

# (Ultra) Thin Glass

Development of low mass curved adaptive panels/structures

**Rafael Ribeiro Silveira**

**4413113**

**First Mentor:** Christian Louter

**Second Mentor:** Peter Eigenraam

**TU Delft**

**Faculty of Architecture and the Built Environment**

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## Problem Statement

(Ultra) thin glass is a material with big potential to be used in the built environment; its high flexibility is an advantage, however it constrains its use in certain applications. By adapting its geometry it is possible to develop ways to use it in the built environment.

## Research Question

What would be an adequate application of thin glass on low mass curved adaptive panels/structures, making use of its unique characteristics?

## Method

The methodology of this thesis is based on research by design.

Thin glass is a new material in the built environment and research has not been deeply developed regarding this material related to building needs and standards.

Considering this, it is necessary to understand the material itself, its behavior to be capable of understanding its possible applications in the built environment.

The first part (P1-P2) of this research was used to better understand the material characteristics and identify the research already done in relation to it. At the same time a geometric exploration regarding alternative uses in the built environment was developed. The objective of this phase was to answer the research question raised in the beginning of the thesis development: "What would be the adequate use for (ultra) thin glass in the built environment, making use of its unique characteristics?"

The result of the first phase of the research was a better understanding of the material itself and the direction of the research.

The second phase (P2-P3) of the research will focus on the development of a design or a case study to apply the concept of adaptive glass panels/structure. At the same time, material (Aluminum) will be ordered to the development of study mockups/scale model. The progress of the design/case study and mockups will be followed by FEM models to analyze the structural behavior of the design/case study.

The third phase (P3-P4) of the research will focus on the development of a mockup/scale model in thin glass of the final design/case study. At the same time, laboratory tests will be performed to be compared to the numerical calculations.

The last phase of the research (P4-P5) will focus on reflections about the outputs of the research and suggestions for further developments and studies of this material.

The outcome of this research will be a better insight on the material properties of thin glass and the possible applications of this material in the built environment.

# Literature

Considering that thin glass is a relatively new material, and that in the built environment its use has not been yet explored, very few research has been done regarding its use. Due to this reason the literature and general references are limited. The material available and to be used as reference is the following:

- Specification sheets of manufactures (Corning, AGC, SCHOTT) regarding material properties
- HUNDEVAD, J. Super lightweight glass structures – a study. GlassCon Global. pg324. 2014.
- HUNDEVAD, J. A movable canopy. International Conference on Building Envelope Design and Technology. Graz. Advanced Building Skins. 2015. p.324.
- J. Spitzhüttl, G. Nehring & I. Maniatis. Investigations on determining the bending strength of thin glass. Challenging Glass 4. 2014
- Overend, M., et al. The mechanical performance of laminated hybrid-glass units. Composite Structures 110 (2014): 163-173.
- Maniatis I., Nehring G., Siebert G.: Studies on the strength of thin glass, IABSE - Symposium, Madrid 2014 **(if can get access)**.
- Spitzhüttl, H. 2013. Testing the bending tensile strength on thin glass, Master Thesis, Universität der Bundeswehr München. **(if found)**.
- Simoen, C. Ultra-thin Aluminosilicate glass as a new lightweight building material. Master Thesis. TU Delft. 2016.

# Relevance

(Ultra) thin glass is a relatively new material, the emergence of the mobile electronics industry pushed the development of this material to the standards we see today. This material is under an ongoing progress of getting each time thinner (lighter) and more resistant.

Common glass elements in the built environment have usually to be stiffened by lamination (either by structural or safety reasons) or geometry (curvature). However, these processes result in heavy or expensive/complicated (if hot bending is necessary) elements.

(Ultra) thin glass can be presented as an interesting alternative to these problems. As it is lightweight it can be used for the development of glass panels or lamination for reducing the weight of elements. Its flexibility allows it to assume curved shapes without the need of hot bending.

Nevertheless, the use of thin glass instead of common glass implies in a reduction of raw material (glass) and reduction in the total load in the general structure of the buildings. The substitution of one material for the other could considerably reduce the amount of structural material necessary in a building only due the reduction of dead weight of the panels.

This research aims to grow the knowledge and research about the use of this material in the built environment, providing data and examples that may collaborate with future applications of this material in this field.

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*Every new material means a new form, a new use if used according to its nature.*

*Frank Lloyd Wright*

# GLASS

THIS chapter has the objective of describing the current and past uses of glass in the built environment. It starts describing the connection between the technological advances in glass production with its use in the built environment. Then, its material properties are described followed by the post production technologies. After this, are listed its common uses in the built environment and the limitations connected with the current use of this material.

# 1.1.History

This section aims to describe the use of glass throughout history and the connection between the evolution of technologies related to glass production to the characteristics of the built environment.

Glass first appeared in the form of artifacts like pots and vases, around 1500 B.C. [17]. However not transparent yet, these examples are the predecessors of the glass we produce today.

Regarding the built environment glass most common use, is to allow light in spaces while separating the inside from the outside. Assuming this function, glass is a material mostly found in buildings together with an important element of architecture, the window.

Employed initially in window panes, glass was an expensive material, and the production techniques only allowed for small plates to be produced.



Figure 1-Glass window pane ca. 1AD - 70AD found in Herculaneum, Italy. [9].

However, the development in the technologies of glass production allowed for the development of plates with bigger dimensions and better optical qualities, while reducing its price. The chart below (pages 6 and 7) shows the relation between the evolution of glass technologies, plate dimensions and the use of this material in the built environment.

One conclusion that can be taken from the history of glass, which is also valid for other materials, is that the new technologies that were developed along time, triggered changes in the built environment as a whole.

Regarding glass specifically, it was first a noble material, expensive and exclusive, which was produced only in small plates (as the technology for bigger ones was not yet developed) for very special

uses. The first example in the chart is the windows of the Notre Dame Cathedral in Paris; common households would use lower (optical) quality glass or other alternatives. However, in the 18th century, with the addition to soda to the composition of glass, the costs to produce this material dropped significantly, spreading the use of higher quality glass; for instance the second example in the chart shows windows of Victorian houses in England on the same 18th century.

The next important milestone that should be considered is the use of the properties of glass. Formerly almost only considered for its optical qualities, in the 19th century this material started to be applied with a different function.

"Victorian green houses were perhaps the first architectures to exploit the heat capturing properties of the glass enclosed space" [12], in addition, these buildings introduced a new way to build using this material. A composition of iron frames and small glass panes constitutes the technique used for these buildings. These were the first buildings using glass as one of its main materials, in addition they used the small plates to compose (complex) curved shapes.

This technique culminated in the construction of the Crystal Palace in 1851, one of the most remarkable (and largest - 564 x 139 meters) glass buildings of all time. This period also holds a transition in the conception of the use of glass in buildings, as it no longer was constrained to the window, but to become the façade of building itself.

With the beginning of the 20th century, a new development in the glass industry, the Foucault process allowed glass plates to go beyond the dimension of 2 meters. At the same time, the fascination of architects about this material started to grow.

In 1914, Bruno Taut designs the Glass Pavilion, a building showing many potential uses for this material, including glass stairs, roof, bricks and other elements. In the following years, the modernist movement gave great importance to this material. Mies van der Rohe in his unbuilt proposal for the Friedrichstrasse Skyscraper designed an all glass façade. The Bauhaus Dessau school main building facade is recognized as one of the first curtain wall systems developed, using glass to provide the desired transparency effect.

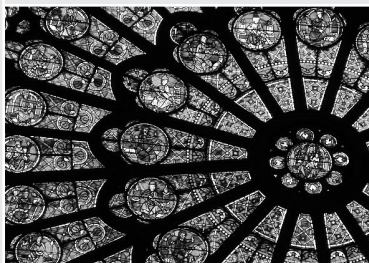
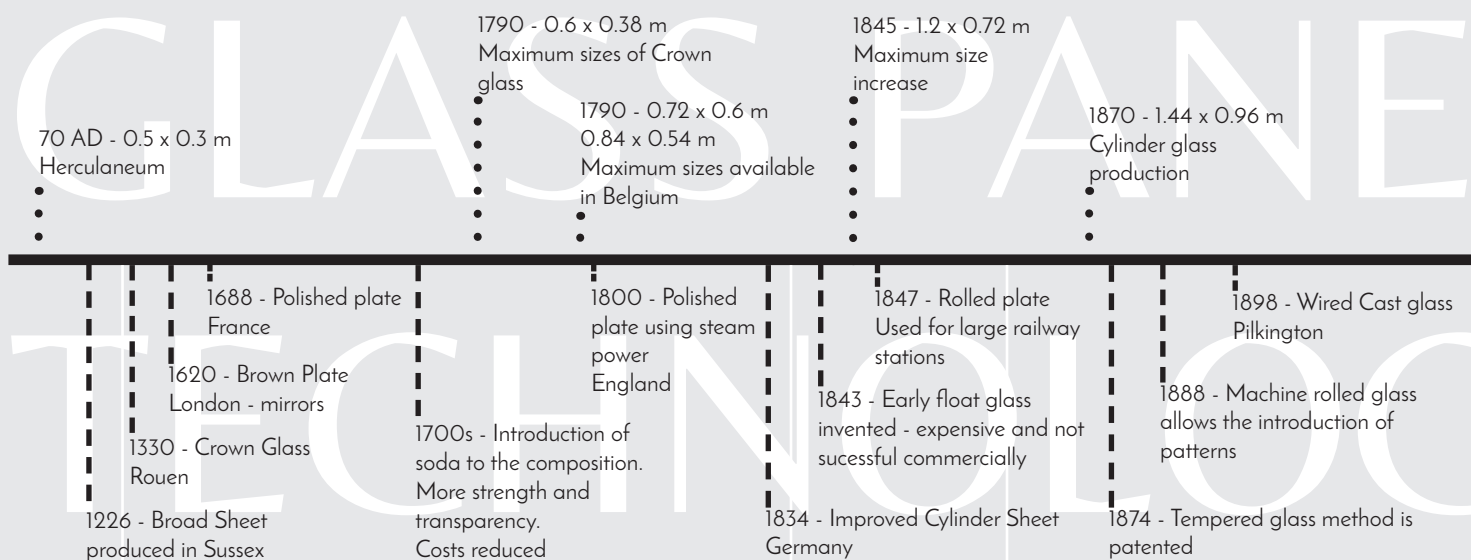


Figure 2-Notre Dame de Paris - 1260



Figure 3-Victorian houses - ca. 1850

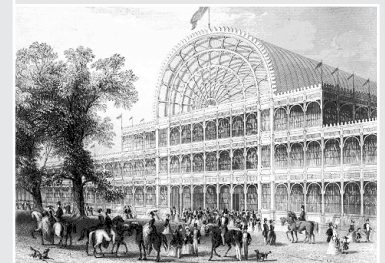


Figure 4-Crystal Palace - 1851

The development of the production technologies allowed the growth of the dimensions of glass plates along time, and architecture followed it, using the new available products to produce innovative solutions. In the beginning of the 21st century, new developments allowed the production of even bigger glass plates, pushing architects and engineers to new solutions.

In 2006, one of the most remarkable series of glass buildings in history started with the building of the Apple flagship store in New York. The brand adopted glass buildings as its identity, and since then it has been pushing the industry to provide then even larger plates to their new designs. The Istanbul store, used as an example in the chart has a prism volume above it, composed of four glass plates with the dimension of 10 x 4m.

## 1.2. Glass - material

"Glass is a state of matter" [3].

Glass is a solid that is the result of a melted material - silica ( $\text{SiO}_2$ ) -, that when heated has its molecular

arrangement changed, becoming an amorphous solid - "a solid material with the chaotic structure of a liquid" [14].

The most remarkable of glass qualities, transparency, is the result of the atomic configuration of this material. Unlike other solids, electrons in glass atoms do not absorb visible light photons as they do not provide enough energy for them to change their energy level. On the other hand, UV light photons provide the ideal amount of energy for these electrons to change level and therefore it is absorbed.

