Structural Opportunities for Glass

by

Elise Bon

Submitted to the department of Civil and Environmental Engineering in partial fulfilment of the requirements for the degree of

MASTER OF ENGINEERING IN HIGH PERFORMANCE STRUCTURES
AT THE
MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2003

Signature of the author...
Department of Civil and Environmental Engineering
May 9th, 2003

Certified by...
Jerome J. Connor
Professor of Civil Engineering
Thesis Supervisor

Accepted by...
Oral Buyukozturk
Chairman, Department Committee on Graduate Studies

Structural Opportunities for Glass

by

Elise Bon

Submitted to the Department of Civil and Environmental Engineering on May 9th, 2003, in partial fulfilment of the requirements for the degree of Master of Engineering in High Performance Structures in Civil and Environmental Engineering

ABSTRACT

The use of glass has increased in the last decade. But glass is still not well known by designers because it has an unusual behavior when loaded, it is brittle. Glass acquires many of its characteristics during it manufacturing process, which is described. Then different structural improvements can be obtained, by treatments and assemblies and its latest developments. Mechanical behavior of glass is studied, and this completes the description of glass as a structural material.

A second step is to study how glass is used in civil engineering, in a building's structural system. The tendency to "make the most of glass" has motivated designers to seek to improve the support system, often a weak aspect of glass in building. They are thus described as an important development that permits high performance glass structures. Finally, the latest improvements in the structural design and model of glass that have led to elaborated structures using glass are described.

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

Acknowledgments

I would like to sincerely thank

My family for giving me the opportunity to do this master, and for being a vital support,

Dr. Connor for his availability, his interest in his student's projects, his support for the thesis and the project,

Eric Adams, for making this year in MEng an exceptional year,

Paul Kassabian and Lisa Grebner for their support, availability and time all year long during the project and the thesis,

The Department of Civil Engineering and the Dean of Graduate Studies for the Financial help that permit to study here,

Professor John Fernandez for his precious help on the subject.

Index

Introduction

Glass is a key element in modern construction. It is used to give to the structure transparency or translucency, allow natural light inside, and provide elegant façade, roof or even wall, floors or stairs. The trend in contemporary architecture is to maximise the use of glass versus its frame, and to increase the size of the glazed area. Low insulating properties of float glass, the basic surface, used to limit the use of important glazed surface, in cold climates, but also in hot climate where the greenhouse effect of glass can lead to unbearable temperature. In order to have comfort while using such a glazed surface, the use of mechanical heating and cooling was important and the consumption of energy was very high. The high price of energy did limit the demand for large glazing and had slowed the development of technologies for high-performance glass. But the development of insulating units and energy efficient glazing (Low-E glazing) restarted the development of a large use of glass in buildings.

Glazed areas have to be considered more as a part of the structure than as a barrier element, separating the comfortable inside space to the exterior environment. This structural glass is subjected to numerous loads, such as wind, snow, thermal stresses, people weight and impact. Glass has a different behaviour than other structural material, which needs to be understood to make an efficient use of glass in buildings. In effect, glass has very good mechanical properties (compressive strength...), but the main drawback is its brittleness. Unlike steel, glass cannot accommodate local high stresses. Instead, it cracks and, when the level of energy is so high that the cracks propagate on the glass' surfaces, it fractures. Glass can fracture without warning, and for this reason is under used in construction.

In general, the properties of glass vary widely depending on its composition, manufacture, treatments and assembly. These factors are closely linked to the progress of the glass industry (shape and size of glass available, scale production etc.). Once glass as a material has been described, the different configurations in which glass is used need to be studied. The behaviour of glass will depend on its shape and the type of load. Due to its particular brittle property, design with glass requires a specific care and understanding of, first, the load that glass has to support and how it will react. Designers are unfamiliar with the behaviour of glass under load and the modelling of it. It is, however, essential to optimise the use of glass, and in the same way, the use of glass truly dictate the description of it. This is the reason why each arrangement of glass is studied separately.

Once the behaviour of glass elements is understood, the concept of "glass system" can be introduced, meaning an arrangement of glass and other elements to fulfil a structural role in a building. The recent improvements in the glass industry and the building industry have allowed designers to create "all-glass systems", and very interesting combinations of glass plus an other structural material, that use the strength of each of them.

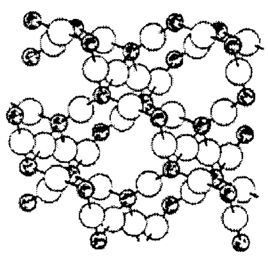
This thesis is not a guide for choosing the thickness and type of glass for a given purpose, but rather an effort to understand how glass behaves and how it can be used in order to find improvements of the material itself, and to increase its structural role in buildings.

1 Glass as a material

1.1 Definition of Glass

Glass is basically made of these three raw materials: Soda, Lime, and Silica. The proportions of these materials can vary widely. Various types of glass can have other substances (especially metal oxides) or not have all three of these components. The molecules almost take on a random arrangement, which gives the material its transparency. This also explains the isometric quality of the glass.

Figure 1.1: The atomic arrangement of glass (1)



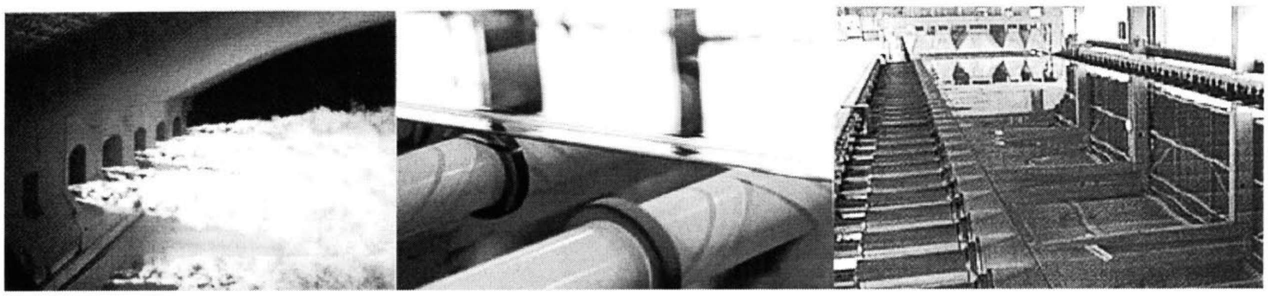
These materials are mixed and then heated around 2000°F (1093°C) to a special temperature to create GLASS. The material in this process becomes viscous. Then glass is cooled gradually and quickly, that the molecules do not have the chance to arrange themselves, and do not create a crystalline structure. "They are 'frozen' into the structure because of their lack of mobility in the highly viscous state of the mass" (2). One can say that glass is a "Solidified Liquid". This "frozen" molecular structure is the reason of the glass' brittleness.

1.2 Process of Manufacturing Glass

1.2.1 Float Glass

This is by far the most used process today. It is used to make annealed glass (mostly soda-lime-silica glass, which is labelled as "float glass" in most texts). The raw materials are weighed and mixed precisely. Then the materials are poured into a furnace (1500°C) and heated to form a molten glass. The molten glass is poured over a thin bath, which is more dense and cooler than the forming substrate. The glass can spread over and acquire a smooth surface and a natural polished finish. The thickness is also controlled. When the glass is hard enough, it is driven on rollers (or annealing lehr) and is gradually cooled by air. This process also controls the thickness of the glass by changing the speed at which the glass passes through the lehr.

Figure 1.2: The process of float glass (3)



Some changes in the composition can be done during this process. For example, controlling the amount of Fe_2O_3 can lead to a variety of float glass called "Clear White", almost colourless. Some oxides are also added to increase the durability of glass, like aluminum oxide (Al_2O_3), calcium (CaO) and magnesium (MgO) oxides.

Figure 1.3: Schematic of the process of float glass (4)

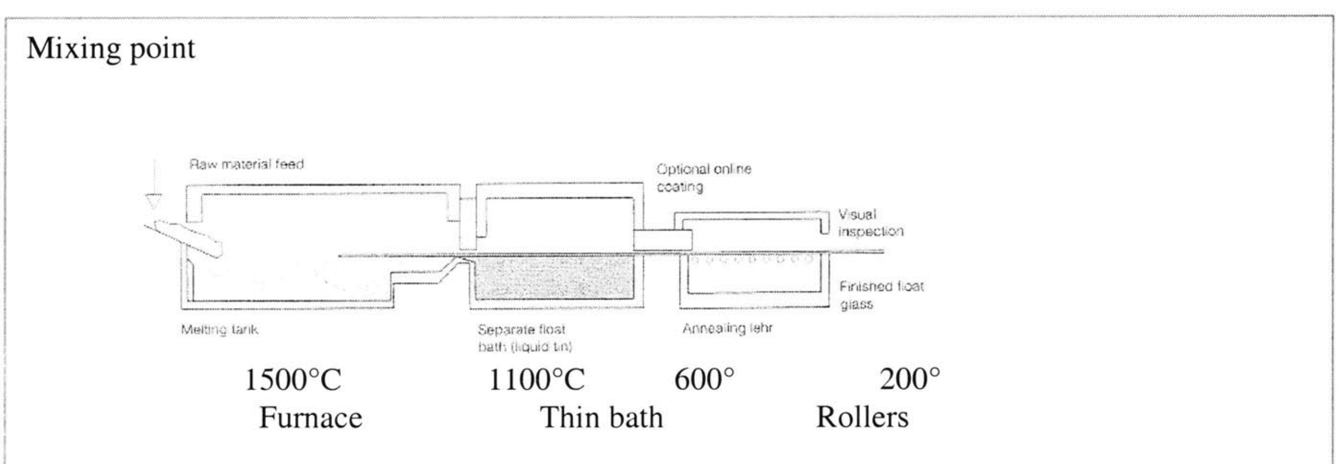


Figure 1.4: Thickness available for float glass (4)

2.1.5 Float glass is available in these thicknesses

Glass thickness	Tolerance
2, 3, 4, 5, 6 mm	± 0.2 mm
8, 10, 12 mm	± 0.3 mm
15 mm	± 0.5 mm
19, 25 mm	± 1.0 mm

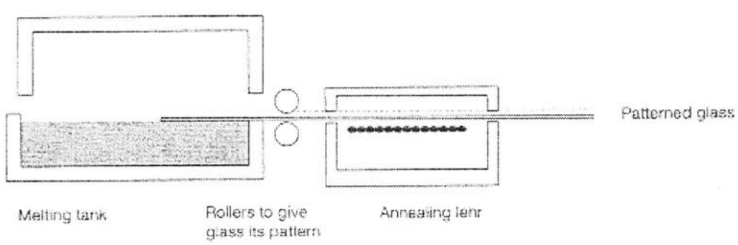
The properties of clear and body-tinted float glass are stipulated in European standard EN 572 Part 2.

One of the advantages of the float process is the scale of production that this in line and continuous process allows. Float glass is thus one of the cheapest types of glass.

1.2.2 Patterned (or Rolled) Glass

The pattern glass process is used to confer different surface textures. The glass does not go through a thin bath as in the float glass process but between rollers that can "print" textures to the glass. The glass only remains translucent. It is possible to insert a wire mesh in the glass, and the product is known as wired glass. The characteristics are the same as float glass except that the bending strength is a little lower, due to the pattern.

Figure 1.5 Schematic for the process of patterned glass (4)



1.3 Substrate

Various types of substrates can be created by altering the ratio of components in the formulation of the glass during forming process. In contemporary construction one type of substrate is mainly used. Since our goal in this research is to look for other structural uses of glass, all the primarily types of substrates are worth describing here.

1.3.1 Pure Silica Glass (99,5% of SiO2)

Pure silica glass is not used in construction. The temperature that needs to be reached to get pure silica is higher, and thus it is more expensive. But Pure Silica has a very high service temperature and a Low Thermal Expansion, and consequently it is used for these characteristics in the space industry.

1.3.2 Silica Glass (96% of SiO2)

Silica Glass is more rare since it fabrication is even more difficult. It is made by forming an article, larger than the required size, from a special borosilicate glass, leaching out the non-silicate ingredients with acid, and closing the pores. It also has good thermal properties, a service temperature higher and an expansion coefficient lower than borosilicate glass.

1.3.3 Soda-Lime-Silica Glass

It is the most common type of glass, and the one used in the construction industry. It is composed of 70% of SiO_2, 15% of NaO_2 and 10 % of CaO. The process of floating has been refined enough now, that a higher degree of transparency can be achieved. Its thermal fatigue is around 30°C.

1.3.4 Lead Alkali Silicate Glass

In this type of glass, lead is added, in significant proportions (up to 65%!).
This lead gives a glass the " crystal" appearance that is known in the vessels, and even jewellery.
Its constituents are: 30 – 70 % of SiO2, 18 – 65 % of PbO, and 5 – 20 % of NaO2 and/or K2O.

1.3.5 Borosilicate

Borosilicate glass has a lower thermal expansion coefficient, and a higher thermal fatigue temperature. It is primarily used for utensils, (Pyrex) in everyday kitchens and in laboratories.

1.3.6 Aluminosilicate

Aluminosilicate glass is made of silica (5 - 60 %) and two metal oxides (20 – 40 % of B2O3 and 0 – 10 % of Al2O3). It is not used in construction, but where a high chemical stability is desired, and is used in airplane windows and also can be formulated to create E-glass that constitutes Glass Fibres.

1.3.7 Exception: Glass-ceramic

Glass ceramic is derived from glass, obtained by controlling the crystallisation of the constituents. They cannot properly be called glass because glass is not crystallised, but they are produced as float, drawn and sheet glass, and their broken profile is similar to that of glass. This type has interesting structural properties and that is the reason why it is mentioned here.

