

Flexible Transparency

Development of thin glass adaptive façade panels

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Introduction

(Ultra) thin glass is silently present in the daily life of people today. It is a very common material for protecting mobile electronics screens from scratches and impacts.

Although these functions do not seem appropriate for a brittle material like glass, (ultra) thin glass presents a much different behavior than common glass.

A combination of material composition, production process and strengthening, make (ultra) thin glass harder, stronger and surprisingly, flexible.

On the other hand, glass design for the built environment faces challenges related to weight and material use, due to the high density of glass and the necessity of laminating many layers of this material together to ensure stiffness and safety. But also challenges regarding achieving complex geometries - as hot bending glass can become cost and energy inefficient and cold bending has a limited geometry range (large radius).

When looking back at the history of glass design in the built environment it is clear that the embracing of new technologies was fundamental to the development of the field; but also to the built environment we experience today, as glass is one of its most important elements (it is challenging to find buildings that do not employ it).

This research was developed with the objective of linking these two points: the recent developments of glass technology and the challenges faced by glass design in the built environment.

(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 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.

However, its high flexibility has both advantages and disadvantages, constraining its use for certain applications, but also opening opportunities for others.

However, these applications are yet unknown, as there is very few current examples of the use of this material in the built environment and also few research that relates it to build related purposes.

The development of this research helps on the growth of interest and knowledge of using this material in the built environment by studying its employment in this context and selecting and further investigating a possible application.

This research main focus is on embracing the flexibility of this material in an adaptive facade panel, showing the potential of thin glass as a building material and challenging the concept of glass as a static material.

Problem Statement

(Ultra) thin glass is a new material with big potential to be used in the built environment. Its many

characteristic, the flexibility, can be faced as a constrain, but also as an advantage. By embracing the characteristics of this material it is possible to show the potential of thin glass as a building material and to challenge the concept of glass as a static material.

Research Objectives

Main Objective

Design a thin glass adaptive panel for a double skin façade by researching the benefits and constraints of using this material in this application.

Sub Objective

Raise awareness of the possibility of using the technology of (ultra) thin glass in the build environment.

Growth of the (current small) knowledge and research over the use of this material in the build environment, more specifically on façade design.

Research Question

How can a thin glass double skin facade panel be made adaptive?

Sub Questions

To what purposes can a thin glass panel be made adaptive?

How does bending influences the stress generation in the thin glass panel?

What are the influences of bending and thickness on the load resistance of the thin glass panel?

What are the possibilities of movement for this panel?

How can supports influence the movement and geometry of the thin glass adaptive panel?

How to translate the necessary degrees of freedom to the detailing of the panel?

Methodology

The development of this research started by trying to understand what would be a possible application for thin glass in the built environment as an alternative to common glass according to its characteristics.

The first phase of the research was guided on that direction. This question was addressed by comparing thin glass and common glass on a literature study and then to explore possible alternatives based on the knowledge from literature (Chapters 1 to 3).

This defined the focus of the research on embracing the flexibility of the material and relating it to its possibility to adapt.

Based on literature, adaptiveness on the built environment was analyzed together with the possibilities of using of thin glass in this context (Chapter 4).

The next step of the research was to narrow the research to a specific building element. To identify which building element would be more suitable for the development of the research multiple case studies were selected and the advantages of using thin glass on each of them was explored (Chapter 5).

The analysis of the advantages and disadvantages of this study determined the development of the research to be focused on double skin façade elements.

This was followed by trying to understand the behavior of thin glass in this context by developing and comparing physical and numerical models (Chapter 6).

Based on the results of the models it was possible to study the relation between movement and supports which is fundamental for the development of an adaptive panel.

This was made by identifying possible types of movement of the panel and studying what is the influence of the supports and degrees of freedom on the final geometry and stresses (Chapter 7).

After analyzing these results, design principles were developed and compared according to the needs of an adaptive double skin façade.

From this comparison a single principle was selected and developed into a design and also to prototype (Chapter 8 and 9).

Relevance

The relevance of this research starts by following the history of the development of glass in the built environment in which the new technologies allowed the creation of new applications to the point we see today.

It also mainly aims to increase the knowledge on the use of this material on the built environment and serve as a base for data and examples for possible future applications and research over this material

Nevertheless, the use of thin glass as an alternative to glass implies in a reduction of raw material and dead weight on the building structure. As well as saving energy and economic resources if used as an alternative to hot bending glass.

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

Frank Lloyd Wright

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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. [1]. 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. [2].

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" [3], 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.

GLASS PANE

70 AD - 0.5 x 0.3 m Herculaneum	1688 - Polished plate France	1790 - 0.6 x 0.38 m Maximum sizes of Crown glass	1845 - 1.2 x 0.72 m Maximum size increase	1870 - 1.44 x 0.96 m Cylinder glass production
1226 - Broad Sheet produced in Sussex	1620 - Brown Plate London - mirrors	1790 - 0.72 x 0.6 m 0.84 x 0.54 m Maximum sizes available in Belgium	1847 - Rolled plate Used for large railway stations	1898 - Wired Cast glass Pilkington
1330 - Crown Glass Rouen	1700s - Introduction of soda to the composition. More strength and transparency. Costs reduced	1800 - Polished plate using steam power England	1843 - Early float glass invented - expensive and not successful commercially	1888 - Machine rolled glass allows the introduction of patterns
		1834 - Improved Cylinder Sheet Germany	1874 - Tempered glass method is patented	

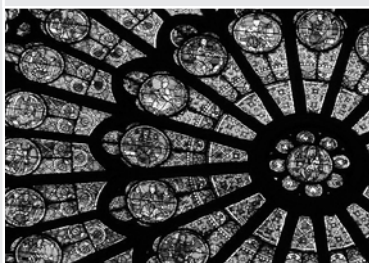


Figure 2-Notre Dame de Paris - 1260



Figure 3-Victorian houses - ca. 1850

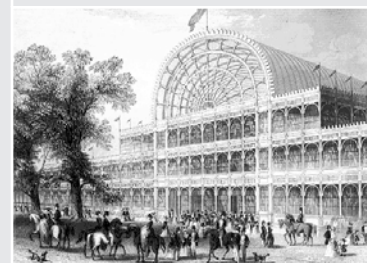


Figure 4-Crystal Palace - 1851

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" [4].

Glass is a solid that is the result of a melted material - silica (SiO_2) -, that when heated has its molecular

arrangement changed, becoming an amorphous solid - "a solid material with the chaotic structure of a liquid" [5].

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 [3]



Figure 5-Glass Pavilion - 1914



Figure 6-Bauhaus Dessau - 1928

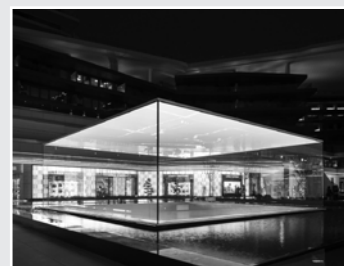


Figure 7-Apple Istanbul - 2014

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" [6], 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" [6].

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. Although in theory sheet glass can achieve a tensile strength of 6500 to 8000 N/mm²; in practice due to "surface flaws, notches and cracks" this value is reduced to 30-80 N/mm². "Failure in glass is the result of a combination of flaws and stresses" [7].

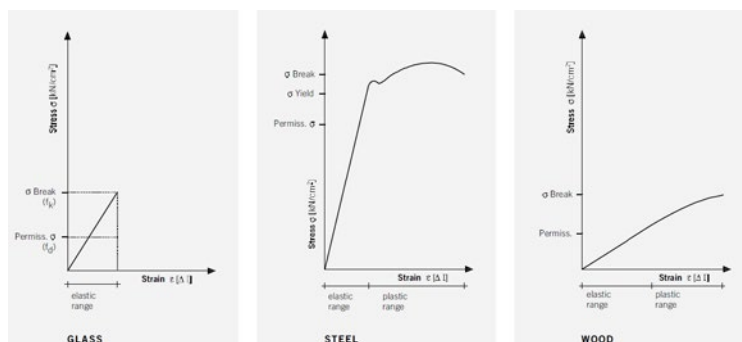


Chart 2-Qualitative comparison of the stress-strain graphs of glass, steel and wood. [8].

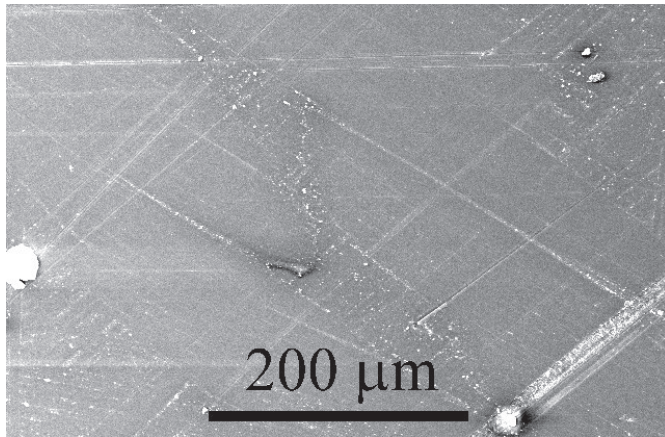


Figure 8-Surface flaws on glass.

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 [9]

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

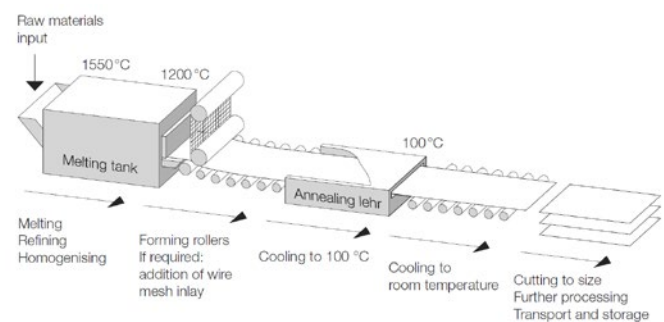


Figure 10-Float glass production

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.

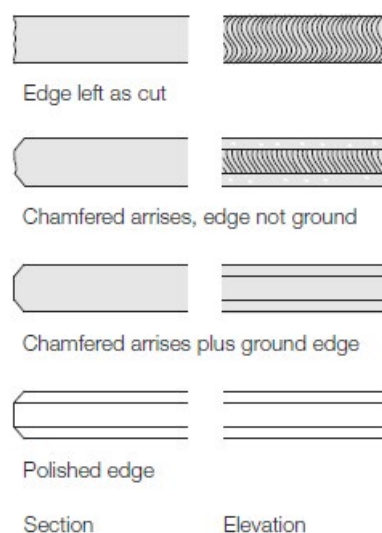


Figure 11-Edge quality of glass

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.

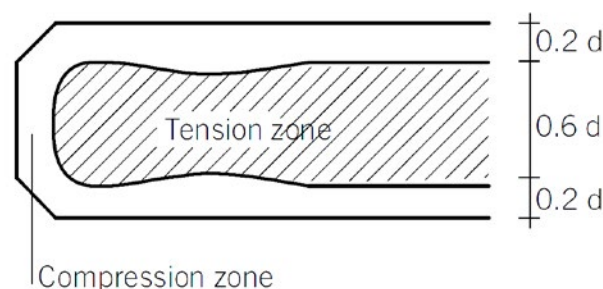


Figure 12-Illustrative section of a tempered glass pane showing the tension and compression zones

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.

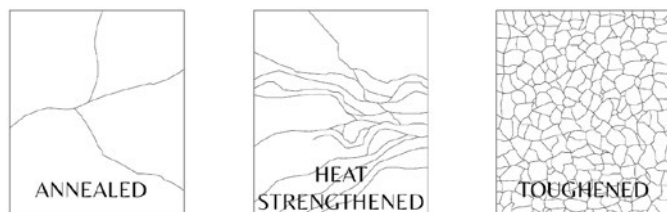


Figure 13-Breakage pattern of annealed, heat strengthened and toughened glass.

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". [10].

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" [8].

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." [8].

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" [8].

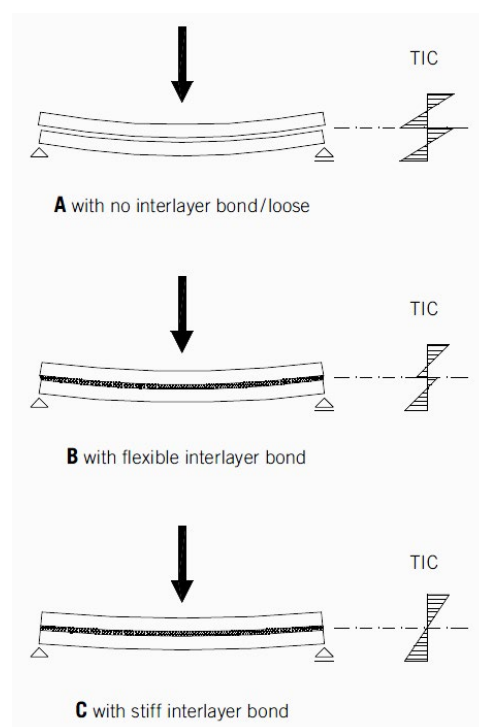


Figure 14-Shear stress distribution according to the characteristic of the interlayer in symmetric laminated glass panels

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

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." [11]. 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.

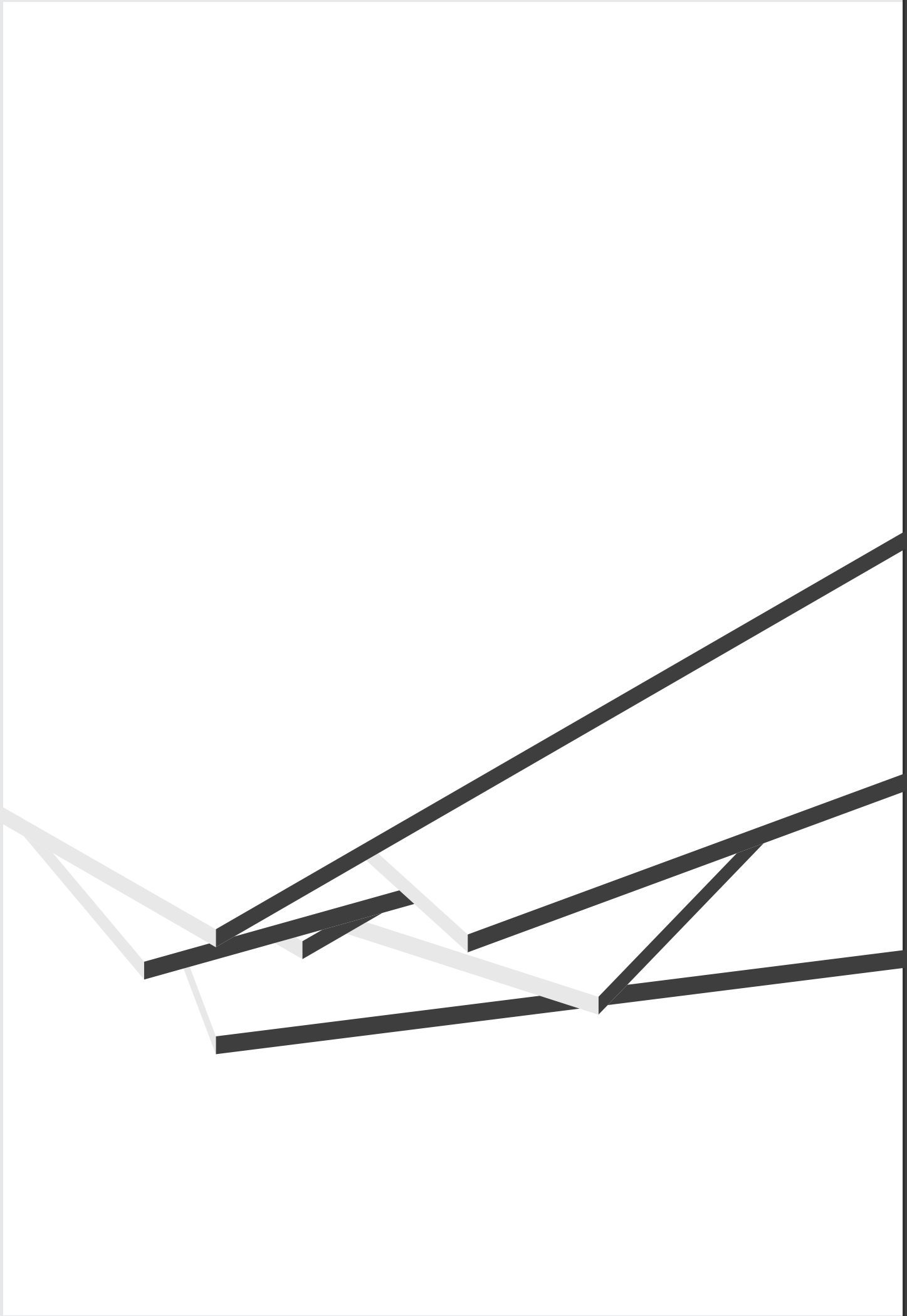
These characteristics lead to different solutions.

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 μ m) [12]; as for the current date, glasses at the thicknesses of 25 μ 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.

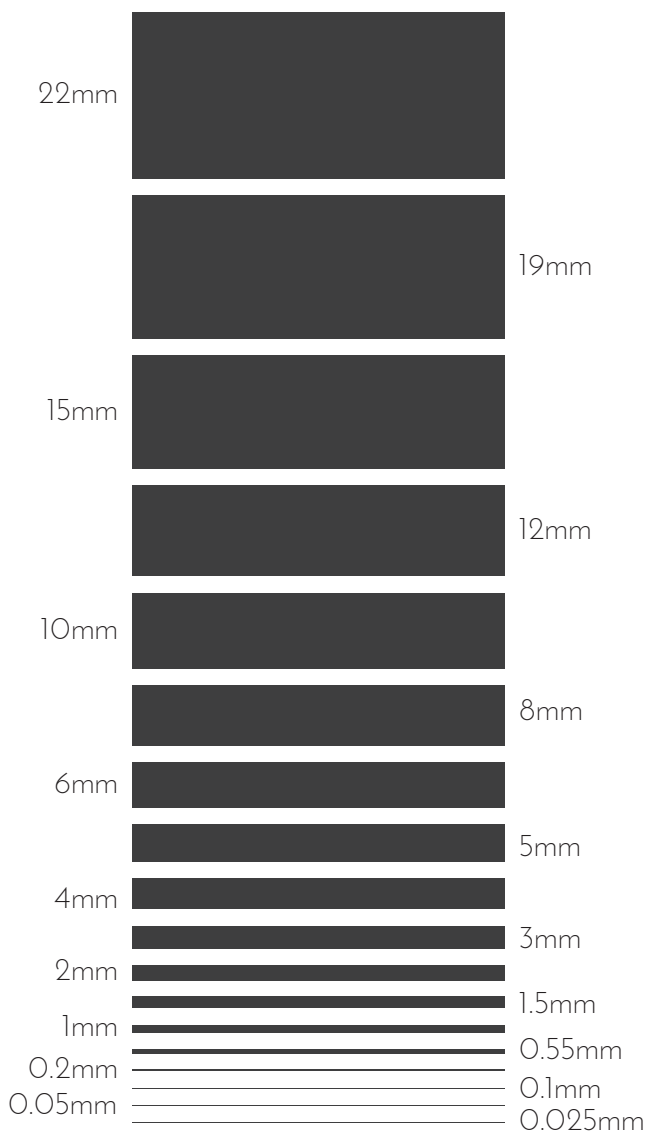


Figure 17-Glass thicknesses at 1:1 scale - from 22mm to 25 μ m

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"[13] (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"[14] 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"[13].

