The Effect of Reinforcement on Loadbearing Capacity of Structural Glass

by

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ABSTRACT

The transparent property of glass makes it a favored choice of material in the design of structures because it maximizes light and creates an illusion of larger spaces. However, it is a very brittle, making it difficult to use as a common building material. Laminated glass significantly improves the strength through a layer of resin called polyvinyl butyral (PVB). Laminated glass is typically used for buildings in which human impact is vulnerable, such as hurricane prone areas or important government buildings. However, laminated glass still lacks the residual loadbearing capacity that one would find in reinforced steel, for instance. Residual loadbearing capacity is important to ensure the safety and reliability of glass as a structural material. This thesis will provide an overview of the common glass treatments, fixings, structural systems, and design methods used today. Additionally, two research studies investigating the effects of reinforced glass will be examined. Finally, the author will provide a simulation of a three-layer laminated glass stair tread with an applied design load. The simulation compares the stresses and displacements of the unreinforced glass tread with a glass tread reinforced with a 4 mm thick steel plate. The results from the simulation are inconclusive. However, experimental results from the two research studies show promise for the use of reinforcement in glass to improve load bearing capacity.

Thesis Supervisor: Jerome Joseph Connor
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Thank you Mom, for somehow providing me with everything out of nothing. You are my biggest inspiration.

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1. Introduction

Transparency has always been a driving force behind maximizing the amount of glass used as a building material. Because of this, many innovations have been made with the goal to make glass a better load-bearing material. In particular, recent advances have attempted to improve the behavior of this brittle material by increasing the loadbearing capacity of glass. The first part of this thesis will provide an overview of glass properties, strengthening procedures, design considerations, and two research case studies on the more recent advance in glass technology: glass reinforcement. Reinforcement has been closely examined over the last few years as a progression towards improving glass residual loadbearing capacity. The second part of this thesis will use the finite element model software SJ MEPLA to provide a model of a loaded reinforced laminated glass tread and compare it to results from a typical, unreinforced laminated glass tread. The simulation will be used to examine the similarities or differences between the simulation results and the experimental case studies and to provide a perspective on the difficulties of modeling the complex behavior of glass.

2. Material Properties

Glass is transparent because the molecules that make up glass are in a completely random order, that is, glass exhibits amorphous isotropy, thus preventing a crystal lattice to form. Glass is composed mostly of silicon dioxide. Other substances found in glass are calcium oxide, sodium oxide, magnesium oxide, aluminum oxide, and trace amounts of other substances used to influence certain properties. During its production, glass is heated to a high temperature until it becomes viscous. Subsequent cooling of the glass prevents the ions and molecules from arranging themselves into a crystalline structure.

Since glass consists of a combination of various bonds, it has no chemical formula. It also does not have a melting point. Rather, it gradually changes from a solid sate to a plastic-viscous and finally a liquid state. The transformation point, or the point in which glass changed from the solid to the "soft" state, is at about 640 ^{o}C [16].

The glass surface is considerably hard. It has a scratch hardness of about 6 on the Mohs scale (steel has a hardness of about 4 to 4.5). Therefore, it is easy for sharp objects to cause hairline cracks on the surface. So although glass has strong atomic bonding forces and thus has a high mechanical strength, "Griffith Flaws" arise from damage to the microstructure and scratches on the surface, which cause high stress peaks when a load is applied. Since glass is an elastic-brittle material, it is not possible to dissipate these stresses through plastic deformation [16].

2.1 Glass Treatments

2.1.1 Thermally toughened/Tempered safety glass

In thermally toughened (aka tempered) safety glass, an entire flat glass pane is heated beyond its transformation point. Then it is abruptly saturated with bursts of cold air, a process known as quenching. This causes the surfaces to cool faster and consequently contract at a faster rate than the core of the glass. As a result, compressive stresses are formed on the surfaces, and the ultimate bending strength and thermal fatigue resistance is increased due to the prestress. If it is loaded beyond the prestress, fracture can occur, causing the glass to break into many small pieces with dull edges. Because of its fracture pattern and higher ultimate bending strength, toughened glass is classified as a safety glass.

2.1.2 Heat-soaked thermally toughened safety glass

Glass contains tiny inclusions of nickel sulphide (NiS) that have an important influence on toughened safety glass. During the glass treatment, these NiS inclusions are converted into a crystalline form with a smaller specific volume than usual. They are unable to convert back to their crystalline form with a larger specific volume during the abrupt cooling. It therefore needs a sufficient supply of energy over a longer period of time, which can be obtained through solar radiation after the panes have been installed in a building. As the crystals increase in size, this produces stresses on the glass, which could lead to fracture. This creates an unsettling situation, since one is unable to predict when the NiS inclusions will cause the glass pane to break. Heat-soaked thermally toughened safety glass addresses this problem by heating up the glass again to 290 ^{o}C and holding it there for at least two hours after the initial heating and abrupt cooling [20]. This allows for all the NiS compounds to quickly return to their initial state at this temperature, possibly causing a fracture during the production process. This process reduces the overall risk of glass breakage.

2.1.3 Heat-strengthened glass

Heat-strengthened glass production is similar to thermally toughened glass in that the glass is heated and then cooled with air. The difference is that the cooling occurs more slowly so the compressive stresses formed at the glass surface are lower than those formed from toughened glass. This results in a completely different fracture pattern. The broken glass pieces are much larger than with toughened glass. However, when heat-strengthened glass panes are joined together with a plastic interlayer or made into laminated safety glass, the fracture pattern can change with the stiffness of the interlayer and its bond with the glass.

2.1.4 Chemically strengthened glass

Glass may be prestressed chemically through ionic exchange. This process involves immersing glass in a hot molten salt and allowing an exchange between the smaller sodium ions in the glass surface and the larger ions in the molten salt. This process creates compressive stresses at the surface as well as strengthens the edges of the pane. This strengthened zone is not very deep, however.

2.1.5 Laminated Glass

Laminated glass is the assembly of two or more glass panes bonded together by an intermediate layer during the manufacturing process. The glass panes can be made up of any of the aforementioned types of treated glass, as well as the basic float glass (commonly known as window glass, and made by floating molten glass on a bed of tin). The interlayer can be made from casting resins or other organic and inorganic compounds.

In the case of laminated safety glass, the broken fragments must be held together and the glass must meet certain requirements upon load impacts. One commonly used material for the interlayer is polyvinul butyral (PVB). When a PVB interlayer is used, the plastic sheet is placed between the panes and the whole unit is pressed together in an autoclave under heat and pressure. Because laminated glass has the ability to bond glass fragments together and multiple panes are held together by interlayers, laminated glass is the most ideal treatment for maximum load-bearing capacity

3. Connections

When using glass as a construction material, it is important to be careful of local stress peaks that may arise and cause brittle failure. The arrangement and placing of glass components governs the locations and magnitude of stresses. When detailing glass connections, it is important for the glass to not come into contact with harder materials or actions that may cause cracks. To address this problem, various materials, such as synthetics, casting resins, or aluminum alloys can be used to place between glass and the connections so that they may absorb any deformations and ensure a maximum area for load transfer.

Various types of supports for glass are available depending on its intended use. The methods of securing the glass are partitioned into non-positive, positive and bonded joints [19]. As the name implies, bonded joints are those in which the glass may not detach from the connection. The connection is made by adhesion (attraction between similar molecules) and cohesion (intrinsic attraction of molecules of the same substance).

Conversely, positive and non-positive connections allow for subsequent detachment. Positive joints are held together by interlocking with the glass through various geometries. Non-positive joints are held together by applying a force via friction or contact that clamps the glass together. Within friction connections are clamping discs, which provide a point support, and clamping bars, which provide linear support. The intermediate bearing pads on the clamps can be made of soft metals, plastics, or other materials. If the clamps supporting the glass are weakened, or if moisture or other forces interact with the glass, then the panes could slip out of the fixing. In contact connections, the force-transfer mechanism is compression. Failure through this type of connection can occur by excessive compression or by the glass pane slipping out of the fixing when there is severe deformation. The following sections will describe in more detail the most common types of connections

3.1 Clamp fixings

Clamp fixings can be regarded as a combination of a positive and non-positive connection. They have an advantage over point fixings in that as opposed to point fixings, the loads are transferred evenly to the glass and stress concentrations are usually avoided.

3.1.2 Clamped linear supports

The most common type of linear clamp support originates from the rebate and glazing bead. In this case, the glass is placed in frame rebate and wind suction by continuous glazing bead (See Figure 1A). The rebate is ventilated so that the pressures on each side are the same and thus water cannot leak through the joint. Patent glazing bars (Figure 1B), which clamp the edges of two adjacent panes and press them against the supporting framework, can accomplish large areas of glazing. The glazing bars can be made of aluminum, steel, wood, or plastics. In this arrangement, an elastic sealing strip is placed between the glass and the supports, and between the glass and the glazing bar. A common arrangement is glazing with two linear supports on two sides and the other two sides unsupported but sealed. The Technical Rules for the Use of Glazing on Linear Supports (TRLV) covers glass on linear supports for glazing that are at angles >10^{o} to the vertical [14].

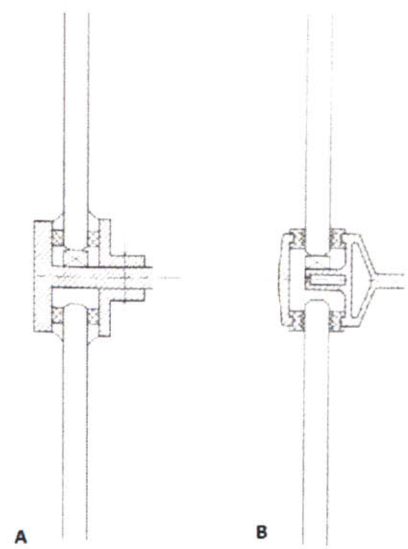

Figure 1. A) Rebate with glazing bead. B) Patent glazing bar with capping strip [20].

3.1.3 Clamped point supports

Whereas linear clamps withstand the loads due to wind pressure, clamped point supports resist the wind suction effects on the glass panes. Clamped point supports must be positioned along the edge of the glass or in the corners of the pane. For detailed instructions on technical requirements, one can refer to the Technical Rules for the Design and Construction of Point-Supported Glazing (TRPV) [14]. Figure 2 is an example of individual clamp fixings.

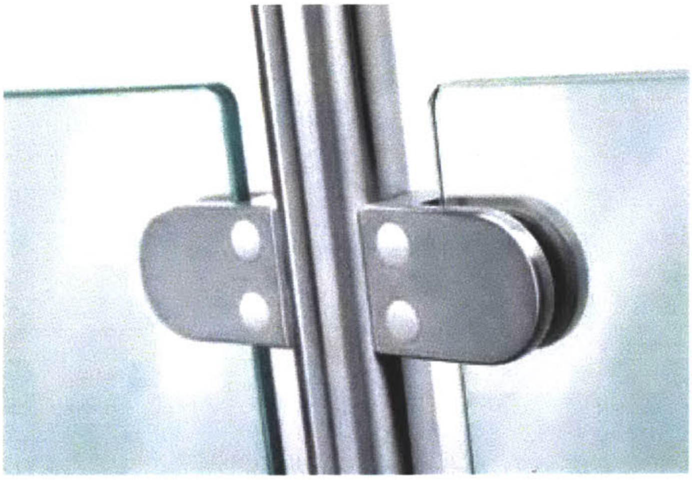

Figure 2. Example of individual clamp fixings (Photo obtained from Google.com).

