radiation, while permitting low altitude winter sun. These properties translate into energy and financial savings. In addition, the interlayer provides a damping effect that minimizes unwanted external noise—truly a boon to high-density urban areas where noise reduction can lower stress and increase productivity.

CHAPTER 3: Structural Adhesives

3.1 Structural Adhesives/Sealants

Although structural adhesives and sealants have been in use roughly 30 years, they remain the only alternative to mechanical fixation of glass panels. Double-sided structural bonding tape and modified epoxy adhesives have the requisite stability, adhesion, and movement capability necessary to withstand the demands of structural glazing applications. Structural adhesive glazing is touted to be one of the "most versatile forms of curtainwall construction in the commercial façade business." Structural adhesives may be touted as the best available façade technology, but they also have a limited lifespan of approximately 20 years, at which time repair or replacement may be necessary.

The first usage of structural silicone in America was seen in 1971. It wasn't until the design of New York City's Park Avenue Tower, completed in 1983, established structural adhesive curtainwalls as an architectural landmark. The façade of the 37-story building required over 220, 000 ft^2 of reflective glass. The two-sided structural glazing system was affixed with an adhesive/sealant manufactured by Dow Corning.

Engineers and architects specify structural adhesives for a multitude of reasons. The aesthetic value of adhesive fixation is obvious. This provides a seamless façade uninterrupted by metal connections and framing. Visually, this was a major objective in the Thames Water project depicted in Figure 15. Each 450 kg glass roof panel was bonded to laminated glass beams using structural silicone. Silicone, in particular, has excellent levels of adhesion, movement capability, and a wide service temperature ranging from -40 C to 150 C. Silicone is able to resist wind load, dead load, and thermal dilation. In addition, the silicone connections provide improved acoustic and air infiltration performance, permit more uniform heating and cooling of the façade, and provide superior weather sealing. The watertight bonds adhere through extreme weather conditions and withstand designer-specified joint movement. Other benefits include easy replacement of damaged glass elements, and simplification of seal inspection.

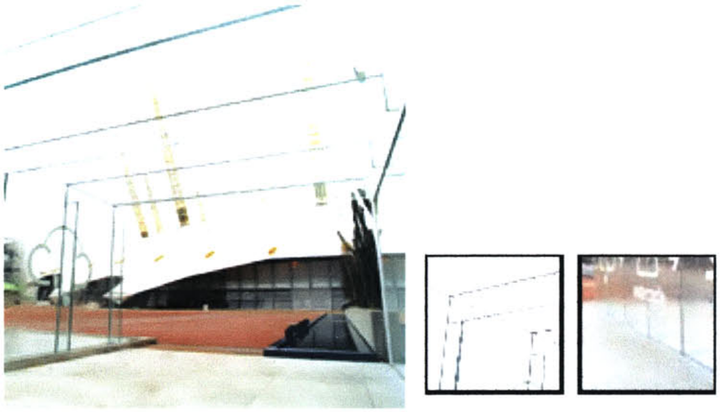

Figure 15: Thames Water, London [31]

Structural adhesives have been used in the past to support and withstand short-term tension between panes of glass and their supporting structures. The self-weight of the glass has generally been carried by other means, primarily because insufficient research has been conducted regarding the long-term integrity of adhesives. Designers depend on the ability of these adhesives to resist wind loading, thermal stresses, and shear force. When the design, specifications, and fabrication are appropriate and of high quality, the system can withstand flexure, tension, compression, thermal shear stresses, and continuous movement. In additions, it also resists weathering, extreme temperature changes, and chemical corrosion. Reluctance of engineers to specify structural adhesives supporting considerable loads has stemmed from the lack of information available regarding the long-term integrity of these joints. The Center for Window and Cladding Technology and other industry peer institutions have only begun studying the behavior of several adhesives in recent years in an effort to provide reliable research on which to base such judgments, to enhance our vision for applications, and offer viable alternatives to traditional technologies.

The strength of adhesives depends on environmental conditions including chemical composition of the atmosphere, UV exposure, moisture, temperature, thermal expansion of connected elements, rate of load application, surface roughness, joint geometry, quality of construction, and curing. Studies by Gutowski *et al.* (1994) indicate that the joint dimensions and geometry influence the limiting stress and strength of a joint a failure. Other research has proven that:

- Adhesives tend to flow and are sensitive to the rate of application of the load
- Adhesives with a low shear modulus are appropriate for holding glass elements in place, but a higher modulus is necessary to sustain shear forces.
- The behavior of adhesive-based joints is dependent on degreasing and priming of the contact surfaces.
- Etching may improve adhesion but will ultimately decrease the strength of the glass.
- A decrease in temperature will shrink glass and metal while increasing the stiffness of the adhesive joining the elements.
- Capillary action by water can undermine joint adhesion. Debonding can be avoided by employing a suitable primer such as Silane.
- Surface treatments of the glass, like low-e coating, may influence the behavior of an adhesive joint.
- Joint construction, including curing, application thickness, etc. is integral in the structural success of an adhesive joint.
- Energy absorption may be a better representation of a joint than a finite element model.

Once a structural sealant is applied to a glass element, it vulcanizes and adheres the glass panel to the supporting framework, whether the supporting structures are made of glass, steel, wood, or other building material. The demonstrated dependability of structural adhesives during their 30 years in use has garnered confidence in the engineering community. Structural adhesives have shown little damage during significant earthquakes and have prevented dangerous glass shards from falling, thus indicating the flexibility and resilience of the connections. Given these characteristics, it is not surprising that special adhesives have been manufactured to resist impact and blast loading following the attacks of September 11th.

Structural silicone is the most popular variety of structural adhesive. There are two basic forms of structural silicone glazing: two-sided and four-sided. The term "glazing," for the purposes of this chapter, is intended to mean the adhesion of glass sheets to a supporting assembly. Both systems can be either glazed in the factory (shop-glazed) or glazed directly on the job site (field-glazed). As with most structural assemblies, shop-prepared elements are fabricated under better-controlled conditions. This improves quality assurance by providing a cleanlier environment that limits exposure to airborne dust and debris, and ensures the sealant cure and development of adhesive properties by regulating temperature and humidity. The elements are then transported to the job site and mechanically attached to the framing structure.

The International Conference of Building Officials (ICBO) describes two-sided structural silicone glazing: "Vertical edges of glass are adhered to the substrate with silicone sealant. Horizontal glass edges are retained in permanent channels or otherwise mechanically attached to the structure for out-of-plane movement." (Figure 16a). The figure illustrates vertical joints structurally adhered to the supporting structure. The dead load of the panel is supported mechanically, and the live load is divided between mechanical support, for example, at the head and sill, and structural silicone/sealant on the sides.

Four-sided structural silicone glazing is desirable because it is less susceptible to leakage due to the continuous sealant around the perimeter. The definition provided by ICBO states that "All glass edges are adhered to the substrate with silicone adhesive. The silicone adhesive provides restraint for out-of-plane movement. Temporary supports used to restrain out-of-plane movement of glass glazed in the vertical position are removed after adhesive has cured." This system provides no mechanical support for the facade-fronting materials (Figure 16b). Dead loads can be supported either by a horizontal fin or by the silicone sealant, depending upon the design.

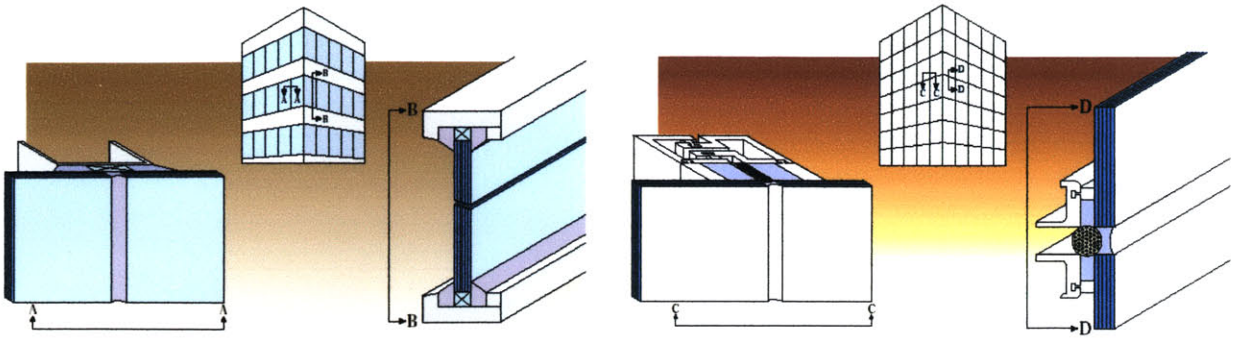

Figure 16: a)Two-sided silicone support; b) Four-sided silicone support [39]

A more detailed graphic of the adhesive/sealant connection is shown in Figure 17. Although the Figure is labeled for a Silicone sealant, it is broadly applicable to various other adhesives.