Another characteristic that is important considering this material is its heat capturing possibilities. The examples of greenhouses discussed in the item 1.1 take advantage of this property. Glass allows the short infrared waves to go through it, however, when these waves hit objects are re-emitted as long infrared wave they can no longer pass through glass and remain trapped, heating the space.

Along time, different other materials were added to the composition of glass, in order to make the production easier, or to adapt its properties.



# SIZE

1906 - 3,8 x 1.9 m  
Fourcault process

1925 - 4 x 2.3 m  
Fourcault process improved

1927 - 4 x 2.5 m  
Pilkington process

1951 - 15.24 x 2.4 m  
Exhibition glass  
Britain, power and  
production pavilion

1970 - 6 x 3.21 m  
Jumbo float glass

2009 - 9 x 3.21 m  
New Jumbo float glass

2010 - 18 x 3.3 m  
Insulated glass at  
Glasstec

1903 - Machine drawn  
cylinder technique  
U.S.

1903 - Laminated glass  
is invented  
France

1923 - Polished plate  
England

1913 - Flat drawn sheet technique  
Belgium

1959 - Float glass  
Pilkington

Chart 1- Evolution of glass  
Based on chart by Alejandro  
Zaera Polo in [12]

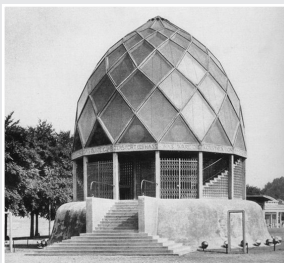


Figure 5-Glass Pavilion - 1914



Figure 6-Bauhaus Dessau - 1928



Figure 7-Apple Istanbul - 2014

The most common type of glass, and also the most relevant to the building industry, today is the soda-lime glass.

## 1.2.1. Material Properties

"Its fragility and, above all, its sudden failure characterize glass as a typical brittle material" [20], this has constrained its use in the built environment to window panes, façade cladding and other uses, such as decorative.

The graph O1 shows a comparison between glass steel and wood when subjected to stress.

Glass has no plastic behavior (around 0.1%), it has a very low elongation at failure, making it "impossible to predict failure" [20].

It is important to consider, as emphasized by Weller et al., that the tensile strength of glass does not only depends on its material properties, but mainly on the physical condition of the sheet glass. However, in theory sheet glass can achieve a tensile strength of 6500 to 8000 N/mm<sup>2</sup>; in practice due to "surface flaws, notches and cracks" this value is reduced to 30-80 N/mm<sup>2</sup>. "Failure in glass is the result of a combination of flaws and stresses" [19].

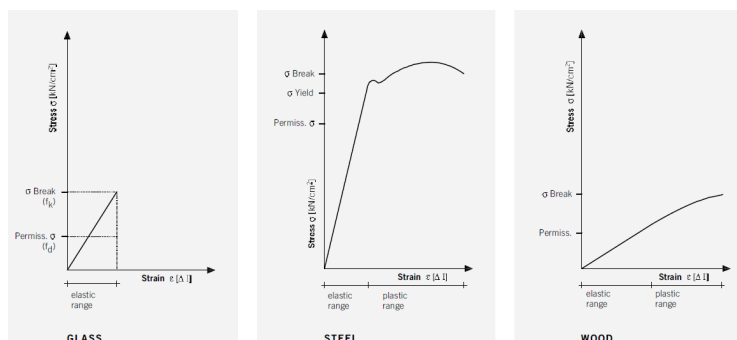


Chart 2-Qualitative comparison of the stress-strain graphs of glass, steel and wood. [21].

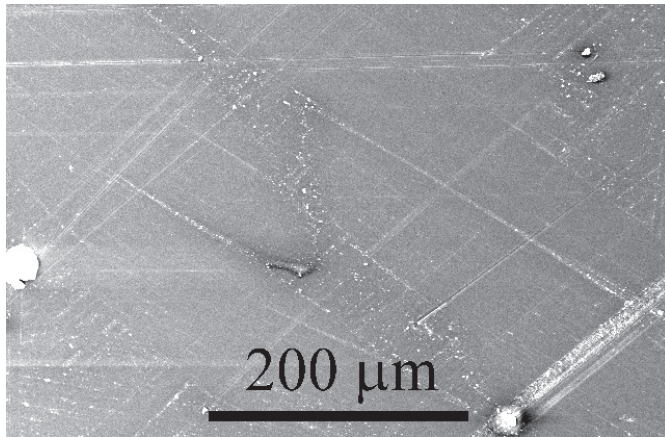


Figure 8-Surface flaws on glass.

On the other hand, glass has a very high compressive strength, a fracture toughness comparable to concrete; in addition, the flaws described above do not affect this property as much. The study of this characteristic pushed designers to use this material for loadbearing structures, challenging the fragility concept. Along the last decades studies and built designs have proved the possibility of glass structures.



Figure 9-Temple d'amour - Dirk Jan Postel - 2000

Besides, glass is a very durable material, its high resistance against the natural elements (water, UV light) and acids, makes it suitable when long durability is necessary. In contrary to other translucent or transparent materials, its properties (like color) do not change along time.

The Table 1 summarizes the material properties of soda-lime glass, concluding this section.

Table 1-Soda lime glass material properties [5]

<b>Density</b>	2.47e3 - 2.52e3	kg/m <sup>3</sup>	<b>Shear Modulus</b>	27.9 - 29.6	Gpa
<b>Young's Modulus</b>	68-72	GPa	<b>Poisson's ratio</b>	0.21 - 0.22	-
<b>Tensile Strength</b>	30.3 - 32.2	MPa	<b>Hardness - Vickers</b>	89 - 98.4	HV
<b>Elongation</b>	0.04 - 0.05	% strain	<b>Fatigue Strength</b> (at 10 <sup>7</sup> cycles)	28.2 - 31.2	MPa
<b>Compressive Strength</b>	303 - 322	MPa	<b>Fracture Toughness</b>	0.63 - 0.65	MPa.m <sup>0.5</sup>
<b>Flexural Strength</b> (modulus of rupture)	39.4 - 41.9	MPa	<b>Thermal Expansion</b> <b>coefficient</b>	8.92 - 9.28	μstrain/°C
<b>Shape Factor</b>	15	-			

## 1.3.Production

As described before, glass is the result a molten composition; the whole process starts at very high temperatures, that are progressively reduced to produce the final material. This section will give a brief description of the production of float glass - as it is the main glass product used in the built environment - and of the consequences of the production process to the final quality and properties of the material.

To produce float glass, the raw materials that composed it are homogenized and mixed, then they are poured into a melting tank, where they are heated up until the melting point of the composition. These molten solution floats (this is the derivation of name of the product) over a bath of molten tin in order to produce two parallel faces of the product. The product is then slowly cooled down and then it is cut in the desired sizes. The different thicknesses of glass are produced by "Adjusting the top rollers - serrated wheels resting on the edges of the ribbon of glass at the front end of the float bath".

It is also important to consider that this process produces a material with two different sides, with different chemical compositions. As the bottom side of the glass is in contact with the tin bath it "has a higher content of tin ions than the so-called air side".

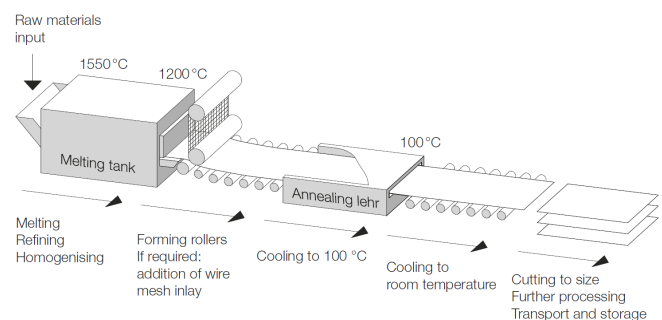


Figure 10-Float glass production

Finally, it should be considered the last part of this process, the cutting. Cutting glass is done by damaging its surface (as it is a very hard material) and then breaking it. The edges of glass remain irregular surfaces that have to be then chamfered or polished according to its future use. Due to this process, both the cutting and the finishing, glass edges have lower strength than the surfaces of the material.

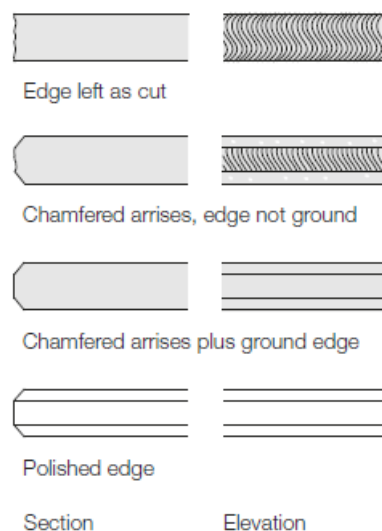


Figure 11-Edge quality of glass

## 1.4.Post production processes

As described in the section 1.2, glass is a strong but fragile material, it is an interesting material in which these two divergent characteristics coexist.

However, due to its fragility, along time strategies and technologies have been developed to improve the strength and failure behavior of this material. This section will describe the processes of toughening and heat strengthening of glass, followed by an overview of the failure behavior glass under these improvements. Finally, a description of the lamination solutions in glass is given.

### 1.4.1.Toughened

Toughened glass or tempered glass is the oldest technique of toughening glass presented in this section. This method consists of heating the glass "approximately 100 C above the transformation point" and then cooling it down rapidly. The result of this is that the outer surfaces of the glass cool faster

than the inside, getting stiffer; while the inside volume of the glass pane is still hot it tries to expand but is constrained by the already cooled surfaces, this generates internal stresses in the glass pane. The final result is that the external surfaces of the glass remain in compression while the inside is in tension.

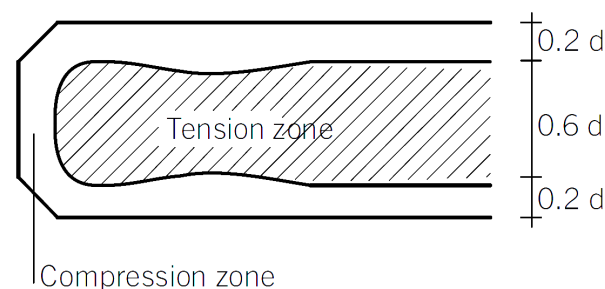


Figure 12-Illustrative section of a tempered glass pane showing the tension and compression zones

This method, first developed in the 19th century in France is based on a much older principle, that of the Prince Rupert's Drop, developed in the 17th century, in which a drop of molten glass was dropped on cold water, cooling it down rapidly; the drop of glass can resist a hammer blow but will disintegrate when its tail is cut.

### 1.4.2.Heat strengthening

Heat strengthened glass is produced by the same method as tempered glass, the difference between them is the speed in which the glass is cooled down. Heat strengthened glass is cooled slower, generating less stresses in the material. This distinction is noticed on the failure pattern and behavior of the glass.

Both toughening and heat strengthening processes may cause defects to the surface of the glass panes. "Because of its fluidity at higher temperatures, glass also is inherently susceptible to roller wave, bow and warp while it is being heat-treated".

### 1.4.3.Failure pattern and behaviour

The failure pattern and behavior of glass varies according to the process in which the material was treated. The production of float glass produces annealed glass, which then can be tempered or heat strengthened, by the method described above.

The Figure 13 illustrates the different breakage

patterns of the types of glass described above. Annealed glass breaks in larger and sharper parts, which can cause injuries. Toughened glass shatters into small pieces, which reduce the risk of injuries. Heat strengthened glass has a breakage pattern in between annealed and toughened, still generating sharp edges.

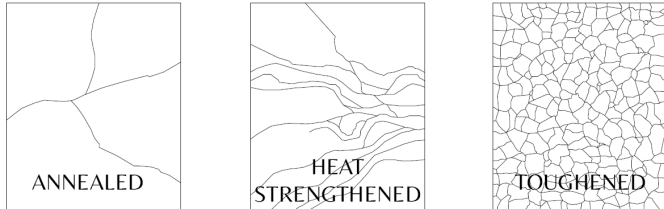


Figure 13-Breakage pattern of annealed, heat strengthened and toughened glass.