3.2 Drilled fixings

Drilled connections by means of screws or bolts are advantageous in that they can be easily dismantled. The force transfer through drilled fixings cause high local stresses in the glass at the point of contact. Therefore, drilled fixings must be made from either toughened monolithic (having uniform thickness) glass or laminated glass made from toughened safety glass, heat-soaked toughened safety glass, or heat-strengthened glass.

The drilling fixings may be either rigid or hinged depending on whether the point can accommodate any twist. For rigid point fixings, the glass pane can be held by two discs on elastic bearing pads which are connected to the support through a threaded rod.

To reduce the restraint stresses on the fixing, hinged point fixings can be used. Several options include spherical or universal joints, or point fixings with hammer-head screws and soft rubber inlays.

As mentioned earlier, there should always be a bearing between the shank of the fixing and the glass to dissipate high stress peaks. Some examples of materials that can be used are prefabricated, tight-fit sleeves made from plastic or aluminum, two-part composite mortars, epoxy resin-based adhesives, or glazing compounds that can be mixed on-site [19].

3.3 Bonded fixings

Fixings that are connected through adhesives demonstrate improved thermal, sound, and weather insulation.

3.3.1 Structural Silicone

There has been much experience with using structural silicone adhesives for sealant glazing. Structural sealant glazing (SSG) is a type of construction in which glass is permanently connected to an adapter frame via a load bearing, waterproof silicone joint [19]. The component is attached to a post-and-rail framework, and the supporting construction can consist of anodized or powder-coated aluminum or stainless steel. Figure 3 shows an example of a structural sealant configuration.

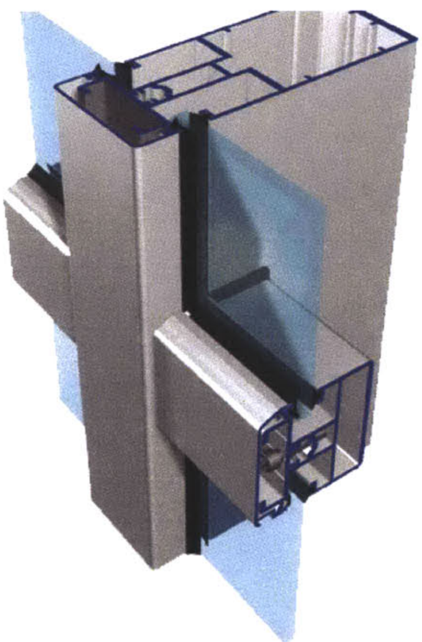

Figure 3. Example of structural sealant configuration for a curtain wall system (Photo obtained from Google.com).

3.3.2 Glued and Welded Connections

With an increased demand in transparency, connecting structural glass by welding melted glass and gluing are natural areas to pursue and improve on. Current research shows that the structural performance of glued or welded connections is acceptable. However, the available options for glue material, which include epoxy resins, UV hardening glues, and silicone based glues, are degradable and thus not feasible for long term exterior designs. Another concern is the difficulty of applying glue to tight corners. DELO industries, a German company, has recently developed a family of adhesives, PHOTOBOND, for glass connections [16]. Case studies suggest that this glue may overcome the deficiencies in other glued connections. However, additional research is needed to improve the long-term behavior of glued and welded connections.

Table 1 provides a summary of the advantages and disadvantages of the main types of glass fixings.

Table 1: Pros and Cons for the main types of fixings

Type of fixing	Pros	Cons
Clamp fixings	Loads transferred evenly to glass, reduces stress concentrations	Susceptible to panes slipping out of fixing
Drilled fixings	Easily dismantled	High local stresses
Bonded fixings	Improved insulation, greater transparency	Glue material often degradable

4. Structural Systems

4.1 Linear elements

Linear structural elements, such as bars, rods, and columns, are subjected solely to axial loads. Girders or frames, for instance, ties and struts are only subjected to tension and compression, respectively. When designing compression members, the stability is the most crucial component, whereas the strength of the material governs in tension members.

For linear glass members made with only one glass pane, the maximum height of a compression member can be no more than about 1 meter. This is because strips of float glass can usually only be up to about 19mm thick [14]. Taking a maximum slenderness ratio of 1:50 results in about 1 meter. Therefore, glass tubes or solid cast glass struts are a better alternative for compression members.

Even so, linear glass elements are not often used for struts and ties. One way to improve the load bearing capacity of these linear elements, however, is to combine the glass with plastic, metal, or timber. For instance, concentric prestressing of glass puts the entire cross-section of glass in compression, which can then be used as a tension member to neutralize these compressive stresses [13]. These glass tubes have already been used as members of glass bridges and in tensegrity structures, as shown in Figure 4.

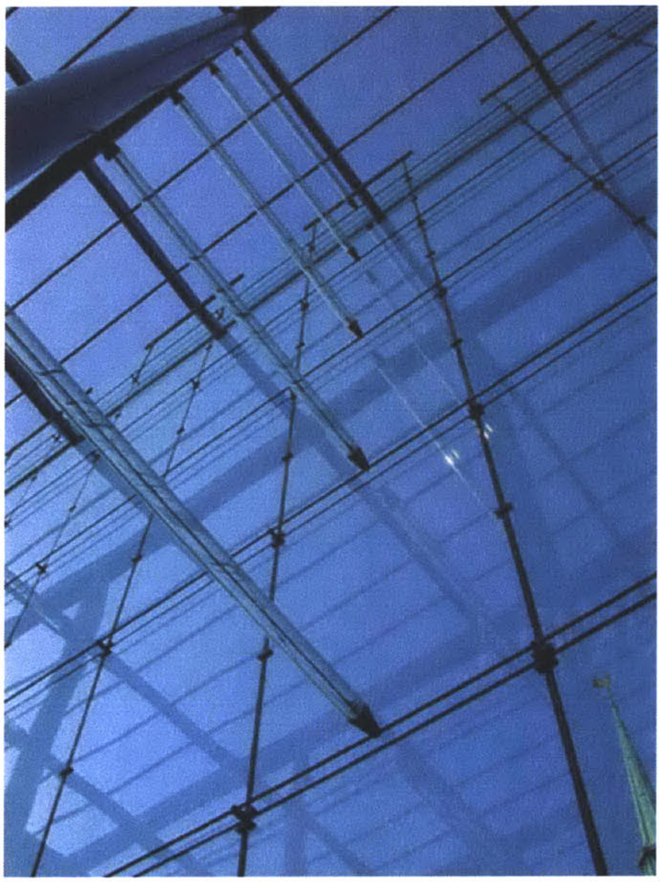

Figure 4. Structural glass tubes used in the Tower Place, London. Structural engineers: Ove Arup & Partners (Photo obtained from Google.com).

4.2 Girders and Beams

Beams can be subjected to bending, shear, and torsion. Glass beams are typically stressed primarily through bending about their major axis, resulting in high stresses in the edges. One example of redistributing these high stresses for a curtain wall are to include glass fins that are able to provide lateral support for carrying dead loads and wind loads (Figure 5). This way, although a fracture in the glass could still cause deformations, the dead loads and wind loads can still effectively be carried.

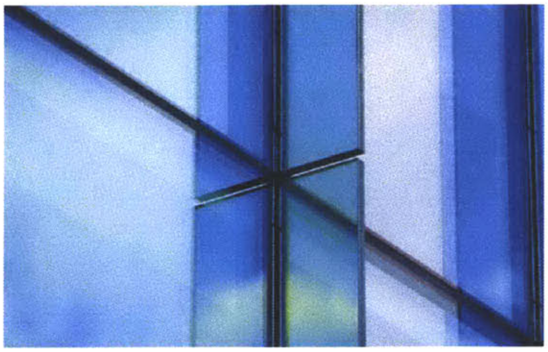

Figure 5. Glass fins used for lateral support on curtain walls (Photo obtained from Google.com).

Glass beams can be made highly efficient if their sections are combined. By combining even two glass beams in any given cross section in a clever way, one can add a significant amount of strength and rigidity to a structure. An example of this is the cantilevering glass roof at the Tokyo International Forum in Japan. The 10.6 meter long glass canopy was designed by Dewhurst Macfarlane and Partners.

Figure 6. Cantilevered glass canopy in Tokyo, Japan [1].

The canopy is comprised of cantilevered beams that are each made up of 4 smaller beams pinned at their middle and end points to form an arch. The constituent beams are made of laminated glass that vary from 4 panes to 1 pane from the base of the cantilever beam to the tip. At the 1997 British Construction Industry Awards, the Yurakucho canopy received special recognition for "demonstrating British expertise in the design and construction of glass structures" [1].

4.3 Slabs

Single-ply slabs (slabs made of a single glass pane) made of float, toughened safety or heat-strengthened glass are the most common type of glass slabs. All window panes act as slabs and thus exhibit bending stresses upon wind loading. Glass panes acting as bending slabs are very thin; for instance, a 1 x 1 meter float glass pane with an average wind load of 0.8 kN/m^2 (~16.7 psf) is only about 6 mm thick (this is a span/depth ratio of about 1:160) [20].

If a rectangular slab linearly supported on all four sides experiences large deflections (greater than about the thickness of the glass itself), it begins to act as a membrane and a compression rings forms at the edges. At that point, the slab is not only subjected to bending; it starts to become subjected to axial loads, much like a stretched fabric. Consequently, the slab also becomes stiffer as it begins to behave like a membrane

When the slab is supported in individual points, the slab will exhibit greater bending and shear stresses and thus larger deformations than in the previous case, as intuition will confirm. Slabs supported at points are generally thicker than slabs linearly supported.

Multi-ply slabs may consist of multiple panes laid loosely on top of each other or bonded by a viscoelastic interlayer (laminated glass). Although it would be ideal for the interlayer to be stiff enough to be able to withstand bending forces, it is more important for it to be able to hold the glass pieces together if they become broken. When the glass is held loosely, each pane must be able to support its share of the total load in proportion to its flexural strength. However, if the glass panes are held together by a viscoelastic layer, the unit behaves compositely. The maximum stress acting on the unit would be reduced to one half and the deflections would be reduced by a factor of 4 [14].

4.4 Plates

Plates are subjected to forces acting on the plane of the slab. Glass is not typically designed to act only as plates; the extent to which glass behaves solely as a plate is typically restricted to glass beams. In any case, plates can be designed to take loads either mainly in tension or compression. Laminated safety glass is often required for sufficient residual stability for plates in tension and compression. The stress transfer for plates in tension may cause problems because only point fixings or friction-grip connections can be regarded. Using point fixings leads to high stress concentrations in the load transfer zone. Because of this, friction-grip connections are often employed.

Plates subjected to compression are fairly easy to support; often, the forces are transferred through contact. For instance, setting blocks are typically sufficient for low loads. However, there are limitations to the pane sizes because high compressive stresses produce instability problems.

4.5 Shells and curved members

Since glass panes can be bent in a furnace, many different curved shapes are possible (cylindrical, conical, spherical, etc). Considerable savings can be made with curved glass members because this shape allows for the stresses on the shell to be taken in compression. Panes bent in double curvature are even more effective. Although curved glass members are aesthetically pleasing and result in cost savings due to thinner glass requirements, they are also difficult to make, especially if the curved member must be laminated. The lamination procedure is complex because when producing the multiple glass panes, it is imperative that they have almost exactly the same curvature to ensure effective lamination and to prevent the possibility of cracking between the multiple glass panes.

5. Design for Glass Structures

Glass as a structural material is being used quite often due to advances in material technology. Understanding the behavior of glass is imperative when designing with this brittle material. As mentioned earlier, it behaves almost completely elastically and thus the maximum stresses it can withstand are local stress peaks at flaws, chipped edges, or at crack tips. Therefore, it is very difficult to come up with a step by step design manual when the strength of glass is highly dependent on the degree of inherent flaws in any particular glass pane. Nevertheless, there have been many advances in the understanding of the material, and thus improvements have been made to allow glass to go from an enclosing, fragile material to a load-bearing, structural material.