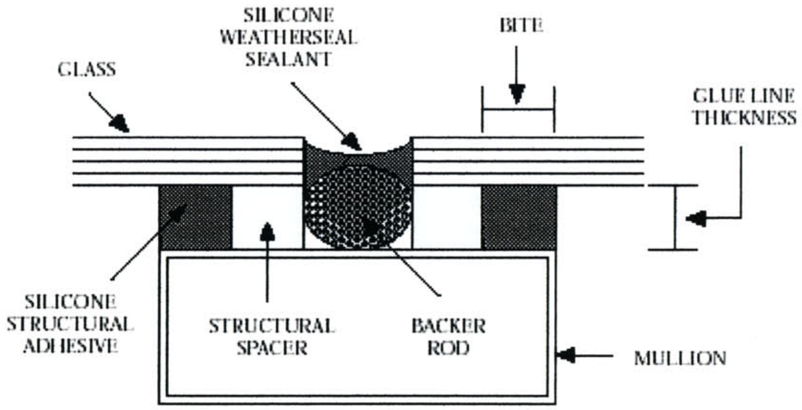

Figure 17: Detail of structural adhesive/sealant joint [39]

Deflection Consideration

Shear Modulus of different Adhesives (IStructE Table 11.2) [38]

Adhesive	Shear Modulus
Cyanoacrylates	Highest
Modified Epoxies	Higher
Polyurethane Resins	Lower
Structural Silicones	Lowest

Using structural silicones, panels weighing roughly 550 kg per unit have been bonded. The glass panel size that can be used in conjunction with silicone adhesives also depends on the capacity of the lifting equipment. Predominant façade companies generally can lift 3 UK tons using a crane, and 450 kg by a vacuum lifter. Other companies may have access to 1000 kg lifters. Availability of machinery and equipment may either necessitate a change in the design or limit the number of contractors eligible to bid on the project.

3.2 Polyvinyl Butyral (PVB)

With a perfect cohesion of the glass layers, PVB laminated glass achieves the transparency, durability, and scratch resistance of standard float glass. In addition, however, it provides impact resistance, better acoustic insulation, and enhanced regulation of solar impacts. Currently, Germany is one nation that does not permit design using the composite behavior of laminated glass, meaning that a member composed of separate lites bonded by PVB should not be considered to have the same behavior as a single member of glass of equivalent dimensions. This is primarily due to the lack of understanding of shear transfer between glass lites. PVB is responsible for the shear transfer; so much more research is necessary before engineers may consider monolithic behavior of glass layered using a PVB interlayer.

The behavior of PVB depends largely on the load duration and the temperature (Figure 19 and Figure 18a, respectively), with secondary effects stemming from thickness of the foil and buckling length of the member. Thus, the shear modulus becomes the critical factor when determining the design strength of a composite laminated member. Research by Albrecht *et al.* discovered that the aging process aided by UV light and humidity also produces an effect on the shear modulus of PVB. This study showed the current importance of investigating laminated members using a finite element analysis that links the deformation of individual lites, using the properties of PVB. Fortunately, the shear modulus of PVB can be adequately described as a linear function of temperature and load duration. Even though finite element calculations are more labor intensive, it may lead to a more economical and safer laminated glass design.

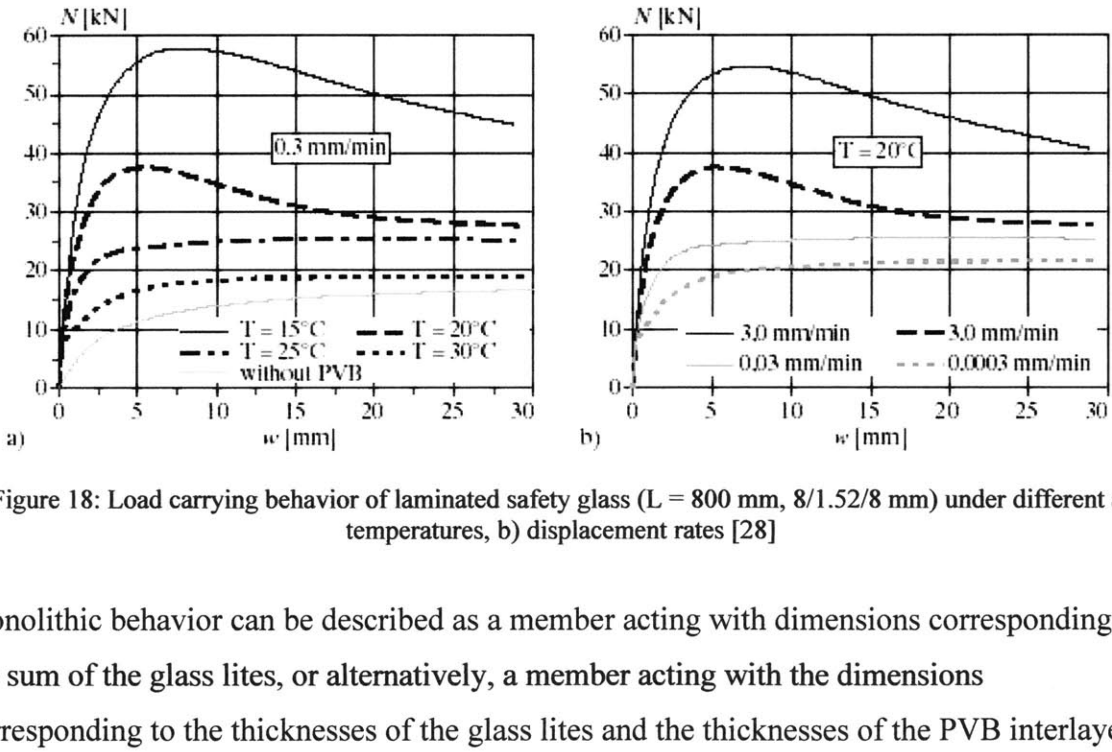

Figure 18: Load carrying behavior of laminated safety glass (L = 800 mm, 8/1.52/8 mm) under different a) temperatures, b) displacement rates [28]

Monolithic behavior can be described as a member acting with dimensions corresponding to the sum of the glass lites, or alternatively, a member acting with the dimensions corresponding to the thicknesses of the glass lites and the thicknesses of the PVB interlayers. The former definition would be the more conservative of the two. A laminated glass assembly behaves more like a monolithic glass member when experiencing short duration loading at low temperatures. However, results from this study showed that it is not accurate to assume the same composite behavior at every point within the member. The area around the point of support displays a much lower composite behavior than the more flexible midsection, indicating that the stiffness of the framing and support systems influence the design. Until further studies are conducted, it is not responsible to assume fully monolithic behavior for design.

There are several new German design codes being considered—one that recommends a layered limit for long-term loads, essentially disallowing shear transfer between glass lites, and a monolithic limit for short-term loads. Another proposed code implements a time- and temperature-dependent shear modulus for the PVB interlayer.

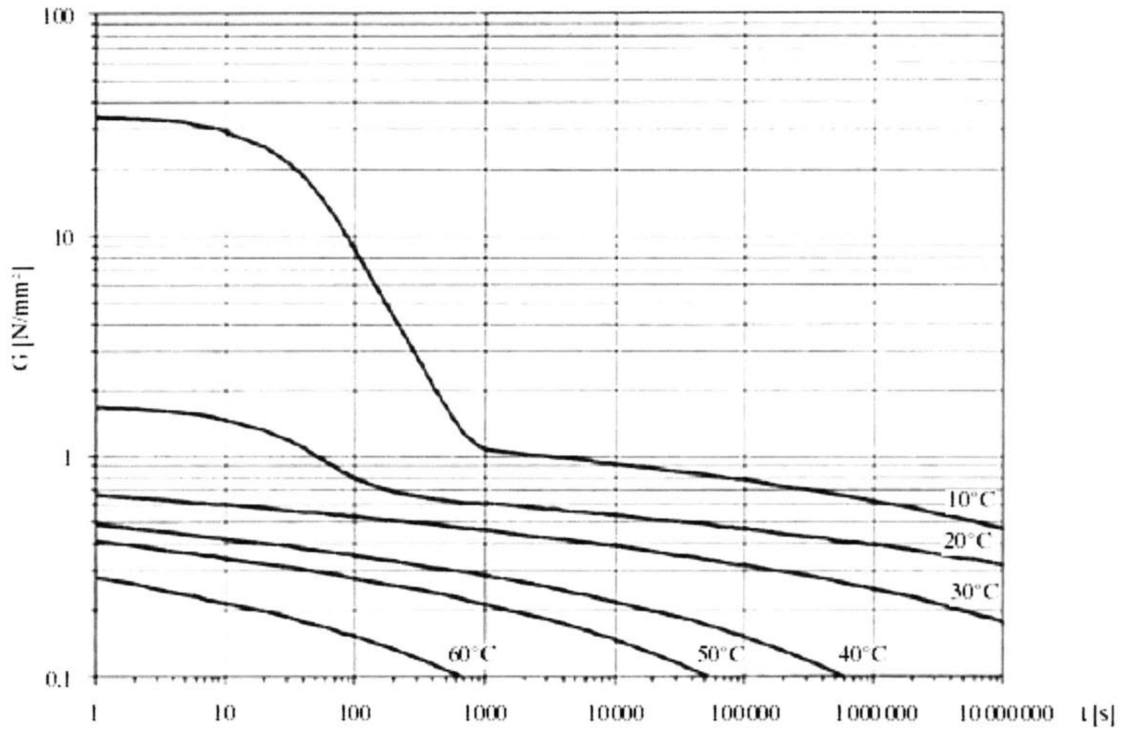

Figure 19: Shear modulus G of PVB depending on temperature and time [5]

CHAPTER 4: Structural Glass Elements

Art and creativity are an essential part of human life. Structural glass allows us to capture the attributes of light and transparency by integrating glass in load-bearing elements. Exploring the behavior of glass in a structural context provides engineers with the basis from which to develop new applications.