The choice between these different types of glass depends on the final use of the product. Certain uses require more resistance of the glass pane, in addition to that the breakage pattern has to be taken into consideration.

For instance, toughened glass may seem like the best option as it's small parts reduce the chance of injuries. However, this material "is much more likely to fall from the glazing system immediately upon breakage", while heat strengthened glass's "breakage pattern prevents the glass from falling and injuring someone". [4].

## 1.4.4.Lamination

Laminated glass consists of two or more layers of glass (or other materials) bonded together with an adhesive layer. It has been developed with the objective of making this material safer after breakage; if one of the layers of glass fails the panel still maintains residual structural integrity, and the shattered parts remain bonded to the adhesive. This technique was developed in the beginning of the 20th century, aiming the automobile industry with the objective of reducing injuries.

This has become a common solution for using glass structurally and safely as it avoids the sudden failure behavior and keeps the fragments from detaching from the panel. In addition, by this technique, it is possible to combine the different types of glass described in the previous section, taking advantage of their specific qualities.

The process of producing laminating glass starts by cleaning the individual glass panes; then they are

positioned and the interlayer is placed in between them and the ensemble is pressed together. Finally, it is put into the autoclave under "high pressure and temperatures of about 140°C" so the adhesive bonds completely to the glass sheets.

The dimensions of the autoclave become the size constraints for glass elements. "Specialist glass processing companies are able to laminate (...) sheets up to a jumbo panel size of 3.21 x 6m. (...) For special applications, companies (...) can produce laminated glass up to 12 meters long" [21].

The choice of the interlayer depends as well on the application of the panel. The most common interlayer used in laminated glass is "polyvinyl butyral (PVB film) because this material exhibits optimum mechanical properties for this type of usage plus high tear elongation and tear strength." [21].

Besides PVB, the most used interlayer materials used are cast-in-place resin (CIP), ethylene vinylacetate (EVA) and sentriglas plus (SGP). The latter, is a stiffer interlayer that was "originally developed for glazing in hurricane-prone areas" and differently than PVB it resists to high permanent temperatures; however, as its thermal expansion coefficient is higher than that of glass, "it is particularly necessary to consider long-term temperature stresses" [21].

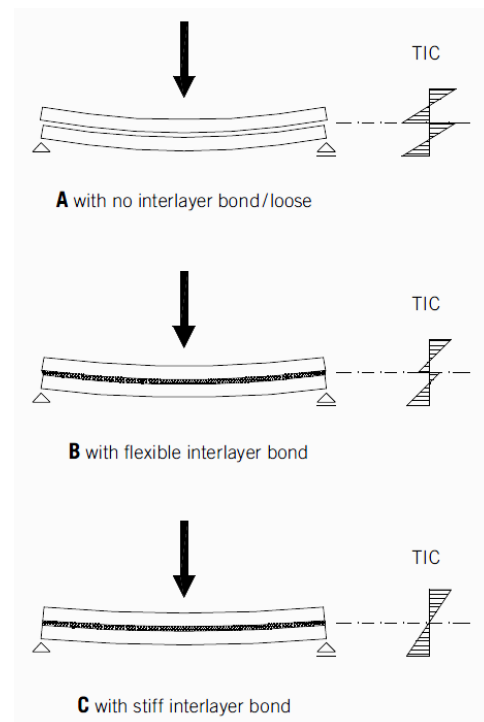


Figure 14-Shear stress distribution according to the characteristic of the interlayer in symmetric laminated glass panels



Lamination of glass can also be used to connect or even to reinforce glass elements.

As described in section 1.3 cutting glass damages the surface of glass, and if the cut surface is used as a connection point there will be concentration of stresses in the same area as the damage occurred before. This type of connection, although not ideal is commonly used in glass.

An alternative to this connection method is the lamination of metallic inserts in between the glass plates; the connection between the glass elements and other elements can then be done through these inserts. A very remarkable example of this strategy is the Apple store at New York, in which laminated inserts have been used to connect an all glass cube.



Figure 15-Apple store connection detail

Other than connection points, metallic inserts may also be used to reinforce glass beams. In the Delft university of Technology (TU Delft) this strategy has already been tested and researched along the last years. In the Figure 16 it is possible to see a reinforced glass beam still deporting the weight of five people even after cracking.



Figure 16-Laminated reinforced cracked beam supporting the weight of five people

## 1.5. Bending glass

Glass is not only constrained to flat plates; some applications require curved elements of glass, either for structural or architectural demands. This section will describe the techniques of bending glass.

### 1.5.1. Hot Bending

Glass is not only constrained to flat plates; some applications require curved elements of glass, either for structural or architectural demands. This section will describe the techniques of bending glass.

This technique follows the principles of the production of the material. Hot bending glass consists in heating the glass plate "at a temperature of about 600 °C" until it can be shaped in the desired shape.

However simple it might seem to be, it implies on the creation of specific molds for each of the desired shapes, making the process expensive.

### 1.5.2. Cold Bending

"In cold bent materialization, glass does not seem to be the most obvious choice." This is because cold bending implies in shaping the material in room temperature, to the desired shape. This technique is much cheaper than hot bending, as it does not imply in the creation of molds, and neither on the use of high amounts of energy to soften the glass plates.

However, in cold bending, stresses are introduced to the glass plates, which may reduce the final structural capacity of the panel; and limits the radius a glass plate can achieve. In addition, the frames or the interlayer have to keep the plates in place, which also might constrain the detailing of the final design.

## 1.6. Limitations

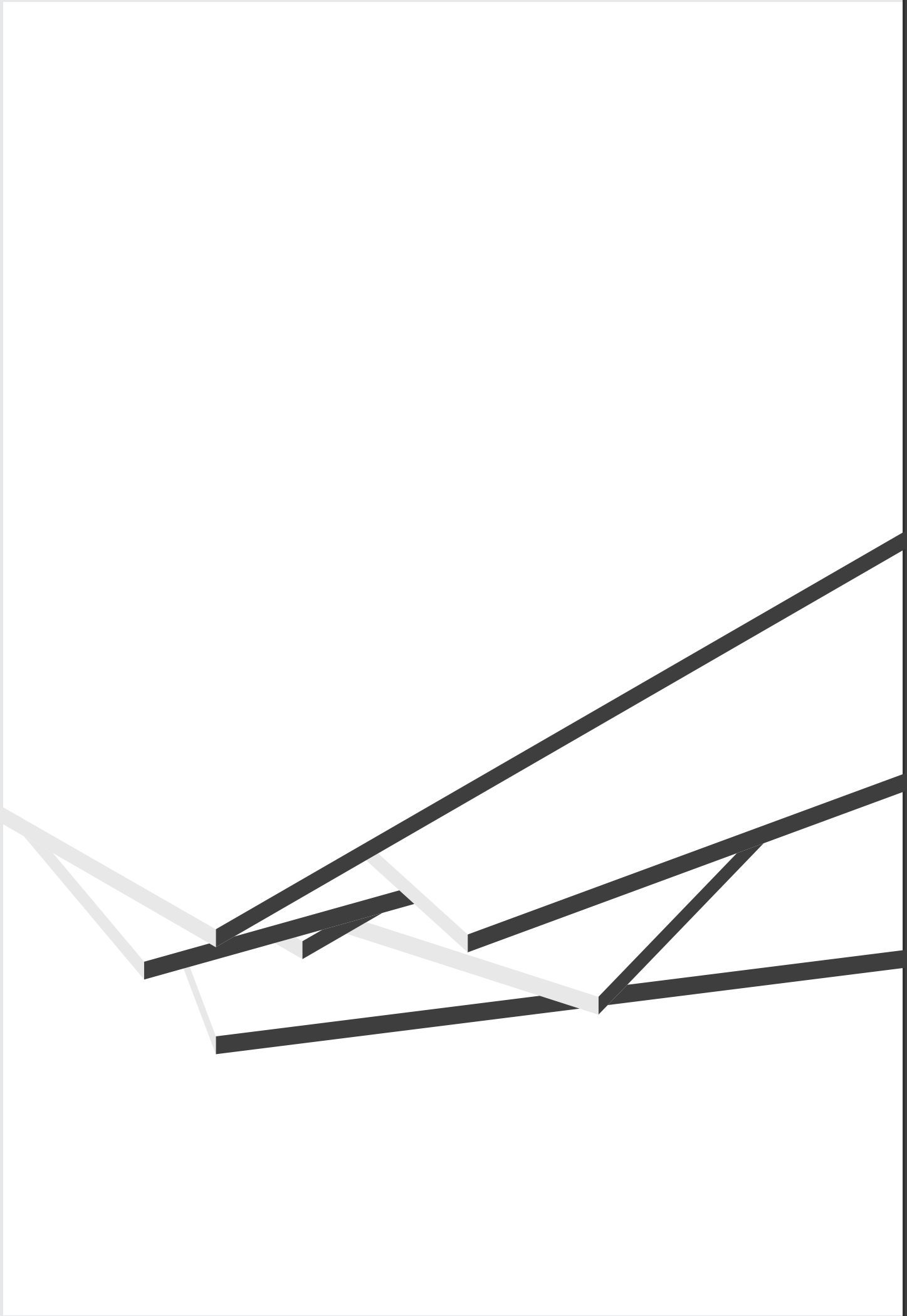
As described before, glass is a fragile material which has sudden failure behavior. In addition, due to the high slenderness ratio of a glass pane, it is vulnerable to buckle under loads that are lower than its material limits.

These characteristics lead to different solutions.

An alternative is to laminate multiple layers of glass together, so if one or more of them fail the remaining ones can take the loads; in addition, laminating many layers reduces the slenderness ratio of the element. However, this solution considerably increases the weight of the element, increasing the loads on the other parts of the structure.

Another alternative is to change the geometry of the glass pane, by adding curvature to it. As discussed in the previous section it is possible to make it by hot and cold bending, however the first is costly and the second has a low limit for curvature.

The next chapter will introduce (ultra) thin glass, a material that has the potential to overcome some of the limitations of float glass and be a feasible alternative to glass in some applications.



# (ULTRA) THIN GLASS

In this chapter, thin and ultra thin glass are going to be presented. Initially the history of this material will be presented, followed by its material properties. Then, the current applications of this material in the built environment. Finally, the potential of using this material will be discussed.



## 2.1.Introduction

Thin glass is considered under the thickness of 2 mm, as this is the minimal standard glass thickness of float glass (although thicknesses as thin as 0.1mm can also be achieved by this process). As of ultra thin glass are usually classified as glass under the thickness of 0.1 mm (100 $\mu$ m); as for the current date, glasses at the thicknesses of 25  $\mu$ m (0.025mm) are already being produced.

The Figure 17 illustrates a comparison between the common float standard glass thicknesses until the ultra thin glass that can be produced.