5.1 Material

5.1.2 Failure Behavior

Because stress peaks formed on glass cannot be dissipated by plastic deformation, and surface flaws cannot be avoided at edges or around drilled holes, it is necessary to design glass with only a fraction of the real material strength. When the critical tensile stress is reached on the glass surface, the crack begins to grow around a small notch called a crater. Sometimes this growth occurs at intervals and eventually stops. This "stable" crack growth is known to be subcritical and is mostly determined by the duration of the load.

5.1.3 Surface Structure

The surface of glass can be expected to experience many different types of loads (scratches, cleaning, wind erosion, distributed and point loads) and therefore damage throughout its design life. Additionally, the various treatments also affect the surface. Cracks on the surface can be reduced by means of prestressing (described later) or by chemical or thermal processes during manufacturing.

The most common glass product (float glass made from soda-lime-silica glass) exhibits parallel surfaces free from distortion. During this process, the continuous ribbon of liquid glass floats on a bath of molten tin, resulting in high-quality glass surfaces on both the air side and the tin side [20]. When making laminated glass, sometimes these two different sides have to be considered. For instance, when using Sentry Glas Plus interlayer material, the tin side must be bonded to the interlayer because it provides a rough surface capable of bonding more effectively. Moreover, coatings on float glass for modifying thermal insulation or radiation reflection properties are applied to the air side in order to avoid uneven color effects on the finished coated panes.

Another way in which the glass surface can be modified is through thermal toughening. When the glass is removed from the furnace, it is conveyed on rollers and cylinders while being cooled abruptly. This produces small corrugations on the surface. Also, the strong cool air blasts can cause localized compaction on the surface.

5.1.4 Strength

As previously mentioned, the strength of glass is highly dependent on the amount of inherent damage on the surface. When designing glass, one needs to take into account the probability that a local stress produced by some load will coincide with a critical inherently damaged area. This can only be done statistically. Thus a design method based on the probability of failure, have been conducted in many cases.

To illustrate, even though glass that is fresh out of the production line exhibits a wide range of strengths, the average strength is relatively high. Throughout the life of the pane, however, damage on the surface accumulates and thus the probability of a critical crack forming increases. Consequently, inherently damaged glass has a lower average strength as well as more narrow statistical distributions than glass right out of the factory.

5.1.5 Prestressing

When the glass surface is subjected to tension due to applied loads, vents and chips may lead to crack propagation. Prestressing the glass is an effective means to increase the amount of tension that the glass can withstand. Several prestressing techniques have been described in the glass treatment sections of this thesis.

5.2 Codes and Standards

The various design methods for glass used by industry have led to a limited number of design codes and standards. There is, however, no official glass design code book such as the AISC book for steel design. In no way do these cover all the possible structural applications by glass. Most of the unique structures that have been built have been experimental or designed by firms that specialize in glass. There are simple design tables offered by manufacturers for patented glazing systems for pin connections, cable-trussed panes, glass handrail and guardrails and other systems. However, they are usually only in-house design guidelines obtained by empirical testing and field experience of the firm [16].

5.3 Design Methods

As noted, there is no standard method of designing structures that use glass in an innovative or creative way. The first principles of mechanics must be used. The European Draft Standard, prEN 13474 can be used as a good starting point, as it provides fundamental equations for strength and stiffness of glass in various conditions [14].

Designers of glass also make sure to investigate alternative load paths or levels of redundancy for scenarios and locations where the glass might break.

There are three well-known methods for designing glass. They each have a distinct theoretical approach but are not contradictory and thus can be used in combination with one another.

5.3.1 Allowable Stress

This design method is based on permissible stresses. However, this method is flawed in that it often does not accurately take into account the complex and concentrated behavior of glass. To compensate for this, high safety factors are required (about 2.4 times higher than the minimum strengths determined in bending tests).

5.3.2 Probabilistic Approach

This method, which has been briefly described previously, uses fracture mechanics to describe the statistical nature of strength in glass due to load duration, areas under stress, and ambient humidity. This method is more accurate than allowable stress design, but often much more complicated.

5.3.3 Limits States Design

Limits States Design is the most common approach for designing glass. It considers probabilistic distributions from loads and materials. It looks at the probability that a load case may occur or that a component may fail in determining the modes of failure. Duration of loading is also considered in some cases. For instance, in the American standard "Standard practice for determining load resistance of glass in buildings," (ASTM E1300-00) short-term loads, such as wind loads, are accounted for with a certain factor [20]. Additionally, the shear bond between the interlayer and the glass panes are accounted for depending on the duration of the load.

When structural engineers design steel, timber, or concrete structures, they design these structures based on fundamental idea that each individual member must meet certain design requirements without considering the application of that member within the whole structure. This "safe-life concept" is undoubtedly unrealistic when designing glass building components. Because glass strength is extremely scattered for any particular glass pane and therefore spontaneous failure is not impossible, a "safe-life" guarantee for every individual glass component is not attainable.

Therefore, it has been recognized that when designing for glass, it is possible to divide glass components into those that require a safe-life guarantee and those that could cause local failure but may not severely affect the structural integrity of the structural purpose as a whole (aka the "fail-safe" concept).

In this fail-safe concept, the structural system as a whole and the consequences of the failure of individual glass components on the whole structural system are examined in various scenarios. The objective is to prove that the failure of various individual components in each scenario will not affect the stability of the structure. In other words, this method is used to prove that the structure possesses a residual stability.

prEN 13474 and a few others use the limits states design philosophy. The design for strength and serviceability using this method is briefly described. Design for strength is accomplished by comparing the effective stress (the weighted average of the distributed main stressed on the glass surface) with the maximum tensile resistance of glass. The maximum tensile strength of the glass is a function of the size and quality of glass surface, accumulated load duration, and environmental conditions [16].

Design for serviceability is also imperative for glass structures. However, not many guides make reference to deflections. An example of the deflection limits for the use of continuously supported vertical glazing is provided in Table 2, which was taken from the German National Code [6].

Table 2: Allowable deflection limits for continuously supported vertical glazing. From the German National Code (Adopted from [16]).

Type of glass	Type of linear supports	Deflection limit	Definitions
Single glass		d ≤ L/100	L: span in main load-carrying direction t: glass thickness*
Insulated glass unit	Four sides	d ≤ L/100 and d ≤ t	
	Two or three sides	d ≤ L/100, d ≤ t and d ≤ 8 mm	L: length of free glass edge t: glass thickness*

* The nominal glass thickness of a laminated safety glass unit is $t = \sqrt[3]{t_1^3 + t_2^3}$

Some argue that the deflection limits should be more stringent. The deflection of the main steel frame to which the glass is attached is a good reference point for determining the deflection allowance. The supports must also be flexible enough to prevent high concentrated loads in those regions. Another consideration is the relative displacement between the glass panels. Control for deflections is also important from an architectural standpoint. For instance, panes with too much deflection create negative lens effects on the façade surface, which is aesthetically undesirable.

The limit states method thus accounts for the damaged condition of the components. This way, the residual load bearing capacity of the glass component and its mode of failure could be verified. The next section will describe the concept of residual load bearing capacity in glass in more detail.

5.4 Residual load bearing capacity

The residual load bearing capacity in glass is dependent on the broken pieces of a glass pane mutually supporting each other. In this respect, individual glass panes have a very limited residual load bearing capacity. Laminated glass, in which two or more panes are bonded together by a viscoelastic intermediate layer, is often used to improve the residual load bearing capacity. In this case, the system could be held together by the interaction with the interlayer and additional panes even if one layer of glass is broken. There are several factors that influence the load bearing behavior of laminated glass. These factors can include: the type of glass used (thermally toughened, heat strengthened, float glass), the type of support, the glass pane geometry, the type of material used for the intermediate layer (Sentry Glas Plus, PVB, casting resin), the magnitude and duration of loading, and the fracture pattern upon failure. It is necessary that when designing overhead glazing and walking surfaces made of glass, each individual pane must pass a threshold of residual load bearing capacity; that is, it must be able to withstand the load of the broken pieces above it and the external loads acting on it without becoming detached from its supports or failing at its supports for a certain period of time.

An additional method that is currently being developed to improve the residual load bearing capacity of glass is by reinforcement, as discussed in the next section.

6. Embedded Glass Fiber Reinforcement

6.1 Background

Increasing the residual load bearing capacity is accomplished by improving the strain stiffness, adhesion, and tensile strength of the intermediate layer. Up until now, this intermediate layer has been made from a homogeneous PVB sheet. This intermediate layer could be improved by incorporating a reinforcing element. Some types of reinforcing materials are textiles made from high-strength synthetic fibers, stainless steel wires, perforated sheet metal, glass fiber, or carbon fiber products. These reinforcing materials are not typically visible to the eye from a normal viewing distance. The thicknesses and patterns of these reinforcing materials could be controlled for to achieve a level of desired transparency. On the same note, the reinforcement could also provide a means for sunshading and even serve as a nice architectural feature. This section will review several experimental research studies that have recently been conducted to test the behavior of reinforced glass.

6.2 Description of Bending Tests

The following studies utilize the three-point bending test and/or the four-point bending test, so it is therefore important to realize the significance and differences of these tests. The three-point test and four-point test measures the force required to bend a beam under three point and four-point loading conditions, respectively. The four-point method allows for uniform distribution between the two loads, but the three-point method is only stressed at one locations. The flexural modulus is used to indicate the material's stiffness. Figure B provides a simple graphical illustration of these two methods.

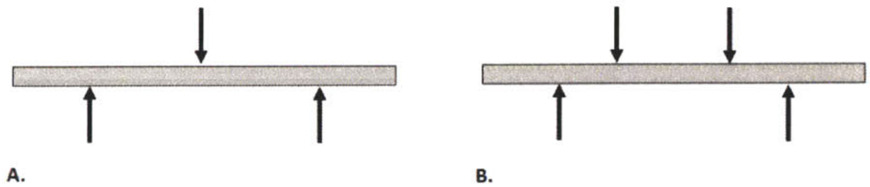

Figure 7. Procedure A represents the three-point test; Procedure B represents the four-point test.

6.3 Case 1: "Reinforced Laminated Glass"

This research study, conducted by Steffen Feiraband from the University of Stuttgart in Germany, looks at reinforcing the interlayer with stainless steel-wire meshes, thin perforated metal sheets, and fabrics of high-strength fibers (Figure 8) [7]. The reinforcement acts similarly to reinforcement in concrete in that an applied force is effectively transferred by a force couple consisting of tension in the reinforcement-interlayer matrix and a compression in the glass fragments. When the glass panes are completely broken, the interlayer ensures that all the glass components remain bonded, which allows for the shear transfer of forces between the reinforcement and the broken glass segments.

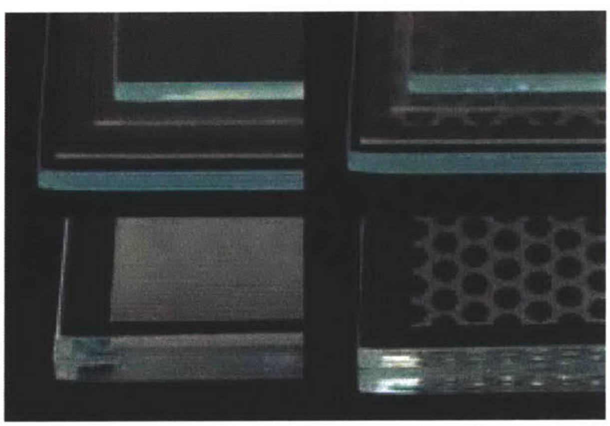

Figure 8. Steel-wire meshes and thin perforated metal placed in the interlayer for reinforcement [7].