1.4 Properties of Glass

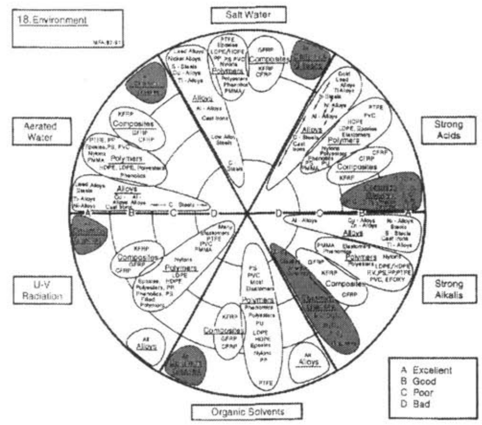
Figure 1.6: Principal characteristics of glass ((5), except when specified)

Density at 18°C	2500 kg/m3
Modulus of elasticity	70-74 GPa
Shear Modulus	30 GPa
Poisson's ration	0.22
Yield Strength	3600 MPa (Theoretical Value) but behavior is governed by fracture
Compressive Strength	Vary widely with the sources, because glass is governed by tension, thus will break during the test because of a tensile failure and not because of compression. In *Glass in Building*, 21 000 MPa In *Structural Use of Glass in buildings*, >1000 MPa
Tensile Strength	5000 MPa but behavior is governed by fracture
Tensile Ductility	0
Hardness	6 (MoH)
Loss Coefficient at 30°C	10-5 to 10-4
Toughness	0,01kJ/m^2
Fracture Toughness	0,7 kN/m
Softening Temperature	530°C (vary widely with composition)
Glass Transition Temperature	570°C (vary widely with composition)
Maximum Service Temperature	~=280°C
Coefficient of Thermal Expansion	7.7 – 8.8 10 –6 /K

1.4.1 Durability of glass

Glass is one of the most durable materials used in construction. This durability is due to its complex and random molecular structure. Molecules hardly can get exchanged with the substance they are in contact with. Glass is highly resistant to acid and water, even salted. Only alkali substances can alter the substrate, but in specific conditions, like glass in contact with water for a long time. In buildings glass as an exterior envelope is wet and dried continuously, this alteration is not going to be analysed any further.

Figure 1.7: Durability of glass (5)

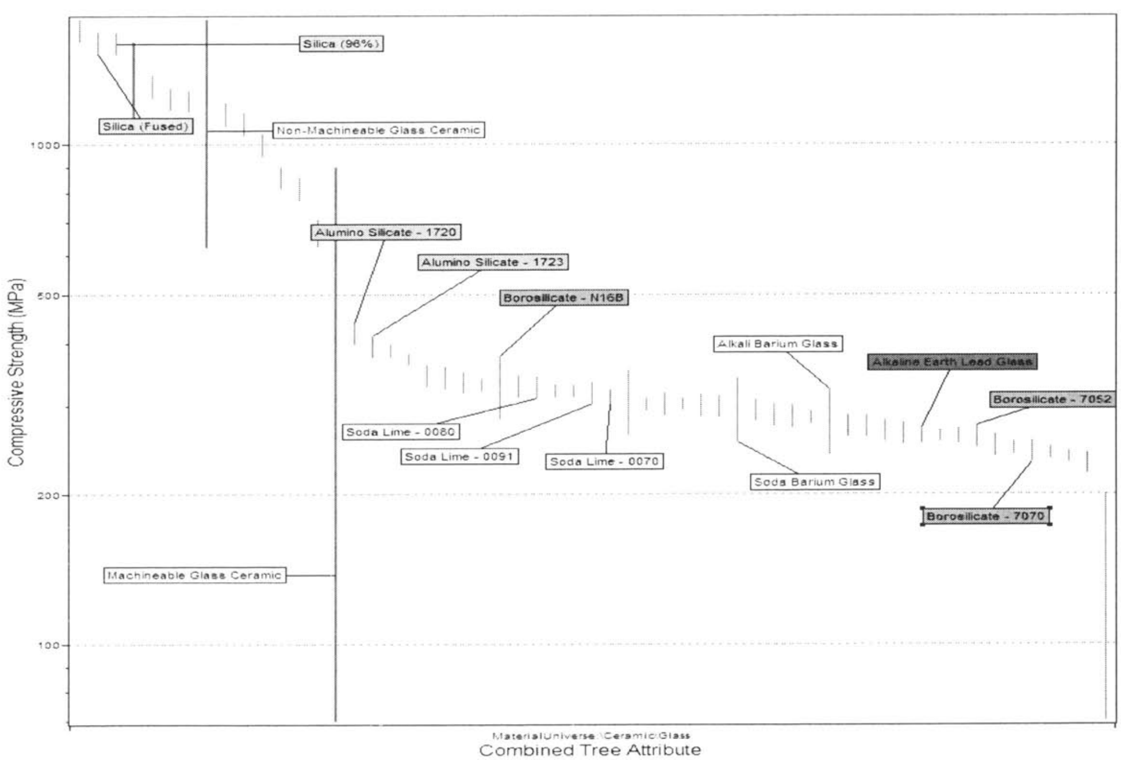


1.4.2 Mechanical Behaviour of glass

In theory glass, possesses very high mechanical properties. The following tables characterize the different substrates and compare glass with other structural materials.

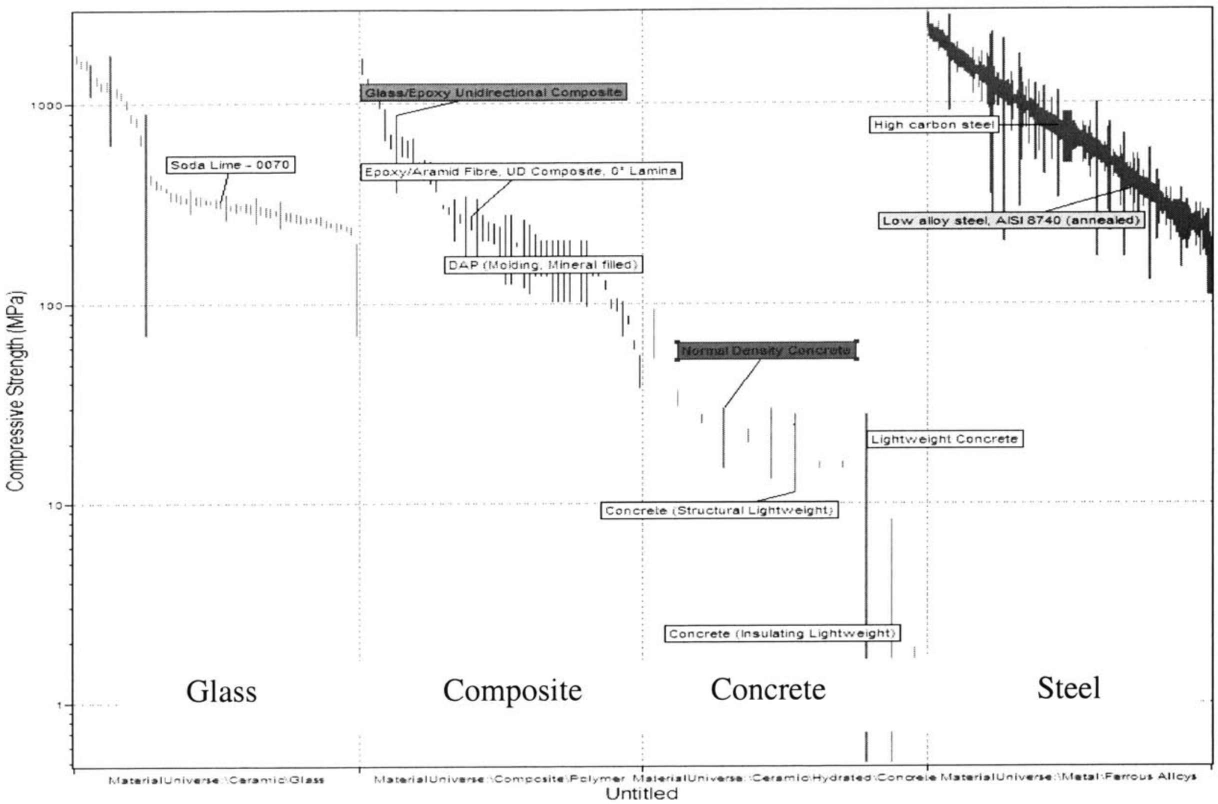
Compressive strength

Figure 1.8: Compressive strength of the different substrate



This table shows that compression strength of glass can vary widely (factor of 5) but a majority of substrates are within 200MPa and 600Mpa

Figure 1.9: comparison of the compressive strength of Glass, Polymer-based Composites, Concrete, and Steel.



The compression strength of glass is comparable to steel and composites, and higher than concrete, that are all three structural materials. But glass cannot take advantage of from its strength because its structure cannot prevent cracks from spreading all over, like these materials do. In practice these glass substrates cannot handle the same compression stresses as the other structural materials.

Tensile strength

Tensile strength is lower then compressive strength (factor of 10). The comparison with other structural materials emphasizes the weakness of glass in tension. Still, it has a better tensile strength than concrete.

Figure 1.10: Tensile Strength of glass.

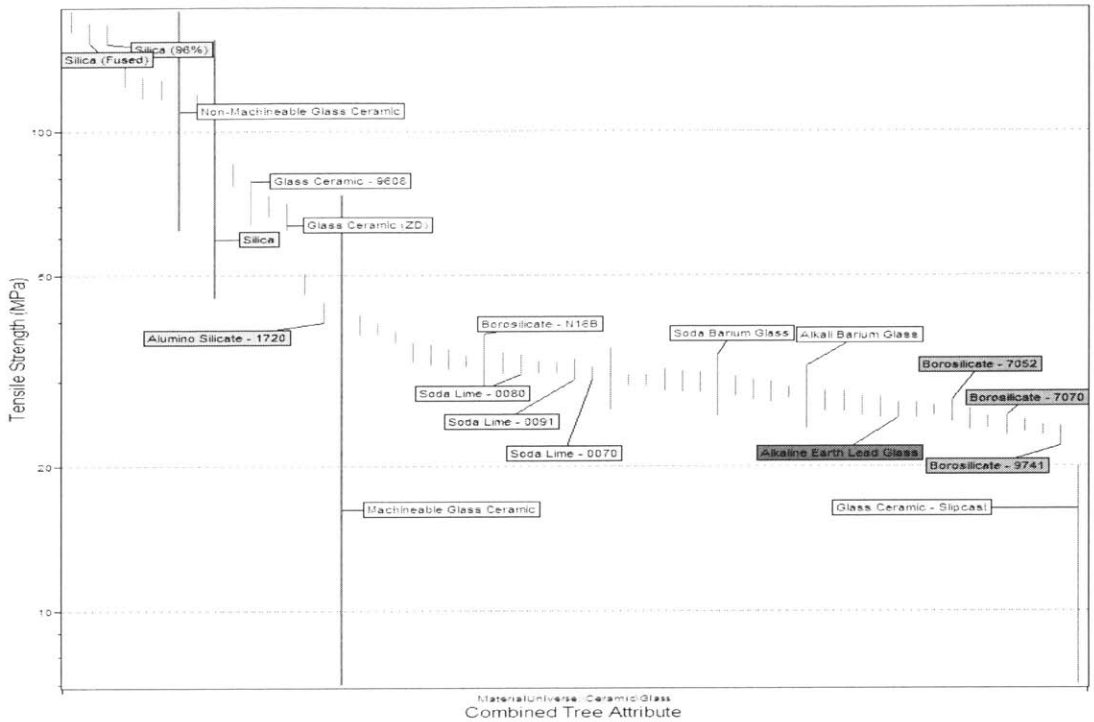
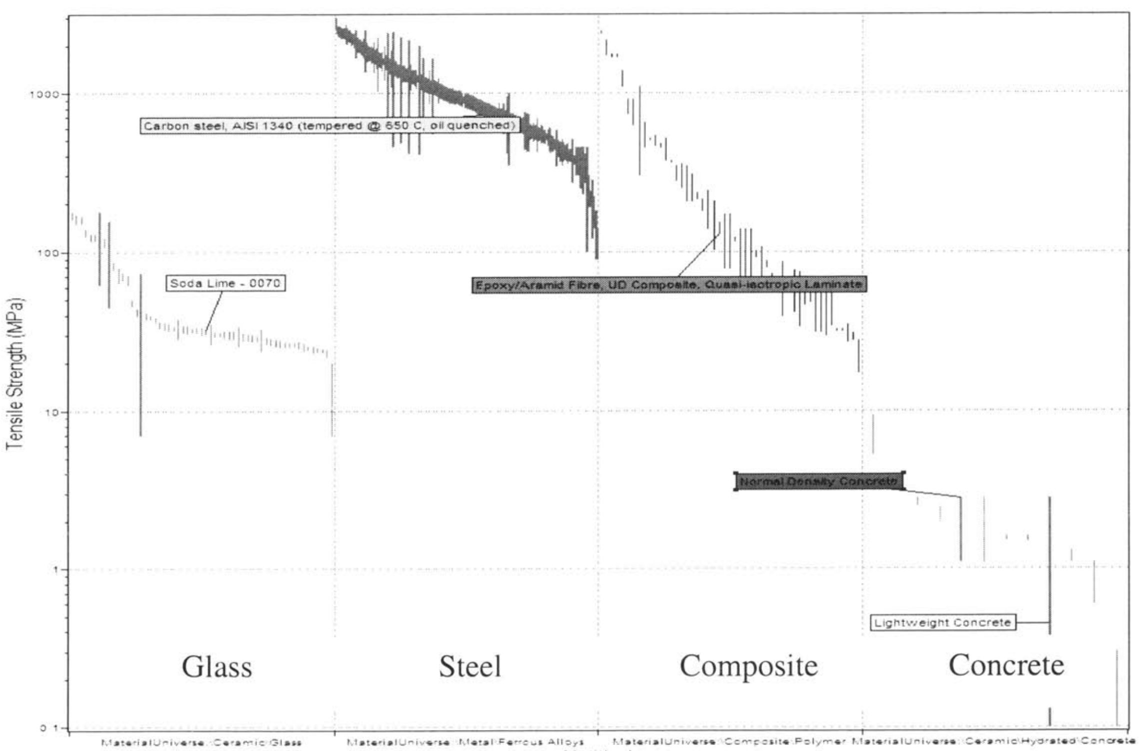


Figure 1.11: Comparison of tensile strength of Glass, Steel, Polymer-based Composites and Steel.