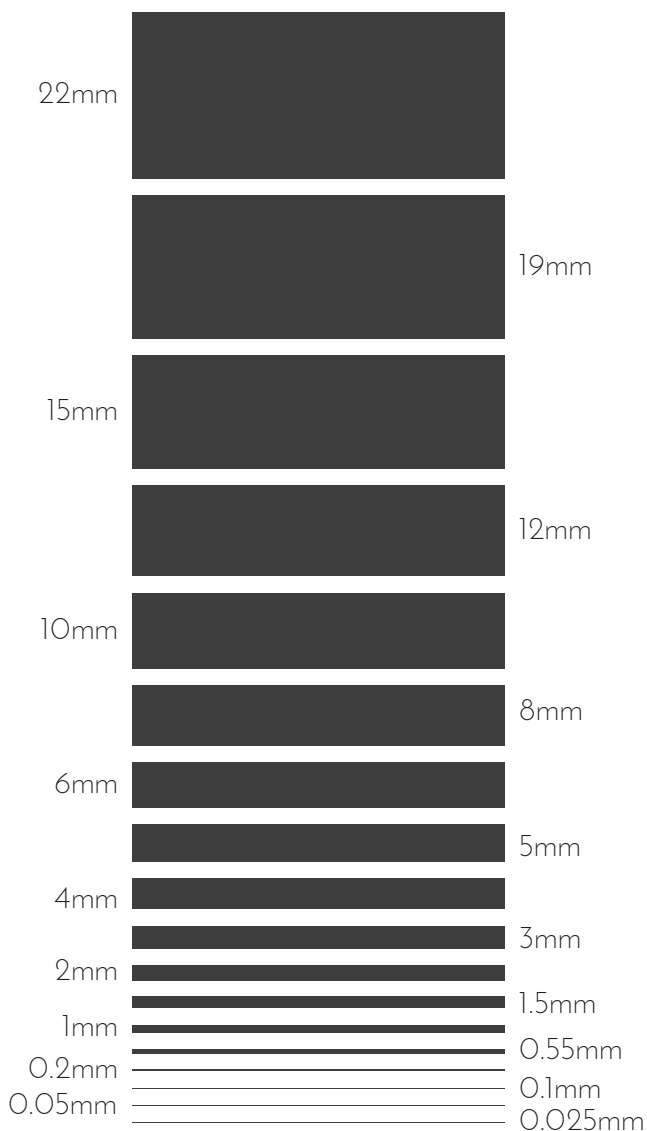


Figure 17-Glass thicknesses at 1:1 scale - from 22mm to 25 $\mu$ m

Although this material may seem like a very exclusive material used for very special purposes, it is very common on smartphones and mobile devices; the evolution of this products in the past decade has pushed the glass industry to produce ever thinner

and harder products, attending to the necessities of scratch and fall resistance and low weight.

## 2.2.Material Properties

Thin glass material properties depend its composition; "typical glass types used for thin glass are borosilicate glass, aluminosilicate glass and the well-known float glass"[2] (or soda lime glass).

Considering these three types of glass, some general characteristics may already be presented. Float glass, although thinner, maintain the same material properties as described in the Section 1.2; borosilicate glass has excellent chemical durability and thermal resistance; aluminosilicate glass, however, presents a "comparatively high Young's modulus, hardness, fracture toughness, chemical durability, lower coefficient of thermal expansion and reduced electrical conductivity"[6] associated with high softening points.

Due to its capacity of withstanding mechanical influences, aluminosilicate glass "have thus far primarily been used in technical glass, for example, as cover glass in the electronics industry or as glass substrates in laboratories and bio-technology"[2].

However, the most remarkable characteristic of this material is its allowance for deformation.

Due to the particularities of the manufacturing process (not considering the float glass process), thin glass has a surface with higher quality, with an almost flawless result, as the glass surface does not have contact with any solid during its production. The surface quality together with its higher strength, make thin glass more resistant to bending stresses, allowing it to bend to smaller radius. The minimum radius this material can bend is directly related to its thickness. Generally, the thinner the glass the smaller the radius it can achieve without breaking.

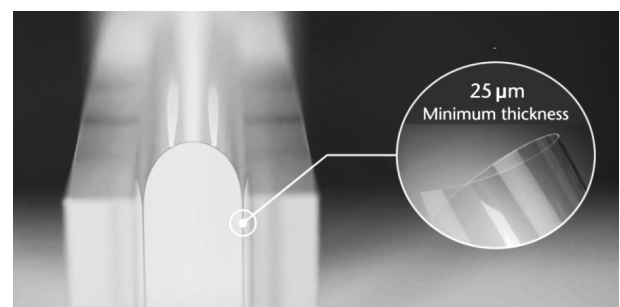


Figure 18-Bended 25 $\mu$ m glass sheet

Table 2-Aluminosilicate glass material properties [6]

<b>Density</b>	2.49e3 - 2.54e3	kg/m <sup>3</sup>	<b>Shear Modulus</b>	33.9 - 35.6	Gpa
<b>Young's Modulus</b>	84.8-89.1	GPa	<b>Poisson's ratio</b>	0.23 - 0.22	-
<b>Tensile Strength</b>	39.9 - 43.9	MPa	<b>Hardness - Vickers</b>	477 - 525	HV
<b>Elongation</b>	0.04 - 0.05	% strain	<b>Fatigue Strength</b> (at 10 <sup>7</sup> cycles)	35.6 - 39.4	MPa
<b>Compressive Strength</b>	376 - 414	MPa	<b>Fracture Toughness</b>	0.7 - 0.72	MPa.m <sup>0.5</sup>
<b>Flexural Strength</b> (modulus of rupture)	48.9 - 53.8	MPa	<b>Thermal Expansion</b> coefficient	4.5 - 4.69	µstrain/°C
<b>Shape Factor</b>	15	-			

The Table 2 gives an overview of the material properties of aluminosilicate glass. Comparing the values of this table with Table 1 (which refers to the material properties of soda lime glass) it is clear that aluminosilicate glass is a stronger material. The most remarkable changes are the young's modulus which is about 20GPa higher; the hardness of the material, which is around 5 times higher; and the thermal expansion with is about half as of the soda lime glass.

In addition, this glass does not contain iron, so the glass has higher optical quality, the edges do not present the common green tone of soda lime glass (which happens because of the iron in the composition).

### 2.2.1.Production

As mentioned before, thin glass is usually produced by a different process than soda lime glass; "thin glasses are produced using different processes: the float process, the down-draw process or the overflow-fusion process" [2]. In this section the overflow-fusion process and the down-draw process are going to be explained, as the float process has been described in Section 1.3.

The basis of the overflow-fusion process has been patented by Corning in 1964 aiming at the automobile windshield industry. However, at that time, there was very little, or no market for that kind of product. This changed in the 80's with the need for thin and flat glass for LCD screens, and this production technique started to be further developed.

Currently the overflow-fusion process follows the same principle as in 1964. The process starts by the melting and mixing of the raw materials, producing molten glass. This composition is then poured onto a bath until it overflows its capacity simultaneously by both edges. The molten glass flows over the outer surfaces of the bath and when

it reaches its bottom the two flows join each other. The resulting molten material flows down vertically by gravity. The glass then cools down as it flows without getting in contact with any surface. When the composition is stiff enough, the plate is cut and stored. The Figure 19 illustrates this process.

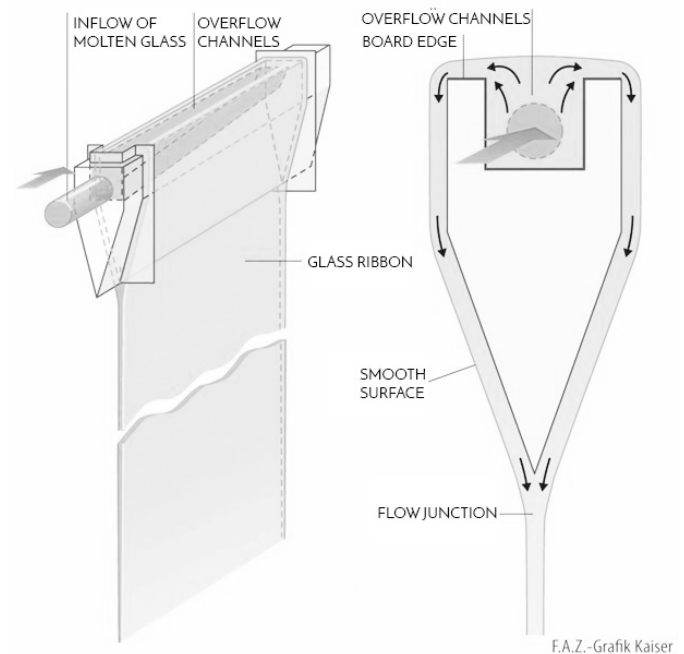


Figure 19-Overflow-fusion process

The down draw process has been already patented in the 1970's. However, like the overflow-fusion process, the market for this type of product was developed later. This process is very similar to the overflow-fusion, the difference is that "the molten glass is pulled down out of a furnace through an orifice" [2]. After leaving the orifice the glass ribbon is already annealed and then cut in panels.

An interesting development possible due to the development of these processes - float, the down-draw or overflow-fusion - is the possibility to create (ultra) thin glass rolls over a 100 meter long.

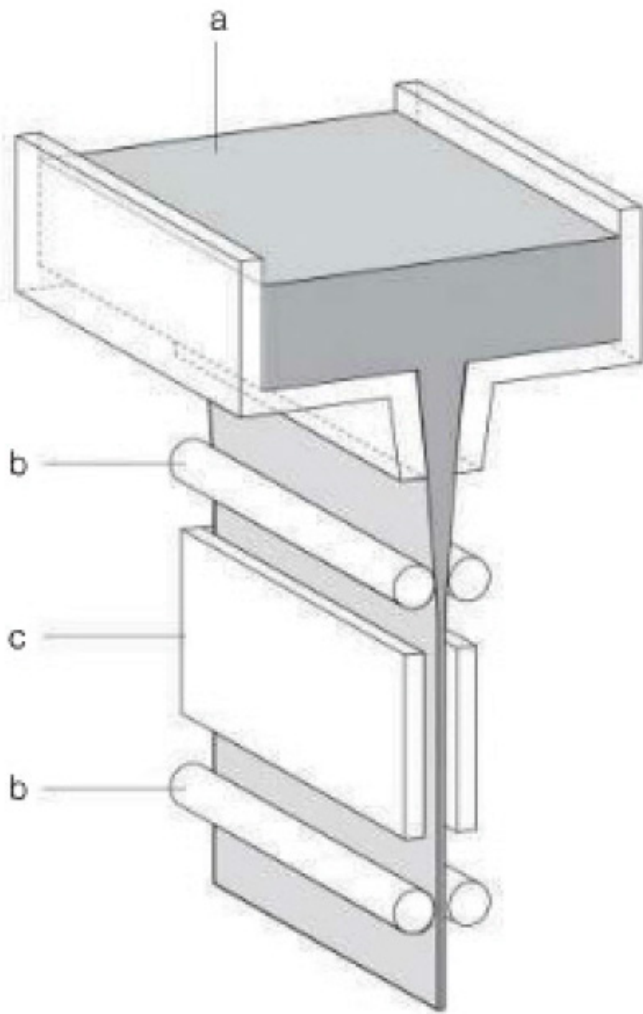


Figure 20-Down draw process

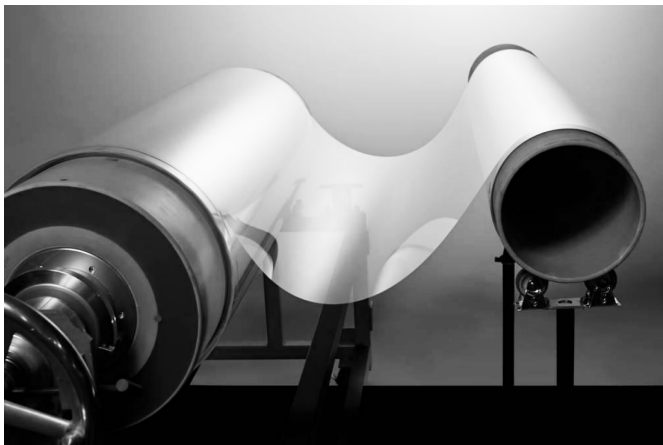


Figure 21-Ultra thin glass roll. 0.05mm thick and 100m long

## 2.2.2. Chemical strengthening

In order to improve the material properties of thin glass this material is usually pre-stressed by chemical strengthening, this section is going to elaborate on this strengthening method.

Although also suitable for glass of larger thicknesses this process is more appropriate for thinner

glass sheets - "whereas it is very hard to provide reinforcement to glass thinner than 2mm on an industrial thermal tempering installation" [10] - and therefore was not addressed in section 1.4.