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.

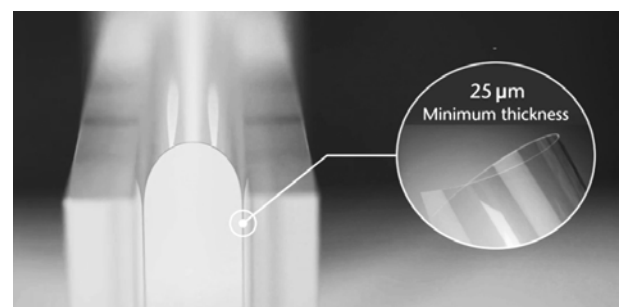


Figure 18-Bended 25 μ m glass sheet

Table 2-Aluminosilicate glass material properties [14]

Density	2.49e3 - 2.54e3	kg/m ³	Shear Modulus	33.9 - 35.6	Gpa
Young's Modulus	84.8-89.1	GPa	Poisson's ratio	0.23 - 0.22	-
Tensile Strength	39.9 - 43.9	MPa	Hardness - Vickers	477 - 525	HV
Elongation	0.04 - 0.05	% strain	Fatigue Strength (at 10 ⁷ cycles)	35.6 - 39.4	MPa
Compressive Strength	376 - 414	MPa	Fracture Toughness	0.7 - 0.72	MPa.m ^{0.5}
Flexural Strength (modulus of rupture)	48.9 - 53.8	MPa	Thermal Expansion coefficient	4.5 - 4.69	μstrain/°C
Shape Factor	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" [13]. 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. [15].

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.

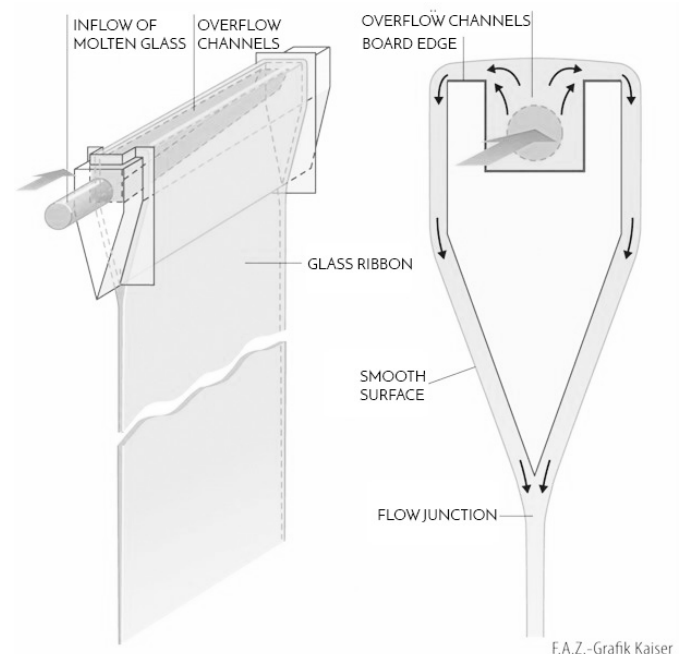


Figure 19-Overflow-fusion process

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 and orifice" [13]. After leaving the orifice the glass ribbon is already annealed and the 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.

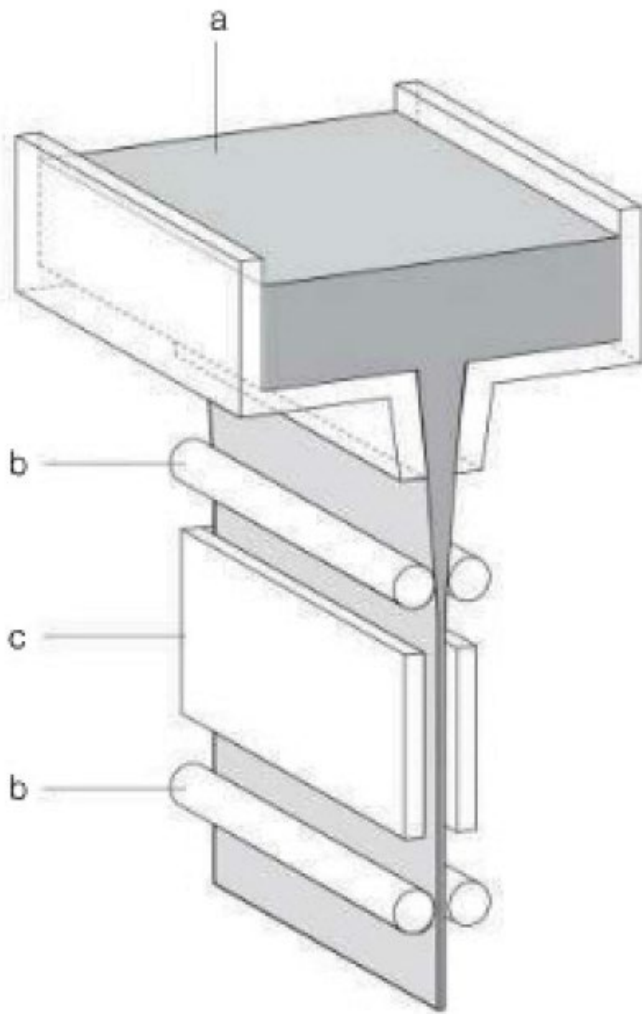


Figure 20-Down draw process

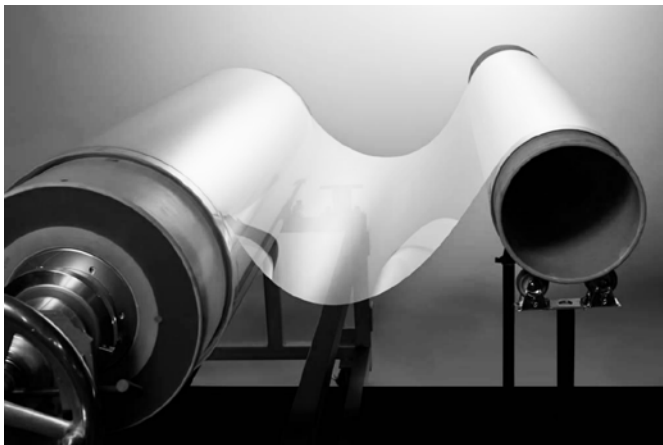


Figure 21-Ultra thin glass roll. 0.05mm thick and 100m long

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" [16] - 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.

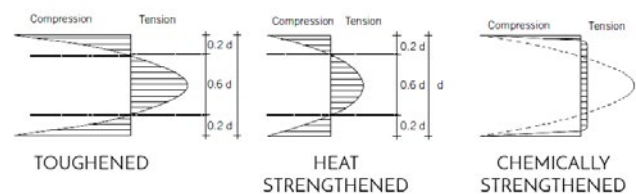


Figure 22-Stress distribution comparison by strengthening process

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."

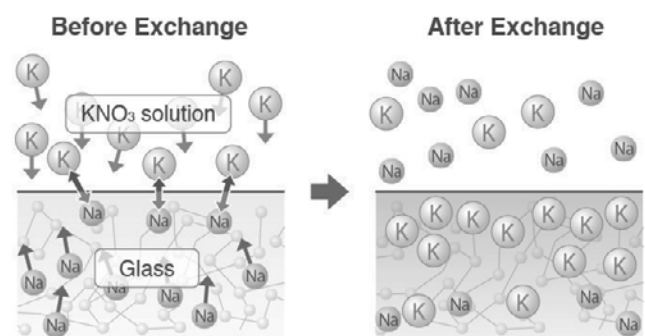


Figure 23-Chemical strengthening ion exchange

This method allows the strengthening of complex shapes, as the material is immersed in the solution, which is "not feasible with thermal tempering" [16]. However, "the maximum dimensions are limited by the size of the tubs holding the salt bath" [6], 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 [17], 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 to that of annealed glass, “a monolithic sheet of chemically strengthened glass is not safety glass” [6].

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 [16]).

Others state that thin chemically strengthened, “breaks into much smaller fragments, almost exhibiting a powder like state” [19].

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 [20] 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.

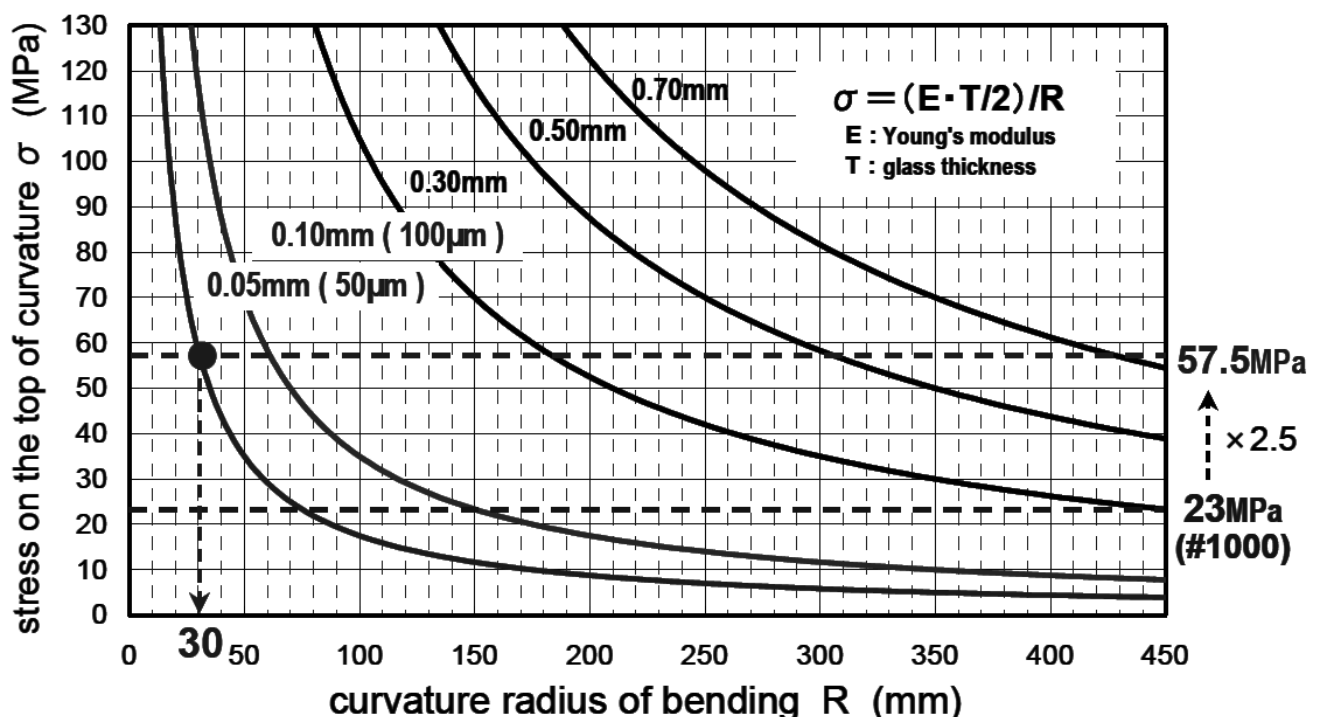


Chart 3-Stress generated by bending different glass thicknesses.[20].

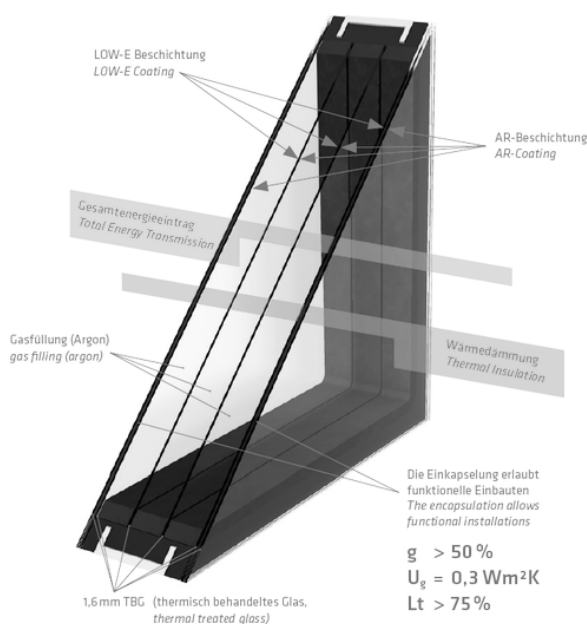
2.3.Current Applications

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.

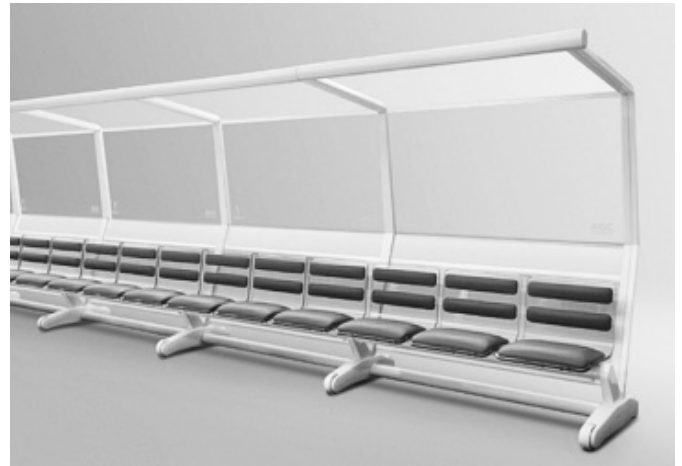


Figure 25-2014 World Cup bench

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.

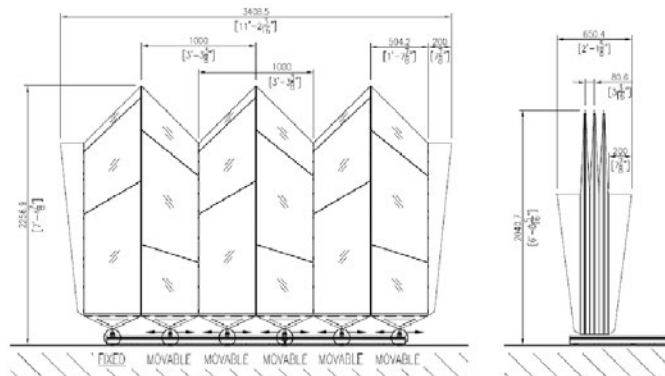


Figure 27-Thin glass movable canopy design

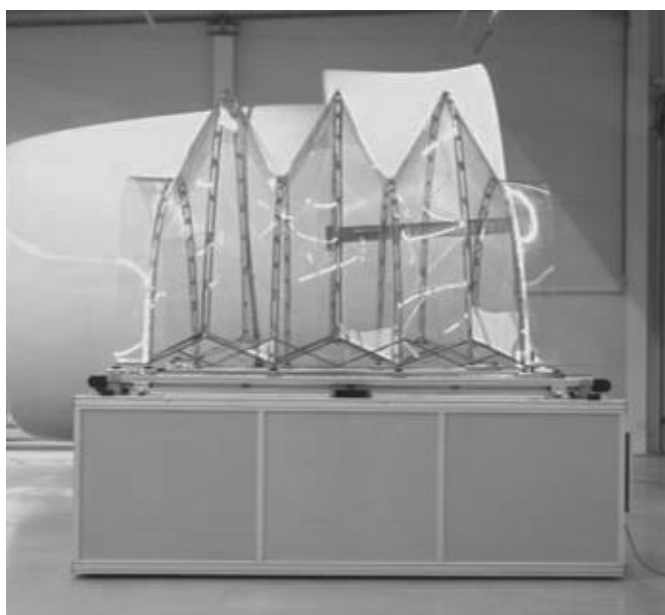


Figure 28-Thin glass movable canopy realized

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

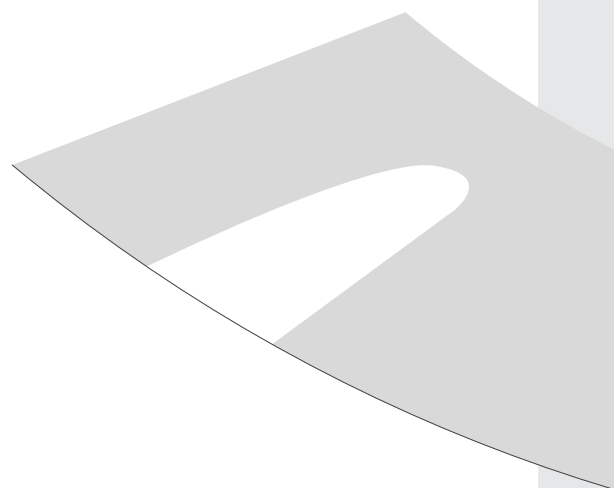
substitute for thicker glass. As mentioned before, glass elements tend to be heavy because of the necessity of laminating multiple layers (either to increase its stiffness or for safety reasons). Thin glass has the same or better strength characteristics as common glass, however, as it is much thinner 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 [8], 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