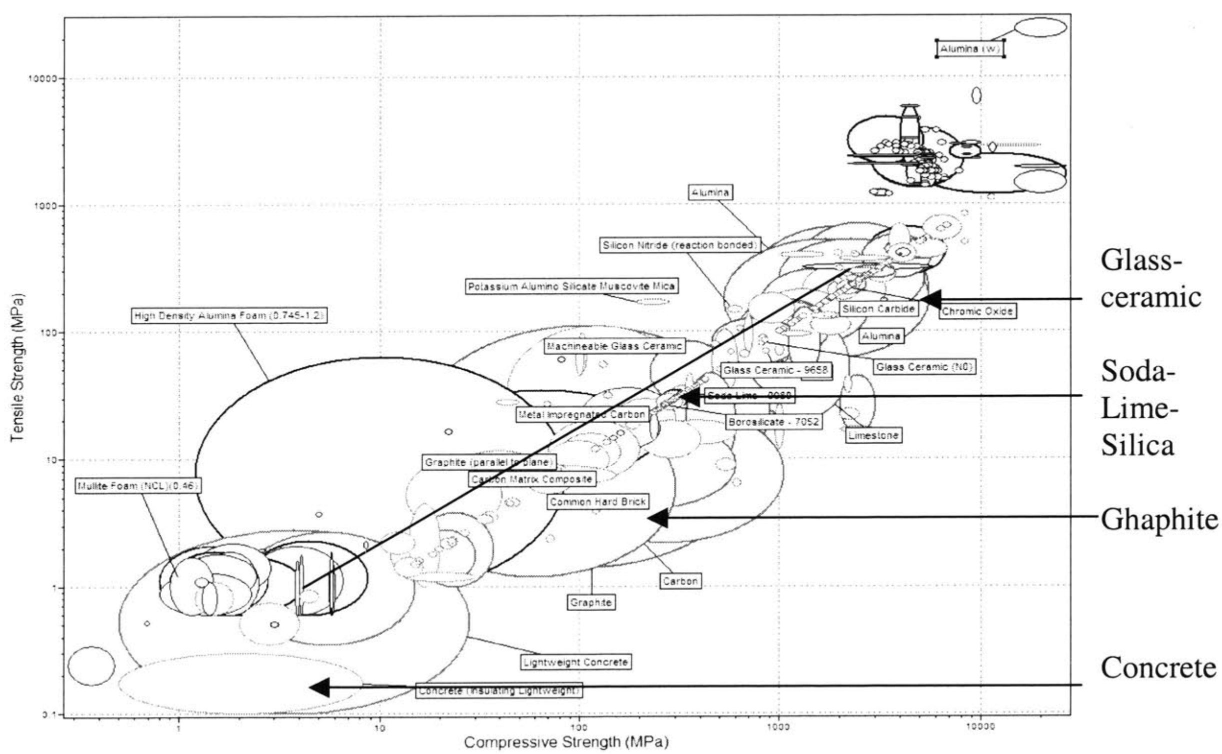


To counteract its weakness, concrete is reinforced with steel, that has better tensile properties, and this two materials are suitable each other (same thermal expansion for example). Then one can think of a similar process of reinforcing glass with a material that would compensate the low tensile strength of glass. Though, the composition of these materials should maintain transparency, and preventing crack to happen. It is going to be discussed later.

Comparison of compressive and tensile strength for ceramics and glasses

Tensile strength compared to the compressive strength for all ceramics. All materials have a similar attitude and we can draw a straight line.

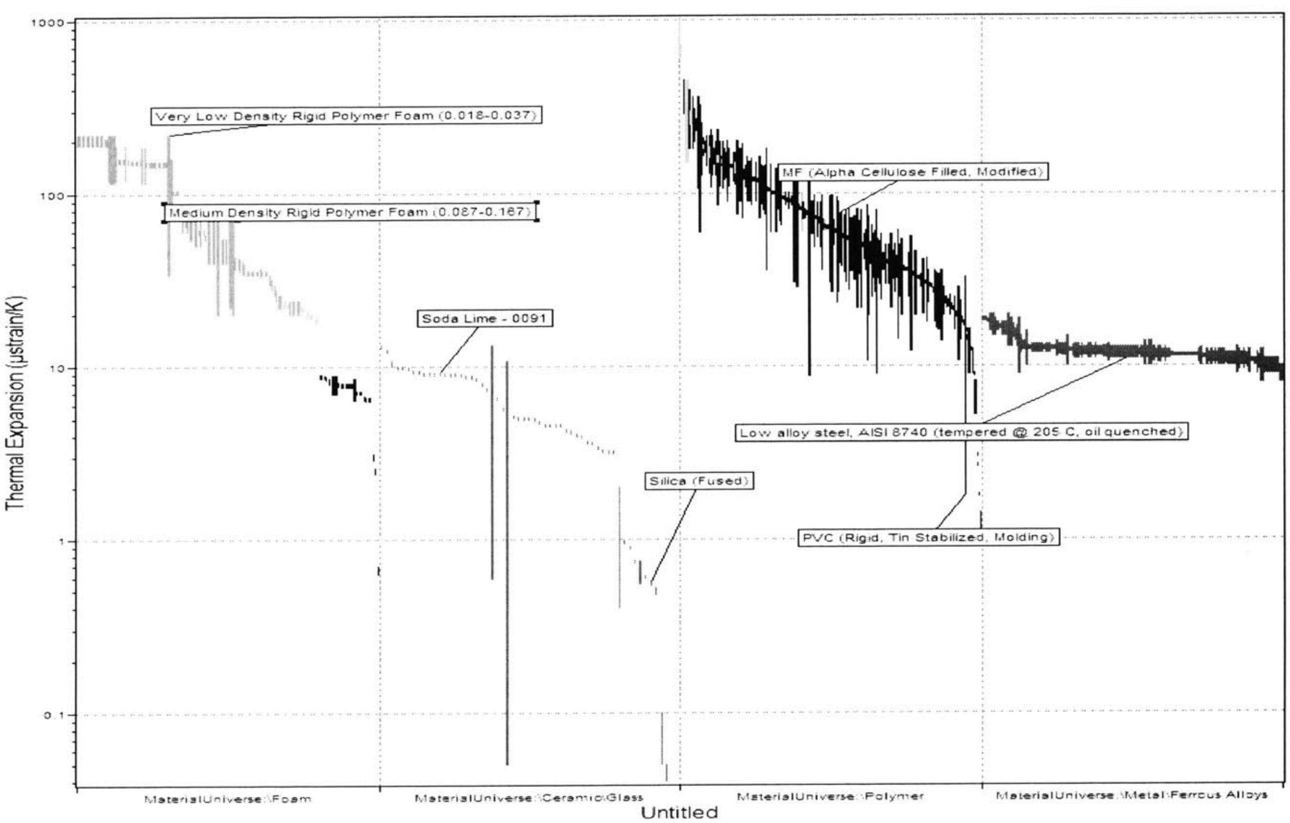
Figure 1.12: Tensile Strength compared to Compressive Strength for Ceramics and Glasses.



Thermal Expansion

Steel and glass are often assembled together (steel frame for example); it is relevant to see that they have a comparable thermal expansion.

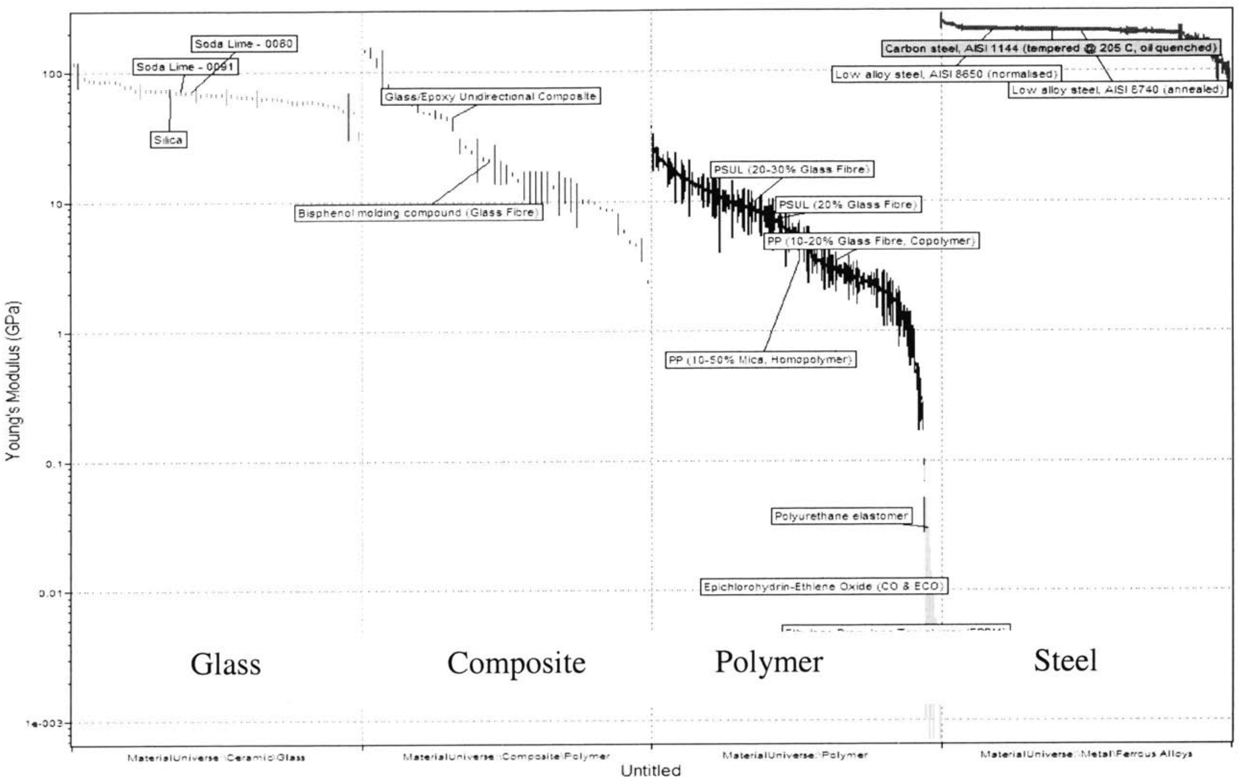
Figure 1.13: Comparison of the Thermal Expansion of Foams, Glass, Polymers, and Steel.



Stiffness

Glass is a stiff material. It stiffness is similar to steel and composite, that are both structural materials. Again, the opportunity to make glass a structural material looks possible.

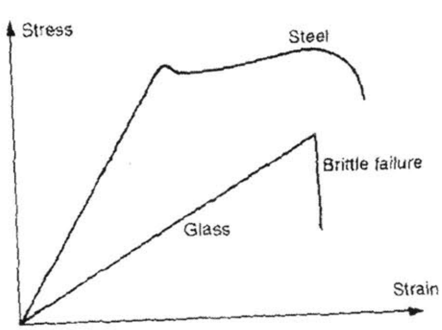
Figure 1.14: Comparison of the Young's Modulus of Glass, Polymer-based Composites, Polymers, and Steel.



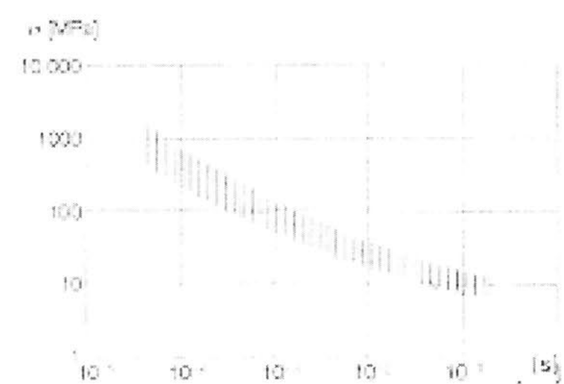
1.4.3 Fracture behaviour

Figure 1.15: Relationship between a)Stress and Strain for glass and steel (5)
b) Strength of glass and depth of surface cracks (4)

a)



b)

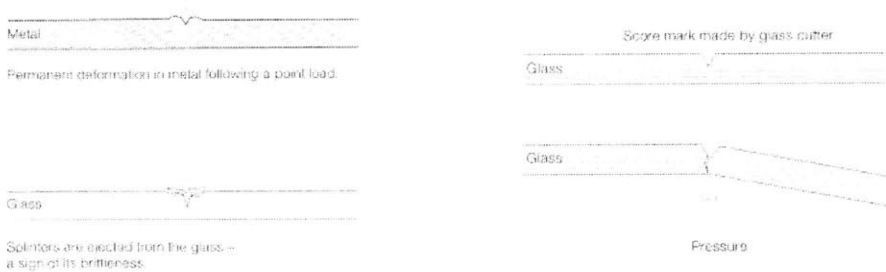


Glass is governed by its fracture behaviour: Like many materials, loaded glass behaves perfectly elastically. But the particularity of glass is that it is not ductile, it does not have a plastic behaviour when increasing loading (see figure 1.15 a)). It breaks suddenly, that is, it fractures.

In theory, the fracture limit of glass is very high. Then, glass should have very good mechanical properties. But, the surface and even the interior of the material are not perfect and flaws, especially on edges or drilled holes leads locally to high stresses. Because glass does not have a plastic behaviour, these local stresses are not dissipated within the material, and it fractures locally (micro fracture). As a comparison, when similar high stresses occurs on cracks on steel, it reaches locally the plastic zone and the regular molecule orientation allows molecules to readjust themselves and to dissipate energy by spreading the stress on the material.

Under tension, these micro cracks can be spread easily. They do not lead to a global fracture of the glass until the crack grows to a certain limit, called "critical": crack can keep a "stable" growth, when it grows in small steps, under smaller stresses. It is then considered subcritical cracks. If the crack's growth reaches a certain velocity, the crack becomes unstable, and the glass fractures. The material property that relates that relates this critical stress to the size of the crack is the **fracture toughness**. Other structural materials like steel have a high fracture toughness, and are not governed by toughness, but by yielding. For typical cracks size, the critical stress is much higher than the yield stress (12).

Figure 1.16: Illustration of the brittleness of glass (4)



The relationship between the size of the cracks and the stress applied that result on a fast fracture is given by: (5)

$$\sigma*\sqrt{\pi*a}=\sqrt{E*G_c}$$

Where *a* is the half-length of the crack,

E is the Young's Modulus

and *Gc* (kJ/m²) is the toughness of the glass.

This equation shows that a fracture will occur, if, for a given stress σ the crack reaches the length *2*a,* or, if, for a given crack of 2*a, the stress reached is σ. (4)

Other parameters influence the growth rate of these micro cracks. Short-term loads lead to higher allowable stress than long term ones. Chemical reactions also increase the growth of cracks, particularly water reactions. Thus the mechanical properties of glass are drastically reduced by these local stresses caused by flaws (known as Griffith flaws, because they characterised for the first time by Griffith) on mainly the surface.