6.3.1 Influence of Fracture Pattern

Tests have shown that broken laminated glass made out of annealed or heat-strengthened glass has a higher residual strength than laminated glass made out of tempered glass. This is because large pieces of glass interact more with each other and thus exhibit greater stability. However, this is not necessarily the case under an unusual loading scenario. For instance, in this research study, four-point-bending tests of reinforced laminated glass units were studied under short term loading. The results indicate that tempered glass damaged by a center punch had a higher residual strength than annealed glass damaged with a cutter.

6.3.2 Influence of Time and Temperature

These properties of the interlayer are highly dependent on time and temperature. If the temperature of the interlayer exceeds the glass transition temperature T_G ($T_{G,PVB}$ = 10-15 °C, $T_{G,SGP}$ = 55 °C), then the polymers start to move and this results in a reduction of strength and stiffness.

In this part of the study, four-point-bending tests were performed on tempered glass with steel-wire mesh used as the reinforcement in the interlayer material. The samples were supported on two rollers in order to model pure bending and to eliminate the effect of membrane forces. Two different types of interlayer material were used: PVB and Sentry Glas Plus. The tests were performed at three different sample temperatures (23 °C, 40 °C, and 70 °C) in order to analyze the change in properties surrounding the glass transition temperatures.

Results have shown that the samples without reinforcement only have a residual strength if the sample temperature is below the transition temperature of the prescribed interlayer. In particular, those samples with PVB used as the interlayer showed a negligible residual strength in all temperature ranges. The samples with Sentry Glas Plus as an interlayer showed residual strength at 23 °C and 40 °C. (Figure 9).

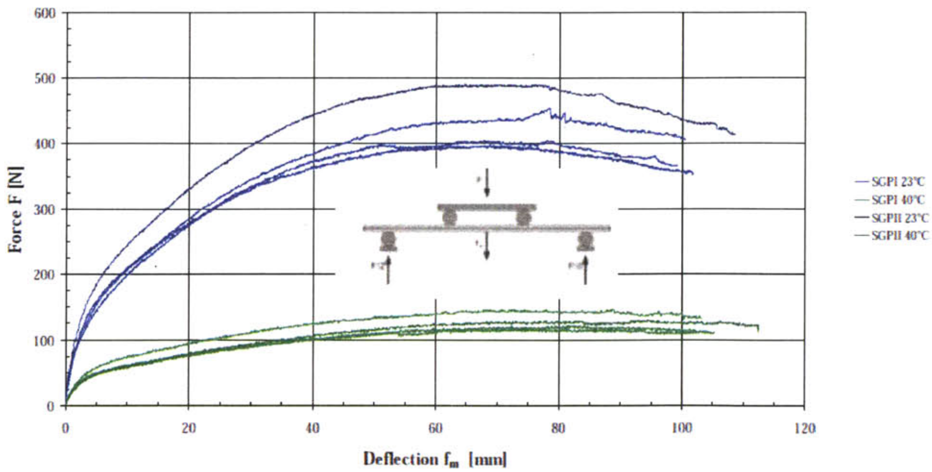

Figure 9. Residual strength of laminated glass using Sentry Glas Plus as an interlayer. SGPI represents glass panes that are 1.52 mm thick, and SGPII represents glass panes 2.28 mm thick [7].

Additionally, only those samples with embedded stainless steel-wire meshes exhibited adequate residual strength at the three sample temperatures, although the residual strength does decrease as the temperature increases (Figure 10 and Figure 11).

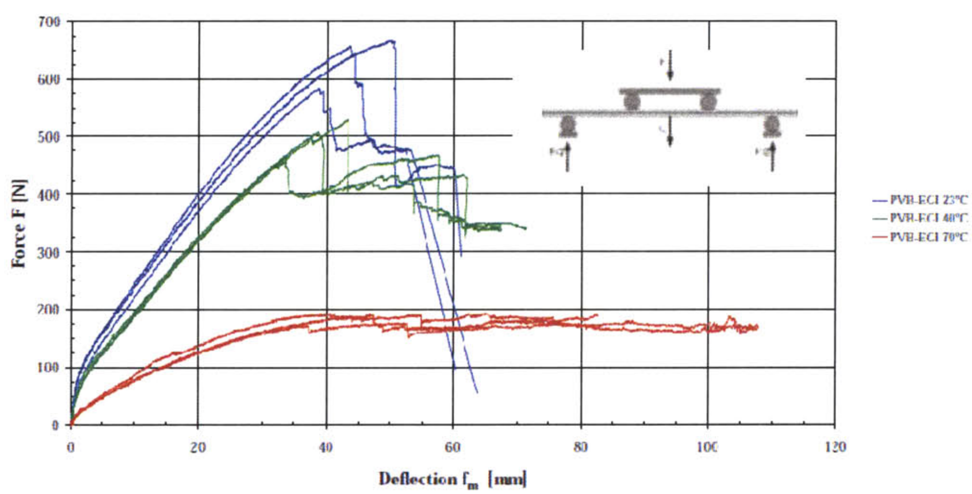

Figure 10. Residual strength of laminated glass with steel-wire meshes (EGI) embedded in PVB interlayer at 23 °C, 40 °C, and 70 °C. Residual strength decreases with increasing temperature [7].

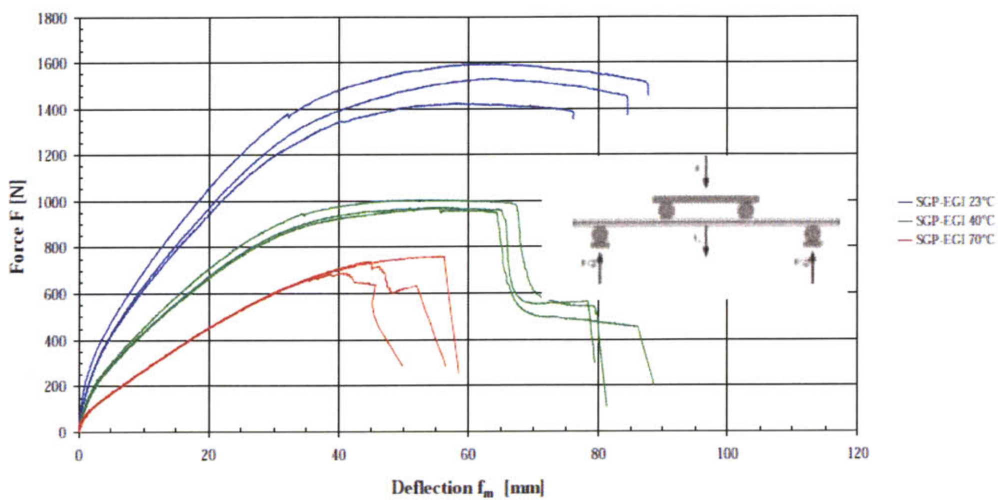

Figure 11. Residual strength of laminated glass with steel-wire meshes (EGI) embedded in Sentry Glas Plus (SGP) interlayer at 23 °C, 40 °C, and 70 °C. Residual strength decreases with increasing temperature [7].

From the figures above, one can also observe that when Sentry Glas Plus is used as the interlayer with the embedded reinforcement, the residual strength is always more than twice as high than when PVB was used as the interlayer.

Tests were also performed to observe how the reinforced laminated glass samples performed under long term loading. As Figure 12 indicates, higher temperatures increase the mid-span deflection under the same loading. Additionally, there is less creep deflection at lower temperatures.

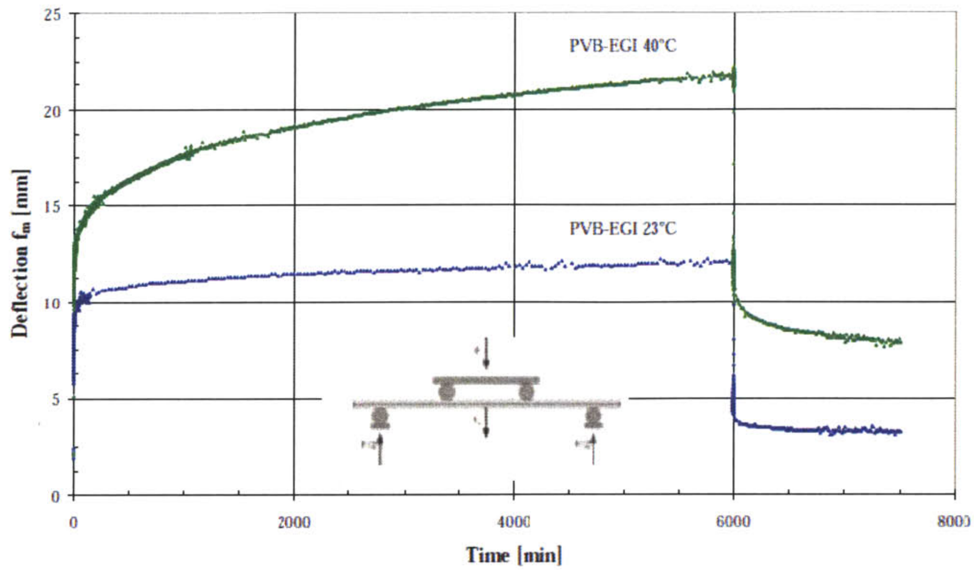

Figure 12. Creep test at 50% of the short time ultimate load for broken laminated glass reinforced with steel-wire mesh in Sentry Glas Plus interlayer [7].

6.4 Case 2: "Structural Behavior of 'Reinforced Glass'"

Another research study, performed by Emanuela Speranzini from the School of Engineering in Italy, looks at the behavior of glass reinforced with one-directional sheets of glass fibre-reinforced plastic (GFRP) or carbon FRP (CFRP) [15]. Three-point tests and four-point tests were conducted on samples of float, tempered, and laminated glass with and without FRP. For simplicity, I will only discuss results from the three-point tests because the four-point tests indicated similar results. The float glass and tempered glass sheets are 8 mm thick, and the laminated glass consists of two 4 mm thick float glass sheets with a 0.38 mm PVB interlayer. In contrast to the previous study, in which the reinforcement was only embedded in the interlayer in laminated glass, this study looks at the reinforcement being connected by epoxy resin.

6.4.1 Carbon vs. Glass reinforcement

Carbon fiber and glass fiber possess different properties. Carbon fiber has a much higher tensile strength resistance than glass (4800 MPa for carbon vs. 2900 MPa for glass). Carbon fiber is also more rigid than glass (E_{carbon}= 230 GPa, E_{glass}= 70 GPa). Aesthetically, however, glass fibers may be the preferred material for glass reinforcement because they are translucent.

6.4.2 Three-point Test

A total of fifty 400 X 200 mm samples consisting of each type of glass were subjected to the three-point test. Twenty samples were tested without reinforcement, twenty were tested with GFRP, and ten were tested with CFRP.

For each type of glass and reinforcement, load-time diagrams were made comparing the reinforced samples with the non-reinforced samples. Figure 13, Figure 14, and Figure 15 show the behavior of float glass, tempered glass, and laminated glass with GFRP and CFRP reinforcement compared to no reinforcement, respectively. For the float glass (Figure 13), the non reinforced samples increase linearly and until they break at their critical load (around 2.4 kN). Although the average critical load is shown as 2.4 kN, the study shows that there is high variability of the critical load for this type of glass; loads ranged from 1.08 kN to 4.44 kN. The reinforced glass behaved differently; the diagram shows two linear parts that are split by a discontinuity. The discontinuity represents the point at which the tensile limit was first reached and the glass cracked. The second linear progression is due to the additional strength provided by the interaction of the fibers and the cracked glass. The samples finally fail when the fibers can no longer keep the broken pieces attached. For the glass samples reinforced with GFRP, the final failure occurs at a load higher than the first cracking. The opposite is true for samples reinforced with CFRP.