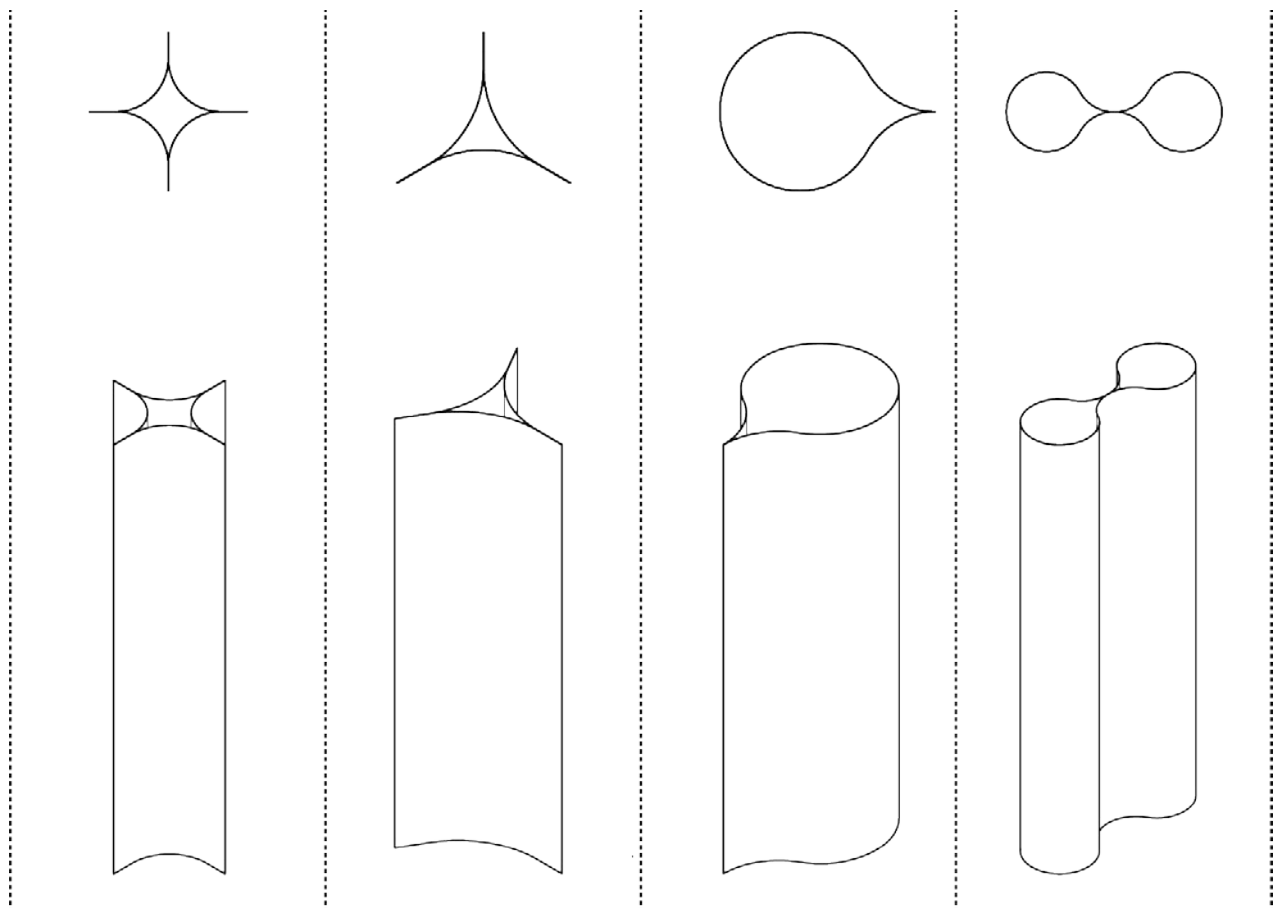


Figure 29-Geometry exploration for glass columns in thin glass. Plan and isometric views.

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 [21].

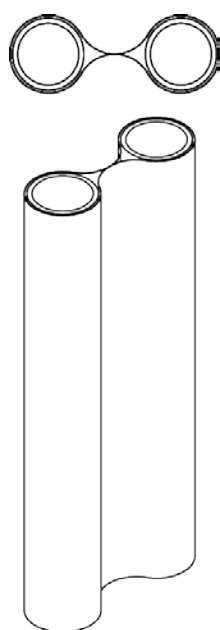


Figure 30-Example of column assembly using thin glass as a protection layer. Plan and isometric views.

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.

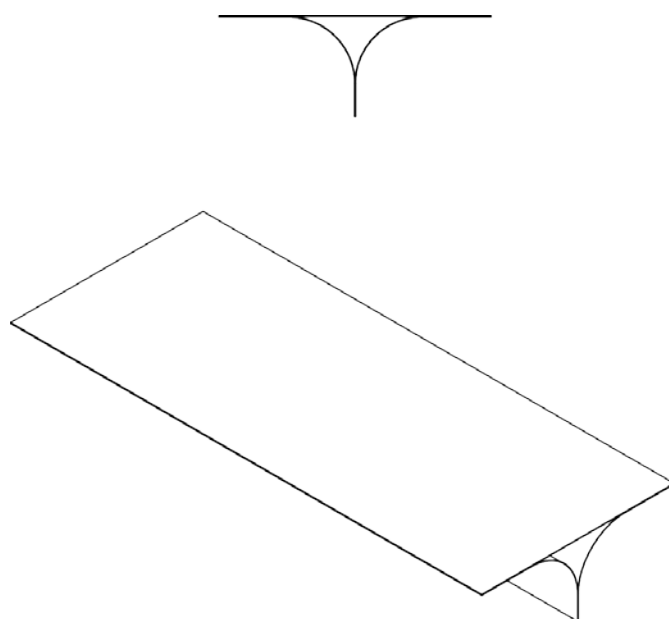


Figure 31-Geometry exploration for glass beams in thin glass. Section and isometric views.

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.

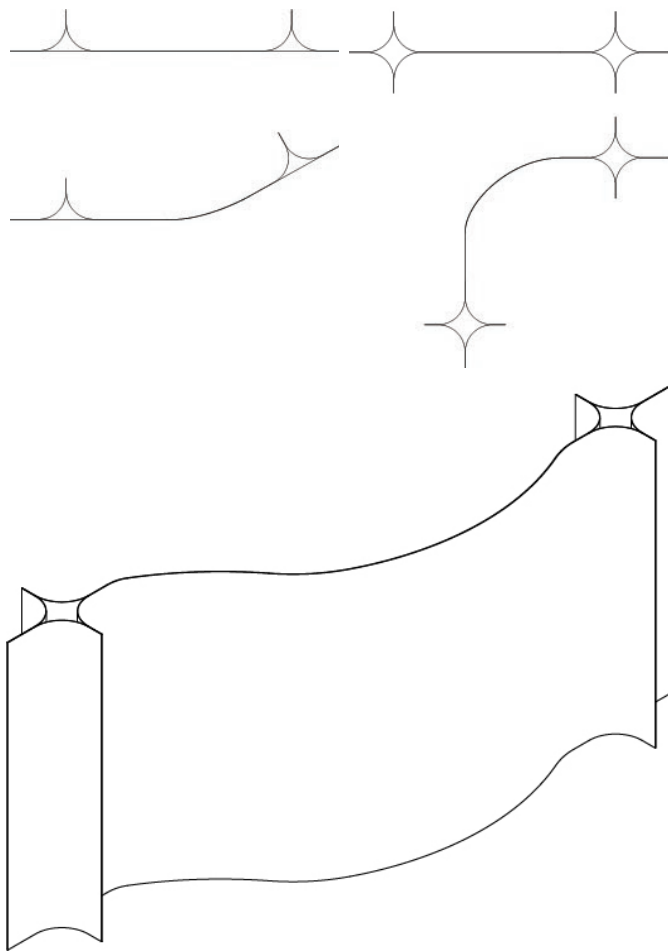


Figure 32-Geometry exploration for one layered glass panels. Plan and isometric views.

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.

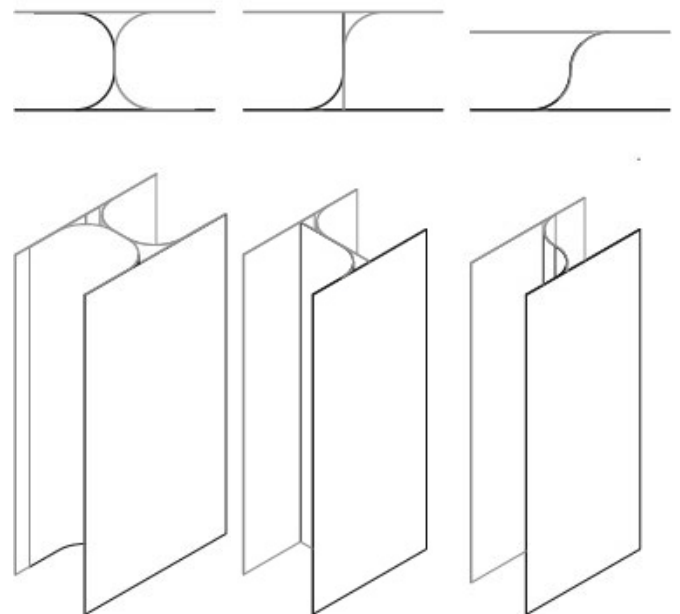


Figure 33-Geometry exploration for two layered glass panels. Plan and isometric views.

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.

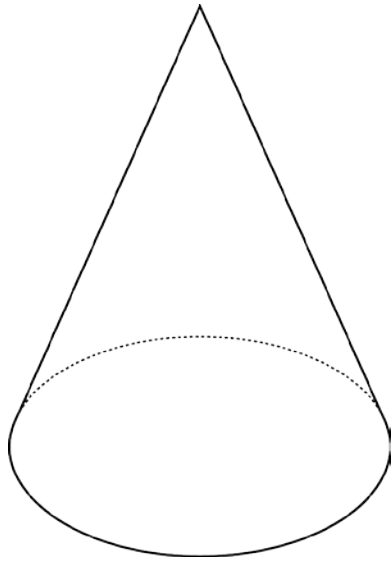


Figure 36-Cone, as a zero gaussian curvature geometry.

3.2. Conclusions for further exploration 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 glass house, 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.

ADAPTIVENESS

In this chapter adaptiveness in the built environment related to thin glass will be explored. It starts by describing the classifications of these elements to then reflect on principles that could be related to the object of this research. After, adaptiveness is related to the benefit it may bring to the building. Finally, the chapter is concluded relating thin glass to adaptiveness in the built environment.

4.1.Introduction

Adaptive elements (i.e. structures, façades, objects) are those who can change their position, shape or properties according to the needs and desires of its users.

Although this may seem limited to technological approaches, very simple and common examples show the opposite; for instance, a curtain is an adaptive object that can change shape and position if the user finds it necessary.

This chapter starts by giving an overview of adaptive elements in the built environment, and then relates it to the object of this research.

4.2.Classification

Adaptive elements can be classified mainly according to their type of movement and to how they are controlled.

By studying these categories, it is possible to understand better the possibilities of this approach. The classification described in this section is based on [23] and [24].

4.2.1.Movement

Movement is the main characteristic of adaptive panels; it can happen by moving the adaptive element or by deforming it. The Table 3 summarizes the classification of adaptive structures based on movement.

4.2.1.1.Element movement

Element movement is related to a mechanical input on the adaptive element. This movement can be of translation, rotation or a combination of both.

Translation movements can happen in-plane or off-plane. In plane movements are the ones which the element stays in the same axis as the element, while off plane are the ones in which the element translates in an axis which is different than its own. For example, a sliding door is an adaptive element that translates in plane; while a push out plate translates off-plane.

Rotation movements can happen also in and out of plane. An example of an in plane rotation is a camera diaphragm, a type of movement present in the *Institut du monde arabe* façade panels. An out of plane rotation common examples are louvers, or window blinds.

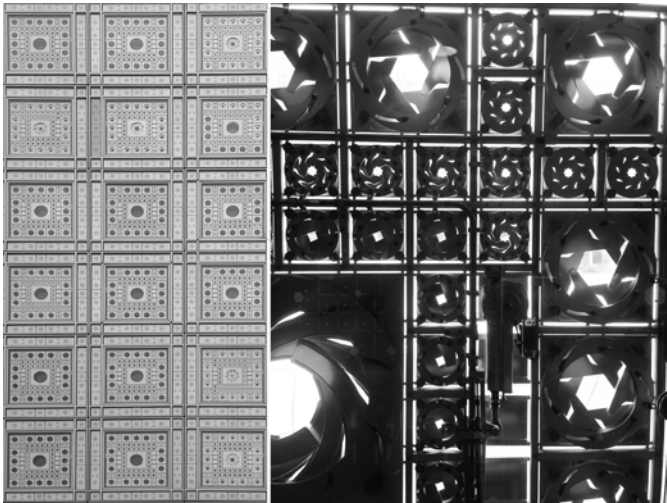


Figure 37-Intitut du monde Arabe, Paris. Exterior view of the façade and close up at the interior of the façade panels.

Movement									
Element movement					Material Deformation				
Rotation		Translation		Hybrid	Self Change		External Input		
In Plane	Off Plane	In Plane	Off Plane		Tempera ture	Humidity	Electricity	Gas Liquid fluid	External force

Table 3-Classification of adaptive elements regarding movement. [24].

Hybrid movements are the ones which combine translation and rotational movements. Folding plates, umbrellas or scissor structures are examples of hybrid movements.

4.2.1.2. Material deformation

It is also possible to create movement by a material deformation, meaning a change of the original shape of the element. Generally, this can happen in two different ways: by the reaction of the material to the environment based on its material properties; or by an external input.

A material self-change can happen according to changes of the environment. This movement is dependent on the material properties. Examples of this type of movement are not yet very common in the built environment, but application for it are and have been target of different studies. An example in material level is the thermal expansion due to the increase of temperature. In item 4.4.2 this type of movement is further explained.

A material can also deform based on an external input, such as electricity, a fluid or a mechanical force. Electrochromic glass is an example of an element that can change from transparent to opaque by an electrical input. Inflatable structures can show how a fluid can deform (stretching) a material to create space. As for a deformation based on mechanical force, the louvers of the One Ocean thematic pavilion of the EXPO 2012 are very interesting examples; this case will be further discussed in the item 4.4.1.



Figure 38- (right) Inflatable element. Spacebuster by Raumlabor. (left) Example of electrochromic glass.

4.2.2. Control

Although movement is the visual characteristic of adaptive element, the way that this movement is generated is also important. The TABLE summarizes the classification of adaptive elements based on the type of control.

The control of the element can be local or central, meaning that it can be integrated in the panel or dependent on an external system. This classification is based on [24].

Control				
Local		Central		
Inner (Material)	Direct (Sensor Based Micro)	Level I (Direct)	Level II (Reactive)	Level III (System Based)

Table 4-Classification of adaptive elements regarding control. [24].

A local control can happen in two different ways, either the material itself control its movement (common for the self-changing movement), or a control system (sensor, microprocessor and actuator) is integrated in the element.

A central control consists on a single processing unit that directs the adaptive elements. This type of control is typically used in high complexity systems to better control the environment of the building, automatically opening windows or moving louvers for instance.

4.3.Movement and shape

In addition to the general classification of adaptive elements, there is an important relation that is interesting to be taken in consideration, that of movement and shape.

In the book *Move-architecture in motion* [25] this relation is explored, the authors show the different types of movement by relating them to rigid or deformable building elements and to its dimensionality (1D, 2D or 3D shape).

The Table 5 and Table 6 show the movement

of rigid and deformable surfaces as classified by Schumacher et al. [25]. The complete table containing the movements related to 1D and 3D objects is presented in Appendix X.

The Table 6, related to deformable elements, can be used as a reference of movements to a thin glass sheet.

4.4.Principles

This section has the objective to filter the general possibilities of adaptive elements, relating them to the use of thin glass.

After researching examples of adaptive elements and structures, I selected a few principles and concepts that I believe could be integrated into thin glass adaptive elements.

4.4.1.Active bending

The first principle of adaptiveness I believe could be applied in the development of thin glass adaptive elements is the one of active bending, "a systemized elastic deformation" [26].

Movement of rigid building elements

Mechanical concept	Rotation	Rotation and translation	Translation
Simple movements of surfaces			
Horizontal			
Vertical			
Level			

Table 5-Relation between movement and shape of rigid building elements.

Movements of deformable building elements

1-dimensional object	Stretch	Roll	Bend	Shear	Flutter	Free	Gather (vertical)	Gather (horizontal)
2-dimensional object								

Table 6-Relation between movement and shape of deformable building elements.

Bending active structures are present in “various empiric construction methods known from vernacular architecture” [26]. This can be related to bending flexible materials in order to achieve the desired shape, an example of this technique are bamboo structures, until today, houses in bamboo are executed by using scale models as a reference project, basing the final shape of the house in the empirical knowledge of bending the material. [27].



Figure 39-Bamboo scale model as reference for construction.

The bamboo example can be characterized as a behavior based approach, as the final geometry comes directly from the bending of the material.

Another approach to active bending is the geometry based approach. While it was not possible yet to simulate this type of structure, methods such as the hanging model served as a reference to developing bent timber structures. Examples of this approach are the Hooke Park Workshop (1990) by Frei Otto and the Polydôme (1991) in Lausanne. [26].

Developed by ITKE department of the university of Stuttgart, a simulation method of form finding for bending active structures is able to combine the two approaches described before. In this way it is possible to predict the final shape and analyze structurally a bent structure before its erection.

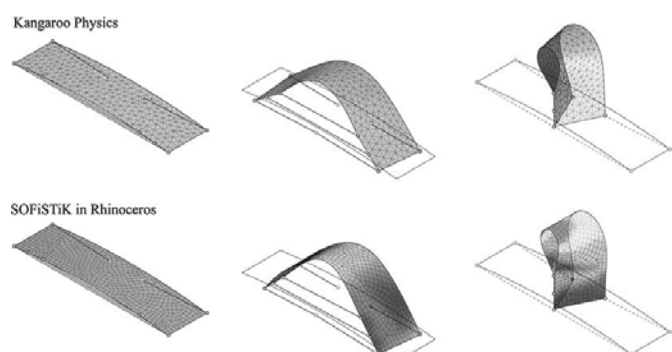


Figure 40-Behavior based geometry approach developed at ITKE.

This method was used in the 2010 ICD/ITKE pavilion and on the louver system One Ocean thematic pavilion of the EXPO 2012.

The first of these examples consisted of “planar strips of plywood subsequently coupled into a self-equilibrating arch structure of 4 m span.” [26]. The form of this structure was developed and analyzed using simulation tools which were able to predict its final bent shape.