Moreover, the fact that theses stresses do not lead to fracture but increase the size of a cracks appears during all the life of the glass, thus the operable strength of glass considered in the design has to take this into account, and not rely only on the tests made by the manufacturers for a new sheet of glass. At this point, one field of research for a higher structural glass rely on the prevention of cracks, by protecting the glass.

1.4.4 Time dependence of glass strength

The linear behaviour of glass until its fracture shows that is does not experiment fatigue. But Sedlacek (6) has shown that the strength of glass is time dependant. Glass can carry a more load for a sort period than for a long time. This is what is called the fatigue of glass.

The relationship can be expressed as

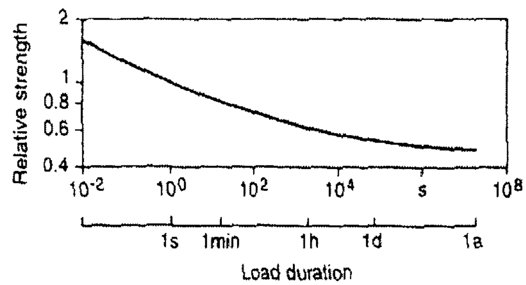
$$A_0*T_0*\sigma_0^n=constant$$

Where σ is stress

T is duration of load

A and *n* are constants for under critical crack growth, which depends on humidity and temperature

Figure 1.17 Relationship between strength and load duration (6)



The time dependence is a major issue in designing with glass because wind, water loads, and especially snow are characterized as long time loads. Codes and standards, depending of the country, base their tests and requirements on different maximum loads and periods of time for these loads, or provide safety factor depending of the time dependence of loads.

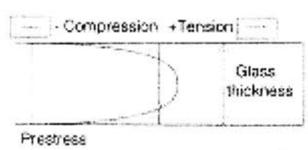
1.5 Treatments

Glass has interesting intrinsic properties but the brittleness of this material limits its applications. It has been the first used of glass when mass production was available, and the first application of an important amount of glass is in the XIX^{e} century, in greenhouses and conservatories, and then bigger exhibition spaces like the Crystal Palace, in London, UK..

Treatment and then assemblies have improved glass' properties: The main treatments discussed here are heat treatment, chemical treatment and coating.

1.5.1 Heat-Treatment

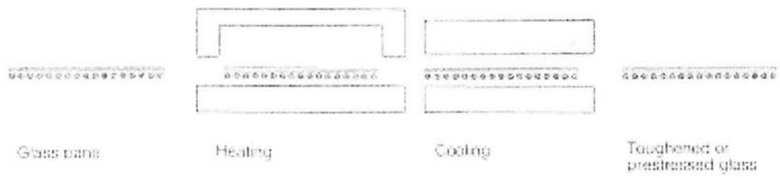
Figure 1.18: Prestressing profile on glass (4)



Heat treatment of glass consists of adding compression to the surfaces that creates a pre-stressing on the glass. Cracks propagate under tension, creating a compression of the surface is a very important improvement for the use of structural glass. The compression created implies that when the material is in tension, surface cracks described in the fracture behaviour do not spread until the tension is equivalent to the compression applied in the prestressing. Then the stresses allowable are higher than for annealed glass.

After the float glass process, flat glass pane (or annealed glass pane) is heated again at a temperature of 620°C. Once the entire mass reaches this temperature, it is cooled in blasts of cold air. The surface of the glass then cools and solidifies before the centre. When the centre tries to cool and thus to shrink, the already cooled and stiff envelope blocks it. Thus, this creates tension in the centre and compression in the surface. One of the issues of heat-treated glass is that it cannot stand any other treatment like cutting, drilling, or edging. It would break the equilibrium between compressed and in tension parts. Any other manipulation must be done before the heat-treatment. Toughening plate with an important thickness (>10mm) is also problematic and expensive.

Figure 1.19: Schematic of the process of strengthening by heat treatments (4)



Heat-treated glass consists of two products, tempered glass and heat-strengthened glass. Temperature reached and speed of the cooling process will differentiate tempered glass from heated-strengthened glass. These products have different compressive strength on their surface and different breakage patterns.

Figure 1.20: Characterisation of the treated glass by its surface stress (4)

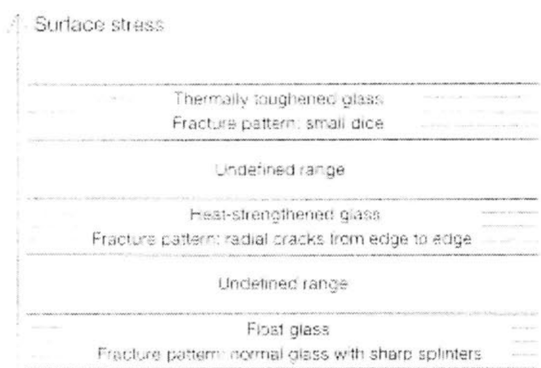


Figure 1.21: Broken pattern for Float glass, Heat strengthened glass, and Tempered glass (4)

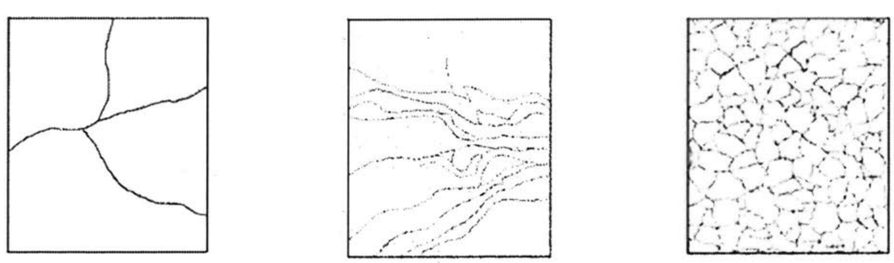


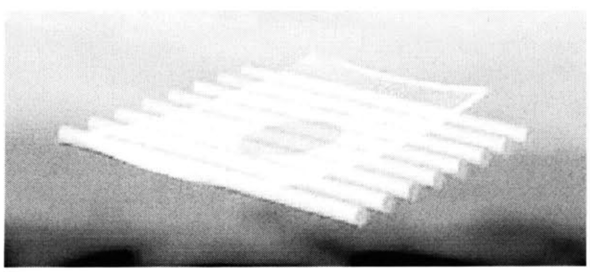
Figure 1.22 Preliminary design stresses (18)

Material	Short Term stresses under unfactored loads	Medium and long term stresses under unfactored loads
Annealed glass	28 kN/mm²	7kN/mm²
Heat-Strengthened glass	35kN/mm²	15kN/mm²
Tempered glass	59kN/mm²	35kN/mm²

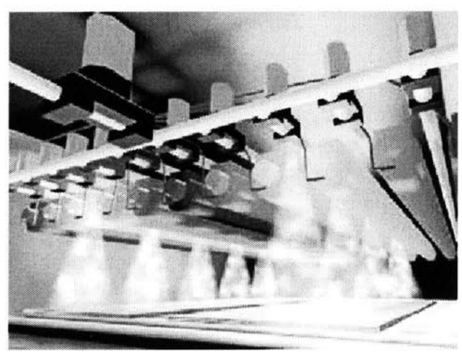
The development of large piece of glass raised an issue for heating the entire pane at the same level to get the same prestressing at the edge and at the centre of the pane. The typical furnace profile induces an over heating of the edge as the airflow would circulate along the edges. Consequently the sheet tends to bend. Large furnaces needed to be designed with a feedback control system that can focus the heat on certain parts based of calculations(Figure 1.23). (4)

Figure 1.23: a) Example of bending of a large glass pane during tempering
b) Focused Heating

a)



b)



1.5.1.1 Tempered glass

The compression reached by tempered glass is for European Standard, 90 to 120 kN/mm². Tempered glass is 4 to 5 times stronger in bending that float glass under long term load (figure 1.22). The ultimate bending strength of toughened glass means that it can resist the load of persons without breaking.

It is considered as a safety glass because it can support the shock of a body and it breaks into small pieces that have no jagged edges or shards. This "dicing" reduces significantly the likelihood of injury from broken glass. This diced effect is due to the high compression on the surface of the glass. The energy needed for an applied tensile stress to exceed the prestressed compression and reaches the centre in tension is so high that it would propagate cracks in all the direction to be dissipated.

1.5.1.2 Heat Strengthened glass

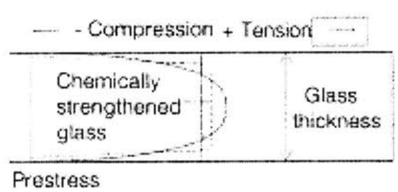
Heat Strengthened glass is 2 times stronger in bending that float glass, and its thermal fatigue is also bigger. The Surface compression is comprised between 40 to 75 kN/mm². The heat reached is lower that for tempered glass and it is cooled in slower process.

Heat-treated glass is not considered as a safety glass because of its broken patterns, similar to annealed glass, with sharp pieces. The bigger the surface compression, the smaller and less sharper the pieces of broken glass are.

1.5.2 <u>Chemically treated</u>

Chemically treated also glass consists of prestressing the surface, but by a mean of an ion exchange at the very surface of the glass. The prestressed profile differs from heat-treated glass (figure 1.24).

Figure 1.24: Comparison of the prestress profile between heat and chemically treated glass (4)



The glass is immerged in a salt bath and bigger ions (30% bigger) from the solution are exchanged with smaller ions of the glass. These big ions create then compression on the **surface** of the glass. The compression can reach 300kN/mm², but in practice the value can be reduced by a factor of 100, and is uncertain. More over the layer compressed is much thinner then the performances of such toughening are lower. The advantage of this technique is that the glass does not support thermal deformation and thinner plates of glass can be strengthened.

1.5.3 Coatings

Coating glass consists basically on covering the surface of the glass to improve one of its properties, that can be aesthetics, insulation, control of light and glare, or durability. There are two primary methods currently employed for coating glass. They are **online coating** and **offline coating**. Online coating is simply applying the coating material to the glass while it is being produced, and offline coating is applying the surface after the substrate has already been produced. Both use high technology processes that assure a high bonding of the metal oxide (titanium, chrome, nickel, or iron) for the majority and the glass.

Coating is mostly used for solar control. The durability of the coating depends on the process, online coating being more durable. Obtaining detailed data about coating is not easy since many of the processes are patterned and can only be obtained at manufacturers. Mainly, coating fits our interest research area if they allow any protection of glass from being damaged. In effect preventing impacts to be transformed into cracks would be a major improvement.

1.5.4 Composite strengthening methods

Strengthening methods of plate glass is adding compression to the surface, or also eliminating flaws issued during manufactures by chemical etching and plasma polish. The institute of Technical Glass in Moscow (7) has developed composite strengthening methods, "combining eliminating surface defects and creating compressing stresses" can increase the strength of glass by 50 times comparing to usual annealed glass.

Figure 1.25 Typical bending limits for the different glasses. (7)

Type of glass	Theoretical bending limit, GPa
Raw glass	30- 60
Annealed glass	90- 120
Heat strengthened glass	120-180
Chemically Strengthened	300-700
Etching	1500-2000
Combined method	1700-2200

According to them, the most effective product is to compose the glass by different sheet of glass treated differently, links by different polymers that protect the glass from shocks and with different coating. They don't give more detailed since their product is on a copyright. The result is bullet resistant, thin and light glass that can be used for floors, aquarium etc...

1.6 Assemblies

1.6.1 Laminated glass

Laminated glass consists of two or more panes of glass, bonded together. There are two different categories of bonding layers: safety/strengthening layers and functional layers. Though two layers of glass is the common arrangement, over 25 layers have been successfully bonded in an assembly aver 100mm thick (5).

Strength behaviour of laminated glass

The determination of the behaviour of laminated glass has been analysed with non-linear analysis theory to account for the important deflection that can occur. Vallabhan (9) has constructed a non-linear model for two plates of laminated glass without an inter layer in between, and compared the behaviour of this glass with a single pane of glass whose thickness is equal to the sum of the two thickness of the laminated glass. Tested were carried (by Beer (9)) and the result is that laminated glass behaves somewhere between the two models but more closely to the monolithic model. This is due to the fact that the interlayer is subjected to shear as the plate bends. The shear is transferred to the glass inducing bending moment. These results lead Vallabhan to build a more accurate model for laminated glass using the minimum potential energy and variational calculus, and an iteration calculation.

Though, architectural laminated glass behaves in a manner similar to monolithic glass of the same nominal thickness under short-term lateral pressure (representative of wind loads) and below room temperature. The temperature at which behaviour changes from being similar to monolithic to significantly different from monolithic under short term lateral pressures is not clearly defined, but is around 49 degree C (120 degree F).

For long terms load, the laminated glass behaves as two-layered sheet of glass, due to the deformation of the softer interlayer. Then they share stresses relative to their thickness. It behaves in a manner similar to monolithic glass of the same nominal thickness under long-term lateral pressures at temperatures of 0 degree C (32 degree F) and below. (5)

Safety Laminated Glass (4)

The first condition to be a safety-laminated glass is that the pieces of glass are held together after fracture, and thus do not injure people nearby. Moreover the structure does not collapse, but is not able anymore to carry load. Often toughened or heat strengthened laminated glass is used where a higher strength than that of normal float glass is required. Heat-strengthened glass has the advantage over toughened glass that it breaks into larger pieces thus giving a better residual load bearing capacity. The second one is that it has to resist the load of a person.

Then the thickness of the glass is calculated based on the impact a person can apply on the laminated glass. That is the length a person can run before reaching the glass.

Laminated glass can then be designed to resist bullets or striking objects. The broken sheets of glass are bonded by the soft interlayer, and provide a very important improvement in the glass resistance.

These assets are used in structural applications of laminated glass, and glass floors and walls seem now to be possible. Providing a redundancy in the structural elements appears to be crucial because once the element is fractured, it looses its load capacity.

Safety/strengthening layers are PVB (Polyvinyl Butyral), Cast In Place (CIP) Resin, SGP (Sentry Glass Plus), etc. PVB is the most common elastomeric interlayer. The maximum size of a pvb-laminated glass (3m x 6m) is dictated by the process to achieve a strong bonding. Other interlayer can be polyurethane based.