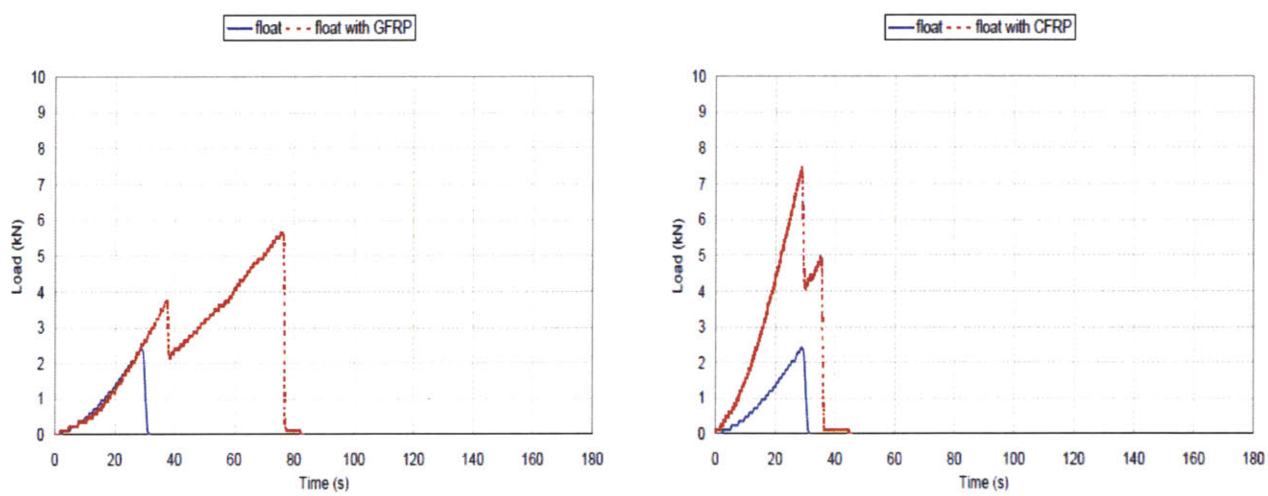

Figure 13. Load vs. time diagrams of: of un-reinforced float glass and GFRP-reinforced float glass (far left), un-reinforced float glass and CFRP-reinforced float glass (far right) [15].

Both cases of the tempered glass (Figure 14) show similar results as the CFRP-reinforced float glass. The unreinforced tempered glass experienced fragile fracture and broke into many small pieces, and as expected, withstood higher loads than the float glass. There was also less dispersion in the critical load values compared to the float glass. The samples reinforced with GFRP underwent fragile fracture at the location of the discontinuity and a slight recovery due to the bonding between the reinforcement and the glass pieces until final failure shortly thereafter. Although the second linear progression did not exceed the first one, the reinforcement still significantly contributed to additional strength of the glass before the first cracking. The samples reinforced with CFRP did not perform as well. The average load at first crack was only slightly above the critical load without reinforcement

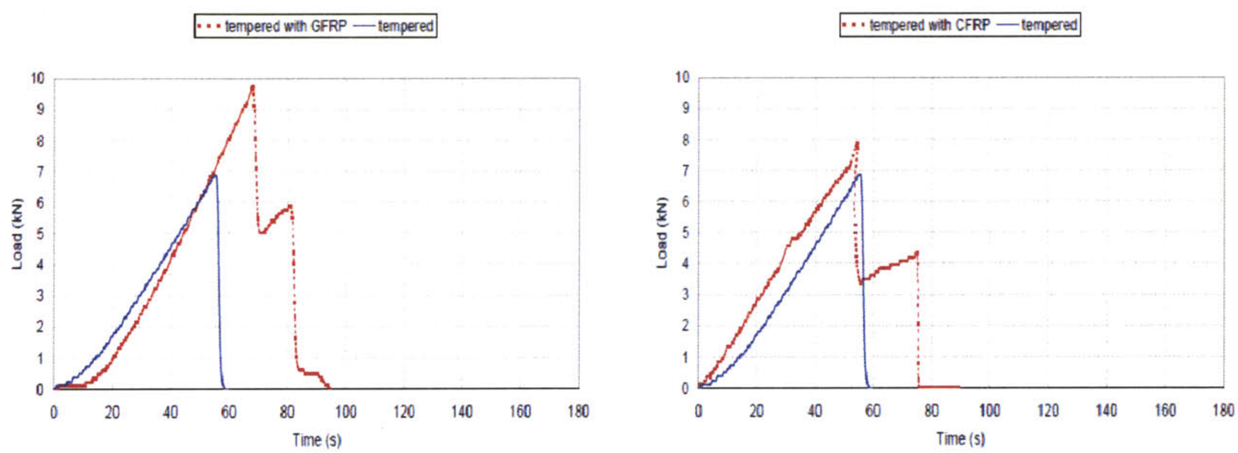

Figure 14. Load vs. time diagrams of: of un-reinforced tempered glass and GFRP-reinforced tempered glass (far left), un-reinforced tempered glass and CFRP-reinforced tempered glass (far right) [15].

The laminated glass (Figure 15) showed significant improvement in strength for both reinforcements. For the non-reinforced samples, there is a discontinuity that corresponds to bottom glass pane breaking until tensile stress. The second progression corresponds to the top glass pane resisting the load until final failure. When the samples are reinforced, the critical load is significantly improved for both types of reinforcement. It is interesting to note that for all glass types, GFRP withstood the prescribed loads for a longer period of time, which is a favorable attribute for glass structures.

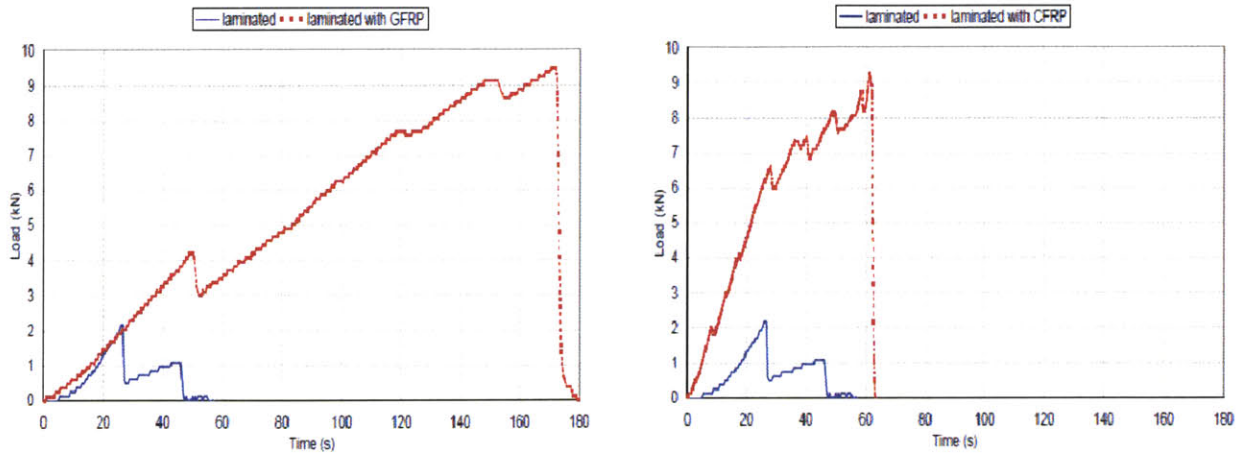

Figure 15. Load vs. time diagrams of: of un-reinforced laminated glass and GFRP-reinforced laminated glass (far left), un-reinforced laminated glass and CFRP-reinforced laminated glass (far right) [15].

As this study shows, float glass and laminated glass samples reinforced with FRP are able to withstand higher loads before collapse. The first decline in strength occurs when the tensile strength of glass is exceeded. Although the glass is cracked in this situation, the pieces are held together by the bonds created from the reinforcement.

6.5 Summary

The two research studies presented here demonstrate the improved residual strength of reinforced glass versus unreinforced glass. Case 1 suggests that when conducting four-point bending tests, unreinforced glass only has residual strength if the temperature is below the transition temperature of the interlayer. Additionally, it showed that samples embedded in stainless steel wire meshes showed adequate residual strength at varying temperatures, although strength does decrease with temperature. Case 2 shows that glass reinforced with GFRP and CFRP exhibits higher residual strength than unreinforced glass. In particular, laminated glass exhibits the highest residual loadbearing capacity compared to singles panes of float glass and tempered glass. The simulation conducted in the next section will build upon the findings in the research studies and model a loaded laminated glass element made reinforced with stainless steel and compare the behavior with a loaded unreinforced glass element.

7. Simulation of Glass Reinforcement

7.1 Background

Simulations were made comparing reinforced laminated glass with un-reinforced laminated glass. These simulations were conducted using SJ MEPLA, a finite element program developed for static and dynamic calculations of multi-layer glazing. This program allows one to make calculations for various types of geometries, types of glass, interlayer properties, fixings, and loadings. After inputs are defined, the program can be called to make linear or geometrically non-linear (for large deformations) calculations. An automated mesh with a preset element size is then generated, and the output of the simulations results, which include stresses and deformations, occur visually and through a computational log. Using SJ MEPLA, the author wanted to model a typical laminated glass stair tread and see how this same tread behaved when a 4 mm thick steel plate was installed in between one of the interlayers. Only a test version of SJ MEPLA could be downloaded by the author, which naturally does not provide all the capabilities offered by the full version.

7.2 Finite Element Model Assumptions

7.2.1 Defining multi-layered degrees of freedom

Before developing the model, it was important to understand some basic theory behind the software formulation. There are several basic assumptions SJ MEPLA makes for the analysis of multi-layered plates. A few important such assumptions are as follows: first, the deformations except the transverse displacements w are small and the material behavior of each layer is isotropic; second, the Mindlin-plate theory is used, which is based on the idea that surfaces remain straight but not necessarily normal to the midplane after deformation; and third, transverse strains are neglected so that plate-like stress behaviors occur [3].

Most finite element software programs describe single layered elements, such as a layer of steel, concrete, or timber. It was necessary for SJ MEPLA, however, to be able to model multi-layered elements. As with any model, the displacements for each layer are defined as follows:

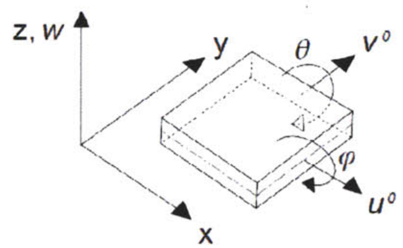

Figure 16. Degrees of freedom for a single plate [3].

Now, each node of a n-layered element has 4n+1 degrees of freedom:

$$u = [w, u_1^o, v_1^o, \varphi_1, \theta_1, u_3^o, v_3^o, \varphi_3, \theta_3, ..., \theta_n]^{'}$$

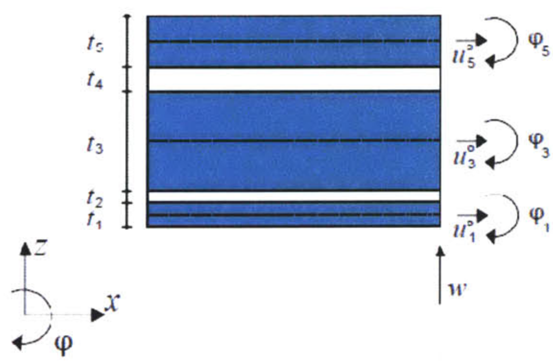

Figure 17. Illustration of the degrees of freedom of a three-layered glass plate [3].