Chemical strengthening is a process that aims to increase the surface compression of glass. The resulting principle is the same as toughened and heat strengthened glass (Section 1.4) a compressive zone in the outer surfaces of the glass and tension in the inner ones (Figure 12)

In Figure 22, it is illustrated a comparison of the stress distribution in the cross section of these types of strengthening of glass. It is possible to see, that the compression layer of chemically strengthened glass is much thinner than that of toughened or heat strengthened.

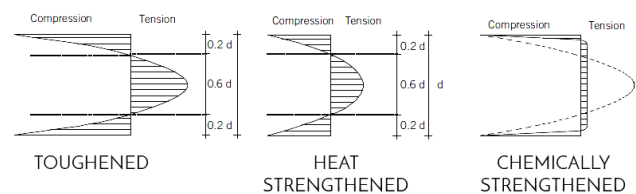


Figure 22-Stress distribution comparison by strengthening process

However, chemical strengthening consists in a process of ion exchanging instead of thermal shock. "In this process, stresses between the outer and inner layers of glass are introduced by placing the panes in a hot salt bath. In this manner, ions on the glass surface are replaced by other ions with a larger radius and the pre stressing is achieved."

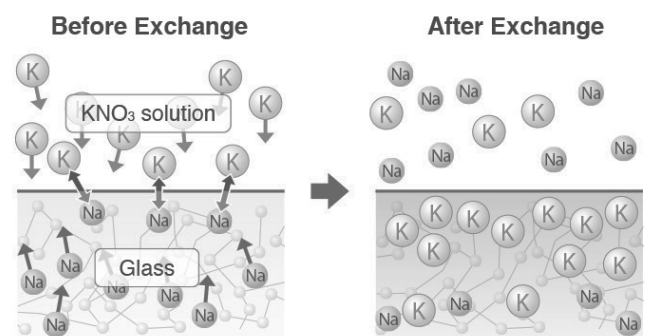


Figure 23-Chemical strengthening ion exchange

This method allows the strengthening of complex shapes, as the material is immersed in the solution, which is "not feasible with thermal tempering" [10]. However, "the maximum dimensions are limited by the size of the tubs holding the salt bath" [20], so larger elements are not yet possible to be chemically strengthened.

The result of this process is a surface compression of a minimum of 230MPa [13], which is much higher than that of toughened (90MPa), heat strengthened (40MPa) or annealed (20MPa) glass [18].

Some of the major thin glass producers – Corning, AGC and SCHOTT – have optimized their (ultra) thin glass production to chemical strengthening, in Appendix O1, a specification sheet for the products of each of these manufacturers. According to these specification sheet, Gorilla glass (Corning), Leoflex (AGC - Asahi Glass corporation) and Xensation (SCHOTT) can achieve a compressive strength of: >800MPa, >600MPa and >900MPa respectively.

### 2.2.3. Breakeage behaviour

Although strong, when under stresses above its maximum supported, chemically strengthened glass fails. As a still developing technology, (ultra) thin chemically strengthened glass properties are not completely studied and understood. This also applies for its breakage behavior.

Chemically strengthened glass has a breakage pattern similar of that of annealed glass, “a monolithic sheet of chemically strengthened glass is not safety glass” [20].

However, the thickness of the glass may influence the breakage behavior; “when chemically strengthened glass is broken there is no such fine

dicing of the glass, except when the glass is very thin, with thickness of the order of few hundreds of microns” (E. Bouyne et al. Glass Technol. C 43 (2002) 300-302. apud [10]).

Others state that thin chemically strengthened, “breaks into much smaller fragments, almost exhibiting a powder like state” [11].

Further research is necessary to determine the correct breakage pattern of this material and if it can be used in a single layer or not. Currently, the best alternative is to use it laminated, in a way that if it fails, the fragments remain attached to the panel.

### 2.2.4. Bending radius

As discussed before, the most remarkable characteristic of (ultra) thin glass is its bending resistance, allowing it to assume curved shapes. There is a relation between the thickness of the glass and its maximum bending radius; generally, the thinner the glass the more it can be bent. The Chart 3 shows a calculated [16] comparison of different glass thicknesses relating it to the stress generated in the top layer by bending it to different radii.

Again, considering this property, more research needs to be done, testing this property of the material and seeing if the calculated values correspond to the real behavior of chemically strengthened thin glass sheets.

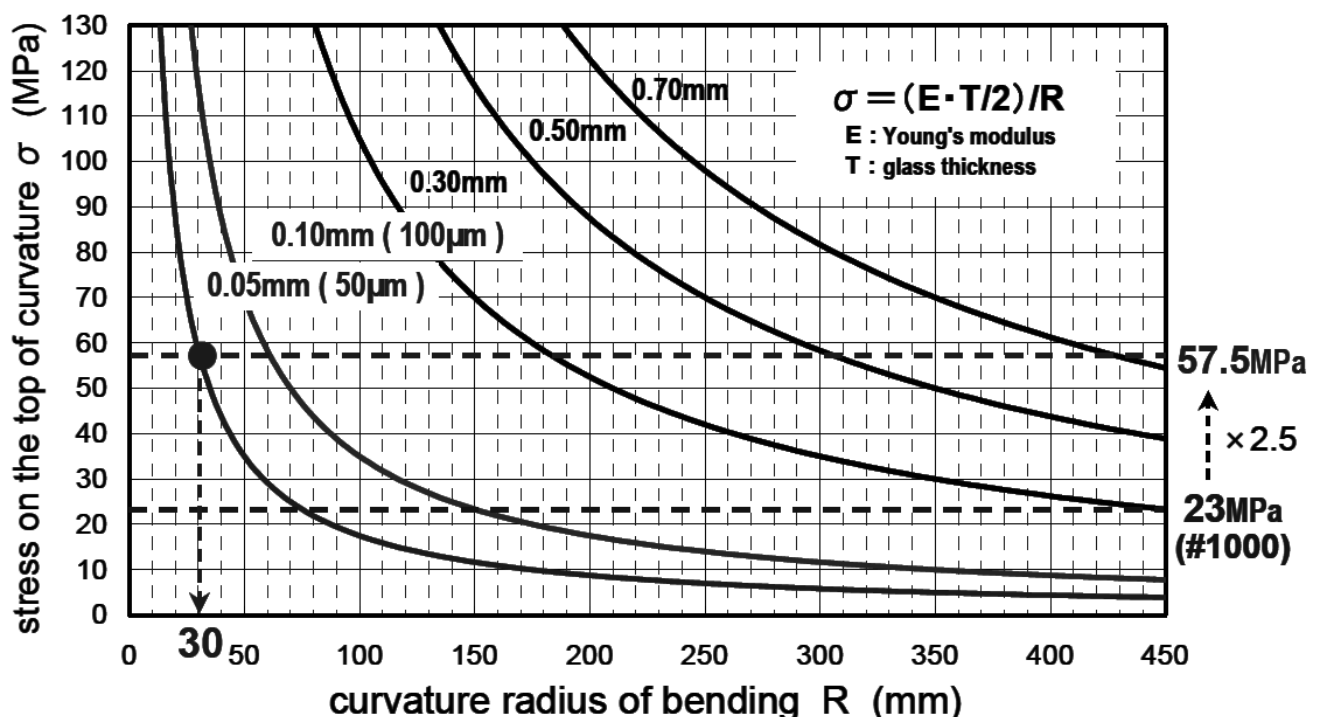


Chart 3-Stress generated by bending different glass thicknesses.[16].



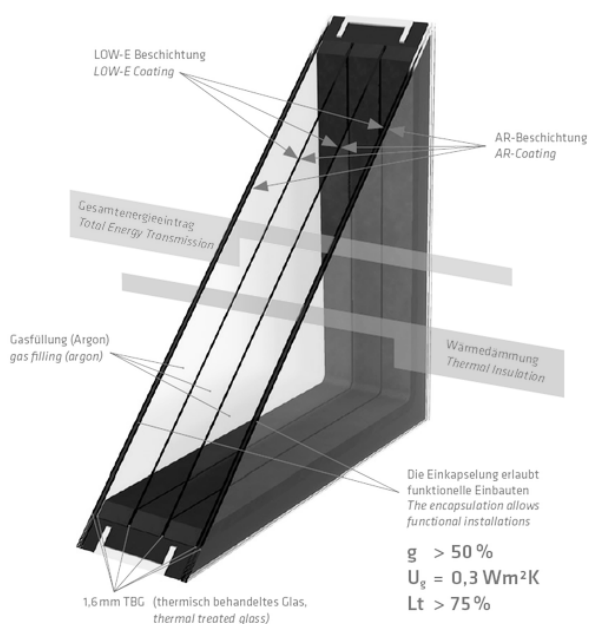
## 2.3.Current Applications

Although available in smartphones and other electronic devices for some years, (ultra) thin glass is still on its first steps in the built environment. In this section, the current applications of this material are going to be presented.

One of the currently most developed applications of this material is at the production of high performance windows. The high market demands for windows with low thermal transmittance, and the development of passive house systems increased the demand of high insulating windows in the last decade. One solution for this demand was the creation of triple glazed systems. However, as the amount of layers of glass increases, the weight of the windows also does.

To overcome this problem, thin glass was selected as a very feasible solution. Having the same optical and heat capturing properties as common glass, but with much reduced weight, thin glass is currently being studied as the middle glass layer of the triple glazed window system.

There is also a European commission funded project studying the feasibility of quadruple glass windows with two thin glass layers, approaching U values of  $0.3 \text{ W/m}^2\text{K}$ .



Schnittmuster der neuartigen IG-Einheit | section of the novel IG-unit

Figure 24-Quadruple window system with thin glass layers

Another example of the use of this material was in the World Cup of 2014. In this event, the player benches were designed to provide maximum transparency, reducing reflections, weather and impact resistance. This was achieved by using thin glass as the main protection material, used in the roof and back side of the benches.

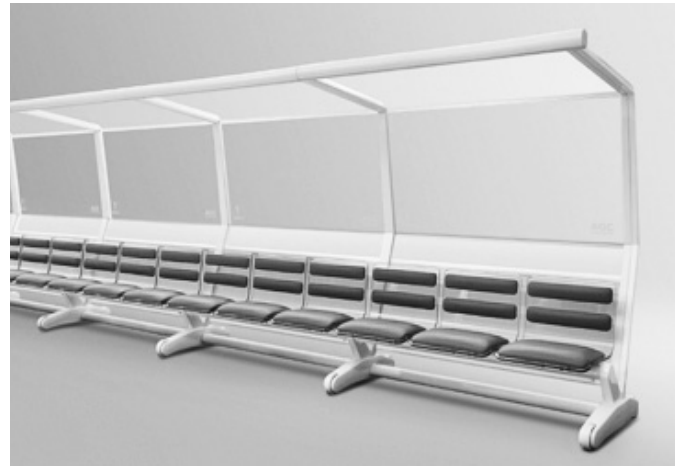


Figure 25-2014 World Cup bench

A different application for this product was also found by one of its main producers. Corning has developed an alternative use for its Gorilla Glass. Due to the impact and scratch resistance of thin glass, together with its optical qualities, this material is currently being used as a protective layer in interior architecture, mainly targeted at elevator's interiors. Its use as an external layer allows the lamination of panels behind it, which can be exhibited with high optical quality, without being susceptible to damages.



Figure 26-Interior architecture panels protective layer.

The last example is an experimental study, developed by Jürgen Neugebauer, and realized by SFL Technologies at the GlassTec 2014 in Dusseldorf. It consists of a movable glass canopy, which can be expanded and contracted in two directions. The

interesting aspect of this example is that it shows the adaptability of thin glass, which can be bent into a double curved geometry and then moved back to its original state.