Architectural laminated glass with SGP layer has enhanced strength, particularly where bending stress states dominates laminate deformation. The polymer structure of SGP imply that the glass transition temperature on the order of 55 - 60 degree C. The stiffness advantage of SGP versus traditional PVB is maintained up to and exceeding this temperature.

The CIP Resin laminate has a lower rigidity, i.e. larger deflection than the PVB systems at 40 and 60 degree C. But resin lamination has the advantage of accommodating the irregularities of the sheets of glass, since it is poured between the sheets of glass.

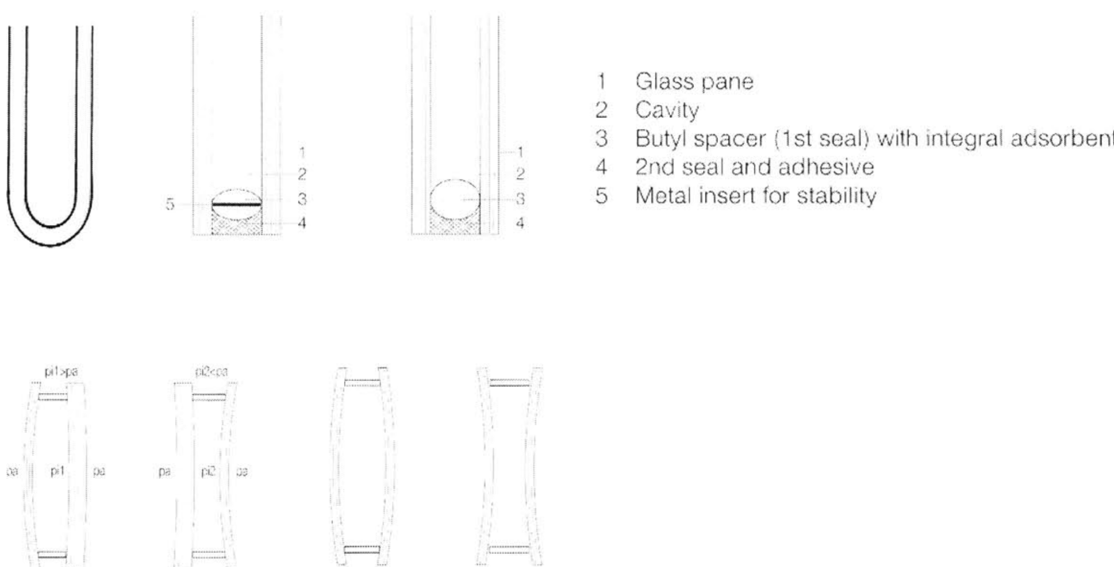
There are many different types of functional layers; Angle selective films, Holographic Diffraction Films, Layers with Photovoltaic Modules, Thermotropic Layers, Thermochromic Layers, Liquid Crystal Layers, Electrochromic Layers, etc. It is not our main interest here.

1.6.2 Insulating glass

Insulating glass consists of at least two separated panes kept apart along the edge by spacers, which seal the cavity and are shear resistant. The spacers are designed to provide good insulation, sound protection, and also help reducing small deflections. Usually the spacer consists of a tube of aluminium, filled with some desiccant to prevent humidity to go in between the panes, condensing after temperature changes, and then obstructing the transparency of the insulating glass. There are many different types of insulating glasses. The most common product is made of two sheets of glass, but triple glazing is also found.

The seals between glass and the spacer are realized on all the perimeter of the glass. They can be all glass seal (that does not need any spacer, and is quite rare because is expensive), simple polymer (epoxy/silicone) based or polymer based and stiffened (figure 1.26).

Figure 1.26: Types of insulating glass (4)



The thickness of each glass panes of an insulating glass assembly may be the same or different. Usual practice is same thickness. However, the side, which is subjected to more pressure –usually exterior side due to wind pressure in tall building façades - can be thicker than the opposite side.

Load sharing by insulating units

Load is shard by the two (or more) sheets of glass, except for small and stiff panes separated by a large space. According to the report *Structural uses of glass in buildings* (5), the deflection of the pane of glass facing the pressure if bigger than the change of volume of the cavity, then the inner sheet of glass carries some of the load.

2 Glass elements

Glass is under utilised when considering its mechanical properties, especially compressive strength. This is due to the breakage of glass, without warning. The design of glass element has to be dictated by that, and designers have to use the principle called "**Redundancy**". A structure has to be able to stand and not collapse when one glass element fail. The structure can stand this situation temporary, for people to notice it and do the repairs or take the appropriate safety disposition.

It is important to understand how the glass reacts to exterior factors in order then to calculate the performances of a glass element and finally to seek to optimise the use of glass a structural material.

2.1 Exterior Solicitations

Manufacturers provide the maximum stresses that each kind of glass can handle. The origin of the load is an important parameter because glass does not behave similarly for short time and long term loads (for example, laminated glass considered or not as a monolithic bloc or a composite with the plastic layer).

Strength is not the only force for the choice of thickness for a type of glass. Deflection is also limited, and as surprising as it can be, not only to meet the deflection capacity of other materials around but mostly to appear to be acceptable by people that consider glass as a stiff and incapable to be deformed, and this way prevent panic or mass movements close to the deflected sheet of glass!

2.1.1 Wind loads

The wind applies a pressure on the glass out of its plane, when the glass is a façade element or a roof element. Wind is considered, for design purpose, uniform on the surface of the glass pane, and applied sort time stresses to the glass. The maximum value to take into account when designing the glass pane and the period time to apply the load varies in accordance with the Code of each country. For example, Belgium uses a 1 in 20 year 10 minutes pressure, and United Kingdom and Holland use 1 in 50 year 3 second gust pressure (4). The design of a façade has to take into account the height of the building (the magnitude can vary from 500Pa at the ground level to 8000Pa for a high-rise building subjected to hurricane) and the suction effects at corners.

2.1.2 Snow loads

Snow loads are applicable to flat and sloped glazing, and are another out-of-plane load to consider. They can last for days, week or even months and are considered as long time loads. Thus the maximum stress allowable in the glass is even lower than for wind loads. Snow loads are uniform on the pane, but snow can slide easily or be drift by the wind, which can lead to uneven repartition of the load on a roof. Codes do provide a precise description of the maximum loads to be considered.

2.1.3 Impacts loads

Sloped and horizontal glazing is more subjected to impact load. In structural systems made of glass, as in floors, stairs, and balustrades, impacts become an important part. In effect, glass is supposed to resist different point loads, and the design must take into account the velocity of the shock. Glass manufacturers, again, provides guides for impacts and thickness required.

2.1.4 Thermal stresses

Thermal stresses are caused by a temperature difference within the pane of glass. Glass that is heated, tends toward to expand and then compress the cooler parts. Thermal stresses are found around the edges, where glass is protected from solar radiation by the framing. They also appear if the glass experiments a fast change in temperature, and is in contact with another material, less sensitive to temperature changes. Two panes constituting an insulating glass unit do not have the same temperature and try to expand in different intensity, create thermal stresses. The last major cause of thermal stress relevant to buildings is shading devices that do not cover the entire glass surface.

The stress occurring in the joined component due to a change in temperature is given by (*4*):

$$\sigma = \frac{(\Delta\alpha * T + \alpha * \Delta T)E_1}{(1 + \frac{E_1 * A_1}{E_2 * A_2})}$$

σ is the thermal stress

α is the coefficient of thermal expansion

Δ is the difference operator

T is the temperature

E_1, E_2 are the modulus of elasticity of glass/ other material

A_1, A_2, are the cross sectional area of glass/ other material

As an example steel has a coefficient of thermal expansion of $12*10^{-6}$ (K-1) truly different that the one of glass ($9*10^{-6}$ (K-1)). Thermal stress can cause breakage and limits the role of glass as a primary element in a building. It is then important to take this factor into account when designing a glass façade or a roof. Increasing the stress capacity of glass would be a major improvement for a structural use of glass.

2.2 Glass panes

Glass has been firstly used in architecture for its transparency, as a cladding device, only to protect interior spaces from the exterior environment or to separate interior spaces. And the dimensions of the panes remained small. But architects have always wanted to increase the glazed surface of a façade. The latest improvements of glass treatments, assemblies and manufactured size available have enabled designs with more important glazing areas.

The primary goal for a pane of glass is not to be a structural material. But vertical elements (e.g. a façade) or horizontal/sloped (e.g. roof or canopy) elements are exposed to different loads that can be substantial, as exposed above: wind, snow, impact, thermal stresses, and strain due to deformation of the frame... Consequently, these non-structural parts of the building envelope still resist loads that can be significant.

A pane of glass has mainly to carry load out of its plane. The only in-plane loads are it self-weight, and the weight of the panes under it (for vertical suspended glazing). During the design process, one wants to limit the in-plane load by carrying it on the support or by allowing in-plane movements. This section is dedicated to out-of-plane loads, and in-plane loads are going to be studied in the beams and columns sections, and can be applied to panes if a special configuration asks for it.

2.2.1 Large deflection theory

Glass panes carry in two directions until the ratio length/width exceeds 1:2. For small deflection, a pane of glass behaves like a plate, and Kirchoff's linear theory is applicable. The stresses are calculated along the pane and also at its edges, that are critical in many cases, discussed in the section 3. But if the predicted deflection exceed the glass' own thickness, the glass pane cannot be considered under linear deformation theory but as a membrane. In effect, the glass tends to take the shape of a suspended membrane, which is an efficient shape. Compression stresses appear in the glass pane and make it stiffer: the glass tends to have a smaller deflection. Then the membrane theory is more accurate, and more efficient and lead to thinner panes. Glass is described by the large deflection non-linear theory. (5)

Different models have been developed to simulate a pane of glass resisting out-of-plane loads under this non-linear large deflection theory. They are all based on Kirchoff thin shell theory, and use finite element analysis. The non-linear analysis developed here is based on a **facet shell** element, developed by A. So and S. Chan *Stability and strength analysis of glass wall systems stiffened by glass fins*, Finite Element in Analysis and Design (8). The curved surface is modelled by a number of small flat elements with different orientations, before and after deformation. One develops membrane stiffness, a bending stiffness and a geometrical stiffness of the sheet of glass, and then obtains a total tangent stiffness matrix, by combination of the 3 stiffness matrices. The calculation presented here is simple and explicit, but only conceptual, further details are available in (8) and (17)

Membrane stiffness

The membrane stiffness of a glass element is obtained using

$$[K_m] = \int_A [B_m]^T [D_m][B_m] t\,dA$$

Where $[D_m] = \frac{E}{1-\upsilon^2}\begin{bmatrix} 1 & \upsilon & 0 \\ \upsilon & 1 & 0 \\ 0 & 0 & \frac{1-\upsilon}{2} \end{bmatrix}$ is the elasticity matrix

[Bm] is the strain vs. displacement matrix that appears in the relationship $[\varepsilon] = [B_m][U_m]$ and $[\varepsilon]$is the nodal displacement, $[U_m]$ is the nine element nodal displacements and rotations of the facet shell.

t is the element thickness

A is the element area

Bending Stiffness

The bending stiffness assumes zero shear energy. The formulation is based on the plate bending theory proposed by Batoz et al. (16).

$$[K_b] = 2A\int_0^1 \int_0^{1-\eta} [B_b]^T [D_b][B_b] d\xi d\eta$$

Where $[D_m] = \frac{Et^3}{12(1-\upsilon^2)}\begin{bmatrix} 1 & \upsilon & 0 \\ \upsilon & 1 & 0 \\ 0 & 0 & \frac{1-\upsilon}{2} \end{bmatrix}$ is the elasticity matrix for plate bending

$[B_b]$ is the strain vs. displacement matrix, and depends on ξ and η (the area coordinates) and appears in the relationship $[k] = [B_b][u_b]$ and $[k]$ is the curvature of the plate assumed to be quadratic and vary linearly along the element side, and $[u_b]$ is the nine nodal displacement degrees of freedom.

Geometric stiffness

The geometric stiffness accounts for the large displacement effects

$$[K_G] = \int_\upsilon [G]^T \begin{bmatrix} T_x & T_{xy} \\ T_{xy} & T_y \end{bmatrix} [G] d\upsilon$$

Where T_x, T_y, and T_{xy} are the product of the average membrane stresses and the plate thickness.

$[G]$ is the derivative of the shape function

Element Stiffness matrix

The linear matrix is expressed as $[K_L] = [K_m] + [K_b]$

Then the total tangent matrix is $[K_T] = [K_L] + [K_G]$

Non-linear Analysis

An incremental-iterative method is developed here

$$[\Delta u] = [K_T]^{-1}[\Delta F]$$

Where $[\Delta u]$ and $[\Delta F]$ are the incremental displacement and force vectors.

Then one can express the incremental stress, $[\sigma_e] = [D][B][\Delta u_e]$, where $[\Delta u_e]$ is the element displacement vector extracted from $[\Delta u]$.

$[B]$ is the strain versus displacement matrix

$[D]$ is the material stress vs. strain matrix (a combination of the membrane and bending matrix)

The iteration process leads to a new stress expressed as $[\sigma_e]_{i-1} = [\sigma_e]_i + [\Delta\sigma_e]$

Finally the resistance $[R]$of the plate of glass to the pressure is obtained with iteration of the formulation:

$$[R]_{i+1}=[B]^T[\sigma]_{i+1}$$

2.2.2 Design

Maximum stress

The calculation is not necessary in most of the cases since manufacturers provide the stresses allowable and deflections for each of their product. An example of these tables is the figure 1.22. Designers, after evaluating the loads applied to the pane, can pick a product and a thickness with of these tables made by glass manufacturers. Since loads are out-of-plane, the glass resist in bending, then tensile stress are going to cause failure of the pane.

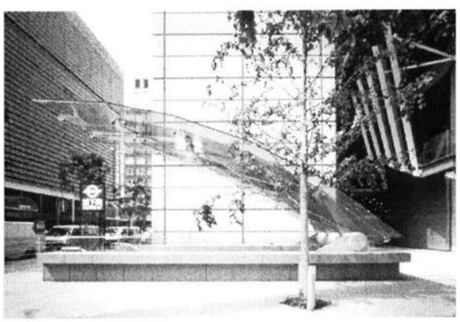
<u>*Maximum deflection*</u>

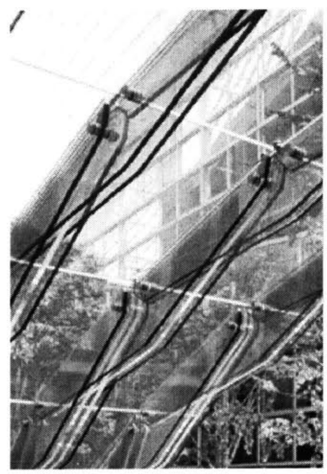
The calculation of the deflection can be done by hand with linear theory, or using Roark and Young table.