4.1 Beams

4.1.1 Definition

Glass beams are simply that—structural beams made of glass. These members are usually simply supported or cantilevered. The span of glass beams is limited to the length that a single piece of glass can be manufactured, which is roughly 4.5 m for laminated annealed glass, and 3.9 m for toughened glass. In some cases, glass beams can be assembled from shorter members to extend past these lengths. For example, the entrance canopy to the Yuraku-cho underground station in Tokyo cantilevers 10.6 m over the entry stairway of the station. Four individual beams bolted together and pinned at their end points created an arch. [29] The Yuraku-cho station was engineered by the British company Dewhurst McFarlane and Partners, pioneers in the area of structural glass.

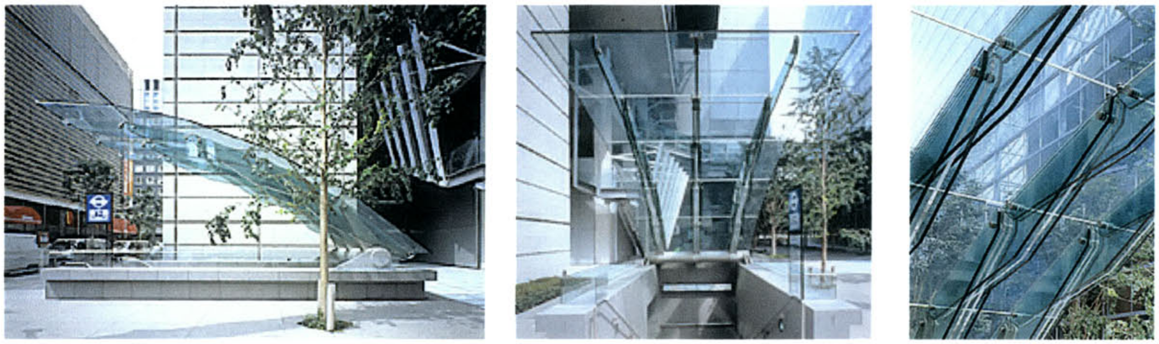

Figure 20: Yuraku-cho underground station in Tokyo by Dewhurst Macfarlane & Partners [41]

Glass fins, like glass beams, are thin load bearing members made of glass. They are vertical or sloping beams used to support facades and to help resist wind and other lateral loads. Regardless of their orientation, fins are assumed to be loaded in bending. The primary difference between fins and beams is the inherent difficulty forming joints with fins that can carry sustained bending moments, particularly in laminated glass. [38] Glass panels are hung from the fins by either silicone adhesive or by bolting. Fins are not generally limited by the length of glass that can be produced, and are often spliced together using friction-grip connections to achieve the desired height.

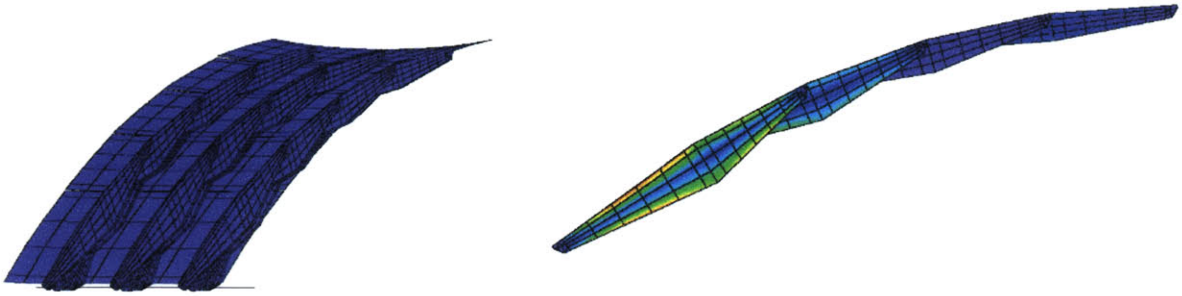

Figure 21: Yuraku-cho Station canopy generated by LUSAS finite element software [29]

The material "gripping" the glass fins must be soft enough not to cause stress concentrations on the glass, and must be elastic enough to accommodate possible differential thermal behavior between the glass and the splice plates. [38] Soft aluminum is often selected to satisfy the requirements of the friction connection interlayer.

4.1.2 Beam Strength

Glass beams and fins should be designed to sustain minimal tensile stress. Tensile stress promotes the gradual propagation of cracks due to microscopic flaws. Most glass beams are designed with substantial redundancy, or are designed so that steel cables carry the tensile loads putting the glass only in compression. Tensile loads imposed on the structure usually result from short-duration wind gusts, vibration, or deflection. Any material imperfection dramatically reduces the beam's capacity to endure tensile loads.

Like most design considerations for glass, shear strength is highly undocumented. Finite element analysis has become extremely popular to calculate maximum stresses, however, manual calculation using the strut-and-tie analogy or Mohr's stress circles is adequate for design. It is necessary to consider mid-span and support regions. Because glass beams must be designed for low levels of stress, deflection is rarely problematic. The glass is often designed to act in compression, while steel members endure the high stresses and potential deflection. It is more likely that vibration will govern the design. Dynamic excitation resulting from pedestrian cadence or wind gusting can dominate a structure and consequently should be considered. The rule of thumb for controlling vibration is:

$$F = \frac{16}{\sqrt{d}} Hz;$$

where F is the frequency in Hertz and d is the midspan deflection of the beam or free-end deflection of a cantilever. The commonly used criterion states the F > 5 Hz.

4.1.3 Elastic Stability

All thin structural members can become unstable if not adequately braced. For example, a glass façade provides some rigidity and rotational restraint for the glass fins affixed to it. This relationship makes instability failure less probable. Rotational restraint is essential to prevent buckling of many columns, fins, and beams. A finite element analysis is preferable for the design of a glass wall supported by glass fins. Local buckling should be investigated in addition to the buckling of the free edge. A basic check of local buckling derived from the study conducted by Yoxon (1987) considers:

$$M_{\max} < \frac{Et^3}{6(1+\nu)};$$

where $M_{\max}$ is the maximum unfactored destabilizing bending moment in the fin. This expression usually determines the buckling limit, and has been confirmed by full-sized testing and non-linear finite element analysis. [38]

4.1.4 Case Studies

Yuraku-cho Station Canopy, Tokyo, Japan

Project Architect, Rafael Viñoly Architects PC, working for the Tokyo Metropolitan Government, designed the glass canopy for Tokyo's most important subway station. The critical element of the design would be the considerations given to the vast amount of pedestrian traffic at this critical stop in the transportation system. Over 100,000 people enter this station every day, and much consideration was given to curved spaces and natural light.

The canopy's beams were created by laminated glass and acrylic blades that decrease in number from 4 blades at the base of the cantilever beam to 1 blade at the tip. 40mm diameter stainless steel pins attach the blades to T-shaped brackets, making up the supports for the glass panels. The end result is the canopy roof, connected at the base by V-shaped stainless steel brackets, which connect each cantilever to a horizontal beam running the full width of the canopy. [40]

Rotterdam Footbridge

Figure 22: a) Loading test on completed bridge using employees from Kraayvanger Urbis, b) Looking upward into completed footbridge [38]

Perhaps the most famous example of glass defying expectation is the Rotterdam footbridge, constructed from 1993-1994. The architectural office of Kraayvanger Urbis was expanding, and the renovated pump station the firm was occupying could no longer accommodate the staff. The firm purchased space in an adjacent building and decided to link the two in such a way where employees wouldn't have to trek outside to reach the new space. It was decided a new footbridge would span the 3.5 m gap between buildings. The decision to create a glass footbridge was purely aesthetic. The architects felt that most modern bridges would clash with the "sober" architecture of the 1950s, so having a glass bridge reduces the imposition of modern style on the existing buildings.