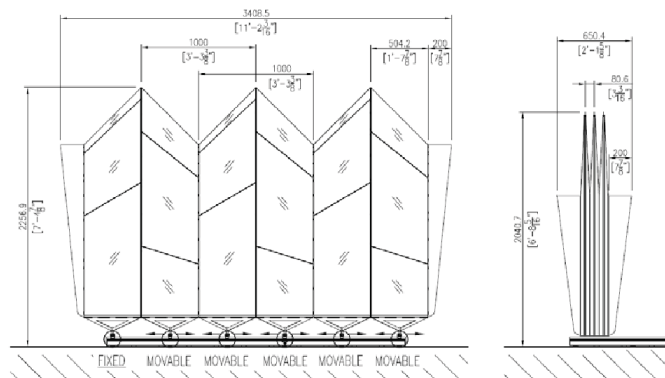


Figure 27-Thin glass movable canopy design



Figure 28-Thin glass movable canopy realized

## 2.4.Potencial and Challenges

As a new material to the building industry, thin glass has not yet been extensively applied or explored in the field. As the previous section showed, there are sparse and very different examples for the use of this material, it has not been developed a consistent use for it in the building industry.

The applications mentioned before, show some of the potentials of using this material, its lightweight, toughness, optical qualities, weather and bending resistance allow it to be use in a multitude of ways.

In some applications, thin glass can be a potential

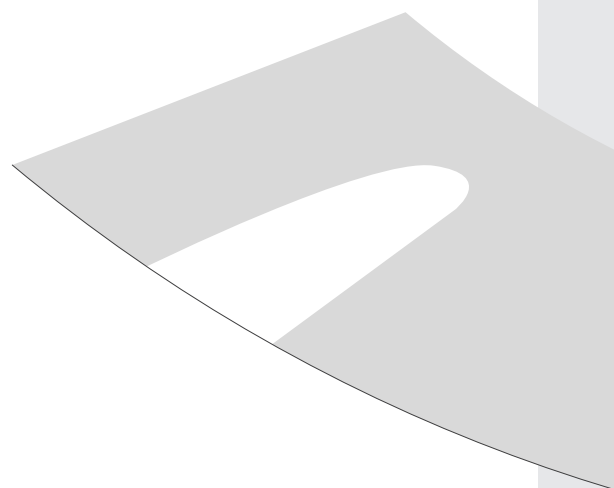
substitute for thicker glass. As mentioned before, glass elements tend to be heavy because of the necessity of laminating multiple layers (either to increase its stiffness or for safety reasons). Thin glass has the same or better strength characteristics as common glass, however, as it is much thinner it weights much less. In the previous section the insulating window example explores this characteristic.

But this change could be much more ambitious, thin glass could be used as a substitute for glass in façade panels, structural elements, curved elements, roofs, etc.

One of the greatest potential and challenges about this material is its bending properties. Compared to soda-lime glass, thin glass (i.e. with other compositions than soda-lime glass; taking aluminosilicate glass for example) can bend to much smaller radius, allowing the creation of curved geometries without the necessity of hot bending.

However, this also becomes one of the main challenges considering this material; which is how to stiffen it. As in common glass elements, the necessity of stiffening it asks for the increasing of layers, or geometry adaptation.

The next chapter will elaborate on the exploration of geometries to use thin glass in multiple applications in which glass is commonly employed.





# EXPLORATION

In this chapter, the possibilities of using thin glass in the built environment will be explored. Applications will be divided in groups in which the explored possibilities will be presented. This chapter is concluded explaining the direction of the research.



## 3.1. Analysis of Possible Uses

After studying the material properties of thin glass and analyzing the current uses of this material in the building industry I started to explore additional possible applications for this material in this field. Considering the classification of forms elaborated by Wurm [21], I selected four main geometry types or applications - *Structural elements, flat panels, single radius elements and double curved elements* - in which glass is used in the built environment and then explored possible alternatives using the thin glass technology.

### 3.1.1. Structural Elements

The first category that was explored was that of structural elements. Structural elements in glass, such as beams and columns, are applications which have been developed in the last decades and are still under research and development.

Considering the column, buckling can be considered as the biggest challenge; although glass has a very high compressive strength, a glass plate will tend to buckle under loads lower than its material capacities. To prevent this, it is possible to adapt the geometry of the element in order to increase the moment of inertia, increasing its buckling resistance.

In this case, thin glass could be an alternative due to its high flexibility, as it would be simpler (cold bending) to create curved geometries to prevent the buckling behavior. The Figure 29 shows some of the geometries explored considering 0.5mm glass elements and a minimum bending radius of 150 mm.

Another advantage of using thin glass in these elements is its impact resistance, necessary to keep the integrity of this element against possible accidents.

However, a disadvantage of using this material would also be related to its flexibility. As the integrity of the column depends on its shape to be stable, if any part of the surface is deformed due to an impact the structural integrity could be compromised. Therefore, there is always the necessity of having another element to prevent the failure

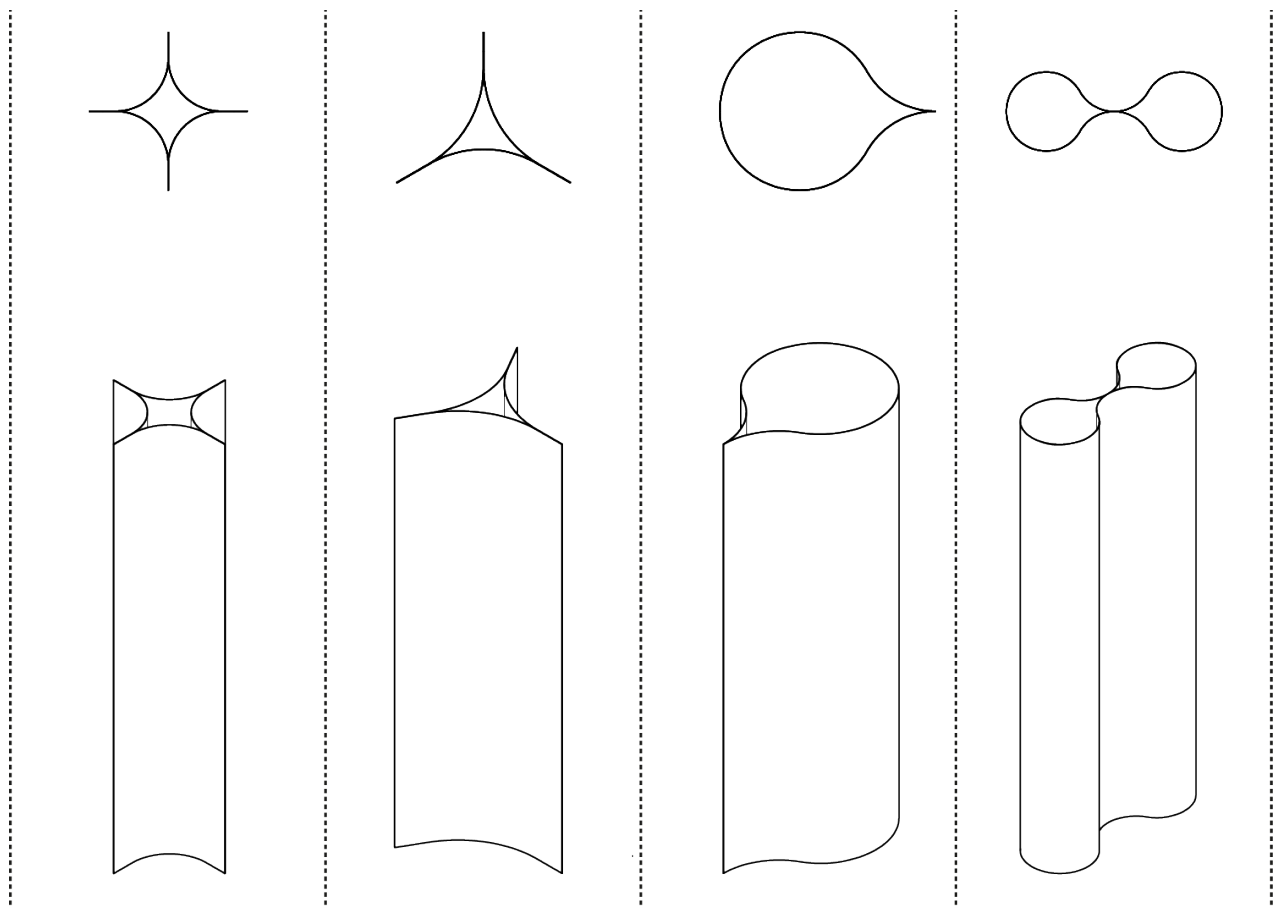


Figure 29-Geometry exploration for glass columns in thin glass. Plan and isometric views.

of the column in case the thin glass layer fails (this is already a standard practice considering glass design).

A possible way use thin glass in glass columns would be as a protection layer to other glass elements. Considering its high impact resistance, this application would also suit well with the necessities of a glass column. For example, taking the last geometry illustrated in Figure 29 it would be possible to associate it with glass tubes in its interior, following the same principle presented in the laminated glass column [15].

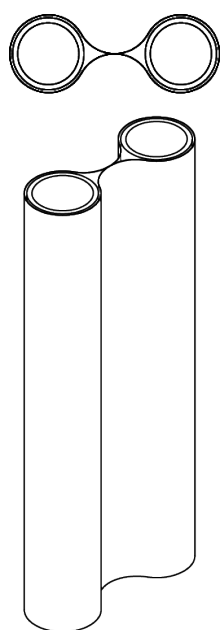


Figure 30-Example of column assembly using thin glass as a protection layer. Plan and isometric views.

Regarding the glass beam, one of the major structural challenges is reduction of tensile stresses on the bottom of its cross section. As described in Section 1.4.4 solutions like higher tension resistant materials (as steel) can be an interesting alternative to prevent these stresses. Considering thin glass, it faces the same challenges of glass regarding tensile stresses, so it does not provide a solution regarding this problem.

However, as in the column examples, it can be used to adapt the beam cross section to increase its moment of inertia and therefore, its resistance to bending moments (reducing stresses in the element); Figure 31 shows an example of this reasoning.

As a conclusion, structural elements in thin glass can most benefit on the properties of flexibility of this material. As described in the previous paragraphs, changing the cross section of the structural element

can improve its performance.

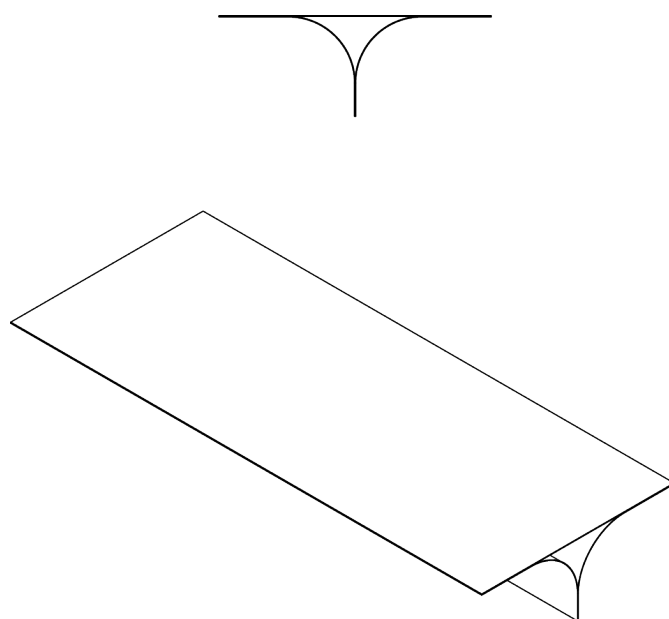


Figure 31-Geometry exploration for glass beams in thin glass. Section and isometric views.

In the other hand, the flexibility of this material can be also be considered as a disadvantage, the glass element can become susceptible for deformations and lose its integrity.

However, as mentioned before, thin glass can be used as a protection-sacrificial layer for glass structural elements. This can be very beneficial considering the low mass of thin glass plates, reducing the total dead load of the glass element.

### 3.1.2.Flat panels

The next category explored was that of flat panels.

As discussed before, flat panels are a big challenge considering the weight of the elements – due to the number of layers of glass necessary to provide safety and structural stability.

One of the possibilities to stiffen glass panels is to improve its geometry, using the same strategy as described in the previous section, to improve its moment of inertia.