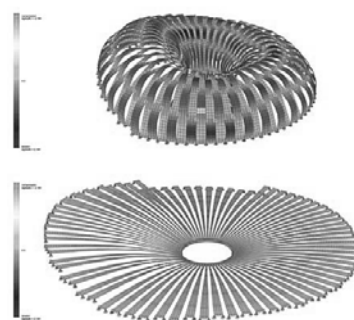


Figure 41-Behavior based geometry approach applied to the form finding process of the ITKE/ICD Pavillion 2010.



Figure 42-ITKE/ICD Pavillion 2010.

The second example is a louver system that is activated by controlled buckling. The same process was also true for this case. Using the bending active method, it was possible to predict the final shape of the louvers and analyze it structurally.



Figure 43-One Ocean Pavillion with open and closed louvers.

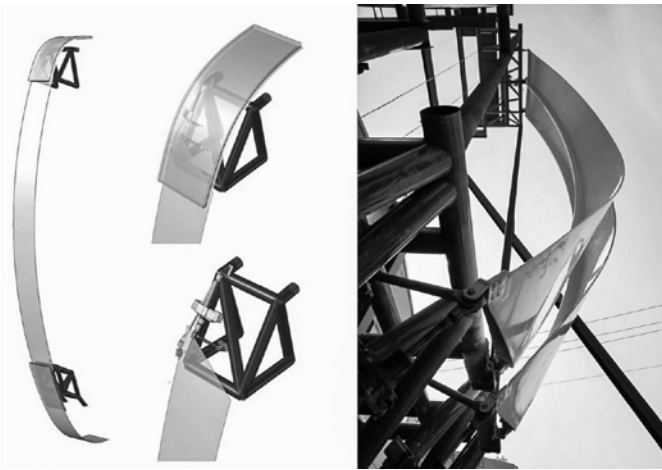


Figure 44-One Ocean Pavillion detail of bending/buckling mechanism.

I believe this approach could be used on the design of thin glass adaptive elements. By simulating the behavior of the bending of thin glass in numerical models, it is possible to analyze different designs and select them according to the desired parameters and necessities.

4.4.2. Material deformation

The second principle I believe is relevant in a thin glass adaptive element is the material deformation.

This principle is more related to the control of the movement of the element than to its final shape. It consists on the direct response of the material to the general environment characteristics, being able to control an adaptive element.

I selected two examples to illustrate this principle.

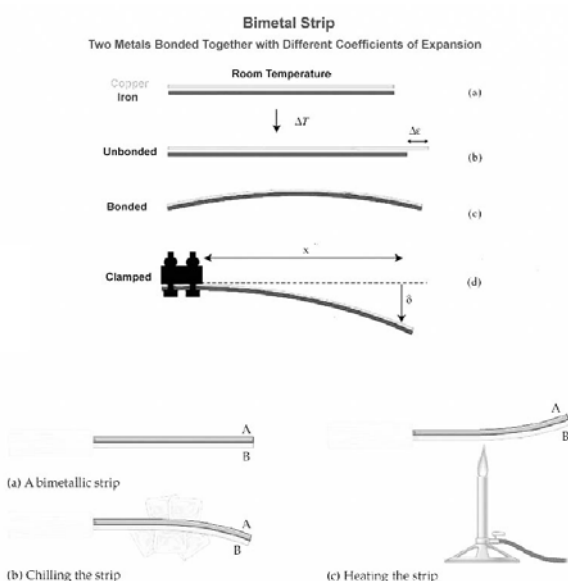


Figure 45-Bimetal principle.

The first one is the Bloom pavilion by Doris Sung in 2012. This pavilion consists of thousands of "bimetallic panels in which two laminated sheets of metal expand and contract at different rates when exposed to heat, in this case direct sunlight." In addition, "the bimetallic panels are thermally very sensitive, with almost real-time de-tection when exposed to solar heat." [28].

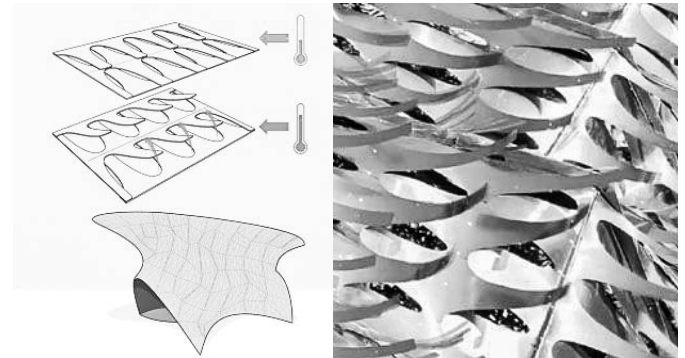


Figure 46-Bloom pavillion.

The second example is also a pavilion, which responds to humidity instead of temperature.

The HygroSkin Pavilion uses "the wood's active bending behavior and hygroscopic actuation of the material" [29]. Although the whole project is very interesting, in this case I want to call attention for the openings, which are controlled by air humidity, when it increases the plywood sheets respond close the opening.

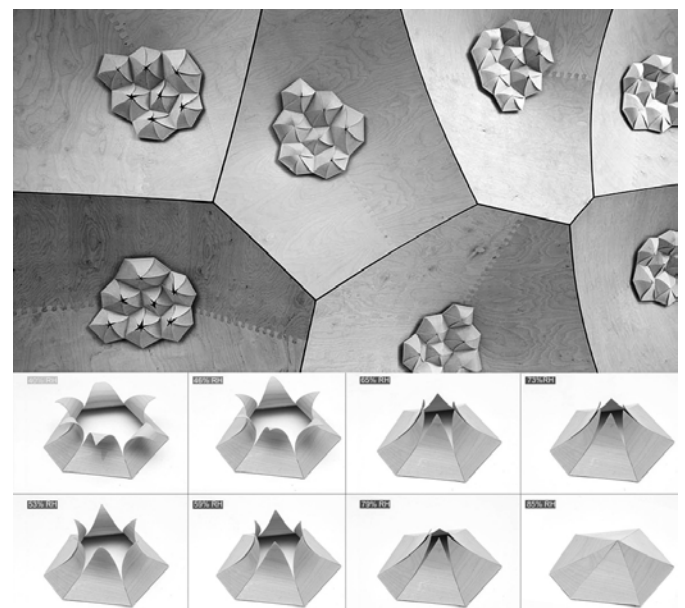


Figure 47-HygroSkin pavillion opening behavior according to humidity.

In the case of thin glass adaptive elements, it would be possible that the movement is controlled by this type of solutions, making the element directly responsive to the desired environmental characteristic.

4.4.3. Adaptive Fritting

This last principle is related to creating a sun shading or visual partition element, that could benefit from adaptiveness to better respond to the necessities of the user.

Adaptive fritting is the creation of a fritted pattern that can be superposed to create different amount of sun protection or visibility.

This principle can be found in the skylights South Campus of the Art Center College of Design in Pasadena [25]. These elements consist of ETFE cushions with three layers, each of them fritted with a different pattern (Figure 48).

According to the necessity, a pneumatic input moves the inner layer of the cushion, overlapping the patterns in different ways. Using this strategy, the amount of light coming to the interior spaces to be controlled, varying "from 16% up to 60% of light transmittance" [25].

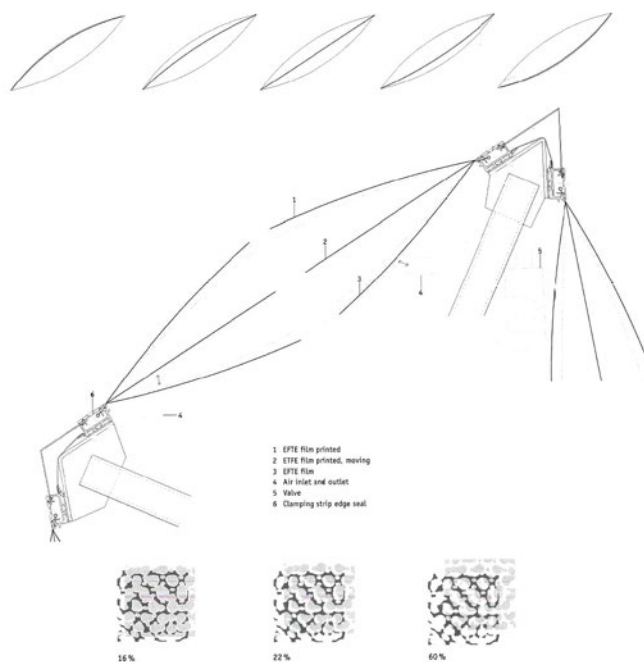


Figure 48-ETFE cushion with adaptive fritting principle.

Another example is in the Adaptive Fritting installation by Hoberman Associates at the Graduate School of Design at Harvard University.

This installation consists in a panel which include four different plates with the same fritted pattern. By an in-plane translation it is possible to change the fritting density of this panel, by placing the different plates in a way that the patterns do not overlap anymore [30]. The Figure 49 shows the change of density of the fritting by using this approach.

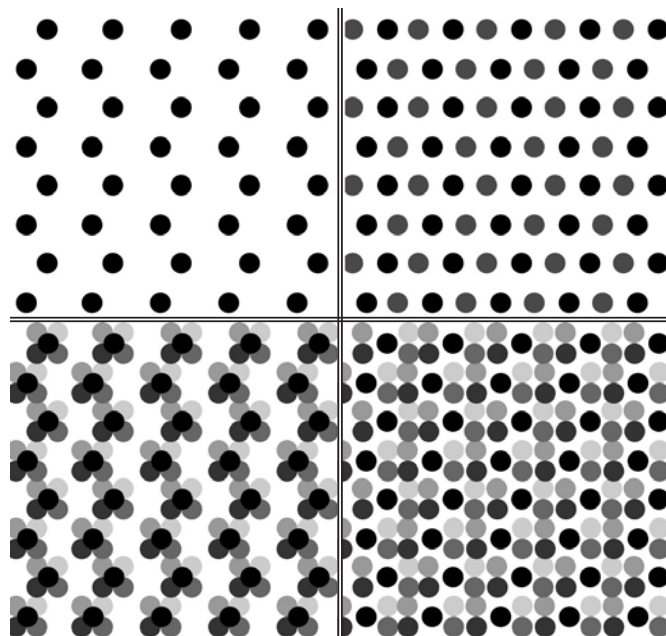


Figure 49-Adaptive fritting panel density change.

Considering thin glass, this principle could be used by bending the panel, and overlapping a fritted pattern, almost creating a sun shading louver (Figure 50).

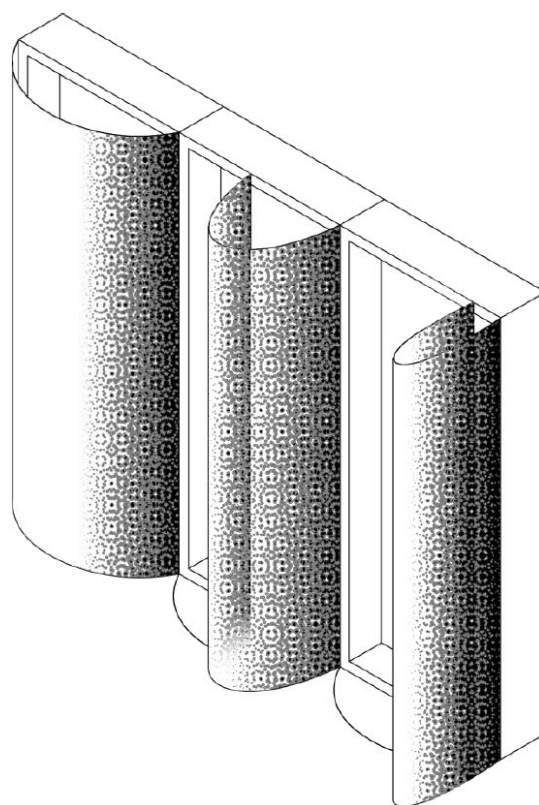


Figure 50-Adaptive fritting applied to thin glass panel.

4.5. Adaptiveness purpose

An adaptive element may have a different configuration based on the purpose it needs to adapt to.

This section describes possible purposes of a thin glass adaptive element, giving an overview that will help on defining the constraints of this research.

4.5.1. Ventilation

One of the most common purposes of adaptive elements is ventilation.

A typical example of this element is an openable window. When closed it allows for light and visual contact between inside and outside; when open it allows for ventilation.

A thin glass adaptive panel could also have the purpose of ventilation, working as a transparent barrier between outside and inside and then gradually opened allowing for more ventilation at each time.

4.5.2. Sun protection

Sun shading is also a very common purpose of adaptive elements.

Common examples are operable blinds and louvers, which can be positioned by the user (or central system) according to the sun position.

Although it may seem strange that a transparent element could have the purpose of sun shading, I believe that by integrating thin glass with the adaptive fritting principle (item 4.4.3) could result in an adaptive element that could combine the transparency necessary for visual and daylight with sun protection (Figure 50).

4.5.3. Sun energy

In addition to sun protection, adaptive elements can also be used to increase the amount of energy generated by solar cells.

An example of adaptive elements with this purpose is the façade of the EWE Arena in Stuttgart. A solar

panel screen of 36 by 7.6 meters "can travel 200° around the perimeter of the building and consists of 200m² of photovoltaic cells" [25]. (Figure 51).

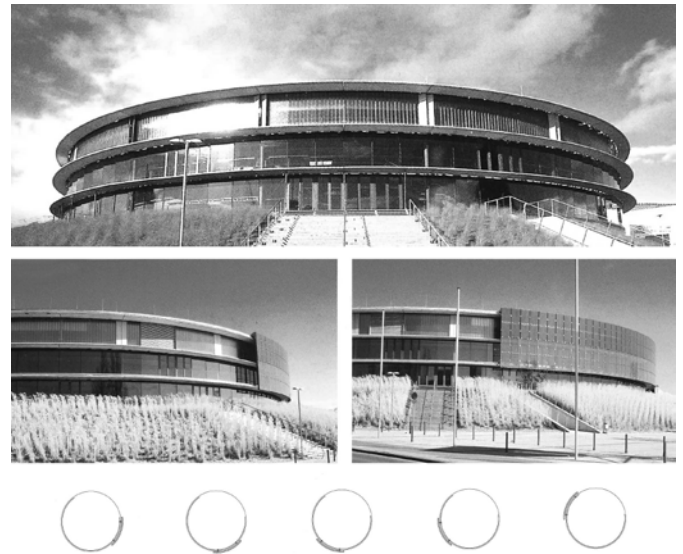


Figure 51-EWE Arena rotating photovoltaic panels.

With the development of solar cell films which can be laminated to glass, thin glass adaptive panels with integrated solar cells could be used to follow the sun path or adapt to an optimal position according to the sun.

4.5.4. Visual Effect

Adaptive elements are not only related to technical demands, they may also be required by aesthetical purposes, to make the building unique.

An example of adaptive elements related to aesthetic demands is the already mentioned One Ocean EXPO 2012 Pavilion. Although also related to ventilation, the elements main function was that of creating a unique effect on the façade, much related to the fact of being in a EXPO. (Figure 43).

Another example of an adaptive structure for aesthetical purposes was the Mega Faces Pavilion of the Sochi Winter Olympic games (Figure 52). One of the facades of the pavilion consisted of "11,000 actuators, each equipped with full color LEDs [...] able to transform in three dimensions to recreate the faces of visitors to the building" [31].

Thin glass elements can also be used with aesthetical purposes. As one of the main characteristics of this material is its flexibility, its presence in the built environment could be something unique, that can create surprise as it can assume shapes that are not

associated with glass; challenging the concept of glass as a static material.

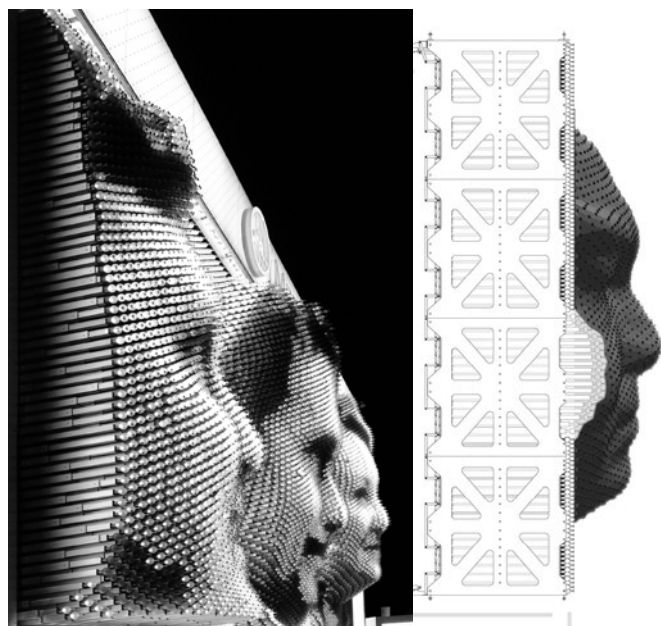


Figure 52-Megafaces Pavillion in Sochi Winter Olympic games 2014.

4.5.5. Wind load reduction

Adaptive elements can also be used to unusual purposes such as wind load reduction in buildings.

Recent research [32] has showed that by adapting the geometry of façade elements according to the wind direction it is possible to reduce the general wind loads on a high rise building (Figure 53).

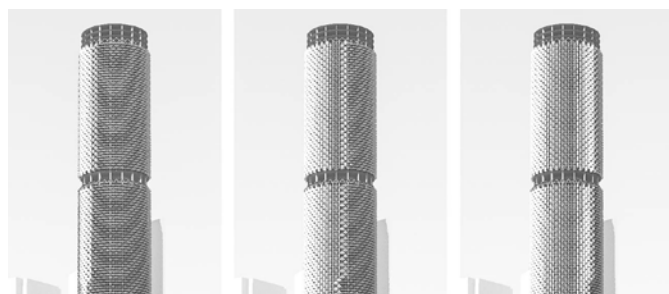


Figure 53-Impression of wind load reduction adaptive façade system for high rises.

This effect could also be achieved by adaptive thin glass elements (as long as they are stiff enough), as they are able to have their geometry changed to the necessities of the building; with the possible advantage of not obstructing the views.

4.5.6. Noise level reduction

Another uncommon use of adaptive elements is that of reducing the noise levels in an urban scale.

This is related to research [33] that façade envelopes with geometry that is noise diffusing or with absorbing materials could reduce the perceived noise level in urban areas. (Figure 54 and Figure 55).