When deflection has to be calculated with non-linear theory, different approximations can be applied. One can use a finite element analysis, or use the model from Vallabhan et al, 1994.

2.3 Glass Fins/ glass beams

Figure 2.1: Yarakucho Canopy, Tokyo designed by Dewhurst Macfarlane and Partners (10)





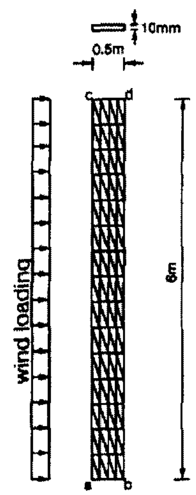
Glass beams are used to support glass roof, floors and even foot bridge (Kraaijvanger/Urbis in Rotterdam, Netherlands). Glass fins are used to reinforce vertical glass panes when supporting lateral loads. Both resist in-plane lateral loads, which are parallel to the shorted direction, in contrary to columns that carry in-plane vertical loads.

One element is limited in size by the manufactured product available. They can be assembled together to increase their length but the design and behaviour of the beam is then different (see figure 2.1:the Yarachucho Canopy, the beams are connected with a pin connection).

2.3.1 Stress on the beam/fin

Glass beams and fins are studied in the same section because they are stressed in the same way. They have one important direction in comparison with the other. Beams and fins are mostly subjected to bending solicitations. They are solicited in their plane in their longest direction (Figure 2.2), but also to transverse bending (buckling).

Figure 2.2: Solicitation of a glass fin (8)



Meshing for Glass

The bending profile induces tension stress at the edge. Since the edges, as seen in the first section, are much subjected to flaws and scratches during cutting and manipulation, cracks are more likely to propagate nearby, and then beams and fins have to be under-used.

2.3.2 Design

Strength

Beams and fins are calculated under linear theory. Tension appears to be, concerning strength, the governing design limit. Tables are provided by codes and manufacturers to express the maximum load (short and long term ones) for the design of a beam. The designer should then avoid tension as much as he can, and then choose to use tempered glass that prevent the cracks from propagating when the tension applied does not exceed the pre-compression. Another solution is to increase the short dimension of the beam to reduce the magnitude of the tension, but increase the risk of bucking in this short direction.

Beams are solicited in bending, thus bucking appears to be an additional issue. The Institute of Structural Engineers, (5), proposes to limit the moment at a free edge of a beam with the formulation

$$M_{max} < \frac{E*t^3}{6(1+\upsilon)}$$

M_{max} is the maximum unfactored destabilising moment in the fin.

Maximum Deflection

Since beams are under used and stiffen an assembly, the deflection is in most of the cases not the governing element in the design.

2.3.3 Breakage of one element

Since glass breaks without warning, the design should be done in a way that the structure that is supported by a glass beam of fins does not collapse with the breakage of one element. One solution found by designers for this issue is to allow high deflections in the structure when one element break, bigger that the one acceptable for aesthetics aspects, but does not lead to the collapse of the entire structure.

2.4 Glass Columns

The use of a single glass column is not common. Fins are more used than columns, still because of this redundancy issue. But redundancy can be found in columns also, and the architectural interest of column is very significant. Walls are calculated in a similar way, short wall assimilated to a columns.

2.4.1 Stresses

A column is solicited along it axe, mostly in compression. Then it is subjected to buckling, that limits the design. Glass columns are stiff members, and then shear is less likely to govern the design. Though if the columns is short enough that buckling is not the limiting factor, then shear becomes the one.

2.4.2 Design

Strength

The load capacity will depend highly on the restrains at both edges of the column. The design is carried in the same way as for another material, calculating the Euler critical load. This reduces drastically the compressive strength of a column (5).

Deflection

Deflection is not critical for column, since columns are stiff and also under used.

2.4.3 Breakage of one element

The major problem is that a column is very exposed to impacts and scratches that reduce a lot its load capacity. Different options have been used in order to prevent the failure of a column and the collapse of a structure. The most obvious one is to increase the number of columns in comparison of the one needed after calculation. Again, a failure of one of them can lead to higher deflection but not the collapse of the structure. Another option is a column constituted of different rods and the failure of one of this rods lead to a redistribution to the load to the other rods with under limit stresses.

The architect Robert Nijsse has interesting proposition: The first is to use the glass on the upper part of the column where it is less likely to be damaged. The second one, more interesting for the goal to use glass structurally, to divide the column into two elements, the centre that carries the load and the exterior part that is just protecting the centre from being scratched, and can be replaced.

2.5 Curved glass

Curved glass is efficient in terms of load bearing capacity, even more that flat panes. It use is limited because of the difficulty to manufacture and the high price of precise shapes and costumed ones, in opposition the repetition of flat panes. Curved glass is obtained by heating annealed glass and giving its form. Curved glass can be toughened or laminated. It is difficult to laminate because it requires a high precision to get radii of curvature that can be bonded together. For more complicated shapes, glass can be placed in a mould.

Some designs, though, have been carried with simple or even double curve glass. In the same way as an arch is efficient, curved glass is interesting in terms of thickness necessary to support the loading. As an example, the Skywalk designed by RFR for the Hanover Exhibition in 2000 is constituted of simple curved panes of laminated glass. The curved shape helps enough the structure not to need any pre-compressed glass; the structure is already in compression. Moreover, when the glass is fractured, the compression holds the parts together and allows the structure to carry some load. This is a very important improvement of the use glass!

Double curved elements are even more efficient in their load bearing capacity because "uneven loads can also be carried as axial forces without bending" (*4*). Double curved glass is therefore more difficult to manufacture. It can handle only important radius of curvature. Some of the use of double curved glass is more aesthetical than structural. But investigation in this area, and especially for processing improvement could be very interesting.

3 Load transfer through the supports

3.1 Framed glass

The principle is a frame (typically steel) that represents the load bearing structure. Glass is inserted between two or more members and is then continuously supported on two, three or four edges.

Historically, framed glass is the first use of glass as a cladding system. The use of steel structures that carry the load thought beams and columns have lead to empty spaces within the envelope of the building. The skin of a building could be differentiated from the load carrying structure. During the Industrial Revolution, palm houses, railways stations, and other palaces took advantage of the progress in the glass industry, to let natural light inside and even create tropical climates. But the relative efficiency of materials still led to stiff structures, with problematic deformations that could lead to over stresses in the glass.

Though, it is not true that glass here is only decorative and does not participate to the structure. Glass has to resist out-of-plane loads listed above, and transmit them to the structure. Then it has to resist stresses due to this frame.

3.1.1 Load sharing

Glass can be supported along two, three or four edges. The advantage of being supported on three or more edges is that even if glass is fractured in one direction, the redundancy allows the glass to be still supported. This is especially interesting for sloped or horizontal glazing, since the glass, still supported, remains in place and would not fall and potentially injure people. However glass cannot carry any more loads if fractured, and this is not relevant for toughened glass in sloped or horizontal arrangements, because of its "diced" fracture pattern.
The glass resists mostly out-of-plane loads in bending and transfers it to the secondary structure. This structure is not the principal load bearing structure in general, since for architectural reason,

this "secondary" structure is to be the most discrete as possible. The "secondary structure" is then itself related to the "primary structure" and transfers its load to it.
The deflection of glass will lead to bending stress concentration around the edge. Thus this type of support does not accommodate large deflection of the plate. Moreover, thermal stress are more likely to happen in framed glass since the embedded part of the glass is not subjected to the same radiation than the rest of the pane and the material can react differently.

For rectangular pane supported on four edges, standards provide tables to chose the thickness of the glass, after specifying loadings.

Figure 3.1: Codes available in USA, Canada, EU, and UK. (5)

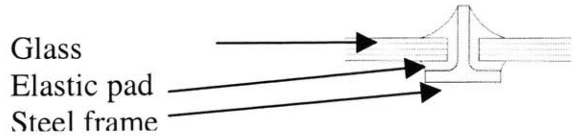
USA	ASTM E1300-94
Canada	CAN/CGSB-12.20-M89
EU	CEN/TC129/WG8 (in draft)
UK	BS 6262

3.1.2 Edge supports

The load transfer to the glazing area to the secondary structure that carry the load leads obviously to stress concentrations on the edge of the glass. For a frame system the loads are transferred by contact. That means that compressive stresses can be transferred to a surface perpendicular to it. The glass has then to be designed to take into account the concentration of stress on the transfer zone.

In most case an elastic pad is necessary between the two surfaces that are in general hard, to accommodate movements and imperfections. The pad also provides in most case the sealing for the pane of glass. The continuous support can be constituted by an H profile bar or a rebate (with or without glazing bed) and the joint is made of a putty type that provides the elastic pad.

Figure 3.2 Putty restrain



3.2 Frameless glass

With larger panes available, the response of the trend to have a glazed surface with the more glass as possible, is to improve the efficiency of the load bearing structure, and to transfer some of the structural role to the glass. Moreover, a more efficient use of structural material and the increasing height of buildings have lead to a shift between critical stresses design to a critical deformation design. Consequently, the interaction between frame and glass was becoming problematic and the need for more freedom in the movements of the glass seems inevitable.
Point supports have been possible with the improvement in the glass capacity to resist concentrated stresses. Thus, tempered glass is the most used for such applications. Point supports are used to link glass panes, but also beams and fins together. The support can be constituted of a bolt, a friction plate, or a more elaborated assembly of bolts and plates.

3.2.1 Load Transfer

The role of the support, by connecting two glass elements or a glass element and another material (mostly steel), is to transfer the load by friction from the pane of glass to the secondary structure. The relationship between the axial load and the shear that can be transmitted is roughly linear (4). These loads can be in plane or out-of-plane, depending of the configuration.

In Plane Transfer

In-plane loads need to be transferred in two cases: in the case of suspended facades or in order to connect two beams together.

In plane load transfer can be a vertical transfer of the load of a sheet of glass (it self-weight) to the one above it. It is widely used in suspended curtain wall. It allows a great flexibility and higher movements of the curtain. The structure has to take the weight of the total glass curtain, each glass member has to support the elements below it, and resist mostly wind loads. The load can be then transferred to ribs (for architectural reason they are mostly made out of glass, or to a lattice type structure). Point supports can be designed to transfer the load horizontally to the sheet next to it. It is not widely used, only in case of a breakage on one element and the load is then shared to the surrounding sheets.

Out of plane transfer

Glass resists some out-of-plane load (wind load, impacts), and transfer it to a secondary structure, that can be made out of steel truss or glass ribs. For sloped or horizontal glass surface, self-weight is out of the plane and belongs to this category. Glass panes work in bending for out-of-plane load, but the increased freedom in movements allows the glass and the non-restriction of articulated bolts to move before having to resist through bending deformation. The improvement here is very important and justifies the advantage of point supported glazing versus continuous supports.

Figure3.3 : Four hole connection designed for the Serres de la Villette by RFR. (13)

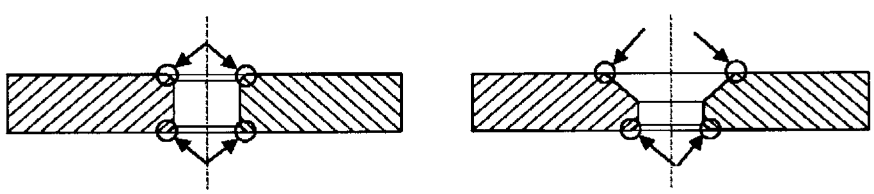
This device connects four panes of glass and is able to take in-plane and out-of-plane loads. A threaded part in the bolt resists wind loads and is more likely to develop cracks for in-plane loads thus the bolt includes a smooth part that resists in shear in plane load. The device is articulated that enables the four panes of glass to move independently.

Many of the systems used for curtain walls or beams/panes assembly are unique and have been designed or modified for the project. Testes and models are absolutely needed and represent an issue of cost and time. Some companies provide a Finite Elements Models for the stress concentration and the moments carried by the glass and/or the bolt.

3.2.2 Stress concentration in the glass

The stress concentration around hole in the glass can be calculated by static FE methods and it shows that the maximum of stress is found on the edges of the hole (figure 3.4). Stress concentration depends widely on the surface condition, and this area is obviously more sensible. Stress concentration is one of the critical design aspects, a special care need to be given to the model of such stress. For bolted glass, tempered glass is always used, and the tempered stress around this holes. FE methods and other 3D methods provide an accurate and detailed measure of the stress around the hole that complete the photoelastic method, the typical one to measure the level of stress in different places of the hole. With this calculation, designer can then choose the thickness, size and point supports profile. (15).

Figure 3.4: Maximum tensile stresses in bending for bolted glass (15)



3.2.3 Type of supports

The connections have to carry high bending moments, thus are mostly composed of steel. Since glass should avoid contact with hard material like glass, these all these systems include washers or gaskets to be the interface between the two elements. (12)

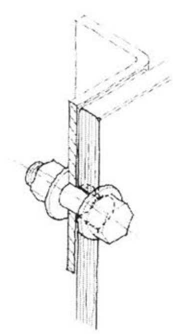
3.2.3.1 Friction plate

Friction plate consists in clamping firmly a plate on each side of the glass to assure adhesion and transfer of the load. The glass is not drilled. The stress on the glass is concentrated in the area corresponding to the plate's area. Consequently, the dimensions of the plate have to be designed in accordance with the allowable stress that the glass can handle. The issue with friction plate is that an adhesive material is needed between the glass and the steel plate, and materials that can do that are subjected to fatigue. (4)

3.2.3.2 Simple Bolt

In this configuration, the weight and out-of-plane loads is transferred through the bolt, in the area of the hole. Then stress concentration is very high around the bolt. The smaller the hole, the higher the stress concentration is. Moreover, the glass pane is tied to the bolt and the pane of glass has to resist bending moments also. This configuration seems appropriate in use to rigid systems, or when the manufactured size of the glass is limited (for example to connect a stiffener to a sheet of glass or two beams together).