Note that v_i is pointing into the paper, and the vertical deflections w_i for i=1,3,5,... are equal.

For a two-layer laminated plate, the total displacements u_i^z, v_i^z, and rotations φ_i^z, θ_i^z result from the existing degrees of freedom for the two enclosing layers:

$$u_i^z = \frac{1}{2}\left(u_{i+1}^0 - \frac{t_{i+1}}{2}\varphi_{i+1} + u_{i-1}^0 + \frac{t_{i-1}}{2}\varphi_{i-1} \right)$$

$$\varphi_i^z = \frac{1}{t_i}\left(u_{i+1}^0 - \frac{t_{i+1}}{2}\varphi_{i+1} - u_{i-1}^0 - \frac{t_{i-1}}{2}\varphi_{i-1} \right)$$

Then, from the Mindlin plate theory, the plane strains, plane shear deformations, and transverse shear deformations are obtained.

Lastly, the internal layers (indices i=2,4,6,…) are coupled with the enclosing plates to build the total system.

7.2.2 Formulation of load vector and stresses

In accordance with the degrees of freedom, the load vector P allows for the following forces:

$P=\{F_z ; F_x^1 ; F_y^1 ; M_x^1 ; M_y^1 ; F_x^3 ; F_y^3 ; M_x^3 ; M_y^3 ;\ldots\}$,

where the superscript refers to the layer.

Our result is thus a 3-dimensional plate element, where transverse strains are neglected and the deflections are linear for each layer.

For each layer, the principal stresses on the top and bottom faces of the glass panel are calculated by:

$$\sigma(+,-) = \frac{\sigma_{xx} + \sigma_{yy}}{2} \pm \sqrt{\frac{(\sigma_{xx} - \sigma_{yy})^2}{4} + \sigma^2_{xy}}$$

7.2.3 Point fixings

The glass fixing accounts for the multi-layered element and the creation of a new node with five degrees of freedom. The core of the fixing is made of steel and is therefore not deformable, but the elastic properties of the imbedded circular disk pad (shim; thickness h_s) and the bush (protective layer at the contour edge used to prevent direct steel to glass contact; thickness t_h) are considered. The distance Z_h may be considered for eccentric loading from the location of the springs to the glass layer. Stiff boundary conditions may be set by high spring rigidities on the order of 1e6 N/mm.

These elements can be seen in Figure 18 below.

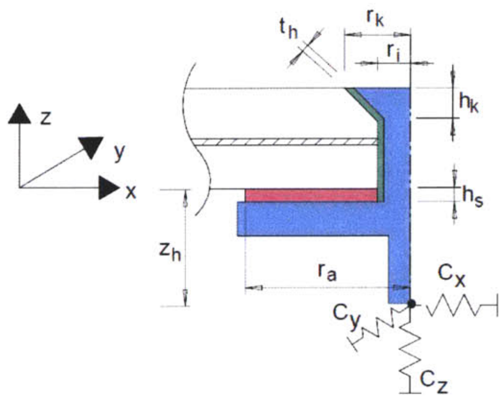

Figure 18. Illustration of a point fixing element [3].

7.3 Model Formulation

A three-layer laminated glass tread was formulated. The dimensions of the glass tread are 1.6 x 0.5 meters. Out of the different glass options available (float, toughened, heat strengthened), heat strengthened glass was selected for all three glass panes. PVB was selected for the interlayer. Although Case 1 suggested that Sentry Glas Plus was a more effective interlayer material, this option was not available in SJ MEPLA. When formulating the reinforced glass tread, the steel was selected as the material of choice for reinforcement. Figure 19 shows the profiles of the unreinforced glass layers and the reinforced glass layers. Table 3 provides a summary of the material properties. The steel layer was placed in between the bottom two PVB layers in order to aid in the tensile resistance when load is applied, since it is known that the bottom of the plate will experience tensile stresses while the top of the plate will experience compressive stresses. When analyzing the stresses, the middle glass layer is selected (layer 3 for the unreinforced plate, and layer 5 for the reinforced plate) in order to more closely evaluate the immediate effect of the steel plate.

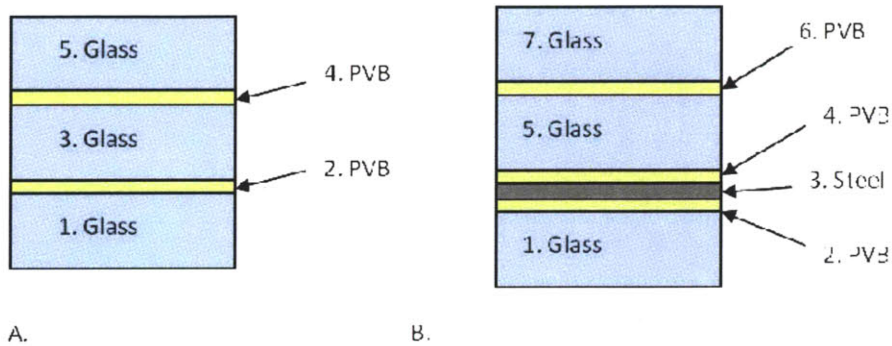

Figure 19. A) Profile of layers for unreinforced glass. B) Profile of layers for reinforced glass. *Note: Figure is not to scale.*

Table 3: Summary of material properties

Material	Young's Modulus [N/mm²]	Poisson's ratio [-]	Thickness [mm]	Mass density of layer [kg/mm³]	Thermal expansion coefficient [1/K]
Heat strengthened glass	70,000	.23	10	2.55e-9	1e-5
PVB	12	.5	1.52	1.07e-9	8e-5
Steel	210,000	.3	4	7.8e-9	1.25e-5

Seven different types of edge supports are available with the SJ MEPLA software. The type of edge support used for simulation was a stiff rotation free clamping type of edge support, as depicted in Figure 20. The other types of supports available were simple supports in the vertical direction, simple supports in the horizontal direction, stiffness only in rotation, and various combinations of those.

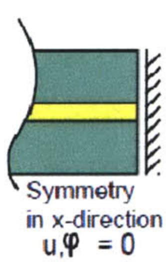

Figure 20. Illustration of glass tread edge support [4].

Four additional fixings were added to provide redundancy to the glass tread. The version of SJ MEPLA used by the author provided seven types of fixings. They include countersunk fixing, disk fixing, circular clamp fixing, angular clamp fixing, circular downholder, angular downholder, and bonded disk fixing. The circular clamp fixing was used for all four fixings; a general illustration is provided in Figure 21. The various dimensions and parameters for the fixing are provided in Table 4.

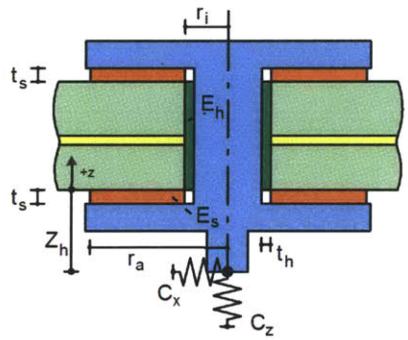

Figure 21. Illustration of circular clamp fixing [4].

Table 4: Dimensions and parameters for clamp fixing.

Symbol	r_i [mm]	r_a[mm]	E_s [N/mm²]	E_h [N/mm²]	t_s [mm]	t_h [mm]	Z_h[mm]	C_x, C_y, C_z [N/mm]	C_ϕ [Nmm/rad]
Description	Radius of the bush	Outer radius of the disk layer	E-module of the shim layer	E-module of the bush	Thickness of the shim	Thickness of the bush	Eccentricity of fixing	Displacement rigidity in spring	Rotation rigidity for y-axis
Value	5	35	60	500	3	2	20	1e6	1e6

The clamp fixings were places at a distance of 100 mm from the short edges and 150 mm from the long edges.

The next step defines the loads. A distributed area load of 0.005 N/mm^2 was applied throughout the whole glass tread (This corresponds to a load of just over 100 psf), which is a typical design load. The dead weight of the glass was included in the calculations. The final step was to define the calculation approach as geometrically non-linear (as opposed to a linear calculation).

7.4 Results

Once all the inputs are defined and the model is run, MJ SEPLA creates an automated mesh (Figure 22), and results can then be seen.

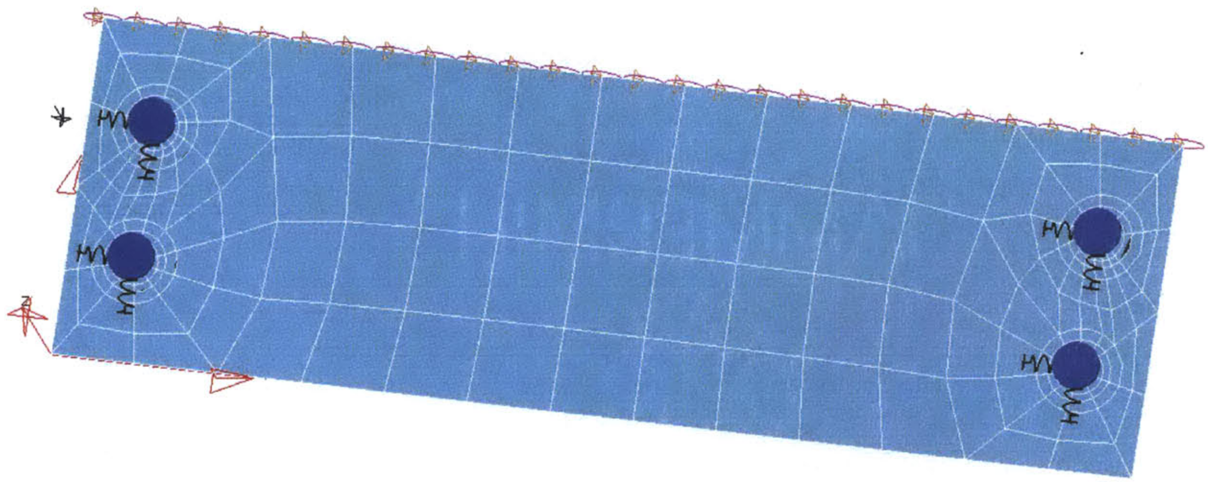

Figure 22. Automated mesh generation of laminated glass tread.

Figure 23 shows the deformation (magnified by a factor of 100.9) of the un-reinforced glass tread. We can see that the glass deforms as expected. Figure 24 and Figure 25 show the tensile stresses on the top side and bottom side of the middle glass layer for the un-reinforced glass tread, respectively. Figure 26 and Figure 27 show the tensile stresses on the top side and bottom side of the middle glass layer for the glass tread that is reinforced with a 4mm steel plate, respectively. As Figure 24 and Figure 26 show, the negative tensile stresses, or the compressive stresses, at the top of the glass panes are concentrated along the center three quarters of the glass tread, with the highest compressive stresses occurring along the unsupported edge of the tread. The highest tensile stresses are concentrated around the clamp fixings and edge support, as expected. The maximum compressive stress on the unreinforced tread is about 1.2 N/mm^2, whereas the maximum compressive stress on the reinforced tread is 1.15 N/mm^2. These results might suggest that the reinforcement just below the middle glass layer helped in alleviating the compressive stresses experienced by that layer. Nonetheless, the compressive stresses on the unreinforced glass is only 4% lower than the stresses on the reinforced glass, indicating that reinforcing the glass is a large price to pay for a small reduction in stress.