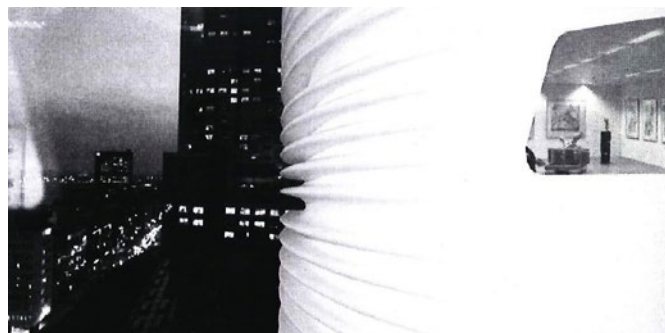


Figure 54-Impression of a noise modulating facade.

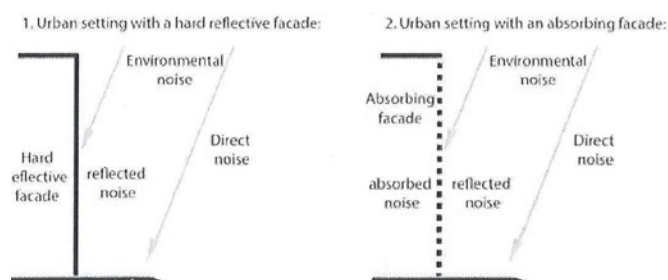


Figure 55-Theoretical scheme of noise reduction principle.

A thin glass adaptive façade element could be developed with this purpose, to adapt its geometry according to the amount of external noise level, helping to reduce it by diffusing it in different directions, possibility with a corrugated geometry.

4.6. Conclusions

This chapter introduced the concept of adaptiveness in this research by first analyzing it by the factors that define it to then relate it to thin glass.

This relation was studied by presenting principles of adaptive structures and the possible purposes for adaptiveness that could be relevant to the use of thin glass adaptive element.

Although I see potential in all the described principles and adaptive purposes, for the range of this research I believe that it is necessary to select them for further exploration.

Regarding the principles, I understand that the active bending is the one that is most related to the development of this research, as computer simulations are necessary to determine and analyze the thin glass adaptive element in order to

understand its behavior.

As for the adaptive purposes I believe that there is much potential regarding visual effect and ventilation.

I also believe that using adaptive fritting and thin glass for sun shading purposes is a very interesting path, however it is highly dependent on how much can the glass bend and if the necessary overlapping is possible.

The remaining adaptive principles and purposes mentioned in this research stand as inspiration and recommendation for further research relate to thin glass building elements.

Once understood the purpose for adaptiveness, it is necessary to restrict the research to a specific building element to be able to establish constraints and necessities for the thin glass adaptive element. The following chapter will further explore this topic together with potential uses for thin glass adaptive panels.

CASE STUDY

This chapter will present the analysis of case studies to identify a suitable building element type and context for a thin glass adaptive element. For each of the studied cases the potential of using thin glass on that specific context was explored. The result was the selection of a specific building element type that showed more potential for the development of this research.

5.1.Introduction

For the development of this research it is necessary to define constraints and context for the thin glass adaptive element; with this purpose, the selection of a specific building element is necessary.

With this objective, a case study analysis was conceived. This analysis has not the objective of selecting a singular building to apply the thin glass adaptive element, but to be able to identify a suitable type of building element to which it can be developed and studied; providing context and boundaries for the development of the next phases of this thesis.

As mentioned in the conclusion of chapter 3, adaptive elements in the built environment are commonly related to façades or roofs. Therefore, the case studies presented in this chapter are constrained to these two categories.

This analysis was made by selecting different buildings and looking at the constraints and possibilities of using a thin glass adaptive element on it.

The intention is to understand, with a brief analysis, what would be a suitable building element type and context for a thin glass adaptive element.

5.2.Case studies

This section will present potential case studies for this research, and analyze the use of thin glass in each of them.

The ideal case study context would be one in which the object of this research would be suitable to be used and that would provide enough possibilities to unlock its potential. At the same time, it would not present constraints that could block its development.

The selection of case studies was based on the following criteria: presence of glass, adaptiveness, reproducibility.

The first criterion for the selection of the case study is the presence of glass in the building. The case study should have glass as an important element in its construction. Although it is also possible a case study has elements that can be substituted by glass, if this

change also fits the other criteria.

This criterion also relates to the adaptiveness purpose of visual effect, meaning that the use of a thin glass adaptive element in a building should be visible, as it is a new material that can add value to the building itself.

The second criterion regards adaptiveness. This means that the case study should have necessities to which the adaptiveness of the glass elements can be a solution. Ideally a case study would already present adaptive elements, meaning that this type of solution was considered as adequate since the design stage.

The third criterion is the potential for replication of the concept. The case study should not have challenges that are singular to itself. Meaning that the proposed solution principles are also valid for other scenarios.

Besides the selection criteria, to each of the potential case studies, the use of thin glass was considered and concept ideas were sketched; in order to understand the possibilities of the use of thin glass in different situations.

These criteria were used to draw conclusions of which context and type of building element would be the most suitable for the development of this research.

5.2.1.Green House

The green house can be understood as a generic structure, repeated in many different environments; it is usually a glass structure, where this material is used for trapping the heat inside.

As discussed in the section 3.2, a green house is a very traditional structure, and its development and importance in the 18th century has expanded the possibilities of glass as a building material.

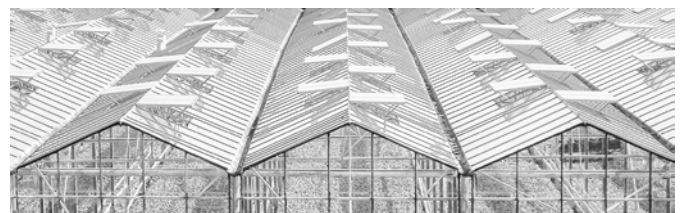


Figure 56-Greenhouses in the Westland region, Netherlands.

In addition, green houses have to adapt. The heat accumulated inside of it has to be regulated, otherwise the temperatures inside may become excessively high. Usually, these structures have

openings in the top of them which allow for ventilation.

Regarding the potential of implementation of thin glass, the green house shows some interesting possibilities; although there is a need for a primary structure to support the glass panels. However, the use of thin glass could give more freedom to the design of typologies, considering its flexibility.

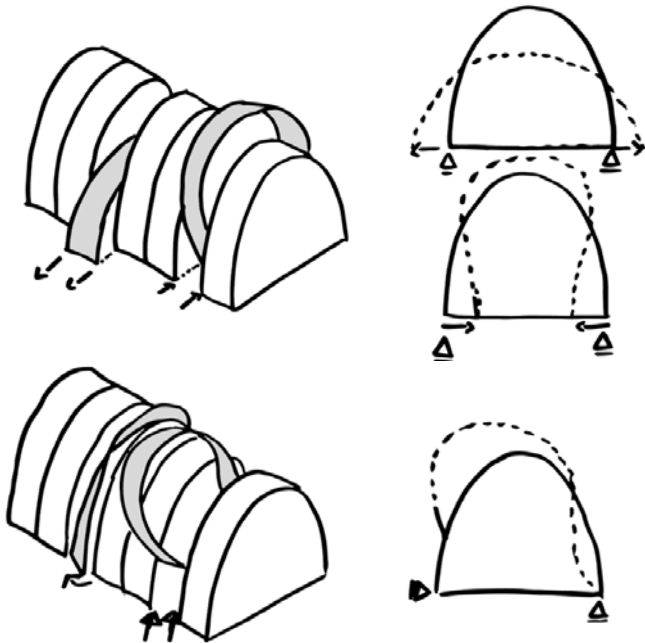


Figure 57-Adaptive thin glass elements in Green house.

Considering the movement of the panel, the ventilation of this structure could be provided by rotating the glass panels or by moving its edges (as they would not have structural purposes).

A possible disadvantage could be regarding water tightness; as the movement of the panels would leave its interior vulnerable - this can also be considered true to most of the single skin adaptive structures.

5.2.2.EWI Building

The EWI (Elektrotechniek, Wiskunde en Informatica) building at the TU Delft is a landmark in the campus. It is the tallest building of the university area at around 90 meters high.

Its main facades are mainly composed by glass; a double skin system that regulates the climate of the building.

The external skin isolates the building from the external environment. The internal skin functions as a light, temperature and ventilation regulator: the

windows are equipped with blinds to protect the spaces from the sun and light; the area underneath them houses the ventilation equipment.



Figure 58-EWI building at TU Delft campus.

Adaptive thin glass panels could be used in the external skin of the building, so its movement would not directly affect the climate of the interior spaces. The modularity of the façade allows for adopting a solution of individual panels to be reproduced on the building skin.

Although the modularity is an advantage, the high wind loads that this building is susceptible constrain the possibilities of using thin glass on its façade.

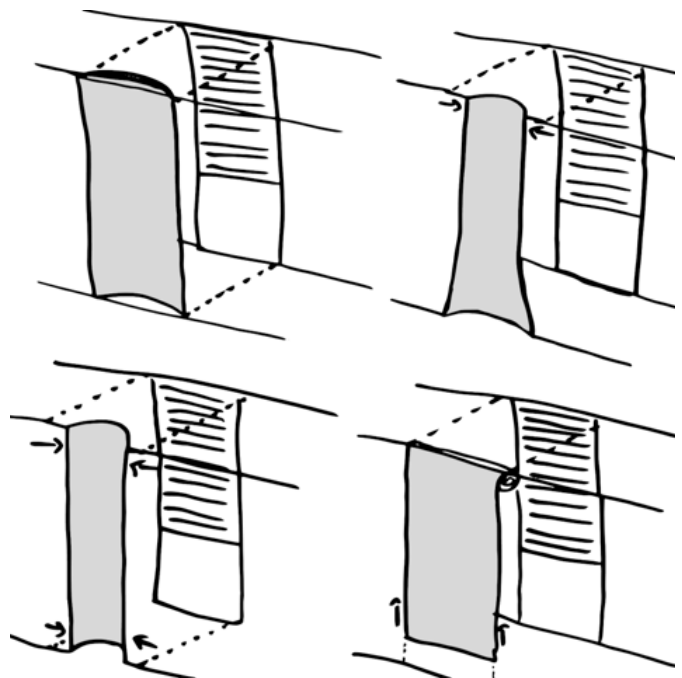


Figure 59-Adaptive thin glass elements on EWI façade.

Alternatives would be on having stiff solutions, with edge supports. One possibility would be to have a flat thin glass panel supported in all edges, when there is the need for ventilation in the cavity the panel is rolled in the same way as a roller blind.

Another alternative would be to have the panel curved to increase its stiffness and then force its buckling by moving its edges inwards, opening its sides for ventilation purposes.

5.2.3. Elbphilharmonie Hamburg

The Philharmonie in Hamburg is a building under construction with main façade is composed of hot bended fritted glass panels.

This iconic building takes advantage of the bending of glass to produce a visual effect as well as allowing for ventilation; the panels also have a fritted pattern corresponding to the needs of the areas behind them.



Figure 60-Elbphilharmonie Hamburg façade.

In this case, similar results could be achieved using thin glass. By pushing two of the vertices inwards, and allowing for the rotation of their edges the geometry

could correspond to the one in the actual building. However, a simpler solution such as lifting one of the edges could be an interesting alternative.

A disadvantage of this case, is that the façade of the building is composed by a single insulating skin. By using adaptive thin glass elements, the internal areas of the building would be directly exposed to the external climate which may cause in discomfort for the users (temperature and wind flows for instance).

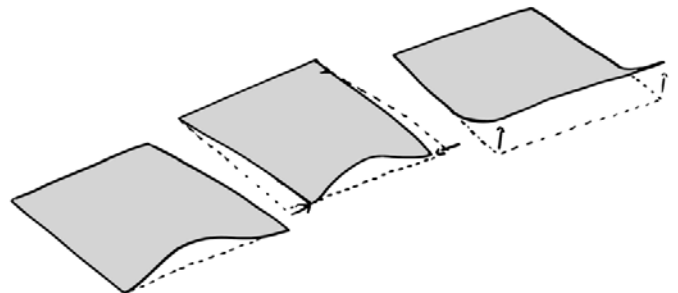


Figure 61-Adaptive thin glass elements on Elbphilharmonie Hamburg façade.

5.2.4. 2050 M

The 2050 M is a building currently under design phase in Washington D.C., United States. It was included in this lists due to its approach to transparency in office buildings.

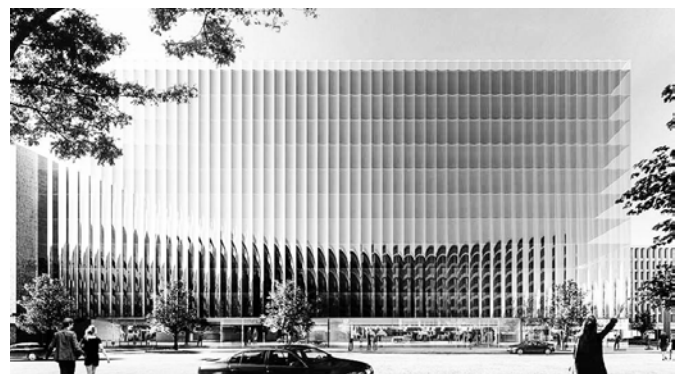


Figure 62-2050 M Office Building Façade.

The main objective of the design is to develop a maximum transparent façade, by adapting the geometry of the glazing elements.

The façade panels are made of insulated curved glass units which eliminate the necessity of the vertical mullions.

Considering the use of thin glass adaptive elements, a similar result could be obtained. The thin glass panels could have its stiffness increased by the curvature and adapt by the translation of the edges

towards the center of the panel. This would create a very interesting visual effect in the façade, as well as allowing for ventilation in the building.

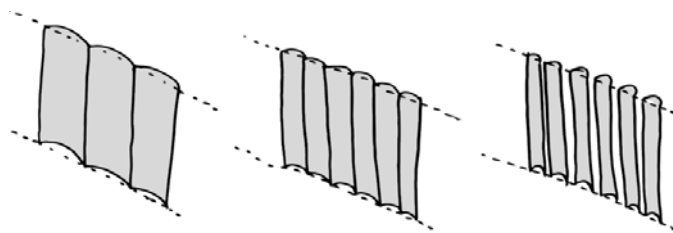


Figure 63-Adaptive thin glass elements on 2050M façade.

However, the same disadvantage regarding single skin solutions (as discussed on item 5.2.3) is also true to this case study.

5.2.5. Glass Dome

As the Green house, the Glass dome is also a generic structure. It represents a common typology in architecture, but also in glass structures. One of the most common use of glass structures is of covering open areas, mostly courtyards or cores, and still allowing the access of daylight.

Recently, there were many different researchers and designers who approached the glass dome. One of the most famous glass domes is the one on the Reichstag in Berlin in 1999.

Besides, there is a series of studies of these types of structures, starting in 1998 (at the Glasstec), 2003 (Stuttgart University), 2002-2004 (Delft Technical University), 2003 Exhibition Pavilion [8].



Figure 64-Glass Dome, Stuttgart University. 2003.

One of these structures (Exhibition Pavilion, 2003) approached the necessity of adaptability of the dome by including fabric bands for sun protection; another used louvers to protect the glass from direct

sun radiation and also an opening in the top to allow for natural ventilation (Reichstag, Berlin).

The use of thin glass adaptive elements in the glass dome can result in interesting solutions. Although a dome is a double curved geometry, it can be simplified to a developable geometry for the use of cold bent glass.

The use of adaptive thin glass panels requires the necessity of a primary structure to support the panels, to allow for their movement and also to guarantee the stability of the geometry while one of the panel is activated.

In this way the thin glass panel could have either its inferior edge or superior vertex translating along the radius of the dome; allowing for the ventilation necessary for this structure.

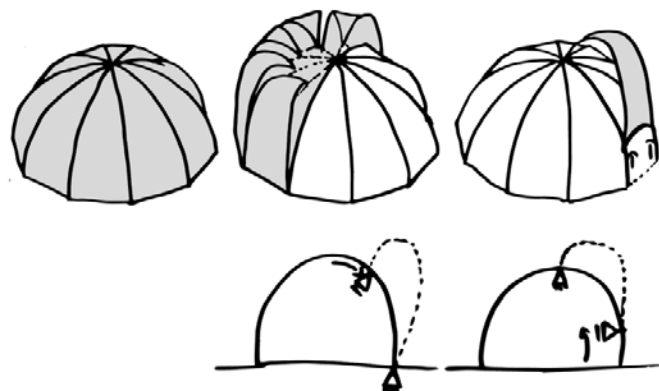


Figure 65-Adaptive thin glass elements on glass dome.

In the same way as the green house, a disadvantage of this solution is the water tightness of the structure, as the movement of the panels would leave its interior vulnerable.

5.2.6. Pavilion Expo 2012

The One Ocean Pavilion, described in item 4.4.1 shows also interesting possibilities (Figure 43).

Even if there are not glass elements present as an identity of this building, the louver system discussed before is very interesting. It raises the question if the same solution could also be achieved using thin glass elements, that could have controlled buckling as a stiffening strategy, creating a remarkable visual effect in the façade.

5.2.7. Kronberg Office Building

The Kronberg office building is located in Germany and is the headquarters of Braun.

Built in 1998 this building exterior façade consist of modular adaptive window boxes. These are individual units in a double skin configuration. The interior skin consists of a glass insulated unit that guarantees the climate insulation of the interior spaces. The exterior skin is an operable glass panel that can be opened to ventilate the cavity if necessary. The cavity also has a venetian blind integrated in its design allowing for sun protection.

By substituting the glass of the exterior adaptive panel by thin glass many solutions of movement are possible.

For instance, it would be possible to have the panel initially bent for increasing its stiffness and then gradually buckling it allowing for more ventilation in the cavity. This solution could be related to the adaptive fritting concept in thin glass presented in item 4.4.3 (Figure 50).