The bridge has two primary structural components: the load carrying portion, and the protective portion. The floor of the bridge is constructed of floor plates and two glass beams. Each 300 mm deep beam spans the 3.50 m. The robust beam design consist of 3 layers of 10 mm float glass. The two outermost protective lites are equally as thick as the inner structural lite. The curvilinear shape of the beams and polished finish are for architectural purposes only. The glass floor plates consist of 2 x 15 mm float glass glued to the top of the glass beams, using structural silicone adhesive tape. Glass walls contain the footbridge and protect pedestrians from the elements. Other than resisting lateral loads, these glass panels need not be designed as structural members. A stainless steel cable connected the wall to the floor.

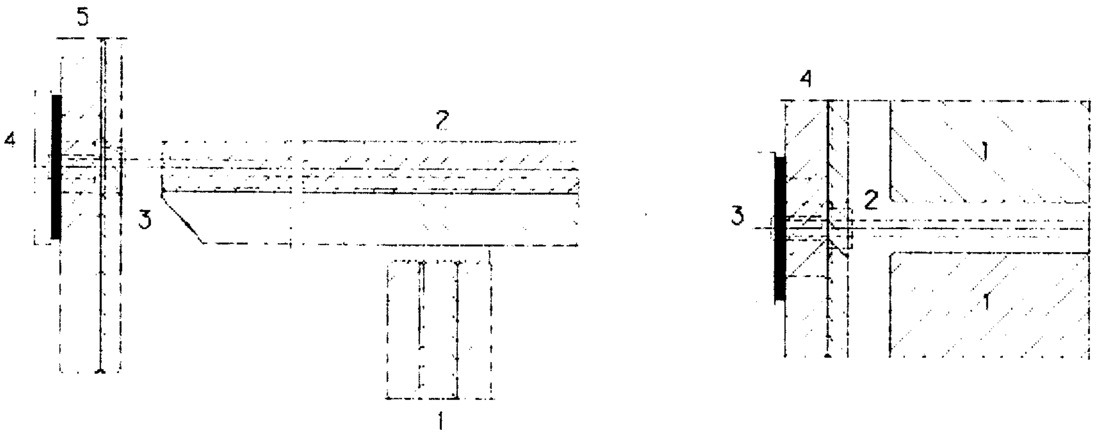

Figure 23: a) Elevation of connection details b) Plan view of connection detail [30]

When the bridge opened, the local building officials required that the designers crash a heavy sandbag against the bridge wall to visually prove the safety. In the years since the bridge opened, a beer bottle thrown against the wall merely stained it with its contents until someone eventually cleaned it. Following the first attack, a street-tile was thrown at the bridge and managed to shatter the protective outer layer, but as planned, the other layers remained intact. Perhaps glass structures beg to have their strength challenged by the occasional inebriated passerby or street vandal. Fortunately, glass has not yet given designers reason to doubt its capacity as an engineering material.

Arnhem Zoo, Arnhem, Netherlands

Similar to the Rotterdam footbridge project, a glass footbridge spanning 3.80 m was requested to join an old and new building at the Arnhem Zoo in the Netherlands. This bridge was made much more cost effective by eliminating expensive and complicated steel joint details. In fact, no steel was used at all. Structural silicone joints were used to transfer the small stresses between members. The laminated glass walls consist of three layers. The two superficial layers are 12 mm thick, toughened float glass intended to protect the inner 6 mm toughened structural layer. The roof was constructed by combining an 8 mm outer layer, and a 12 mm inner layer of float glass. The roof was gently arched to facilitate the runoff of rainwater. The laminated glass assemblies relied on a PVB foil between lites.

Zwitserleven Beam, Amstelveen, Netherlands

So far, both beam case studies illustrated relatively short spans. The following example illustrates the capability of glass beams spanning significantly greater distances.

The Zwitserleven insurance company desired to create three glass structures to foster an updated image of their facility in Amstelveen, Netherlands. The structures included a hanging glass plate intended to dampen noise from the neighboring highway, a “maximum transparency” restaurant roof, and five large glass beams across a courtyard space.

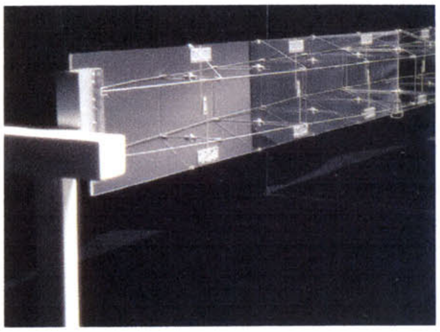

Figure 24: Model made of large glass beam for Zwitserleven insurance company [30]

Although the beams were initially conceived to alleviate thermal gains by directing sunlight away from the façade, their contribution toward this energy efficiency was minimal. Of the five planned beams, two were added as mere architectural elements. The difficulty with the design of these beams was that they must span 26 m, and glass manufacturers in Europe rarely produce glass that exceeds 7 m in length.

The obvious solution, then, was to connect several shorter glass members, much like the Yurakucho station awning in Tokyo previously described. Two schemes were devised for the 21.6 m span and the 27.0 m span. The beams would be constructed of shorter glass panels, 7 and 9 in the shorter and longer spans, respectively. Each panel has 3 plies of toughened glass. The outermost plies are 6 mm and the inner structural layer is 15 mm thick.

Mechanical steel fixtures usually join such members by clamping action. Two steel plates surround the beam member, and steel bolts link all the layers of steel and glass. This requires undesirable oversized holes cut in the glass to accommodate the bolts, and the maximum force is determined by the "maximum compression force delivered by the bolts and by the friction between the unavoidable neoprene interlayer and the glass." [30] The steel joinery does not enhance the image of a glass member whose purpose is to appear weightless and nearly invisible.

A truss system constructed from cables and bars around the glass beam was designed to resist the positive and negative lateral deflections caused by the wind pushing on the vertical glass beam. The lines of the truss gracefully surround the primary member shown in Figure 24. The transfer of forces between the steel truss and the glass was a primary concern. Instead of using friction to transmit the forces from the framing to the glass panel, a detail was developed to transmit the forces via shear. This generated the problem that a bolt, acting in shear, would create large local forces in the glass if in direct contact. The glass couldn't endure sustained loads of this concentration, and would inevitably form cracks that could propagate through the section. To resolve this issue, a large hole, roughly five times the diameter of the bolt, was cut in the glass and filled with a polyacetate (nylon) plug. The plug provided an elastic means of transferring stress to the glass plate. Because of its low modulus of elasticity, the force of the bolt would spread over a greater area in the nylon plug before pushing on the glass itself, subsequently reducing the peak stress in the glass. However, during laboratory tests, small eccentricities caused the plug to rotate within the glass panel, instigating failure. Sandwiching the plug between two smaller steel plates resolved the problem, but it wasn't enough to convince the owners, lawyers, and municipal officials to proceed with the design.

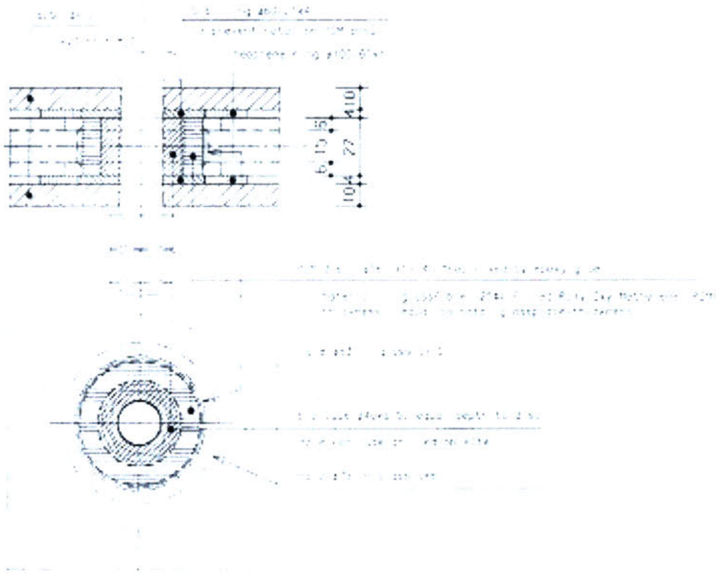

Figure 25: Primary connection in Zwitserleven large glass beam [30]

Sadly, instead of seeing this glorious glass beam spanning a breathtaking distance, the owners and architect opted to install a stainless steel tube with suspension cables to visually enclose the courtyard of the building. Although this project didn't see fruition, the possibility of glass extending over great distances is closer to a reality in engineers' minds.

4.2 Columns

Many architects and owners dislike columns because they obscure views and interrupt space. Designers go to great lengths to keep columns outside of prominent spaces like lobbies and courtyards. The ability to make a column out of glass creates an interesting visual feature, almost sculptural, that doesn't intrude on the openness of a great space.