In this section two different categories of flat panels will be explored: one and two layered panels. This distinction was made regarding the different possibilities each of these typologies may bring and how can then relate to common uses of glass in the built environment.

### 3.1.2.1. One layered flat panel

Considering one layered glass panels, applications could be double skin facades, interior partitions or facades that do not require insulation properties.

The advantages of using thin glass in this applications are mainly the flexibility (for cold bending) of the material – that again allows geometry adaptation – its impact resistance and its lightness. These are important qualities for the applications described before.

The Figure 32 shows the exploration of geometries regarding this application.

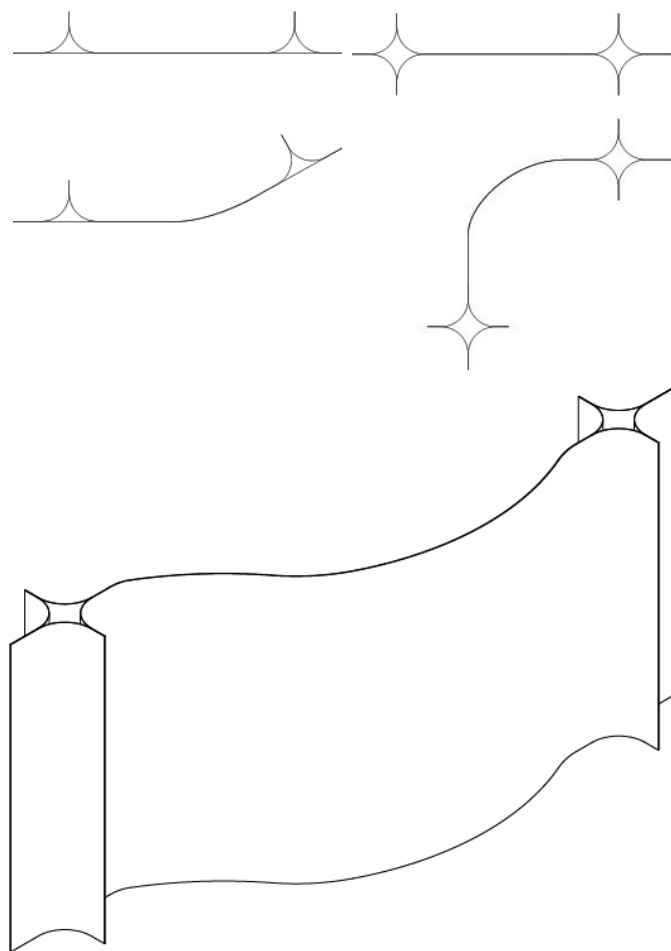


Figure 32-Geometry exploration for one layered glass panels. Plan and isometric views.

Although thin glass allows these applications, flat thin glass elements are susceptible to wind pressure – both positive and negative. Due to the flexibility of the material, it moves, generating noise (a similar behavior as paper when facing wind forces). This may cause discomfort to users.

For window panes, however, it is possible

to achieve an interesting solution by laminating thin glass panes to a stiff interlayer. In this way, the interlayer would keep the thin glass from oscillating by wind, while still providing a light weight solution.

For interior applications however, these solutions are very suitable and practical. The possibility of cold bending this glass allows for the adaptation of the panel to the space it means to divide.

### 3.1.2.2. Two layered flat panel

Regarding two layered glass panels applications could be insulated facades and window frames for instance.

As for this category the same advantages of thin glass apply. The flexibility of the material allows for bending it to make it stiffer, in addition, it is possible to laminate different glass layers together, stabilizing the panel.

The experimentation regarding this application took in consideration the same bending constraints as described in 3.1.1. Due to this reason, the panes acquired a big cavity in between them, of around 300mm. All the geometries explored took in consideration the stiffening of the panel by curvature of the laminated layers.

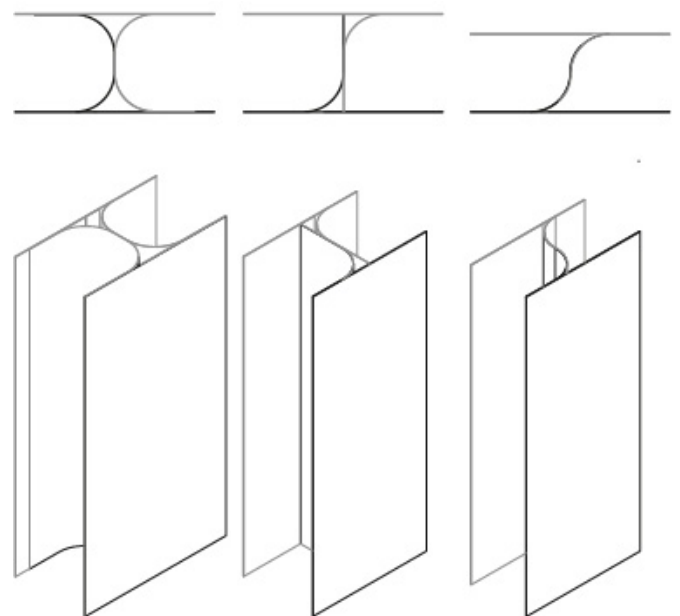


Figure 33-Geometry exploration for two layered glass panels. Plan and isometric views.

Due to the constraint of big cavity sizes, it would be complicated to fit these panels in window frames.

In addition, also for insulating purposes, the

size of the cavity might become an obstacle as it allows for convection of air, reducing the insulation performance of the panel.

Smaller cavity sizes could be achieved by using thinner glass; however, it would still be limited to a bending radius of around 50mm.

However, these examples could work as façade glass panels, ranging bigger spans; as they have low weight, high visual quality, stiffness and weather resistance.

### 3.1.3. Single Radius

The third category explored was that of single radius glass elements.

In the built environment, these elements are usually employed for roofs or for façade panels. Depending on the desired radius these elements can be hot (smaller radii) or cold (larger radii) bended.

Considering thin glass, its flexibility is again the characteristic that most relates to this application. Cold bended, thin glass elements can be used for most of the applications requiring single radius bending. Figure 34 shows an example of a barrel vault in glass, as an example in which thin glass would also be a suitable material.



Figure 34-GUM arcades in Moscow, 1893.

In addition, as discussed before, bending glass is a strategy for increasing its stiffness, which helps to prevent the oscillating effect mentioned in Section 3.1.2.1. Figure shows an example of a façade panel in which glass was bended to increase its stiffness, as an example in which thin glass could also be employed.



Figure 35-MAS Museum in Antwerp.

### 3.1.4. Double Radius

Generally speaking, the interest in double curvature shapes has increased in the last decades. The development of new production techniques (such as laser cutting and CNC [computer numerical control] milling), together with parametric design, has pushed the boundaries in the construction industry. This also applies to glass; currently, more complex geometries are required to be produced using this material. According to the radius desired by the design, glass can be hot or cold bended. As single radius elements, double radius glass elements are usually found in roof and façade applications.

Thin glass can also be applied to this category of glass elements. Taking advantage of its flexibility, thin glass can be used to produce cold bended double curved glass elements, one example of this is the glass canopy (Figure 28) mentioned in section 2.3.

However, considering this application, there is a constraint to the use of thin glass. Due to the material properties of thin glass, it does not allow for elongation and therefore, no strains can be generated by bending this material. This characteristic limits the generation of double curved glass geometries to those in which the Gaussian curvature is equal to zero; or to simplify the shape to developable geometries.[22]. For instance, a cone is a double curved geometry, with a gaussian curvature that equals zero.

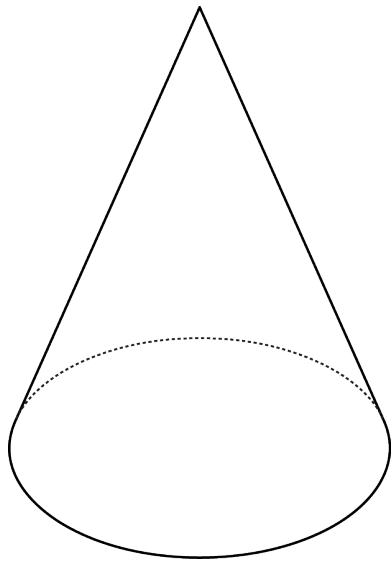


Figure 36-Cone, as a zero gaussian curvature geometry.

## 3.2. Conclusions for further exploitation in the research

The process described in the previous section helped me to get a further understanding on thin glass and the possibilities for using it in the built environment. After exploring different applications, it is clear that the most remarkable characteristic of this material is its flexibility, besides that it was shown that it has also the possibility of adapting to the necessities of application. It is also interesting to mention that, after cold bending, this material does not retain the shape in which it was bended, and therefore can return to its original shape or be bended into a new one.

By analyzing the material properties, current applications and exploring possible applications for this material it was possible to respond to the initial research question of this thesis which looked into finding an adequate and logical application for this material in the built environment.

I believe that this application should aim to take advantage of the properties of thin glass, both those similar to common glass and those exclusive of thin glass. This means that this application should be connected to transparency, but also to flexibility and adaptability.

After concluding the first phase of this research I believe that the direction to be explored now is that

of finding an adequate application of thin glass regarding adaptive transparent curved panels.

This relates closely to adaptive structures, such as roofs of facades, as they open or close to collaborate with the environment (for instance, ventilation and temperature) inside a building.

One of the most traditional examples of these structures is a glasshouse, like the ones who, in the 18th century, expanded the possibilities of glass architecture. Glass houses usually have openings which can be operated to control the temperature inside of it.

Adaptiveness is a quality that is being much explored in facades nowadays, with the development of parametric and programming in architecture. This means that adaptive elements can be programmed to respond to the environment, without having to be controlled by the users.

These concepts will be further explored in the next phase of the research together with the use of thin glass in this context.

# PLANNING

This chapter explains the planning for the next steps of the research. It starts by discussing the expected actions to be taken and concludes with the planning for the further phases of the research.

## 4.1.Expected actions

The result of the first phase of the research was a better understanding of the material itself and the direction of the research.

The second phase (P2-P3) of the research will focus on the development of a design or a case study to apply the concept of adaptive glass panels/structure. At the same time, material (Aluminum) will be ordered to the development of study mockups/scale model. The progress of the design/case study and mockups will be followed by FEM models to analyze the structural behavior of the design/case study.

The third phase (P3-P4) of the research will focus of the development of a mockup/scale model in thin glass of the final design/case study. At the same time, laboratory tests will be performed to be compared to the numerical calculations.

The last phase of the research (P4-P5) will focus on reflections about the outputs of the research and suggestions for further developments and studies of this material.

The outcome of this research will be a better insight on the material properties of thin glass and the possible applications of this material in the built environment.

## 4.2.Planning for the next phases of the research



ACTIVITY		P1										P2	
		2.1	2.2	2.3	2.4	2.5	2.6	2.7	2.8	2.9	2.10		
Understanding the material and adequate application	90%												
Literature study/review	100%												
Finding current applications/experiments	100%												
Research on material properties	75%												
Geometry Exploration	100%												
Report writing													
Finding case study/ Developing design proposal	0%												
Research on possible case study	0%												
or	0%												
General design proposal	0%												
Development of design solutions	0%												
3d models	0%												
Ordering mock up material	0%												
Numerical models	0%												
Mock up studies	0%												
Analysis of design solutions	0%												
(considering numerical models and mockups)													
Selection of solution to be further developed	0%												
Analysis of possible improvements	0%												
Improvements of design solution	0%												
Ordering material for final mockup/scale model	0%												
Final FEM model	0%												
Build you mock up/scale model	0%												
Analysis of FEM model	0%												
Analysis of mockup/scale model	0%												
Conclusions of results	0%												
Reflections of reserch possible improvements	0%												
Improve final results	0%												
Reflections over recommendations for further projects	0%												





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Figure 7 - Foster and Partners. Available at: <http://www.fosterandpartners.com/projects/apple-store-zorlu/>.

Figure 8 - University of Cambridge. Available at: <http://www.doitpoms.ac.uk/tlplib/BD5/results.php>.