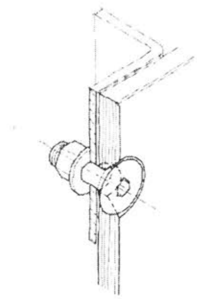
Figure 3.5: Standard bolt (12)



3.2.3.3 Countersunk Bolt

The advantage of a countersunk bolt compare to usual bolt is to get a smooth surface in one side of the bolt (figure 3.6). The loads are taken by the area around the hole. Since the area gets bigger, stress are smaller.

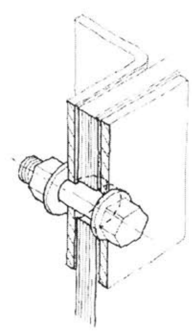
Figure 3.6: Countersunk bolt



3.2.3.4 Patch Plate

This system uses also a bolt, but in order to eliminate the load taken by the hole, a plate is glued to the sheet of glass around the hole. Then the weight of the glass and its out of plane loads are taken no longer by the hole of the glass but by this plate, and transferred to the bolt. Movement are not allowed and imply the presence of bending moments again.

Figure 3.7 : Patch Plate (12)



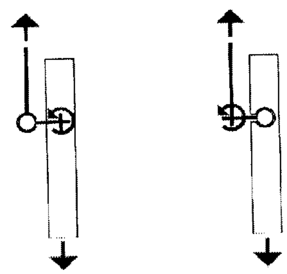
3.2.3.5 Articulated bolt

The goal of his system is to allow movements around the bolt, and then bringing back the moment connection to the support made of steel (figure 3.8). This system is obtained by designing a bolt that allows rotation where it is connected in the glass, and not between the bolt and the secondary system. The articulated bolt is constituted of a head that can rotate, and a series of bearings and flexible washers.

Figure 3.8: Moment transfer in articulated bolts (12)

Left: non–articulated bolt

Right: Articulated bolt



3.3 Structural Sealants

A structural sealant is an adhesive material (mostly silicone) that constitutes the bonding between the pane of glass and the frame or directly between two panes of glass. This section is dedicated to structural sealing without frame, since adhesive between a frame and glass is only a substitution of a putty system. Structural sealants are used in addition with frameless support, and provide the waterproof insulation also.

Silicon based structural sealants are still not very well classified. They can resist short terms loads, and their behaviour concerning long-term loads are still not clearly defined.

3.3.1 Properties of adhesive sealant

- Structural sealants need to be cured, with UV or heat. Thus installation of such devices can be difficult
- Structural sealants performance is time dependent. They appear to be less efficient over time. Their properties are also temperature dependant. Steel and glass trend to skink with a temperature decreasing, sealant are stiffer with a lower temperature, which does not help the adherence.
- Coating on glass has to be tested because they can lower the adhesion of the sealant to the glass.

- Adhesive are more sensitive to chemicals that glass (even water), and can be less durable than glass.
- Stuctural sealant can stop a crack in glass. However, some cracks have spread through a silicone joint (12)

In order to clarify how the stress repartition is done, one can want to model the stress concentration with finite elements analysis is not relevant here. It does not apply for glued joints. Some improvement of a structural sealant that would behave in both short and long term is given with epoxy adhesives and structural tape.

Figure 3.9: Shear Modulus of different adhesives (5)

Adhesive	Shear modulus
Modified epoxies	Higher
Polyurethane resin	Medium
Structural silicone	Lower

4 Composition for structural improvement

Glass can be arranged in different ways to optimise its structural utilisation. An obvious composition is to use different elements made of glass that would be solicited when they are efficient. The point here is to achieve a maximum of transparency, and to use glass where it is good at, by composing with other glass elements or other materials.

4.1 Glass-glass arrangements

Glass fins and ribs are widely used to reinforce panes of glass to resist lateral loads. The assembly of glass pane and fins result in highly transparent structures, and continuous façades. The pane of glass is used to resist wind loads and transfer it partially to a stiffener that is placed perpendicularly and takes the load in its plan loads. One of the issues of glass fins reinforcing a large area is the of change transparency through difference angle. Facing the curtain wall, the structure is transparent, but laterally, the structure can look heavy.

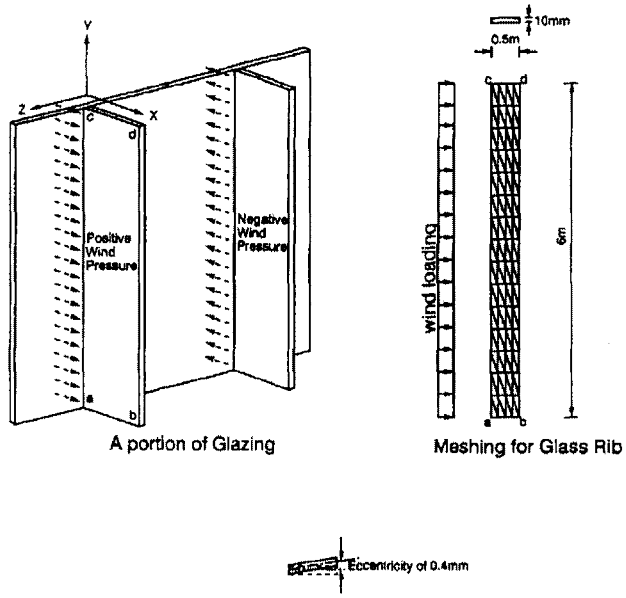
4.1.1 Hierarchy

Two systems can be considered. A façade with stiffeners, providing rigidity to the pane of glass, with a primary structure that has to take the weight of the glass and the stiffeners. The wall is suspended or rested on setting blocks. The second case consists glass beams that act as the secondary structures, transferring the load to the primary structure that can be made of glass also, like the "Glass room" (figure 4.2). In this case, the hierarchy is similar to a typical structural system, but the exception of glass requires a back-up system, when a pane or a beam breaks, the whole structure has to be able stand up.

4.1.2 Stress distribution

The efficiency of ribs lies in that a rib or a stiffener decreases the stress on the flat member by the square of the depth of the stiffener. It also decreases the deformation by the cubic depth of the stiffener. This is the reason why they are used whenever the size of the designed glazing area is loo large to accommodate important stress. The load taking by the ribs depends on the supports of the pane of glass. If the pane is supported such as in-plane load are carried by the glass it self (that is, it is not suspended), the ribs only carry some of the perpendicular to the pane load, that is wind load mostly. Thermal stresses are not dissipated with ribs, since they must be carefully braced to the pane of glass. (4)

Figure 4.1: Layout of glass panes with stiffeners (8)



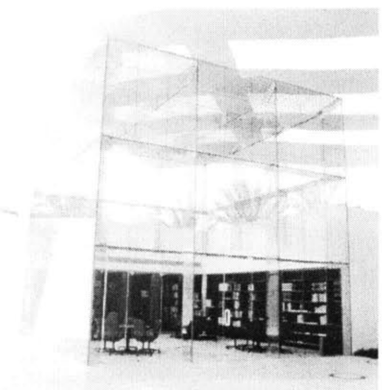
Stiffeners are placed perpendicularly to the facing panels, then experiments in-plane loads, they have the tendency to buckle and deflect laterally, which is the "lateral-torsional buckling" (8) (figure 4.1). Here the large deflection behaviour of a sheet of glass and the bending behaviour of the stiffener need to be combined to model the assembly. So and Chan (8) provide a finite element analysis that simulate the glass panel resisting wind load by bending (axial stiffness) and membrane (flexural properties) actions. The non-linear analysis allows working with shell that have in plane and out of plane stiffness. Moreover, the fin or beam can develop out-of-plane load due to imperfection of manufacture and erection mainly, and the change of geometry requires designer to work with non-linear analysis.

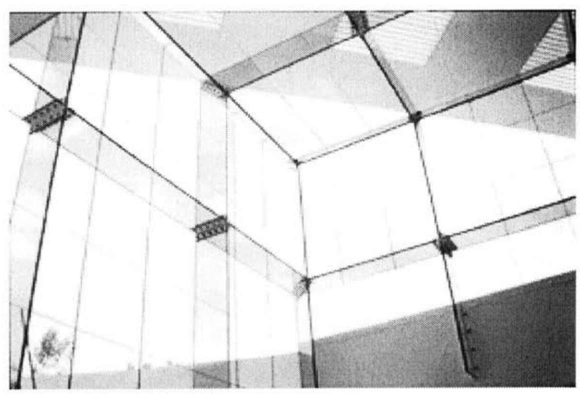
4.1.3 Joints requirement

The jointing is crucial for an effective transfer of the stresses from the pane to the rib. A continuous bonding is required, and the most common process is to use structural adhesives, in addition with a clamping system or bolted joints. A failure of the sealant to provide the continuity between the stiffener and the pane of glass reduces considerably the efficiency of such a composition, and oblige the designer to take important safety coefficients.

The connection between a pane of glass and a beam has to transfer the load in a perpendicular surface, thus the design is specific. Connections that link two beams in the same plan are based on a transfer by fiction, and a pin connection is the most efficient.

Figure 4.2: Example of an all glass structure: Reading Room, Riyadh, designed by Dewhurst Macfarlane and Partners (10)





All glass structures are limited in height because of the buckling of the elements. For higher than 4,5 m, the glazed area need to be suspended or steel reinforcements.

4.2 Glass-Steel Truss

Steel truss is another solution for transparency and efficiency in a structural system using glass. It takes advantage of both material qualities. In these structures, glass can be used to take the compression and steel the tension. The steel truss can be placed through bolting in different directions, in one or two sides of the pane. An issue for these systems are firstly their cost, and the need of major structures to provide reaction to the tension can reduce the elegance of the system (11).

4.2.1 Hierarchy of the System

The arrangement of steel truss and glass requires a specific organisation, because the glass and its supports have specific roles. However, the glass pane and its truss support still belong to a hierarchy in the structure. Each member of this hierarchy carries the loads of those below it and must be able to resist the stresses caused by them and their deformation (12).

From the most subordinate the hierarchy of such a system is:

- The pane of glass and its point supports
- The cable truss system that reduces to the minimum the out of plane loads
- The primary structure that can be widely spaced (in the Parc André Citroen, the primary structure spans 15m).

4.2.2 Stress distribution

The glass' point supports and suspensions system are articulated, described in the previous section. Once the point support is chosen, a device is designed to bring back the load from the point supports to the truss bracing. The cable truss system resists out-of-plane loads in tension. Since wind load can lead to suction, which is a negative pressure, tension can appear in both side of a pane resisting lateral loads in bending. Then the system needs to be able to resist both positive and negative pressure. The most efficient and light solution is to prestress 2 cables, in opposite directions to provide the same resistance for positive and negative pressures. Different arrangements can be considered, as in these different applications:

- Serres de la Villette, Paris, France, Peter Rice and RFR. The articulated bolts are assembled to connect two, three, or four panes of glass and transfer the load to the truss. Depending on the place on the curtain wall some connections transfer only wind load and some transfer the weight of the glass also. The four-holes connections have an H shape, specially designed to accommodate the moment transfer (figure 4.5) . The connections are designed to resist the load if one or more pane of glass breaks. The truss structure is composed of two cables crossing each other, and situated horizontally in the inside of the glass (figure 4.4). They are tensioned against the other, prestressed at 2 tonnes that in extreme loads, one can lose its tension and the other one taking the totality of the load. (12)

Figure 4.3: Views of the Suspended façade of the Museum of Technology and Science of la Villette, in Paris. (13)

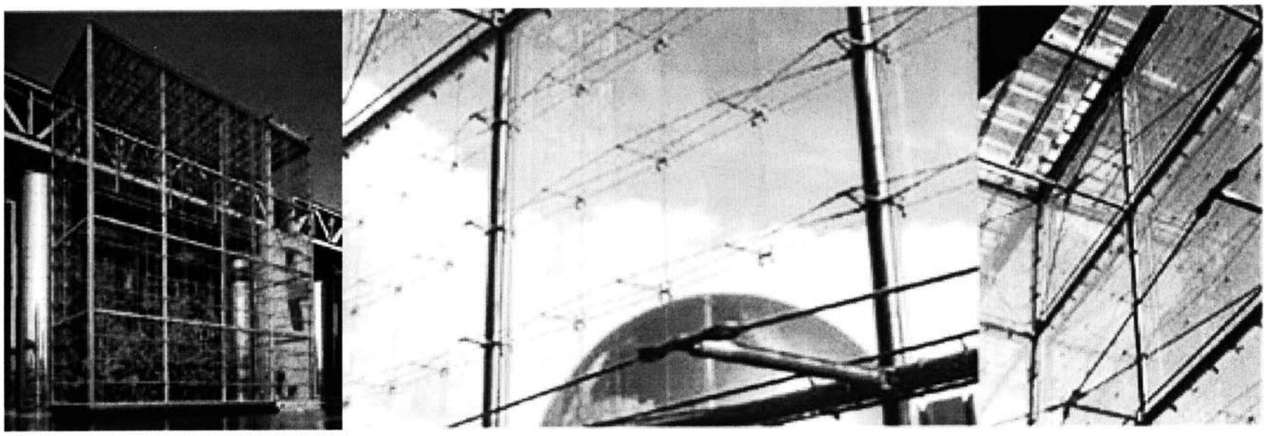


Figure 4.4 Truss arrangement (12)