4.2.1 Column Strength

Although glass performs best under compression, few engineers and architects will design load-bearing glass columns. The reason for the scarcity of glass compression members is the fear of sudden brittle failure. On the occasion when such members are used, the structure must have a robust design that can tolerate the loss of a glass column or wall without collapse, and the member should be protected from accidental damage.

The general design principles for glass columns are similar to those for other unreinforced piers or walls. The applied load, however, must be carefully distributed into the glass column in a way that localized areas of concentrated stress do not develop and trigger a brittle failure. The edges of the glass panels have to be ground with chamfers to avoid stress concentrations at the edges that would cause premature failure of the glass column. Similar caution must be exercised when introducing load into laminated glass columns. It is common for the lites of glass to line up somewhat unevenly at the edges, creating non-homogeneous load transfer into the layers of glass. To ensure structural participation from all layers of glass, steel shoes should be used to support the glass, and injection mortar used to fill the gap between the glass edges and the shoe.

When a load is applied, a column resists and responds by deforming and developing internal and edge stresses. Glass under increasing axial compression will deform elastically until experiencing sudden failure by elastic instability, or by increased stress at surface defect prompted by a lateral load. It is important to minimize exposure of a column to undue impact or abrasion by locating it in a sheltered location, or by restricting glass to the top portion of a column.

It is advisable to make a column using toughened, precompressed glass, even though it may seem counterintuitive to add additional axial force to a compressive member. The precompression serves to reduce the "out-of-straightness" effects or unanticipated lateral load by keeping the glass surface in compression. There are instances where annealed glass is used in lieu of toughened glass, but in such cases, protective laminations must be adhered to either side of the glass compression member. Not only will the additional laminations protect the internal layer, but they also increase the bending stiffness and increase the degree of redundancy. [38]

4.2.2 Elastic Stability

Like glass fins, glass columns are most likely to fail due to lack of stability, which includes column buckling and lateral torsional buckling. Buckling tests performed on laminated glass compression members show visco-elastic buckling behavior. Concepts of Euler buckling are applicable for pinned, axially loaded members in compression; however, a safety factor must be applied. The factor of safety is up to the discretion of the engineer accounting for special circumstances and environmental concerns. If conditions for column buckling are satisfied, then the limit for compressive stresses also most likely satisfied.

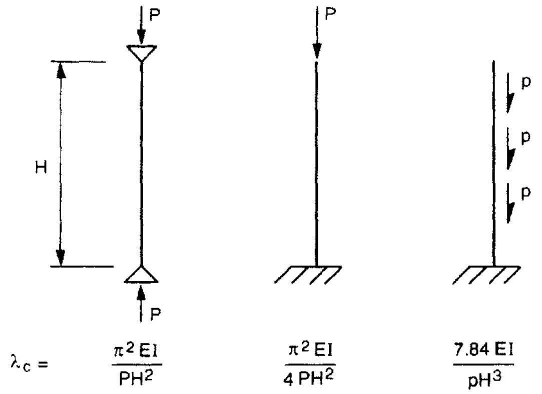

Figure 26: Elastic stability of columns [38]

Columns can be designed to withstand shear and bending forces in addition to axial loads. Under these conditions, the columns would act like a beam or fin and would consequently be designed as such.

Despite the column dimensions, the column should not be subjected to excess compressive stress, since it will fail first along a shear plane instead of a crushing mechanism. The critical load that would induce loss of stability, or bifurcation buckling, can never be attained in practical applications due to inherent material flaws that reduce the member capacity. The most significant factors influencing load capacity include, glass thickness, initial geometric deformation, the visco-elastic PVB, and the breakage stress of glass.

4.2.3 Deflection

According to the Institute of Structural Engineers [38], the high modulus of elasticity, the lack of creep and shrinkage, and the low working stresses that indicate axial shortening should not be an issue. Glass has a modulus of elasticity comparable to that of aluminum, and greater than those of timber and concrete. The Institute goes on to say that lateral deflection of columns is not usually a major design consideration unless the sway of an entire building storey is being considered.

4.2.4 Case Studies

Town Hall Column, Saint Germain-en-Laye, France

The first use of the glass column in building construction was in a glass patio of the town hall in Saint-Germain-en-Laye near Paris. The new Administrative Center was covered with a 700 m^2 glazed roof supported by cruciform glass columns. A large glass cone penetrates the roof and surrounds a single living tree in the center of the courtyard. It was essential that the architecture of the courtyard renovation reflect the traditional architecture of the town.

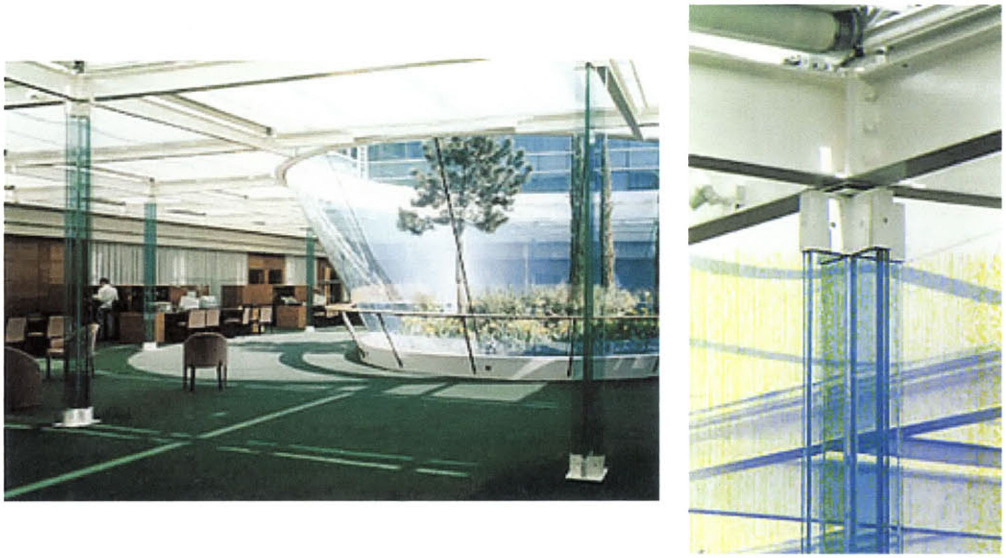

Figure 27: a) Glass columns in the town hall patio, b) Close up of load-bearing laminated glass column [37]

Each column is capable of bearing a weight of 50 tons and is made from a load-bearing sheet of laminated glass 15 mm thick by 20 cm wide, held in a sandwich between two protective glass lites of the same thickness. The structural layer of glass is recessed from the edges of the adjacent panels for protection. The cross is constructed of one continuous glass panel to which two shorter pieces are glued. According to Rob Nijsse, there was sufficient redundancy in the design that if one column should fail, the steel roof system would be able to self-sustain until the damaged column was replaced. This is probably due in part to the steel tension ring around the patio.

This project earned the 1996 DuPont Benedictus Award for the considerable research into glass technology, and the innovative and comprehensive use of laminated glass throughout the courtyard design.

Zwitserleven Glass Truss, Amstelveen, Netherlands

Although the long beam project for the Zwitserleven insurance company building was never built, a successful glass truss was constructed to satisfy the desire to provide a "maximum transparency" roof over the restaurant. Several roof schemes were developed to span the 5 m, but in the end, the architect decided that the solution was a W-shaped glass truss.
With all trusses, it is understood that the diagonals are either in axial tension or compression, and are often specified to be the same member despite the location along the truss or the direction of the force. In this case, all members in compression were designated glass, and all members in tension would be steel. In this way, the forces in the truss could be articulated in the aesthetics of the design.

The top member was a hollow steel pipe with a 120 x 80 x 5 mm cross-section. The bottom chord and all diagonal tensile elements were designed to be steel cable of 10 mm diameter. The glass elements were comprised of massive borosilicate bars 30 mm in diameter. After all the members were specified, the glaring problem that remained was how to connect large glass bars, steel cables, and a hollow pipe.

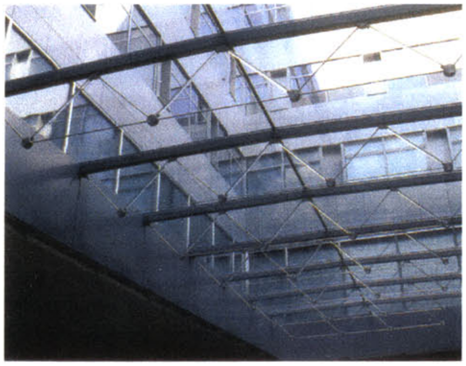

Figure 28: Zwitserleven glass and steel truss system [30]

In the connection of a rigid glass bar and a steel cable, flexibility became an issue. If the diagonal elements were not hinged perfectly, then clamping moments would develop in the structure. By gluing steel caps to the ends of the glass bars and joining them to a sandwich of steel disks, adding neoprene pads would prevent direct contact between the steel and the glass within the cap. The disks would act like a node into which all members would frame (Figure 29).