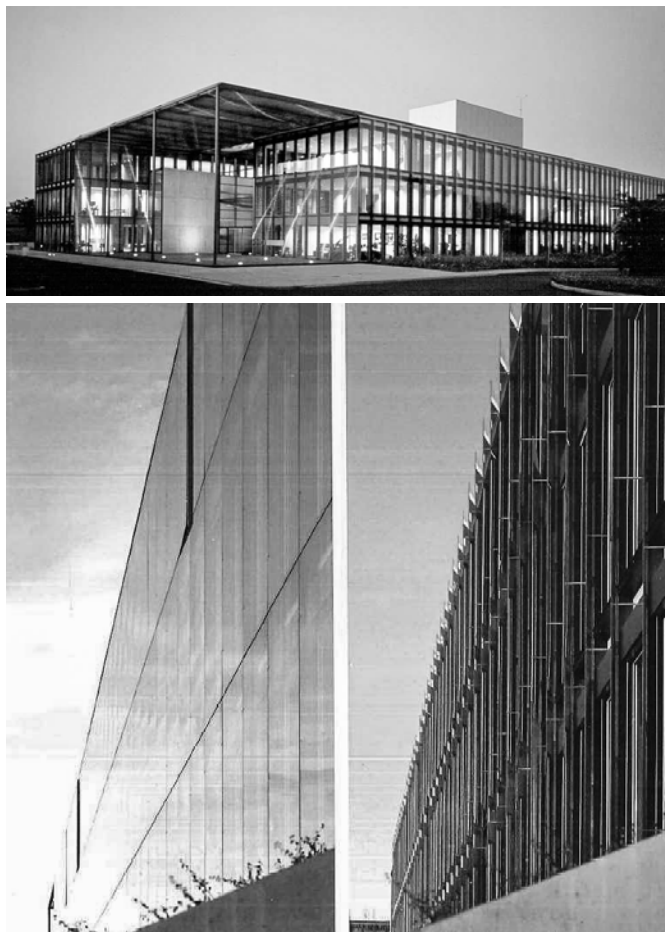


Figure 66-Kronberg Office building facade panels.

Besides that, it would be interesting to try to replicate the current design concept in thin glass, by having one of its edges pushed outwards, also allowing ventilation.

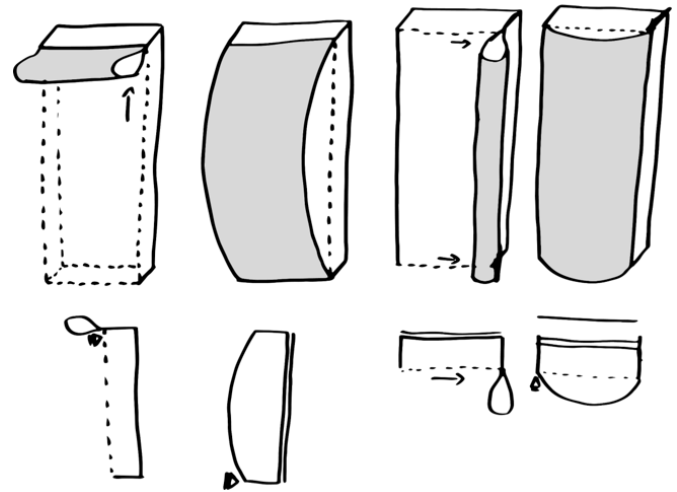


Figure 67-Adaptive thin glass elements on Kronberg office building (1).

This case study also could have the roller blind solution as proposed for the EWI building.

Another alternative would be having the panel supported by all its edges, while its vertices could be bent, in the same way as a sheet of paper, to allow for ventilation. This solution could create interesting visual effects on the façade.

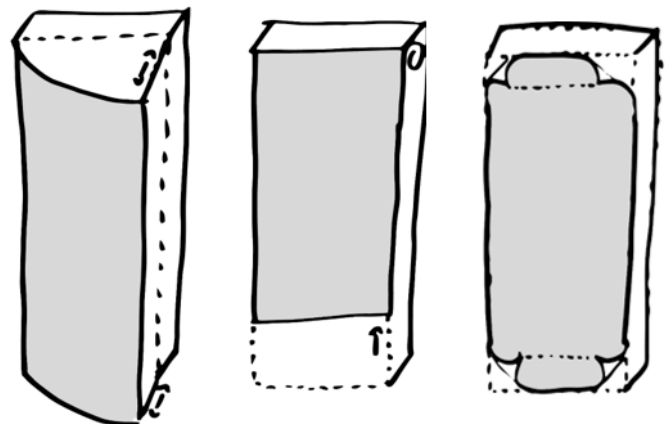


Figure 68-Adaptive thin glass elements on Kronberg office building (2).

5.2.8. Kiefer Technique Showroom

This building main feature is the adaptive shading system of the façade.

Although not in glass, it also generates curiosity

about the possibility of reproducing this effect in glass elements; as louvers and exterior shading solutions are very common in the built environment, this concept could be easily replicated.

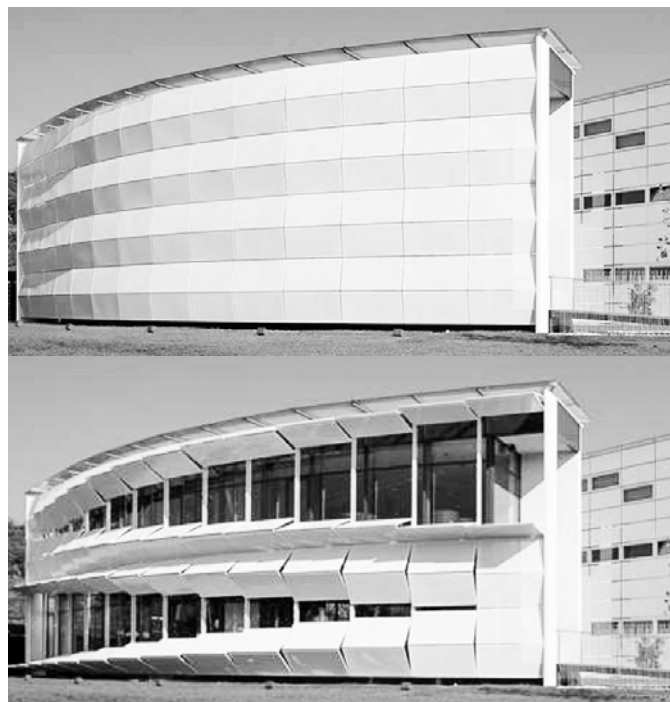


Figure 69-Kiefer facade shading elements.

Using thin glass elements as substitute for the elements in the façade could ring some advantages. The first one would be the elimination of the hinge in the middle of the panel, reducing the number of connections in the façade as a whole. The second is the interesting visual effect that it could bring if the concept of adaptive fritting was integrated in the solution; generating an almost transparent façade capable of sun shading.

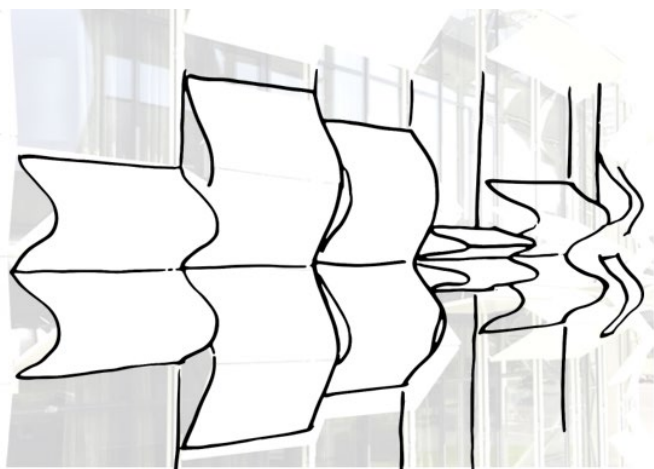


Figure 70-Adaptive thin glass elements on Kiefer shading elements.

5.2.9. 30 St Mary Axe

The 30 St Mary Axe in London is an iconic building of this city. It was included in this list because of the use of flat glass panels to produce a complex geometry, in addition, it also includes automatized operable windows to optimize its ventilation (which is uncommon for high rises, which have normally air tight envelopes with HVAC systems controlling the climate).



Figure 71-30st Mary Axe façade.

The use of thin glass in this building could be constrained by the diamond shape of the façade panels. However, solutions such as the vertex bending or the edge translation could be possible and would create interesting effects in the façade while also allowing for ventilation.

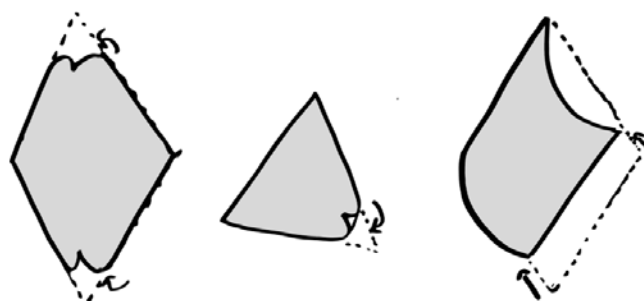


Figure 72-Adaptive thin glass elements on 30st Mary Axe façade panels.

5.2.10. St. Jakob Park Stadium

The St. Jakob Park stadium façade is composed

of translucent adaptive elements that allow for the ventilation of areas behind it. This building was included in this list as it presents adaptive panel solution used in series that give identity to the building but also have a technical function.



Figure 73-St Jakob Park Stadium façade detail.

If made out of thin glass, these elements could present different configurations, moved in different ways to achieve both the technical and aesthetical demands.

The concepts of controlled buckling, rolling and vertex bending also fit this scenario and could provide interesting outcomes.

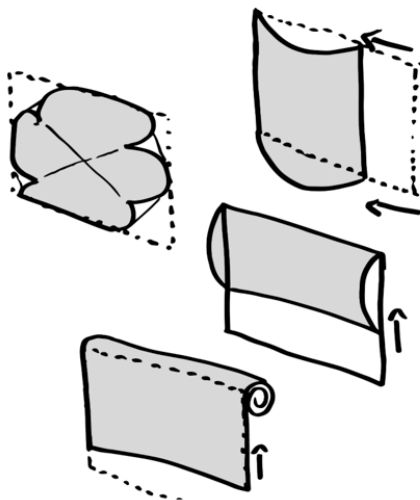


Figure 74-Adaptive thin glass elements on St. Jakob Park Stadium façade adaptive elements.

5.2.11. Glass roof - Gemeente Museum Den Haag

The roof of the courtyard of the Gemeente Museum in The Hague is a 700 square meter all glass roof.

This case study is relevant in this context as it is an example of a contemporary approach to a traditional solution of covering courtyards with glass roofs for allowing daylight. Although a clear

disadvantage is the heat accumulation generated, which demands for ventilation.



Figure 75-Gemeente Museum glass roof.

In this case, an all glass roof with insulated units requires a large amount of material, due very high weight of this solution. If thin glass adaptive elements were employed, the overall loads could be much lower and also the ventilation of the courtyard could be integrated on the panel.

However, a low inclination solution (as in the current building) would not be possible. The thin glass would bend inwards, and even if supported in all edges its center would still probably buckle (or accumulate water).

A possibility would be of creating panels that would have a higher inclination, and if there is the necessity of ventilation, one of its edges could translate allowing for the evacuation of accumulated hot air.

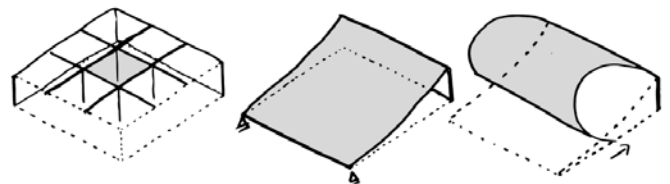


Figure 76-Adaptive thin glass elements on glass roof Gemeente Museum Den Haag.

Again, the same disadvantage as for the green house and the glass dome solutions is also present for this case. The movement of the roof panels leave the inner space vulnerable to water and for the external environment conditions

5.2.12. Agbar Tower

The last case study analyzed is that of the Agbar Tower. This building is located in Barcelona and it is an icon in the city, both by its shape and its colors.

The façade of this building is entirely

equipped with operable fritted glass louvers, which protect the inner envelope from the sun radiation.



Figure 77-Agbar Tower façade elements.

By using thin glass as an alternative to the glass louvers the amount of material could be reduced and a visual effect could be created to complement the façade.

As the floorplan of the building is circular it is possible to mimic and scale the solution of the thin glass movable canopy presented in section 2.3 (Figure 27).

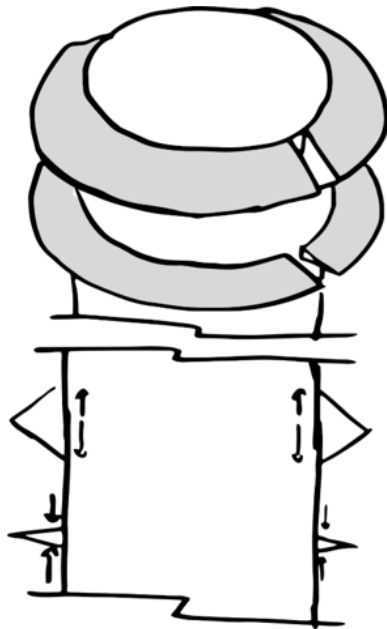


Figure 78-Adaptive thin glass elements on Agbar Tower façade.

5.3. Conclusions

After analyzing all potential case studies contexts and applications for thin glass building elements it is possible to draw conclusions.

By trying to understand the consequences of using thin glass adaptive panels in different contexts it was possible to see potential for the use of this material in the built environment.

Regarding the development of this research, it was also possible to identify constraints to some applications and potential in others.

A recurrent problem of some case studies scenarios was the vulnerability of the interior spaces by using adaptive elements. Adaptive elements should attend to the necessities of the users of the built environment, by directly exposing them to the external conditions, these elements may bring more issues than solutions.

This was the case for the roof structures; using adaptive elements in this cases requires specific detailing and attention to not expose the interior areas to the exterior conditions.

As thin glass is a flexible material that can be susceptible to bending and having its geometry altered by wind forces or material (snow, rain) accumulation. A roof structure with this material as the main external envelope can present major constraints to the way this panel moves.

A similar conclusion is also valid for single skin envelopes. The direct opening of this envelope to the outside environment can present issues to the interior environment. Although this may not be a problem for punctual openings (such as windows) the movement of the whole façade panel can cause problems.

In addition, a single skin envelope of thin glass elements would have to be made out of insulated units, which could constrain the possibilities of movement of the panel; or generate deep façade units, as the concepts explored in item 3.1.2.2.

Therefore, I believe the most suitable building elements for the development of this research would be on double skin façades, with the thin glass adaptive panel on the external skin.

This approach allows for the interior spaces of the building to be insulated by the inner skin, while the exterior skin creates the visual identity of the building and can also serve for other purposes (as presented in section 4.5).

The next chapters of this research focus on the analysis of a thin glass adaptive panel for a double

skin façade.

This also relates to the dimensions of the panel. This panel should be of a floor height and of a common width for building related purposes. The selected dimensions to attend to these parameters were 3000 by 1250 mm, which can be possible to fit in different contexts for facades.

Although currently there are no standard plates available in this dimensions (the maximum dimensions available in catalogues are 2020mm wide and 1365mm high to this date, Appendix 02), the production process of thin glass (item 2.2.1) allows for the increasing of the height of the panel, as the production constraints are related to its width (as mentioned in item 2.2.1 a 100m ultra-thin glass roll was already produced - Figure 21). Besides that, manufacturers also make available the option for custom sizes.

In addition, as the current applications of this material are mostly related to the electronics industry, the standard plate size is also related to it.

As this research is related to opening the possibilities of the use of this material to the built environment, it explores the possibility of using a higher panel (3000mm), while still considering the width constraint of 2020mm.

The following step of the research is to try to understand the behavior of thin glass in a façade, and what are the constraints for its bending and movement.

STUDY MODELS

This chapter aims to explain the process of using study models to develop the final product of this research. It is divided into two main sections: the physical model and the numerical model. The first one refers to a physical model used to explore the possibilities of this study, while the second one relates to numerical simulations in the computer using the FE (Finite Element) method.

6.1.Introduction

After narrowing the scope of the research to double skin façade adaptive panels there is the necessity of understand the possibilities of using thin glass in this context.

The development of potential uses for thin glass in the case study analysis showed that different types of geometry may be achieved using this material.

However, it is necessary to further analyze the stresses on the glass surfaces to identify the consequences and limitations of bending this material.

To be able to analyze this I followed two different approaches. The first one was building a physical model and the second was to develop computer FEM simulations to be able to simulate different scenarios.

In addition to the bending simulations, it is also important to relate these investigations to the façade context.

As thin glass is a flexible material, I developed simulations considering wind forces, which I believe are the ones that can be prevailing in deforming this panel in a façade.

6.2.Physical model

The first step into developing models was by making a physical model of acrylic to try to better understand the behavior and the constraints of bending a thin glass panel.

Although acrylic is much less stiff than thin glass, it is possible to approximate the geometry generated by the movement of the panel.

In addition, it is possible to identify the parts of the panel which are less stiff and therefore more vulnerable to deform under loads; in this case the lower stiffness is an advantage, as it is possible to deform the panel manually.

Besides, different geometries can be simulated to understand which type of solution increases or decreases the stiffness of the panel.

As both materials cannot stretch and have low tolerance to strain it is visible when a certain

movement causes more stresses, making it buckle or generating curvature in unexpected places; the main advantage of simulating this with acrylic is that it does not break.

The model consisted of a wooden frame which served as fixing, making it possible to bend the acrylic in different ways.

The acrylic plate measured 450x450mm and on each of its vertices a metallic hinge was placed. This hinge was attached to the acrylic by adhesive tape, but also by metal wires to guarantee that they would remain attached when moving the model.

The hinge was then fastened to wooden studs which had holes corresponding to those in the frame. Each of these studs had two fixing points in order to avoid it to pivot, so that the movement of the glass was related to the hinges only.

The frame had corresponding holes to the studs located every 50 mm, in order to be able to understand how much these edges were moving and what was the consequence of that specific movement.

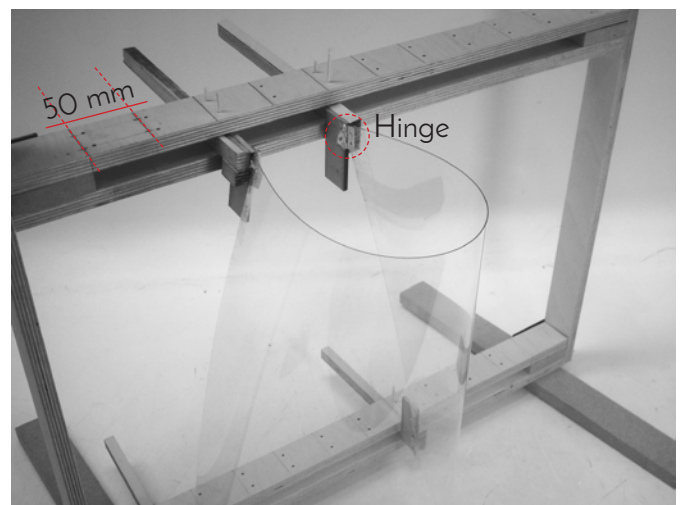


Figure 79-Physical model hinge and frame connection.