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# Appendix

## Appendix 01.



### Specialty Glass Materials Products & Specifications

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#### Corning® Gorilla® Glass

Is an environmentally friendly alkali-aluminosilicate thin sheet glass. Its superior composition allows a deeper layer of chemical strengthening than is possible with most other chemically strengthened glasses, making it durable and damage resistant.

##### Benefits:

- Glass designed for a high degree of chemical strengthening
  - High compression
  - Deep compression layer
- High retained strength after use
- High resistance to scratch damage
- Pristine surface quality

##### Applications:

- Ideal protective cover for electronic displays in:
  - Handheld devices and instrumentation
  - Laptops and tablet computer screens
  - Mobile devices including smart phones
- Touchscreen devices
- Optical components
- High strength glass articles

##### Dimensions:

- Available thicknesses 0.55 mm - 2.0 mm
- Non-standard sizes may also be available upon request
- Available in Gen 5 - 49.21 x 35.43" (1250 x 900mm) sheets

##### Viscosity:

- Softening Point (107.6 poises) 852°C
- Annealing Point (1013.2 poises) 613°C
- Strain Point (1014.7 poises) 563°C

##### Properties:

- Density 2 .44 g/cm<sup>3</sup>
- Young's Modulus 71.7 GPa
- Poisson's Ratio 0.21
- Shear Modulus 29.7 GPa
- Vickers Hardness (200 g load)
  - Un-strengthened 625 kgf/mm<sup>2</sup>
  - Strengthened 674 kgf/mm<sup>2</sup>
- Fracture Toughness 0.7 MPa m<sup>0.5</sup>
- Coefficient of Expansion 84.5 x 10<sup>-7</sup>/°C (0 °C - 300 °C)

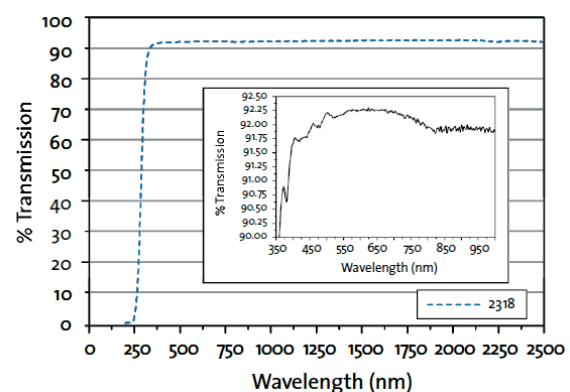
##### Chemical Strengthening:

- Compressive Stress Capable ≥800 MPa
- Depth of Layer Capable ≥40μm



##### Optical:

- Refractive Index (633nm)
  - Core Glass 1.5094
  - Compression layer 1.5116



**Chemical Durability:** Durability is measured via weight loss per surface area after immersion. Values are highly dependent upon actual testing conditions. Data is reported for Code 2318 glass. Unless otherwise noted, concentrations refer to weight percent.

Reagent	Time	Temperature (C)	Weight Loss (mg/cm <sup>2</sup> )
HCl - 5%	24 hrs	95	0.04
NH <sub>4</sub> F:HF - 10%	20 min	20	3.14
HF - 10%	20 min	20	11.96
NaOH - 5%	6 hrs	95	1.10

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## Leoflex Architectural Glass



[Leoflex Architectural Glass \(/index.php/leoflex/37-leoflex-architectural-glass\)](#)

### Literature

[Request Literature \(/index.php/leoflex/37-leoflex-architectural-glass\)](#)  
<mailto:rmetter@agcem.com?subject=Advanced Packaging Information Request>

### Product Features

#### Leoflex™ Features

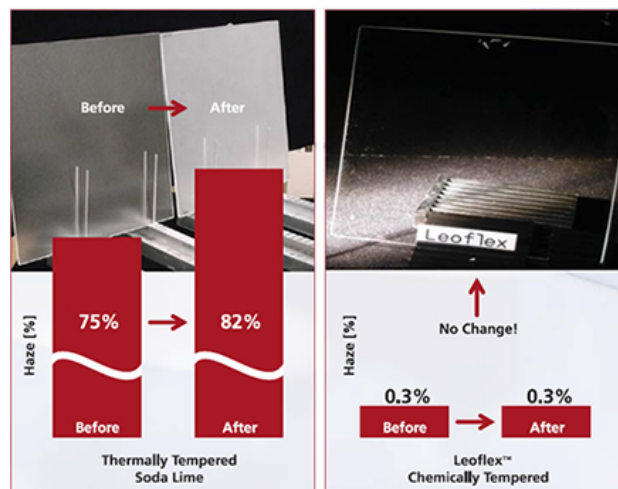
- ✓ 5X tougher than thermally tempered soda lime glass
- ✓ Lightweight
- ✓ Bendable
- ✓ High scratch resistance
- ✓ Outstanding weather resistance
- ✓ High optical clarity
- ✓ High strength compared to soda lime glass

AGC Leoflex™ opens the door to new groundbreaking opportunities for glass. Leoflex is chemically strengthened and 5 times stronger than thermally tempered soda lime. This allows the designer new opportunities to create thinner, curved designs, while maintaining the safety and beauty of tempered glass.

This next-generation glass offers additional benefits in the industrial and building environment. Leoflex offers superior clarity without any green tint, plus outstanding scratch and weather resistance. Architects and builders get the weight benefits of plastic sheets with superior performance and durability of glass.

Leoflex is produced using AGC float technology that ensures the highest-quality and lowest-cost product.

### Weather Resistance Test



Shaping  
the Future



### Leoflex™ Properties

	Property	Measurement	Leoflex™	Soda Lime
Mechanical	Density	g/cm <sup>3</sup>	2.48	2.50
	Young's Modulus	GPa	74	73
	Shear Modulus	GPa	30	30
	Poisson's Ration		0.23	0.21
	Vickers Hardness	Before CT	595	533
	Vickers Hardness	After CT	673	580

### Available Sizes & Thickness:

#### Thickness:

From 0.5mm to 2.0mm

#### Sizes:

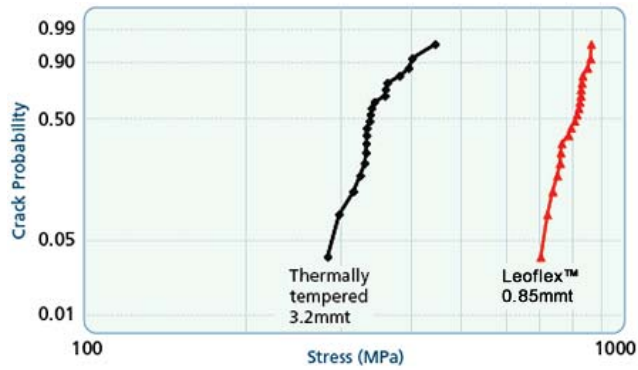
Standard size is 48" x 29".



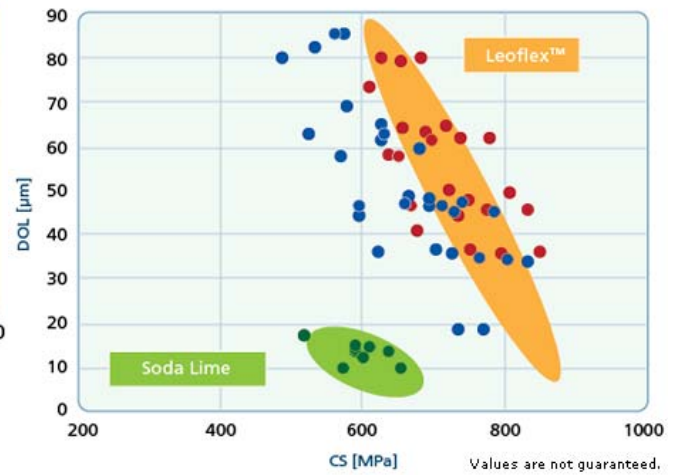
Thermal	CTE	$[10^{-7}](50\sim 200^{\circ}\text{C})$	98	85
	Tg	$^{\circ}\text{C}$	604	550
	Softening Point	$^{\circ}\text{C}$	831	733
	Annealing Point	$^{\circ}\text{C}$	606	554
	Strain Point	$^{\circ}\text{C}$	556	511
Optical	Refraction Index	Nd	1.51	1.52
	Photoelastic Constant	nm/cm Mpa	28.3	25.6
Electrical	Volume Resistivity	log ( $\Omega\cdot\text{cm}$ )	8.4	8.5

Custom sizes available.

#### Toughness Ring-on-Ring Test



#### Chemical Tempering Performance





# Specialty Glass Materials Products & Specifications

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## SCHOTT Xensation™

SCHOTT Xensation™ is a high-quality alumino-silicate glass with outstanding resistance to breakage and scratches for all cover and touch applications, including capacitive, resistive, optical, and acoustic touch technologies.

### Key-Benefits of Xensation™ Cover:

- SCHOTT's unique micro-float manufacturing process gives the Xensation™ Cover alumino-silicate glass its excellent sheet quality.
- Impressively high and very stable Compressive Stress (CS) and Depth of Layer (DoL), ensure that Xensation™ Cover offers outstanding strength.



### Thermal Properties:

Thermal Conductivity $\lambda$ (25 °C)	0.96 W/(m•K)
Specific Heat Capacity $C_p$ (20 °C; 100 °C)	0.84 KJ/(Kg•K)
Coefficient of Mean Linear Thermal Expansion $\alpha$ (20 °C; 300 °C)	$8.8 \cdot 10^{-6} \text{ K}^{-1}$ *
Transformation Point $T_g$	615 °C*
Annealing Point ( $10^{13}$ dPas)	635 °C
Softening Point ( $10^{7.6}$ dPas)	880 °C
Working Point ( $10^4$ dPas)	1265 °C

\*cooled according to DIN

### Chemical Properties: Optical Properties:

Hydrolytic Resistance	DIN ISO 719	Class HGB 1
Acid Resistance	DIN 12116	Class S 4
Alkali Resistance	DIN ISO 695	Class A 1

Refractive Index at	588 nm ( $n_d$ )	633 nm	780 nm
Core Glass	1.508	1.506	1.502
Compression Layer			
KNO <sub>3</sub> pure	1.516	1.514	1.510
Transmittance $\tau$ (Glass Thickness 0.7mm)			
840 nm			> 91.5 %
560 nm			> 91.5 %
380 nm			> 90 %
Photoelastic Constant		29.2 nm/cm/MPa	

Sheet

### Dimensions:

- Sheet Size: 475 x 575mm (18.7 x 22.64")  
1150 x 950mm (45.27 x 37.4")
- Thickness Range: 0.55 to 2mm stocked other requirements available on request

### Electrical Properties:

Frequency MHz	Dielectric Constant $\epsilon'$	Loss Tangent $\tan\delta$
1	7.74	0.011
54	7.49	0.008
480	7.40	0.009
825	7.38	0.010
912	7.38	0.010
1977	7.35	0.012
2170	7.35	0.012
2986	7.34	0.012
Electric Volume Resistivity $\rho_D$ for A.C. at 50Hz		
$v = 250 \text{ °C}$		$1.5 \cdot 10^6 \Omega \cdot \text{cm}$
$v = 350 \text{ °C}$		$8.9 \cdot 10^4 \Omega \cdot \text{cm}$

\*These values are no guaranteed data - for customer orientation only.

### Mechanical Properties:

Density	2.477 g/cm <sup>3</sup> *
Young's Modulus E	74 kN/mm <sup>2</sup>
Poisson's Ratio	0.215
Shear Modulus	30 kN/mm <sup>2</sup>
Knoop Hardness HK <sub>0.1/20</sub>	
Non-strengthened	534
Strengthened	639
Vickers Hardness HV <sub>0.2/20</sub>	
Non-strengthened	617
Strengthened	681

\*cooled according to DIN

### Chemical Strengthening:

Compressive Stress	capable > 900 MPa
Depth of Layer	capable > 50 $\mu\text{m}$
4-Point Bending Strength	cap. > 800 MPa