Figure 25 and Figure 27 show the tensile stresses on the bottom side of the middle glass layer for the unreinforced and reinforced treads, respectively. As expected, most of the tensile stresses occur along the center of the glass. The maximum tensile stresses are located near the corners of the edge support. The tensile stresses then decrease gradually as it progresses towards the free edge. The compressive stresses are mostly concentrated around the clamp fixings. The maximum tensile and compressive stresses on the unreinforced tread are 3.79 and 4.07 N/mm^2, respectively, while these maximum values are 3.49 and 4.36 N/mm^2 for the reinforced tread. We can see that the reinforced glass has higher overall stresses on the bottom side of the middle glass layer, which contradicts the results suggested from the stresses on the top side of the middle glass layer.

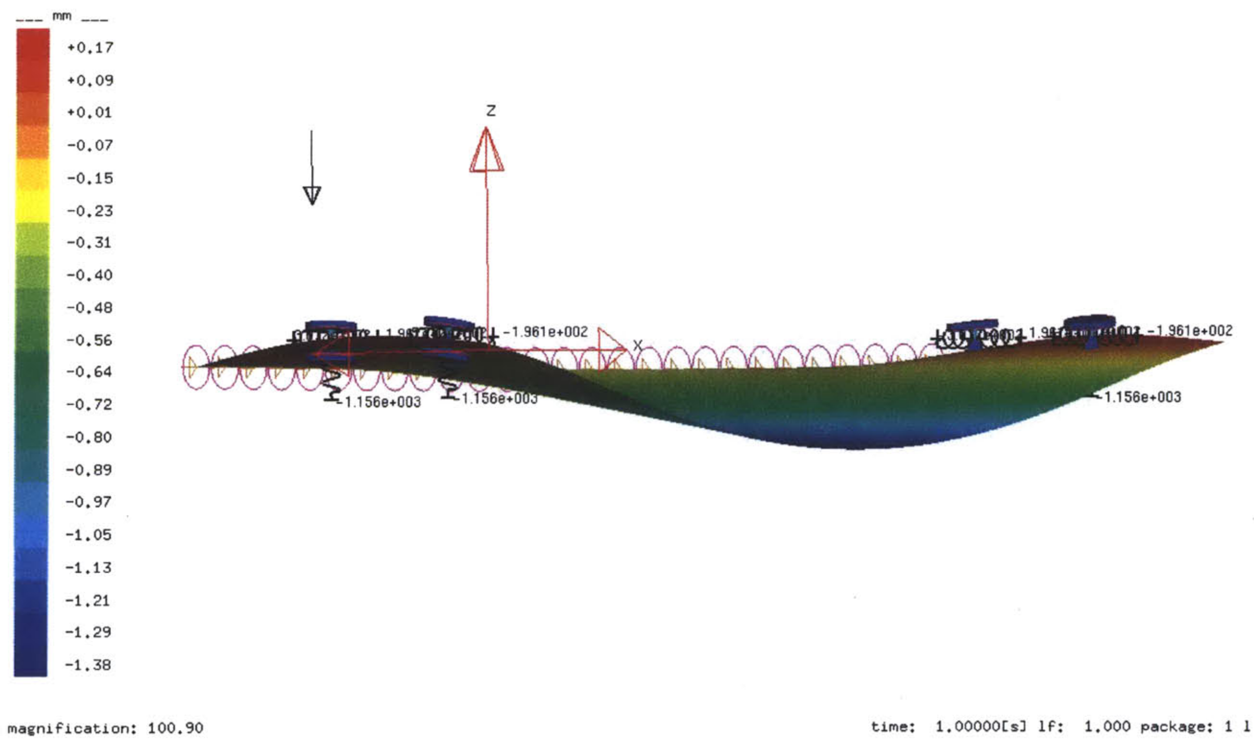

Figure 23. Deformation profile of un-reinforced laminated glass; magnified by 100.9.

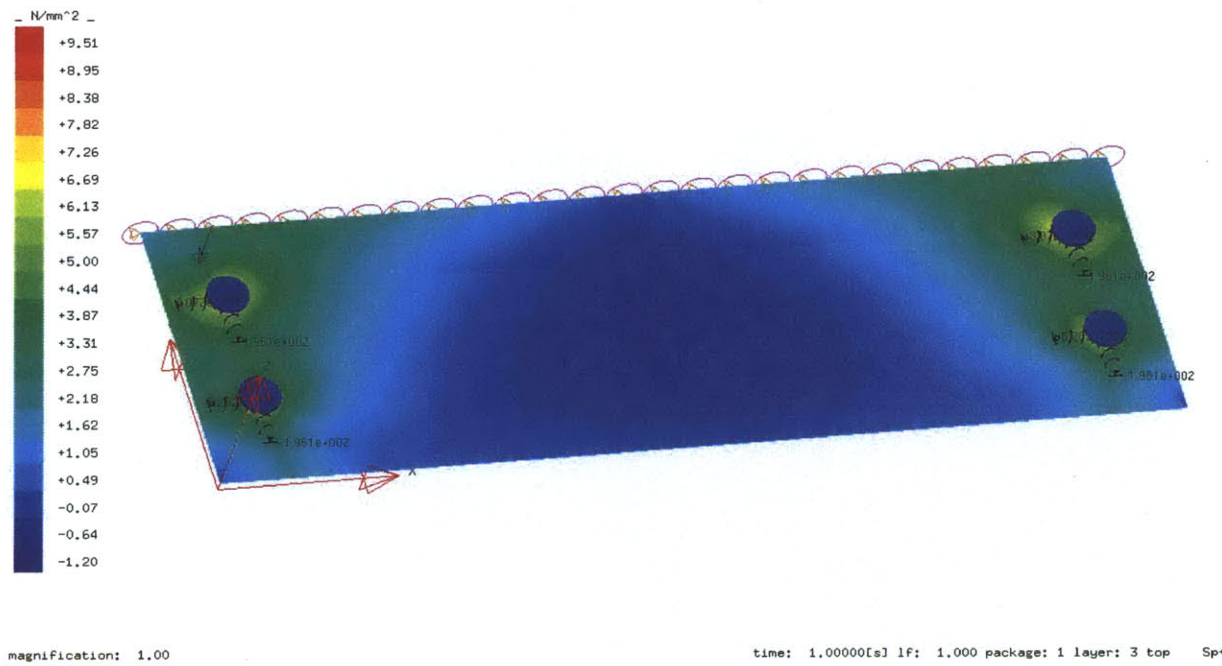

Figure 24. Tensile stresses on the top side of the middle glass layer for un-reinforced laminated glass.

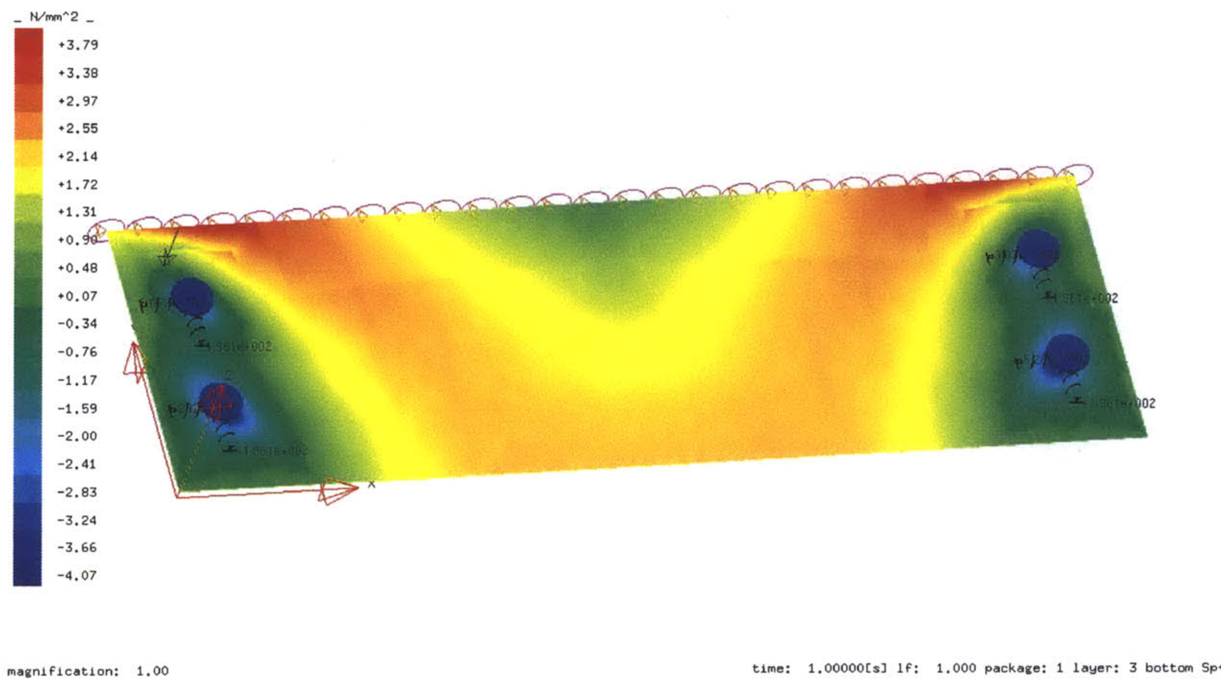

Figure 25. Tensile stresses on the bottom side of the middle glass layer for un-reinforced laminated glass.

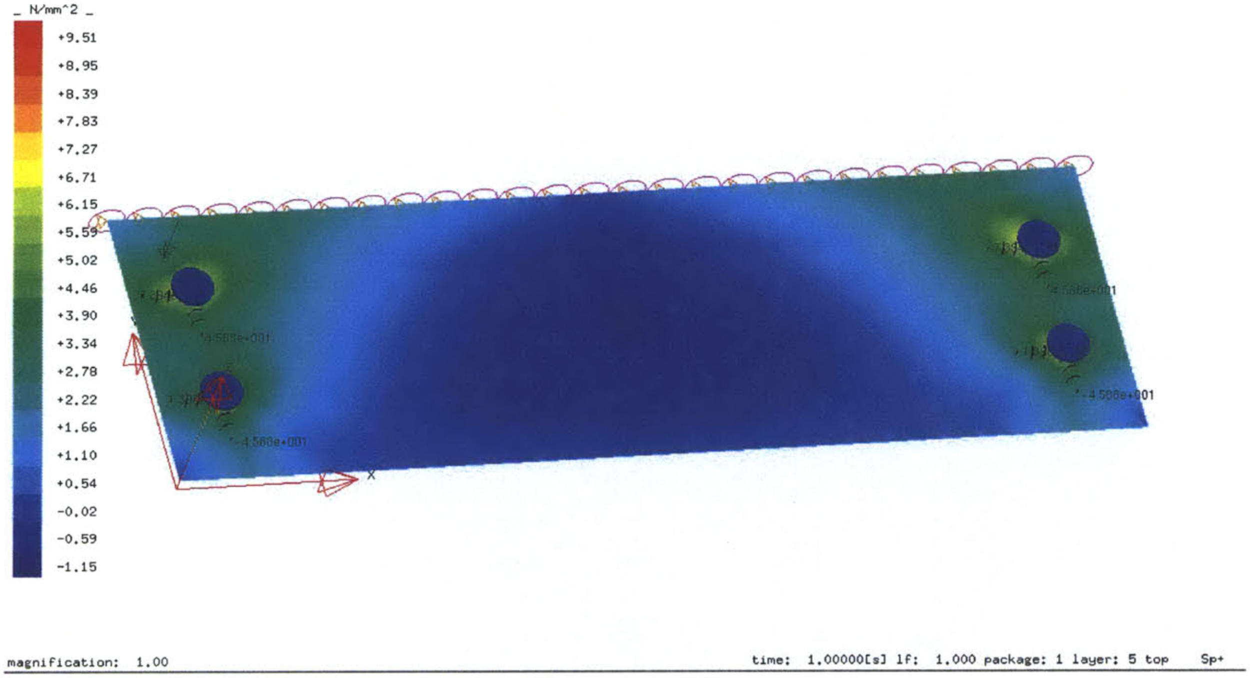

Figure 26. Tensile stresses on the top side of the middle glass layer for reinforced laminated glass with 4mm thick steel plate.