The first step was to attach the acrylic plate to the initial bending state. The edges of the plate were placed in a distance of 350mm between each other, the maximum distance before the geometry of the plate was too flat.

This distance was then reduced in a 50mm step until the minimum distance of 50 mm between the edges was reached.

Bending the panel symmetrically did not guarantee its complete stability. For frontal, perpendicular loads,

the panel would have its stability increased according to the reducing of the bending radius. while for lateral loads there was virtually no increasing in pressure resistance.



Figure 80-Increasing of bending of the physical model. Translation of the left edge.

After that, different configurations were tested. The first one was the bending of only one of the vertices. This movement was limited to 100 mm by the material, as it cannot stretch.

This movement increased the stiffness of the panel on the side the edge was bent, however the other side was still very susceptible to deform under pressure.

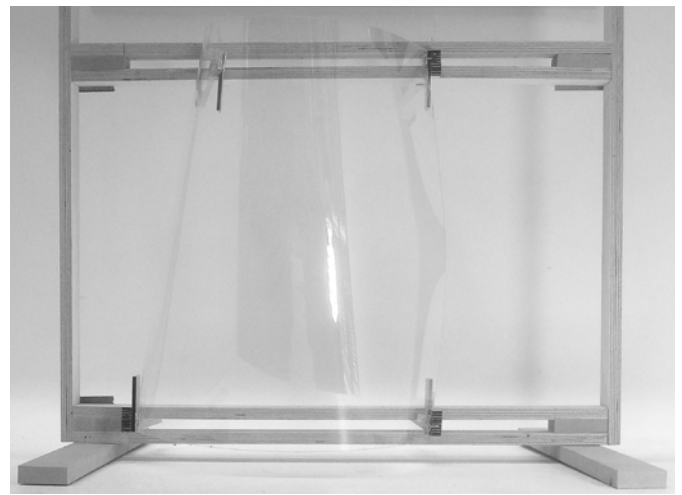


Figure 81-Top left edge displacement.

The last type of geometry tested was an asymmetric movement on the top and bottom tracks. This implied in generating a different radius on the top and on the bottom of the edges of the panel.

This geometry showed much more stability than the other two. The bigger the radius difference between the edges, the more stable it would become.



Figure 82-Asymetric movement. Different radius on the top and bottom edge.

In this case the panel became much more resistant to lateral loading, but was still susceptible to deform on the central area close to the edge with lower bending radius, being this part the one with less curvature and therefore less stiff.

The asymmetric movement also showed the stretching of the lateral edges of the panel, as there was no allowance for vertical movement in the model.

The general conclusions from the physical model are that only a symmetrical bending does not guarantee complete stability of the panel against perpendicular and lateral loads; as there is curvature only in one direction.

Besides that, the asymmetric movement showed an interesting result both for the stiffness of the panel but also geometrically.

6.3. Numerical Models

In order to understand if the results of the physical model in acrylic correspond to the behavior of a thin glass I developed computer simulations using the material properties of thin glass.

The material properties of thin glass used for the numerical simulations in this research were those of the Leoflex Architectural Glass from AGC as it was the material available for potential development of mockups in further phases of the research. Besides that, as it is a thin glass product already aiming the building industry.

Leoflex™ Properties

	Property	Measurement	Leoflex™
Mechanical	Density	g/cm ³	2.48
	Young's Modulus	GPa	74
	Shear Modulus	GPa	30
	Poisson's Ration		0.23
	Vickers Hardness	Before CT	595
	Vickers Hardness	After CT	673
Thermal	CTE	[10 ⁻⁷](50~200°C)	98
	Tg	°C	604
	Softening Point	°C	831
	Annealing Point	°C	606
	Strain Point	°C	556
Optical	Refraction Index	Nd	1.51
	Photoelastic Constant	nm/cm Mpa	28.3
Electrical	Volume Resistivity	log (Ω·cm)	8.4

Figure 83-AGC's Leoflex Architectural Glass material properties.[34].

The thicknesses of the plate studied were of 0.55, 1.1

and 2mm as these were also the available sizes for a potential development of mockups. Along with that, these different sizes cover the general range of thin glass possibilities to be applied in building applications (as thinner glass than 0.55mm can be too flexible and thicker than 2mm is already out of the category of thin glasses.

These simulations were developed in the software Diana mainly due to the reliability of the results and the familiarity with the software by the mentor team and the author.

As the assumptions of linear plate theory do not apply as the deformations of the material can be higher than its thickness [], the computer simulations were developed by a Non-linear analysis

The simulations of the bending stresses were divided by the ones related to the initial position of the panel and the ones related to the movement of the panel.

In addition, to evaluate the panel in a façade context, wind loads were also simulated to understand the vulnerable areas of the panel, and if they correspond to those identified in the physical model.

6.3.1. Initial bending stresses

The two main factors that determine the initial bending stresses are the initial size of the plate and its thickness.

To obtain the width of 1250mm, a wider plate has to be considered to achieve a curved initial geometry. Considering this, simulations were also performed to understand the size of the plate relating it to the geometric results.

The maximum width constraint was set to 2000mm and three different options were tested in a 250 mm step to analyze which of them presented an interesting geometry for the initial bending state.

The Table 7 shows the different plate width analysis and their stress distribution according to the different thicknesses.

Thin glass plate size analysis

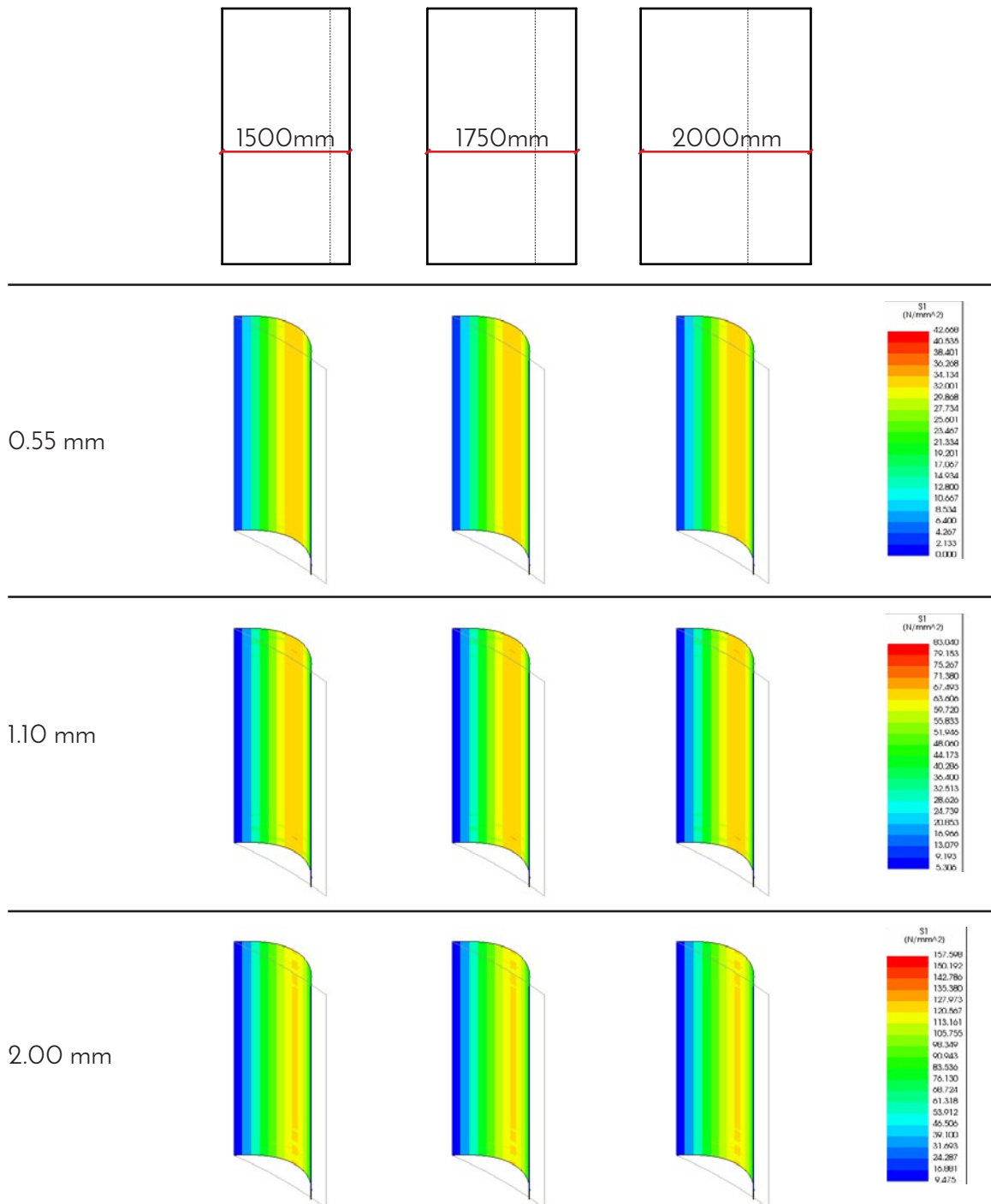


Table 7-Glass plate size analysis. Principal stresses on the top surface.

As expected the larger the dimension of the plate the more the geometry is accentuated. Also, the smaller the dimension of the plate, lower are the stresses as the bending radius is bigger. It is also possible to see the relation to thickness and stress, as the thicker the plate the higher the bending stress for the same radius.

In addition, it is interesting to observe that independent of the alteration of the geometry the stress distribution along the plate presented always a similar pattern.

After analyzing the results, I selected the option of using a 1750 mm plate for the further development of the research as this plate size combines a geometry that is not relatively flat and that also does not protrude much off the façade.

For the determination of the thickness of the plate, there is still the necessity of considering the movement and wind load stresses to have a better understanding of the behavior change according to the thickness.

It is also important to mention that the model used to simulate the plate was not entirely flat, a small initial radius was made to allow for the simulation to be made (otherwise the panel would not buckle if it was entirely flat).

This was made by making an arch with the same length of the panel and displacing its middle point. Different values were tested and related to the number of steps necessary to make the analysis, which also determined the analysis time. For this chapter the models included a displacement of 10 mm in the center, while for the next chapter's simulations were developed with a displacement of 50mm to increase the time efficiency.

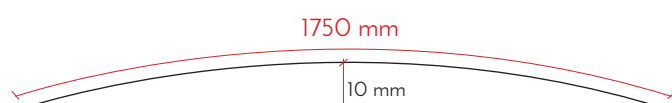


Figure 84-Model geometry initial bending to make simulation possible.

This initial bending implies also in stress, however, as the bending radius is too big the omitted stress is very low. By hand calculations (method to be presented in item 6.3.2), the Table 8 shows the calculated omitted stresses according to the thickness of the plate.

Omitted stress on simulation due to model geometry (MPa)		Thickness (mm)		
		0.55	1.10	2.00
Displacement of the center of the arc (mm)	10	0,53	1,06	1,93
	50	2,66	5,32	9,67

Table 8-Omitted stress on simulation due to initial model geometry. Values in MPa.

6.3.2.Movement bending stresses

After identifying the stresses caused by the bending of the panel to its initial state it is necessary to check the bending stresses related to the movement of the panel.

As in the physical model, the first approach was to first move one edge of the panel and check the resulting geometry and stresses generated by the increasing of the bending according to the thickness

of the panel.

This was made by moving one of the longer edges in a 125mm step until it was at the same position of the other one.

The boundary conditions were determined by using pinned supports on the two edges, allowing for rotation. And to applying a prescribed translation of one of them on the direction of the other.

The Table 9 shows the results of this analysis.

As expected, there is a clear relation between the thickness and the stress on the panel. An interesting fact was that it was almost directly proportional, by doubling the thickness the stress would also increase around two times.

The increase of stress by the increasing of bending presented a linear pattern. However, when comparing the pattern of different thicknesses, the stresses increased more from step to step with the increasing of thickness. This is visible in the Chart 4, where the line referring to the stresses in the 2 mm plate is steeper than the others.

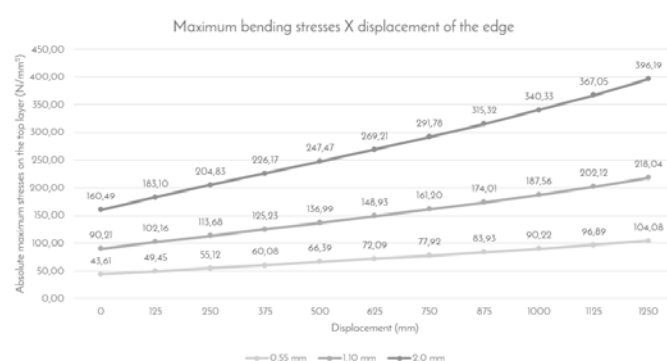


Chart 4-Maximum bending stresses according to movement of the edge for the different thicknesses.

In order to verify the values of the numerical simulation I made hand calculations to compare the results.

In order to compare this results it was necessary to find a way to relate the stress in the surface of the glass with the bending of the plate in literature.

The solution to establish this relation was by using the relation to stress and strain; in this way it was possible to calculate the stresses on the top surface of the glass based on its material properties and the bending radius.

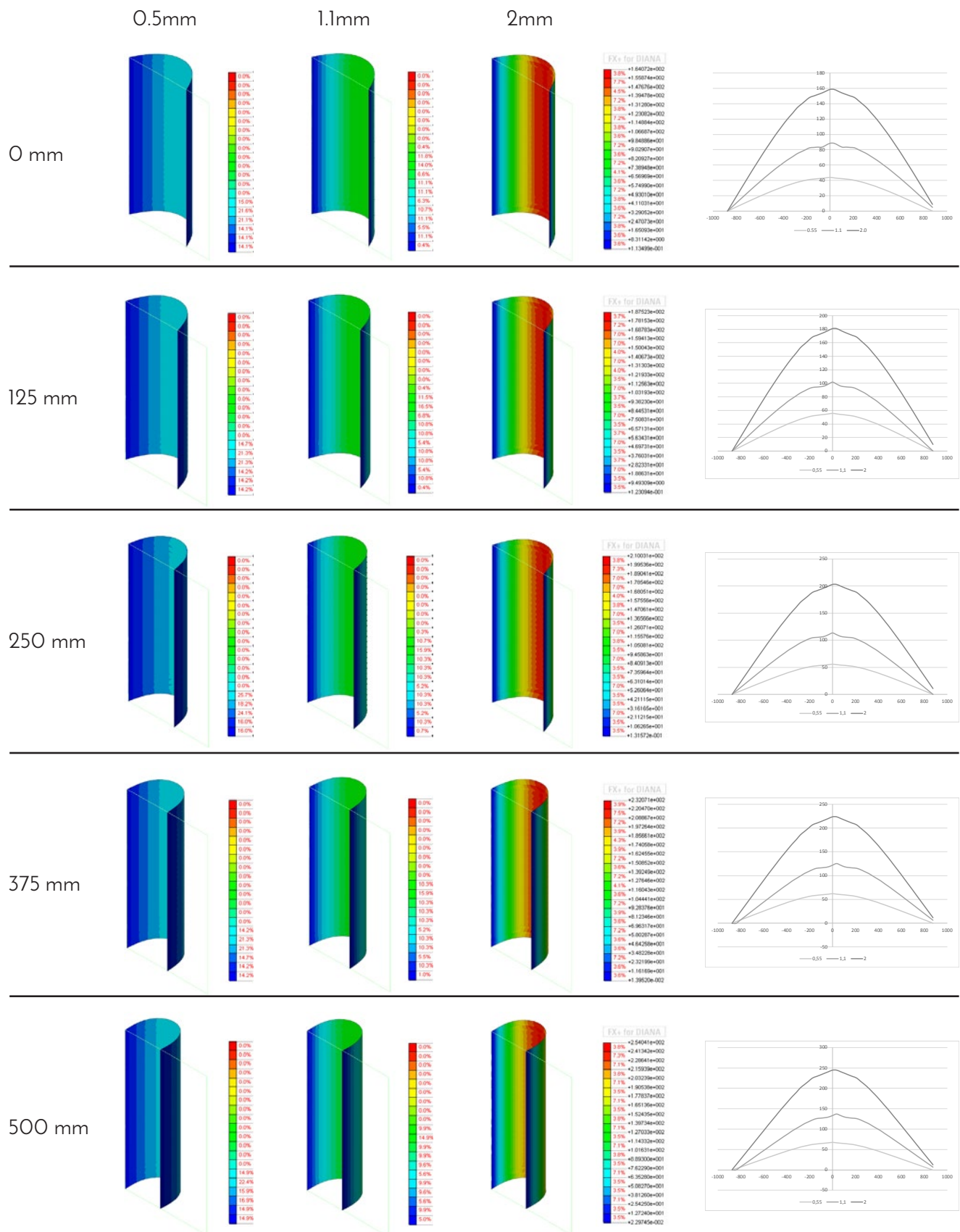
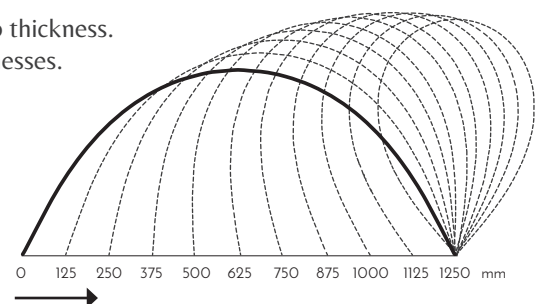
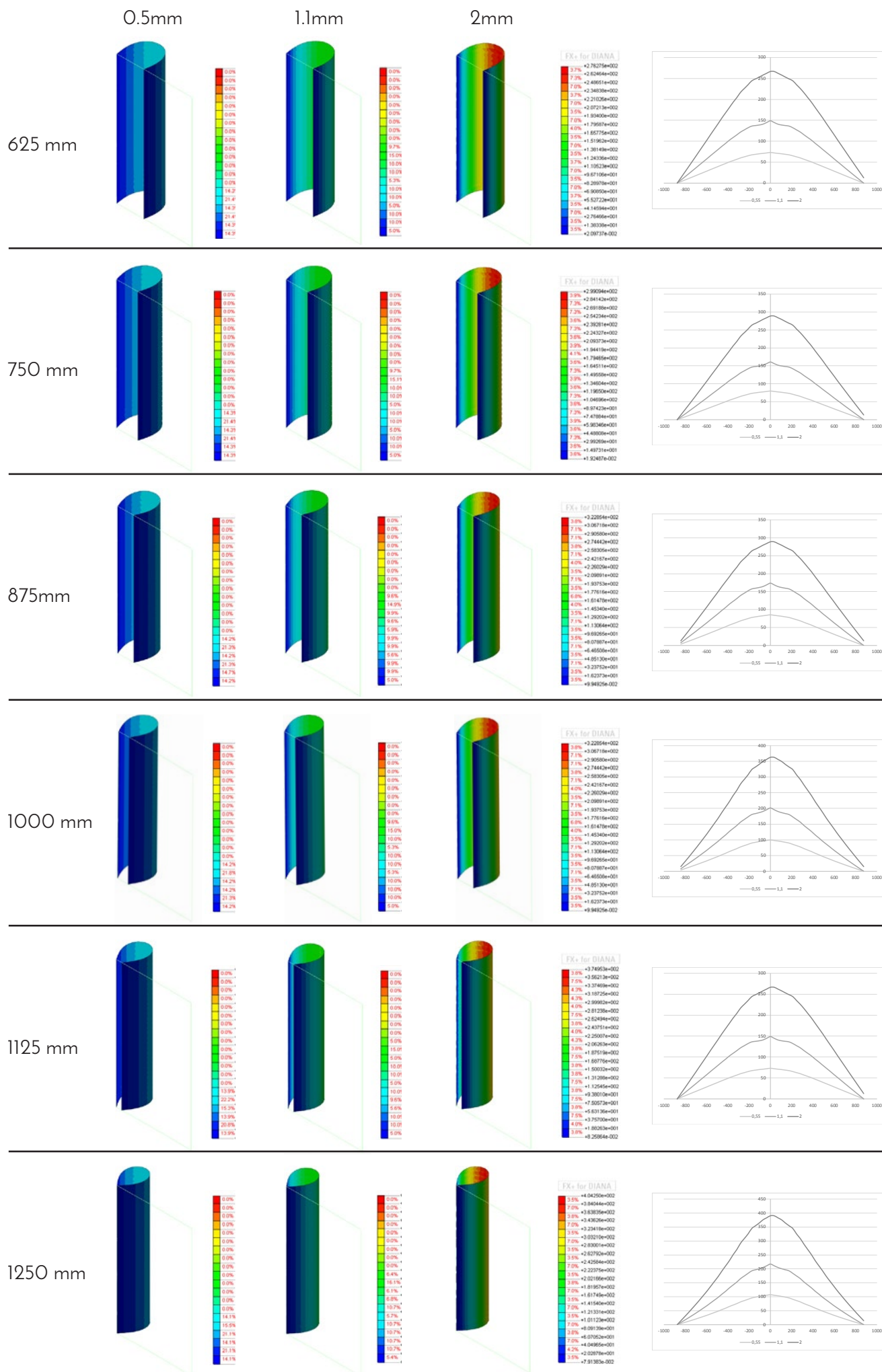