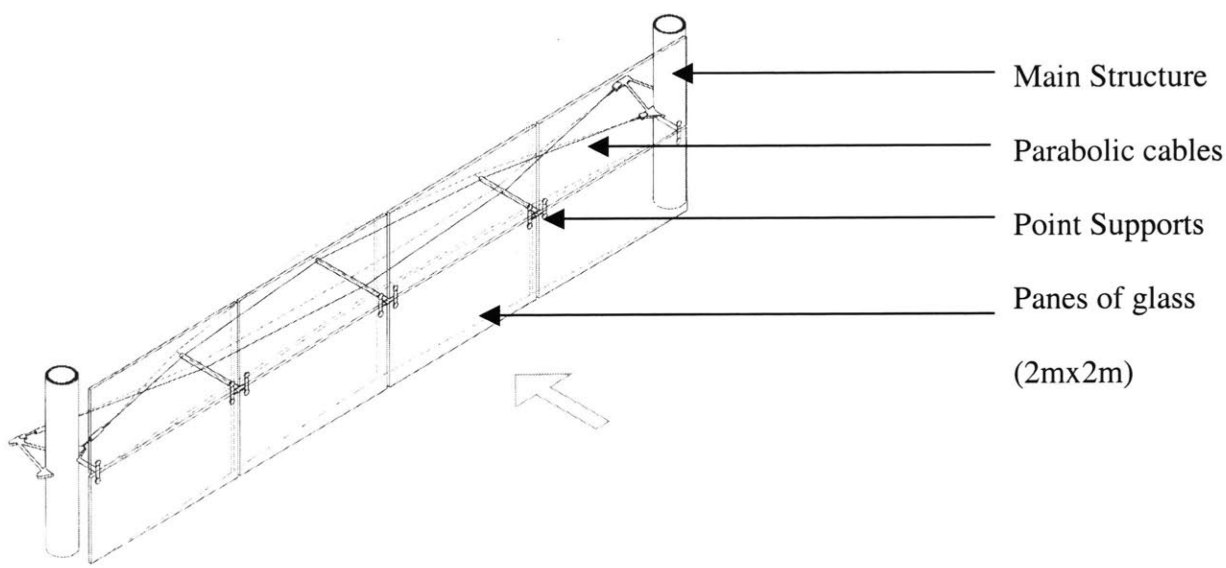
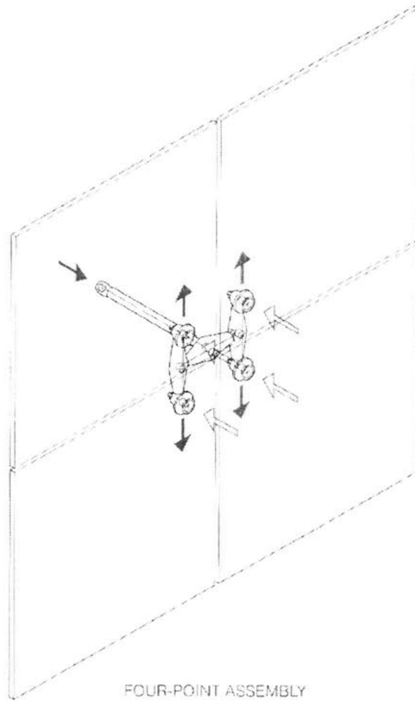


Figure 4.5: Four point assembly at the Serres de la Villette (12)



- Parc Andre Citroen: The cables are in opposition around a centre tubular structure that resist the prestress of the cable. In this 15 m high structure, the glass assembly is suspended from the façade and is braced by vertical and horizontal trusses. The point support has been designed based on the supports of the Serres de la Villette, but needed to be modified. The structure is more rigid and the moments are different. The connections have an X shape, different from the H shape of the Serres.

- Covering of a castle Ruins, by Robert Danz: The structure is different here since the glazing is not vertical. Glass panes are not suspended, and the weight of the glass is out of the plane of the glass sheets. In this system, cables are in both side of the glass. The symmetry enables the roof or façade to be very transparent, but the truss needs to be connected to both sides of the glass, and the realisation of the bolts get more difficult and more expensive. The same system has been adopted for the hall of the CNIT, in la Défense (France), for a glass curtain wall.

Rice explains (13), that in a cable truss, the shear is taken by the curvature of the cables, instead of the diagonal members for a typical truss. The moment is composed of the tension of the cable and the horizontal force applied at the end of it. The equilibrium is achieved when the cable takes a "catenary" shape. The catenary shape of the cables of the truss, subjected to the wind that is uniform along the length, is a parabola. Then the cables have the corresponding shape. They are prestressed because, under a given load, the tension increases in one cable and decrease in the one in the other direction, and they need to remain under tension to effectively brace the pane of glass. Another reason is also to resist asymmetric load, where the truss has to change shape to accommodate the asymmetry. This is possible thanks to the flexible connections at the end of the cables. The prestressing controls the change of shape.

4.2.3 Method of Calculation

The change in geometry of the cables does not allow the designers to use a linear structural analysis. Then a non-linear analysis of the truss has to be carried with numerical iteration, until the equilibrium position of the structure. The calculation method can represent a significant part in the design cost, thus companies that have developed supports have also developed a package including glass, testes and calculation method (example: Plannar system by Pinlkington, Spider System by Saint-Gobain). This is the only way to have this kind of system economically viable.

4.3 Three Dimension glass structures

Shell, because they are only submitted to axial compression load are a very efficient use of material. Glass shells have been designed with glass blocks, because they have to accommodate important compression stresses. They can be considered as a brick dome, and are bonded with mortar. They are not used any more, because their fabrication needs each piece to be manufactured separately and the cost was too high.

Thin glass shell is one of the contemporary development. As we have seen, curved glass is difficult. Though many of glass shells or dome are made of flat pieces of glass. They are in majority imbedded in a steel structure, like the green houses of the XIX^{e} century (in this case glass is just a cladding device). The primary design of such shell was a steel frame as the primary load bearing, then the glass is added with important elastic joint to deal with the uncertainty of the steel motion.

4.3.1 All glass shell

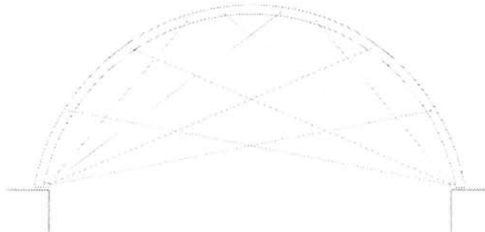
Shells made with thin glass elements and no frames are feasible with individual fixing or clamping plates (4). Then a truss can be designed to maintain the stability and support the individual panes.

The point fixings involve tensile stress locally, which is in opposition of the glass in compression. This system has not been used in a building, but the Institute of Lightweight Structures in Germany has built a "Truss Arch"

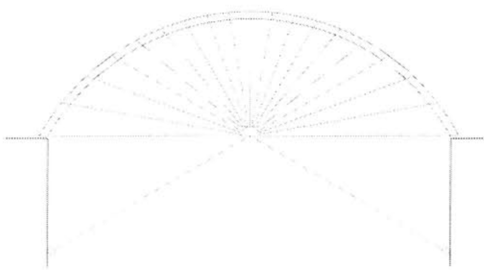
4.3.2 Thin frame shell

The intermediate solution is to have a thinner steel frame. When computer based design permit an accurate model of the steel frame, glass panels could be inserted without a thick interface to damp the motion of the frame. Thin frame shells are constituted of separated flat glass, the load behaviour is establish through the mesh and type of node (4). In order to avoid the nodes to resist bending moment, the systems can be designed with diagonal braces in every bay, taking the compression and the tension. This structure with bracing is the most efficient to provide stability against buckling to a dome and reduces the degree of complication (thus the price) of the nodes design. More over, unbraced structures require a frame that can be significant. Bracing can be either in one or two directions.

Figure 4.6: Two types of dome bracing (4)



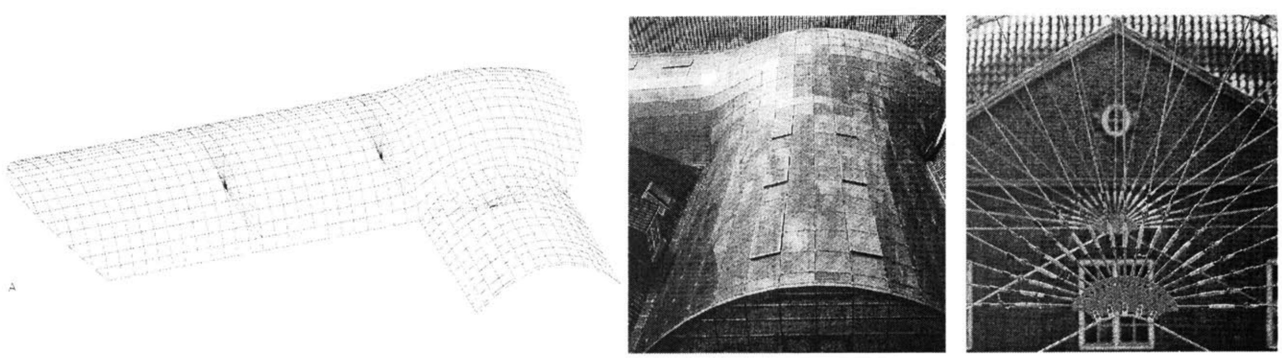
Cable-guyed arch, Machinery Hall, All-Russia Exhibition, 1896, Vladimir Suchov



Cable-guyed barrel vault, Hamburg City History Museum, Hamburg.
Architects: von Gerkan Marg & Partner
Engineers: Schlaich, Bergermann & Partner

In the Dome of the covering of the Courtyard of the Hamburg City History (figure 4.6 and 4.7), the engineer J. Schaich designed an arrangement of the cables that has increased the load capacity of the structure.

Figure 4.7: Example: Covering of the Courtyard of the Museum of Hamburg (4)

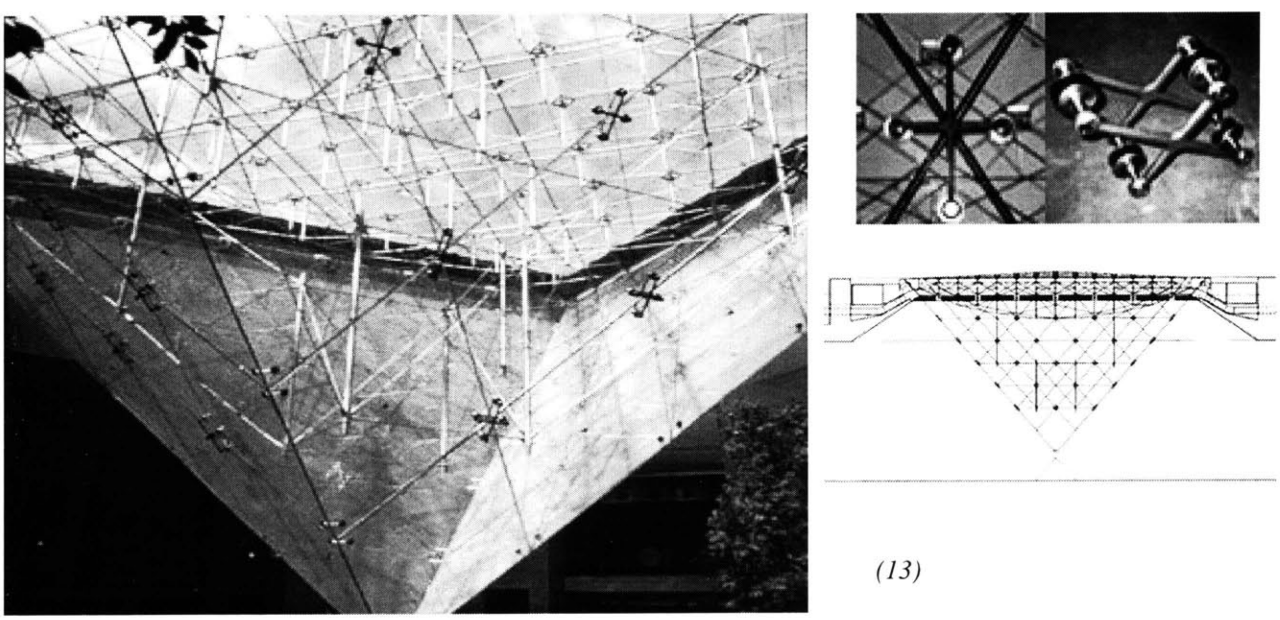


In a shell structure, the movements of the glass are critical and have limited the development of efficient and light domes. The accuracy in design and fabrication of steel and glass elements, the development of structural sealant have lead to inexpensive solution and has enable manufacturers and designer to start a standardization of their products (4).

Example of the inverted pyramid in the Louvre, Paris, France

This structure is an exception because all the panes of glass are suspended to the steel lattice, which is always in tension, and are not framed. The truss is then connected to the concrete structure around. This structure is unique since each pane carries the load of the pane below it, then the connection and behaviour is similar to the one described in the section 4.2, but has the three dimension aspect of a thin shell, up side down. The bracing restrains the panes of glass by the way of slender cables fixed in the middle of the top covering of the structure. (4). This structure is impressive because it seems to challenge gravity and in the same time looks very well balanced.

Figure 4.8: The inverted pyramid of the Louvre, Paris, France (13)



(13)

Conclusion

Glass today can be considered as a high performance structural material. The improvements in the manufactures process, treatments and assemblies have enabled designers to create innovative structures, with the possibility to design entire glass walls, structures and uneven shapes. The future developments of glass structures would seem, however, to be limited by the manipulation of large size glass panes (to be able to be transported on a truck, to be erected without huge cranes, etc.) and the very important increase of cost of elaborated design. In effect, the specific geometry of the latest designs, either three dimensions, high–height curtain walls, etc. and the desire of designers to create something new for each project, have dramatic effects on the costs. For a unique project, in addition to the traditional design, specially designed joints and secondary supports need to be tested, and the whole structure must be modelled and tested. Moreover, the principle of redundancy in these structures adds complication to the design and the test procedure. This is the reason why exceptional structures using glass are found where a specific architectural footprint is wanted (the Museum of Glass in UK, the covering of the main museum in Hamburg, the pyramid of the Louvre in Paris, or office buildings that use their headquarters as a representation of their strength). The effort of manufacturers to standardize their products still seems limited and seen ad a limitation on the creativeness of designers and architects. There should be a way for architects and designers to work together with the glass industry in order to improve the cost and time efficiency of the design of such exceptional structures.

On the other hand, the intrinsic properties of glass, well improved by strengthening and laminating methods, are still under research for more improvements. The combination of glass with a ductile material seems to be an interesting method to take advantage of both materials' strength. Some research is in process for a laminated glass with glass or composite fibres in the interlayer. For the final project of the Workshop " Emergent Material" in Building Technology, the group I belong to has designed a concept of a layered glass/polymer composite that first prevents cracks from happening to the glass surface and in addition provides a healing agent for the glass cracks. The pane of glass is coated with a thin layer composed of an epoxy matrix containing healing agents. The exterior layer is composed of a silicon layer that damps small impacts due to its viscoelastic properties. If a stress or impact reaches the glass, it has reached the epoxy layer, which thus releases the healing agent to the glass surface, preventing stresses from accumulating on the cracks. This project is only a concept project, and so far the composite is translucent rather than transparent. But these researches (and many others) demonstrate that glass is still to be improved and has not yet been fully realized.

List of Figures