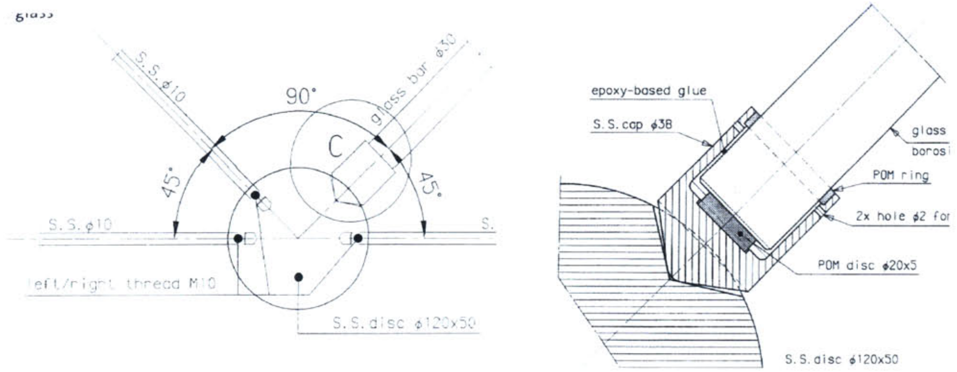

Figure 29: Details of roof truss nodal connections [30]

Redundancy was a major consideration in the design of the roof trusses. Should any of the glass columns in the truss fail, an alternative mechanism would have to support the redistributed load of the truss and the insulated glass roof panels. After much deliberation, a hollow structural steel tube was designed to temporarily support the load of the roof above, as a simply supported beam, if any of the other truss members failed. The steel top chord would sustain this worst case with a 1.1 safety factor, should failure occur. The roof could not be maintained long-term, in this state, due to excessive deflection.

4.3 Glass Walls and Point Supported Glass

4.3.1 Glass Walls

Walls have evolved to allow building occupants to visually connect with the environment on the other side, whether it's taking in the cityscape from the top floor of a high rise, admiring a courtyard garden, or experiencing sea-life at an aquarium. Not only do glass walls connect us to the world on the other side, but protect us from it as well. Transparency has long been sought by man in possessions, which decorate and encompass our lives, from gleaming gemstones to the ubiquitous "picture" windows of the 1950's and 60's tract homes. For example, it was cathedrals—monuments to the glory of god and the achievements of men—that started the revolution that maximized use of structural glass. Seemingly built of light and air, there was no return from that point to the dark and dismal interiors and facades of stone, torches, and cavernous interiors.

Glass walls essentially behave like very wide glass columns. To sustain loads, walls must have substantial thickness and, consequently, multiple plies. Like columns, designers must be careful that load transfer doesn't generate undue concentrated stresses. To minimize this possibility, the support should be as centralized as possible. Also, the most likely mode of collapse is via buckling or plying.

Glass walls present a safety risk in two ways. Glass could fracture and fall out of the pane causing harm to people and property below, or it could allow someone to fall out of the building itself. The development of safety glass was intended to prevent such injuries. To meet safety standards, the glass must be able to stay in place for a minimum of 15 minutes after breakage with no applied load, or it must be able to withstand several cycles at 60% of the design wind load. [8]. This should permit adequate time to evacuate people from dangerous areas. In geographic regions that experience severe weather, such as hurricanes, the criteria are far more stringent.

In these situations, it is necessary that the wall continue to protect its occupants even after breaking. Graham Dodd, Associate Director of Arup Materials Consulting in London, suggests that the wall should be designed to resist the fully-factored, static load with any layer of the safety glass broken and deflection criteria relaxed. The wall with all lites of glass broken should also be able to withstand a reduced load. The design method should reflect the use and the environment. A glass enclosed observation deck on a skyscraper would clearly have higher safety standards than a glass wall of a conservatory.

4.3.2 Point Supported Glass

Most engineers almost immediately associate glass curtain walls with spider connections. The metallic fingers that are supporting today's curtain walls allow the designer to increase transparency and translucency by minimizing the structural framing.

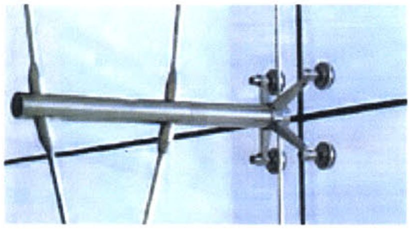

Figure 30: Spider fixture [25]

Toughened glass is a requirement to accommodate the stress concentrations resulting from bolting directly to glass façade plates. Planar fittings support the dead weight of the glass by direct bearing on the bolts, so it is critical to maximize the strength of the glass around these joints. The bolt holes are diamond drilled into annealed glass, and subsequently heat soaked to assure that nickel sulphide inclusions don't cause spontaneous fracture of finished glass panels. [38]

The maximum span for bolted clamp plates of toughened glass is given in the following table from in the Institute of Structural Engineers (Figure 31). Smaller spans correlate with Planar- and Spider-type bolted fittings. Manufacturer product information is integral in making responsible engineering decisions. It is only after extensive product testing and quality control that manufacturer's offer design resources for the application of their products.

Maximum spans for toughened glass panels using bolted clamp plates					
Loading		Maximum span (mm) for UK toughened glass			
UDL in kN/m^2	Point load in kN	6	8	10	12
0.5	0.25	1400	1800	2150	2450
1.0	0.5	900	1500	1800	2050
1.5	1.5	-	-	1200	1650

Figure 31: Table developed by Pilkington Glass Consultants [38]

Deflection of point-support façades can be predicted using rules of thumb, or by conducting a finite element analysis. For example, if the expected deflection is more than one half of the pane's thickness, then its behavior cannot always be sufficiently represented by linear models. The method of calculation is determined by the out-of-plane rotations of the glass surface. If using the Pilkington Planar system of joints (Figure 32), then the connection between the bolt and the glass is capable of carrying a small bending moment compared to the RFR system that allows rotation of the glass relative to the joint. [38] Therefore, a thorough understanding of the permissible movement of the façade is required before proceeding with any finite-element analysis. The Pilkington Planar system was developed to respond to seismic loads. The joints point support the glazing by working with a system of stainless steel cable trusses and aluminum purlins. The joint system can endure 6" of inelastic displacement. [15]

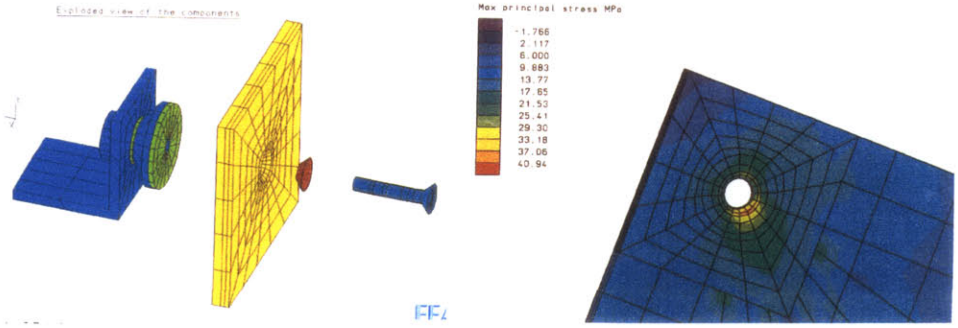

Figure 32: Finite element model of Pilkington planar bolted joint connection [38]

Glass plates deform and develop stresses when coping with uniformly distributed surface pressure, like wind pressure. Deformations are elastic until they exacerbate inherent surface flaws in the material and minute cracks reach a critical length. If the flaw occurs near a concentration of stresses, around a bolt for example, then the tensile stress the panel can withstand is diminished. This relationship between stress and flaws indicates the influence of additional factors including area, loading history, surface compressive stress, and quality of the installation. [38]