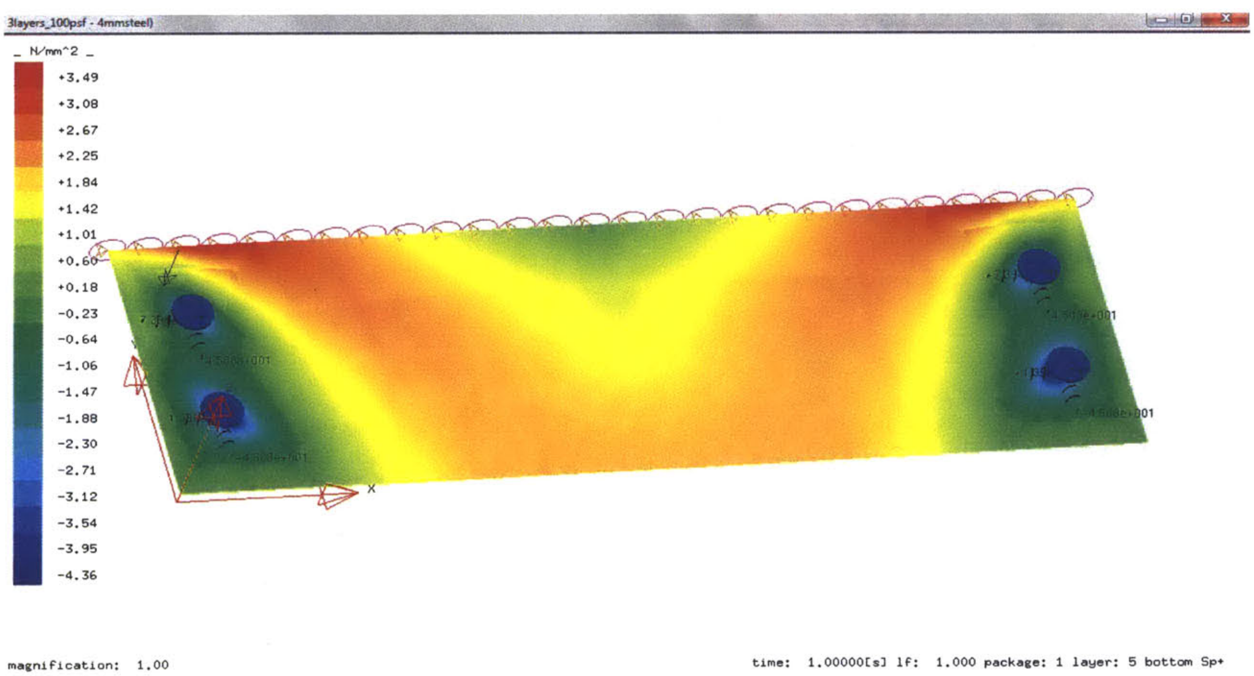

Figure 27. Tensile stresses on the bottom side of the middle glass layer for reinforced laminated glass with 4mm thick steel plate.

Figure 28 and Figure 29 show the vertical displacement of the top glass layer for the un-reinforced glass and the reinforced glass, respectively. We can see that the maximum displacements occur along the free edge of the glass tread. The maximum displacement for the unreinforced tread is 1.38 mm, and the maximum displacement for the reinforced tread is 1.28 mm. Although the reinforced tread gives a smaller total displacement, this is only a 7% difference, rendering this as insufficient to draw any meaningful conclusions.

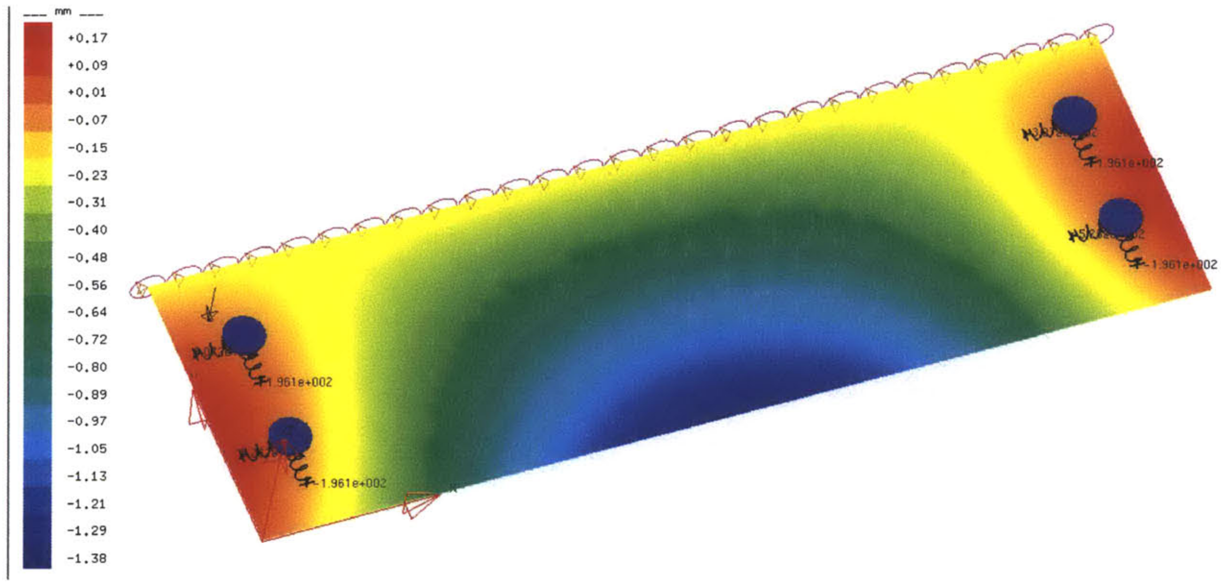

Figure 28. Vertical displacement of top layer for un-reinforced laminated glass

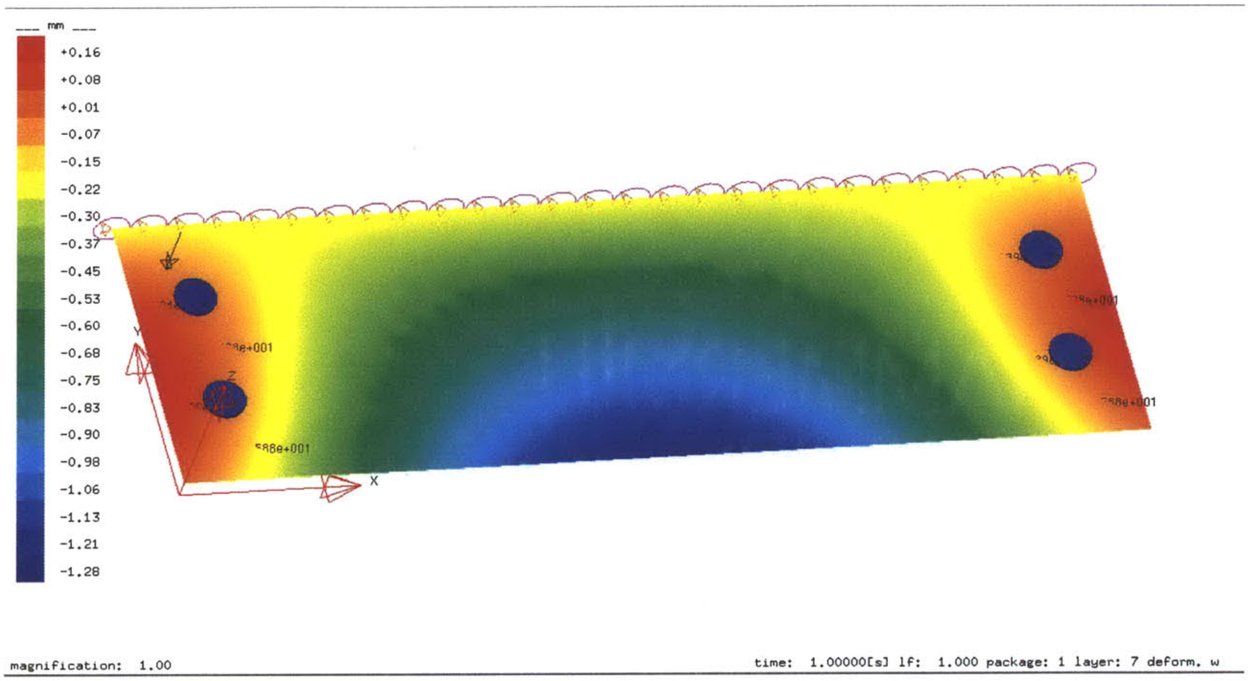

Figure 29. Vertical displacement of top layer for reinforced glass with 4 mm thick plate.

Simulations were also run for glass treads reinforced with 1mm and 2 mm thick steel plates. However, the stresses and displacements were sometimes above and sometimes below those found in the two extreme cases (unreinforced and reinforced with 4 mm steel), and no patterns could be seen from those results.

8. Analysis/Discussion

Although a comparison of the compressive stresses on the top side of the middle glass panel showed that the reinforcement might be responsible for lowering the stresses on the glass right above it, a comparison of the tensile stresses on the bottom side of the middle glass panel shows otherwise. Furthermore, resultant stresses are consistently around the same range, so values cannot be wholly trusted. The same can be said for the resultant maximum displacements seen.

There are several reasons why the simulation results may not be reliable. The most important reason is due to the fact that SJ MEPLA does not model residual loadbearing capacity, which is an important parameter when comparing reinforced glass with unreinforced glass. Rather, it looks at the ultimate stresses on the glass panes, which are indeed, but it does not provide the whole picture.

The various combinations of fixings could also produce different results. The author only simulated a few combinations of fixings and found no significant difference in comparison between the unreinforced and reinforced glass, but the absolute stress and displacement values drastically varied.

There are many factors in this model that have been unaccounted for. Thus, experimental results on the effects of reinforced glass are more reliable. Due to time and funding constraints, the author could not conduct any experiments on the effects of reinforcement on glass. Accordingly, the reader should focus on the two experimental research studies for a more accurate portrayal of the behavior of reinforced glass. However, the simulation does provide a good starting point in looking at how glass behaves when there is another material imbedded in the common laminated glass configurations. The model probably does not account for the complex material interaction between the steel plate and the adjacent interlayers, and more advancements in the software need to be made to account for the possibility of glass reinforcement.

9. Conclusion

Structures require materials that do not suddenly collapse once a critical load is reached. Although many innovations have been made for glass, this has always been a hindrance in the variety of applications that glass may be used for. Glass will continue to be widely used by architects and engineers in building design, and design boundaries will continue to be pushed. This necessitates the pursuit of ways to improve the behavior of glass.

Reinforcing laminated glass has been demonstrated to considerably improve the behavior of glass by increasing the residual strength of damaged glass. This counteracts the inherent brittle nature of glass and may pave the way to utilize glass in a variety of different functions that have not yet been pursued.

This thesis has reviewed the most common glass treatments, fixings, and structural systems. Two research studies concerning the reinforcement of glass have been investigated, and a simple simulation comparing reinforced glass versus unreinforced glass has been provided. Although the simulation results are inconclusive, the two research studies show promise for reinforced glass as a viable option for improving glass loadbearing capacity.

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