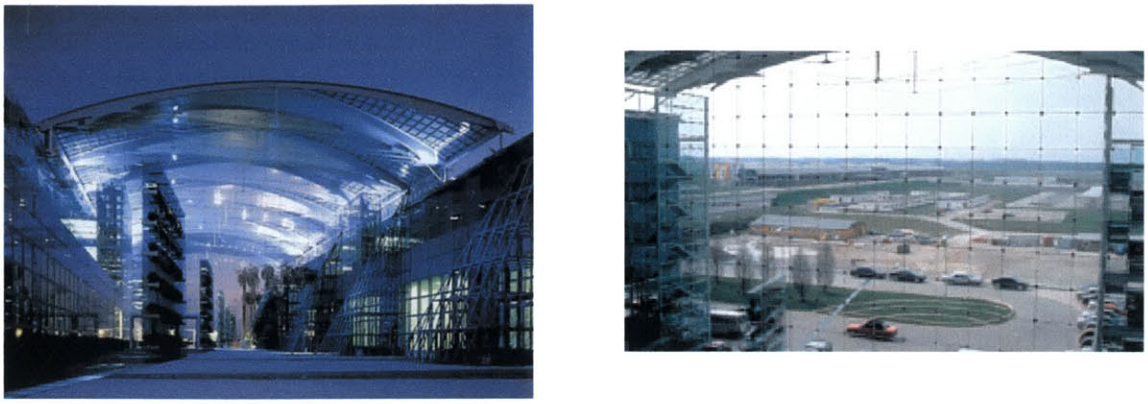

Figure 33: a) Munich Kempinski Hotel, b) Cable net façade [24]

Deflection is, again, not a significant design criterion unless on the macro scale where the sway of the entire structure is being considered. Glass walls can be designed to have low stiffness and tolerate large deflections. The limit of the deflections is then determined according psychological response—human perception of safety. Companies and employees will not occupy a building if they find large deflections alarming, despite whether the building is structurally sound. Rule of thumb, limits glass wall flexibility to roughly span/200. For example, the Munich Kempinski Hotel (Figure 33) permits for 900 mm, and the Tower Place in London allows for 75 mm. The extent of the lateral movement of the Munich Kempinski Hotel is largely considered unacceptable; whereas Tower Place was designed to satisfy perceived safety.

4.3.3 Case Studies

Aquarium Tank at Artis Zoo, Amsterdam, Netherlands

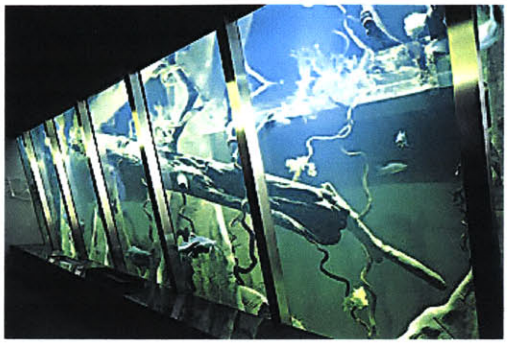

Figure 34: Amazon forest exhibit at the Artis Zoo [21]

As part of the 100-year-old zoo renovation, new aquariums were installed. The glass tank walls were subjected to the pressure of 3 m of water. Part of the design criteria was that the panels could not be supported by mullions, but must span from floor to roof. To be particularly cautious, 6 ply 15 mm thick toughened glass was used for the design despite the calculation that 3 plies of 15 mm glass was sufficient. The edges of the successive panels were cut at an incline, where neoprene and structural silicone was installed. As the water pressed against the glass, the neoprene deformed to better fill in the joint. In this way, the water pressure was working to the designer's advantage. The exhibits contained in the new aquariums were a viewing portal into Amsterdam's canals, a coral reef, and a flooded Amazon forest. Each of these examples employed 6 x 15 mm glass panels supporting up to 3.5 m of water pressure.

Citicorp Skyscraper Façade, Hong Kong, China

The design-build company from the Netherlands, Octatube, devised two glass curtainwall façades for the entrance of the Citicorp building in Hong Kong, China. The façades stand 10m and 12 m wide, by 32 m high in a skyscraper extending 250 m in the air. The tall façades were subjected to high design wind loads of 525 kg/m^2, inherent to the typhoon-prone climate of Hong Kong, although these conditions occur once in a century. This climatic feature also requires that the building envelope be watertight.

The tensile trusses supporting this exterior façade were stressed horizontally, and required much more robust cross-sections than those commonly found in Europe. For example, two rods, 27 mm in diameter, were needed compared to a typical single rod of 10 mm diameter.

In addition, the glass panels were 20 mm as opposed to 8 mm. Each panel was 2 x 2 m in width and height (Figure 35).

When conducting pressure tests on the model of the proposed structure, two glass panels burst at a pressure of 500 kg/m2. A faulty connection between the plywood testing chamber and the model was responsible for the failure. A second successful attempt was conducted months later.

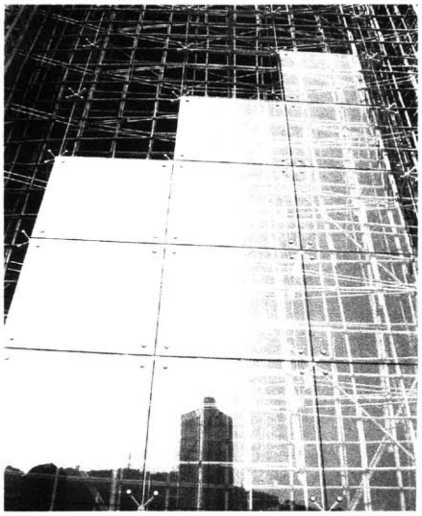
Figure 35: Citicorp Façade, Hong Kong [11]

Although the facades were built in accordance with the Netherlands-based company's construction manual, the rest of the skyscraper utilized local techniques including bamboo scaffolding. This created an interesting contrast between the modern expression of glass and the Chinese tradition of bamboo. From this project, Octatube was commissioned to adapt the point supported façade technology used on Citicorp, to the seismic conditions of Japan.

4.4 Glass Roofs and Floors

4.4.1 Roofs

The roof can be the most distinctive part of a structure. In urban areas where buildings continue to push up toward the sky, they look down upon the "fifth façade." Glass roofs seem to be conventional for horticultural purposes, but they remain elegant nonetheless. The benefit of the glass roof is that it transmits natural daylight, but this feature also leads to undesirable thermal gain. The development of PVB technology and glass tinting allows designers to control the amount of light transmitted and refracted into a structure—an ability that makes glass roofs, once again, highly desirable.

4.4.2 Floors

Humans are fascinated by the prospect of walking through the air, or on water. Although it may make the heart race, glass floors are desirable because they capture the imagination. It is always a very conscious feature of any structure utilizing this design feature.

Because of its perfectly smooth appearance, it may seem to compromise safety using glass as a floor. As long as glass remains dry, there is no need for additional slip-resistant coating or surface treatment. Although there is no standard for the design of glass floors, there exists a slip test that involves sliding a sample of shoe rubber across a glass surface and measuring the amount of energy that it absorbs. This test is supposed to simulate the slipping action of the pedestrian heel.

In most cases, glass floors are found in pedestrian bridges, and a few other applications. The design of the floor then depends on the type of traffic and the location of the bridge. Designers attempt to protect glass from excessive contact and tend to situate it in protected locations, because surface scratches tend to increase tensile forces, ultimately resulting in failure of the member. A floor contradicts this off-limits concept, so the degree of robustness must be adjusted according to the traffic and abuse the floor will see. The glass plates comprising the floor of the pedestrian bridge in Rotterdam joined two carpeted offices where most dirt and coarse debris would get knocked off before setting foot on the bridge itself. Thus, it was located in a relatively ideal setting. In addition to surface abrasion from traffic, floors are potentially subjected to longer load duration.

4.4.4 Case Studies

Floor of the National Glass Centre, Sunderland, UK

A workshop, restaurant, and museum were covered by a sloping roof, that served a dual purpose as a floor. People had access to the glass floor 24 hours a day, which meant many unsupervised hours. The glass area could also be used for an assembly space if desired. At any time, people could test the strength of the floor intentionally or accidentally. This area was designed to experience 5 kN/m2 of distributed load, and 3.6 kN of concentrated load.

Figure 36: Glass floor of the Sunderland National Glass Centre [18]

To ensure safety, laminated glass was used in a 4 lite of 8 mm configuration for the 1.25 m^2 panels. Each lite of glass was bonded by a 1.52 mm thick layer of PVB foil. This was the first instance of heat-strengthened glass for flooring. Heat strengthening was desirable for its resistance to thermal loads and for its improved strength. Amusingly, fully tempered glass was rejected because the designers felt that the loud pop that occurs simultaneously with the glass failure would provoke vandals to continually mistreat the glass.

To reduce slippage, ceramic granules were fired onto the top surface during the heat strengthening process. About 40% of the glass surface was covered with the abrasive surface to improve safety, yet maintain translucency. The grey dots created by the surface treatment also psychologically served to reassure those who were reluctant to cross the floor.

Glass Stairs in Apple Store, New York City, USA

Apple Computer Inc. touts itself as being a leader in computing and electronics technology. They pride themselves on the sleek aesthetics of their products, and they wanted this cutting-edge look translated into the design of their new SoHo store. One of the striking features of the new store is a glass staircase that seems to levitate in the mezzanine of the building.

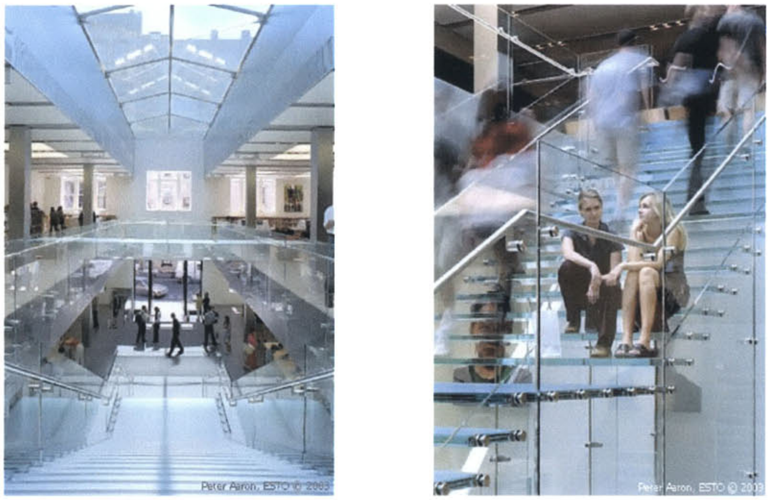

Figure 37: Glass stairs in New York's new Apple Store [37]

Treads of stairs essentially act like a succession of small glass floors, subjected to a dynamic design loading created by people fleeing the building in case of an emergency. The stairs are constructed by using two 8 mm outer lites of plate glass laminated together with two inner structural layers of 15 mm plate glass, using a 1.52 mm thick "ionoplast" interlayers. According to extensive load-bearing tests conducted in Germany, the ionoplast interlayer allowed the treads to be 50% thinner and twenty times stronger than if made with tradition PVB technology. Not only does the laminated glass design provide excellent strength and safety, it also appears to be a monolithic layer of glass with its highly polished edges. Many earlier glass stairs make their lamination very obvious. The treads and landings are supported by vertical laminated glass sidewalls using small titanium fittings.

Dupont stated in its laminated glass newsletter that "Architectural and structure engineering experts have said that the staircase, bridge and mezzanine [of the Apple Store] represent a quantum leap forward in using the strength of glass for a self-supporting structure while demonstrating the aesthetic lightness of glass with a new minimalism."

4.5 Glass Domes

3.5.1 Design

The synthesis of metal and glass structures immediately incubated the generation of domed structures. Domes proliferated over markets and train stations in the 19th century. The earliest notable example is London's Crystal Palace built in 1851. The glass panels were not structural and were fixed onto a lightweight metal frame. The Crystal Palace inspired numerous other glass-domed buildings including the Glass Pavilion in Cologne, Germany (1914), and the Palm House in Bicton, United Kingdom. Although the glass did not actively participate in the load resistance, the structural mullions benefited from the increased stiffness that the glass panes provided. Single panes of glass were used in these early examples of glass domes, which would not provide adequate safety by today's standards. Perhaps, it was the small size of the panes that prevented the entire structure from failing when one pane would break?

Innovation came in 1863 when Schwedler included stiffening diagonals to the ribbed dome. This advancement spawned the membrane shell. The diagonal cables function to ensure dome action and prevent racking. These cables are connected by special rotatable joints. The Gasometer in Vienna, Austria, is an excellent existing example of this concept. Years later, Buckminster Fuller developed geodesic domes using strut-and-tie geometry. His quintessential domes consist of 20 spherical, equilateral triangles covered with a triangular net of equilateral ribs. The evolution of free-formed glass domes came later, around 1989, with the invention of the grid shell. A steel net of rods and nodes can be erected in a seemingly infinite number of configurations, or spatial geometries. Grid shells can be vulnerable to unbalanced loads, like snow. In some cases, heated cables prevent excessive snow build accumulation. If it weren't for modern technology, this design method would be particularly labor intensive. The size and shape of each glass pane is calculated and cut by a computer. Each glass pane is surrounded with neoprene silicone rubber to mitigate the stresses between the glass and frame. A circular plate joins the intersecting edges of four neighboring plates, using a simple bolt fixture. This system provided enough flexibility to accommodate the double curvature structures made renown by Jorge Schlaich.

4.5.2 Case Study

Maritime Museum, Osaka, Japan

An offshore structure was built in Osaka Bay to house a "higaki kaisen," reconstructed timber trading boat, from the Edo period (17th–19th centuries). Three exhibition floors encompass the boat to commemorate the rich maritime culture of Japan. An entrance onshore leads to a 60 m long subterranean tunnel that emerges inside a spectacular 70 m diameter glass dome.

Figure 38: Grid shell dome of the Maritime Museum at night [32]

The total gross floor area is 20,699 m^2, 70% of which is inside the glass dome. An offshore structure is appropriate for Japan, since land area is scarce and construction keeps pushing upward and outward, yet is constrained by the ocean on all sides.

The hemispherical dome is a single layer grid shell fixed at the base to a circular reinforced concrete wall. The glass plates have a squarish geometry rotated into a diagrid configuration to maximize unit repetition. The flat glass panels meet each other at the edges without bending or warping, because the top two sides of the glass panels are slightly shorter than the two lower sides, and the panels decrease in size with height.

The framing consists of straight tubular members 190.7 mm in diameter and 6-12 mm thick, butt-welded to steel nodes and braced by high-strength rods between 25-36 mm in diameter. [32] The rods are prestress to prevent any member from going slack under any loading condition. The diagrid converges at the top, joining into a 3.3 m wide Vierendeel truss ring beam.

A series of 25 nodes extend from the concrete base to the ring beam, and 48 nodes divide the circumference. The ring beam is capped with a 21 m diameter glass structure supported by orthogonal cable trusses.

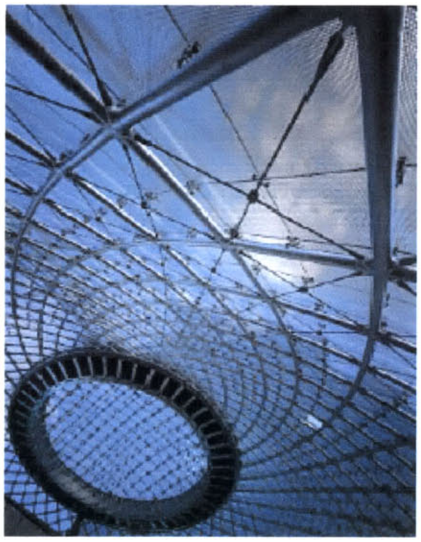

Figure 39: Ring beam of Maritime Museum Dome [32]

Severe seismic and wind load loading conditions had to be considered for the glazing. The local university investigated the impact of typhoon and high tides on the glass dome structure. The analysis concluded that under 4.4 m high waves cycling at 6.6 seconds, the bottom 5 m of the dome could be subjected to loads with a maximum pressure of 100 kPa. Static and seismic analysis including geometric stiffness data, determined that the prestress rods create a relatively stiff structure with a period of 0.3 seconds. The shape of the dome and the moment-connected diagrid effectively create a fairly resilient building under seismic conditions. [32]

Until recently, designers' creativity has been limited to working with materials that traditionally provide for safety and practicality. Structural glass roofs, floors, façades, and members enable engineers to create buildings that evoke sculpture and light in new ways. Building on the ingenuity of the engineers and manufacturers that came before, the next generation of structural glass designers will push the application of glass to new limits.

Conclusion

Glass is the only material that began solely as an architectural element and has transcended its history to become a structural material. For example, it was architectural desire to create glass facades and domed roofs that spawned the technology that permits engineers to exploit its behavior as a load-bearing material. From glass facades, emerged fins that respond in flexure. The mastery of fins led to the validation of glass beams. Despite advances in technology, glass is still highly susceptible to concentrated loads and the development of local stresses. Although glass is an ancient material that predates steel and concrete, it hasn't yet attained the same degree of evolution and adaptation that its other materials counterparts have. Perhaps as designers' imaginations push the limits of glass as a material and as a sculptural expression, new methods and treatments will develop to further our ability to use glass.

We are entering a new era in the lengthy history of glass, where consumer and architectural interests are motivating engineers to take mastery of its structural properties. Joint design for mechanical fixtures and adhesives will most likely garner great attention in -the near future. Adhesive success or failure will become apparent as many early examples of its usage are approaching the end of its estimated design life. Considerable research and development will be dedicated to its improvement. As more engineers and designers work with glass as a structural material, there will be greater urgency for the development of a unifying design code.

For psychological reasons, people will always want to maximize light. Real estate value increases dramatically in proportion to the number of windows and exposure to the sun. I have first hand experience with a price-per-window valuation of property as I begin my search for an apartment in New York following graduation. Studies have suggested that increased exposure to natural light elevates mood and increases productivity in offices. Glass will always be a desirable commodity for its aesthetics and ability to connect humankind with its environment. As engineers and architects respond to this demand, the results will be lucrative industrial and technological advancements, heightened energy consciousness, and enhanced social well-being.

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