Table 9-Edge movement principal stresses on the top surface according to thickness. Charts present the stress distribution on the panel for the different thicknesses.





$$\sigma = (E \cdot t) / (2 \cdot R)$$

σ = stress on the top surface
 E = Young's modulus
 t = thickness
 R = Bending radius

The results for the calculations of all thicknesses of this validation can be found in Appendix 03. Overall, the results obtained by the numerical simulations had an average variation of 6% related to the hand calculations. This could be related to the tolerance of the non-linear analysis simulation.

6.3.3. Wind loads

Considering a thin glass facade panel, it is important to consider the pressure of the wind forces, and understand the behavior of this material.

In order to make this analysis a pressure force (of 1KN/m²) was applied perpendicularly to the panel to the each of the geometries of the previous analysis to see how would the panel behave under wind pressure when bent in different radii.

In general, when the panel deformed too much, or started to move laterally, the analysis of the simulation would not converge or fail (Figure arch bouncing).

Wind failure load (KN/m ²)		Thickness (mm)		
		0.55	1.10	2.00
Movement displacement (mm)	0	0,06	0,39	0,8
	125	0,06	0,44	0,8
	250	0,06	0,43	0,76
	375	0,06	0,44	0,69
	500	0,06	0,43	0,61
	625	0,05	0,43	0,53
	750	0,04	0,09	0,44
	875	0,02	0,09	0,39
	1000	0,03	0,1	0,33
	1125	0,03	0,11	0,3
	1250	0,03	0,14	0,28

Table 10-Failure/Calculation non convergence wind load according to the movement of the edge for the different thicknesses.

The Table 10 shows the equivalent load of the last step calculated by the software, which is assumed to be the load that caused the panel to deform or move

in an unexpected way. However, by looking at all the geometry deformations, in some cases, the geometry did not show this failure behavior (highlighted in the table), but even by increasing the load steps the simulation was still interrupted at a similar equivalent load.

Generally, the thicker the panel the more difficult for it to deform; however, it is visible that, independent of the thickness, or of the bending applied to the panel the wind pressure could deform it.

In the Chart 5 it is possible to compare the resistance to the wind for each panel thickness according to the movement. However, it was not possible to identify any pattern correlating the different thicknesses.

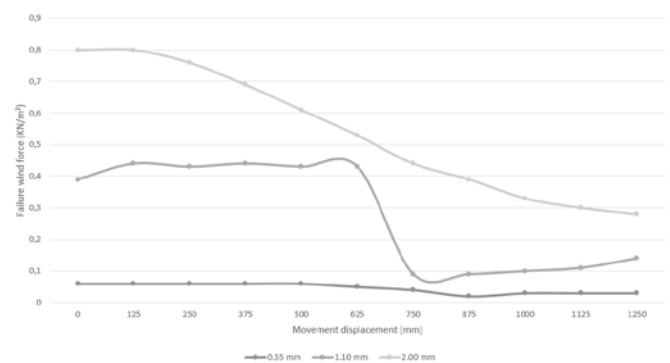


Chart 5-Failure/Calculation non convergence wind load according to the movement of the edge for the different thicknesses.

The expected behavior would be an increase of the wind resistance on the first movement steps. With the increasing of the movement steps, the geometry would start to become more unstable and its wind resistance should be reduced.

However, this behavior was only identified in the 1.1mm panel, which had a constant resistance until a certain point where it was drastically reduced.

While the 2mm plate has almost a linear decay in resistance according to the bending, the 0.55mm panel presented a very low resistance, independent of the bending.

This also shows that the conclusions of the physical model were right, that there was not much stiffness on the center of the panel, independent of the bending radius.

However, it showed that the increasing of the bending only reduced the resistance of the panel to wind loads instead of increasing it as expected.

6.4. Conclusions

By developing physical and numerical models it was possible to better understand the behavior of thin glass in a façade context.

While the physical model helped to explore different geometries and infer their relation to stresses and load resistance, the numerical model helped to check if these conclusions were also valid for the use of thin glass.

The numerical analysis was also very important to define the plate size and thickness of the thin glass panel for the following phases of the research.

The initial size of the plate was defined as 1750mm as mentioned in item 6.3.1. After analyzing the influence of the thickness of the glass to its bending stresses and to its wind resistance, I believe that the thickness of 1.1mm is more suitable for the façade panel.

Although the bending stresses of the 0.55mm plate are lower, this plate showed very low resistance to wind forces. As for the 2mm plate, the wind resistance is higher, however the bending stresses for this case are too high, leaving a low margin for additional stress on the plate or constraining its movement.

The 1.1mm plate showed a good balance between bending stresses and wind resistance (it was also the only wind simulation that corresponded to the expected behavior). By using this plate thickness, it is still possible to explore further geometries, while still having stress margin for wind and impact resistance.

By understanding the behavior of the thin glass plate in the façade it is possible to follow the research exploring what type of geometry would be possible using the knowledge developed in this chapter.

The next chapter will explore the factors that determine the behavior and geometry of a thin glass adaptive panel.

MOVE AND SUPPORT

This chapter covers the main characteristics which allow adaptiveness, the movement, the supports. It has the objective of studying these characteristics independently to them analyze the relations and interdependence between them.

7.1.Introduction

For a thin glass façade panel to be adaptive it has to move, however this movement is determined by the way this panel is supported and how its supports are designed.

This chapter looks into possibilities of movement and support of a thin glass adaptive panel based on the design proposals developed in the case study analysis.

First, these alternatives are presented separately; then the relation between them is analyzed, showing how the boundary conditions can affect the design and the final geometry of the panel.

It is important to clarify that this chapter has not the objective of covering all possible alternatives, as this is beyond the reach of this research; each case requires for a specific solution.

Rather than that, it aims to look into general design strategies, showing different possibilities and conclusions that could also be adapted to other scenarios; increasing the knowledge over the application of thin glass on adaptive façade panels, but also in the built environment context.

7.2.How to Support

Equal to movement, the support of the façade panel has an important role on its design. Considering glass, and more specifically thin glass, the parameters that affect the supports become very specific.

To analyze how to support this panel I considered both technical and aesthetical components as this combination is crucial for façade design.

The first aspect considered was protecting the edges. In the same way as common glass, thin glass's weaker part are its edges. This is due to the necessity of cutting them in the production process to the desired panel size or shape.

The second aspect considered was to avoid stress concentration. Peak stresses are important to be avoided in general design, but in glass this is very important due to the breakage characteristics of this material. Again, the previous consideration regarding

the protection of the edges can also be related to preventing stress concentration, especially in these areas.

The third aspect is the allowing of movement. As the object of this research is an adaptive panel, movement is inherent in the design. The supports of the panel should not obstruct this characteristic, but enhance it as possible. The combination of support and movement is further discussed on section 7.4.

The fourth aspect is related to an aesthetic perspective. The supports should be designed, or positioned in a way to avoid blocking the views from the inside of the building. As a glass façade panel, it is very important that the elements that compose are integrated with its function; which is to give identity and protect the building, creating a (as invisible as possible) boundary between outside and inside.

Based on these four parameters and on the data and ideas developed on the previous chapters I selected possible ways of supporting a thin glass façade panel. (Figure 85).

Not all of them are ideal according to all parameters, the choice between them is very much related to the desired movement and boundary conditions (section 7.4 studies this relations).

The first solution consists of supporting the panel by its four edges. The advantage of this would be that the edges could be protected by its supports, however, at the same time, there could be much stress concentration in those areas. This solution also could pose constrain to the movement of the panel, as all edges should be fixed to the supports, it would be necessary for the support to move and deform according to the shape of the panel. Nevertheless, this solution proposes an almost unobstructed view, as only the edges of the panel are covered.

The second and third solutions are derived from the first one, they consist on supporting the panel by its longer and shorter edges respectively. Compared to the first one they pose a disadvantage concerning the protection of the edges, as the protection provided by the supports is no longer there. However, these solutions remove restrictions for the deformation of the edges, making the movement and deformation of the panel easier.

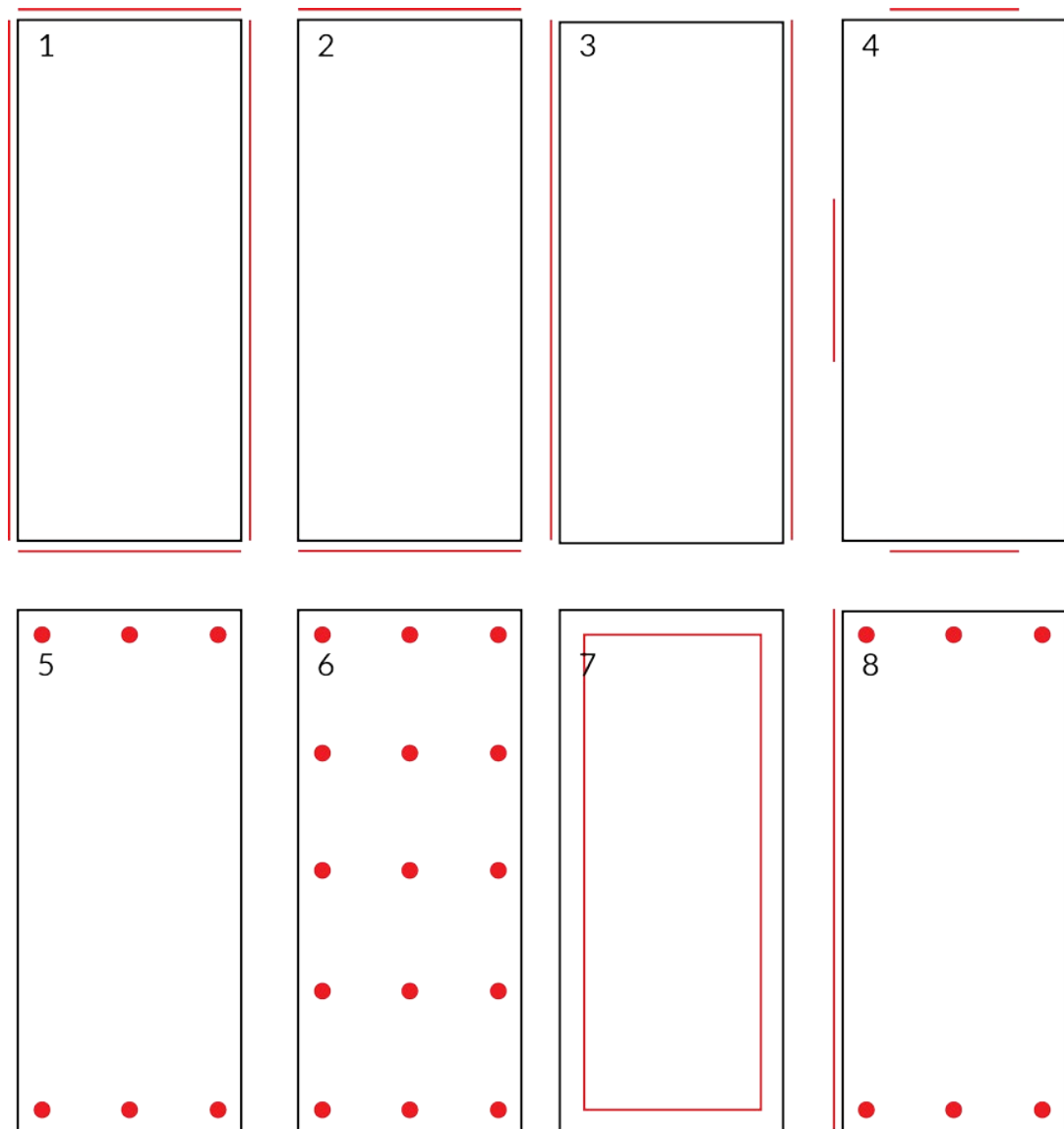


Figure 85-Support solutions based on potential use of thin glass developed in Chapter 5.

The fourth solution is also related to the first one. However, in this case, the vertices of the panel are not supported. Compared to the first solution this one is prone for the movement of these areas of the panel, while still maintaining the rest of the edges protected. Its disadvantage is that the transition areas of the edges, from supported to free are critical when considering stress concentration.

The fifth and sixth solutions introduce a different way of supporting the panel, leaving the edges free. These supports are based on the idea of having an adhesive connection between the glass and the supports.

With the supports detached from the edges, there is less concentration of stresses in these sensitive areas (it remains the necessity of protecting them),

however the ones around these supports may have peak stresses.

These two options have a difference in the amount of supports proposed, they were proposed like this to make evident the relation in this case of stability of the panel (probably achieved with more supports) and the visual obstruction that such amount of supports would cause. In addition, the increasing of number of supports could also limit the possibilities of movement of the panel. In both cases, transparency and movement, the sixth alternative shows more advantages.

The last two solutions are hybrids of the previous ones.

The seventh solution is an offset of the frame proposed in the first solution to the inside of the panel, with the objective of avoiding stress

concentration in these areas. Compared to the first one it has a disadvantage as it obstructs much more the view and might be a constraint to movement.

However, if the same logic is used to create alternative versions of solutions two and three, interesting results may be achieved, by avoiding the concentration of stress on the edges while not obstructing movement.

The last solution shows the combination of the two types of support. This was considered under different scenarios.

The first one being a possibility of using supports distant from the edges in part of the panel, while still using edge support for stiffness in the other direction. This could be a possibility to create a stiffer panel without obstructing the view as in solution number six.

The second one as the possibility of temporary or auxiliary supports. The edge supports could be principal ones while the others act as stabilizers in a closed position of the panel; or the point connectors could be the main supports, while the edges are protected by profiles, keeping them stiff without stress concentration.

These examples show principles that could be used in the object of this study. As it will be covered in section 7.4, and also mentioned before, the selection between them is deeply related to the type of movement desired, aspect which is covered in the next section.

7.3. How to move

The movement of the panel is also a fundamental aspect to consider, this section analyzes the type of movement for the façade panel.

This was made in the same way as the previous section, by selecting important aspects related to the movement of the panel.

Considering first aesthetics, but also the employment and choice of this material in a façade, it is interesting that when using thin glass in a façade it is noticed as different than common glass and its unique qualities are visible.

In this case, the movement of the panel is the way

these characteristics (of bending and flexibility) are made evident.

The second aspect is related to the quantity actuators of the panel. As a façade panel, it is expected that it is reproduced multiple times in a façade. Therefore, it is desired to have a small number of actuators in each façade panel to reduce the number of different inputs regarding a whole façade system.

The third aspect considered relates to the stiffness of the panel. As described for common glass panels, thin glass can also benefit from its shape to increase its stiffness.

The movement of the panel is directly related to its final shape, and to the stiffness obtained from it. Therefore, it is interesting to move the panel in a way that its final shape is stiffer.

The fourth aspect is also related to the final shape of the panel, regarding a limitation. As already described in chapter 2, it is not possible to have double curved shapes with thin glass, because this material has a very low strain tolerance.

Therefore, the selection of the movement of the panel should take this constraint in consideration, avoiding movement that results in a double curvature of the panel.

Based on these parameters, on the ideas developed for the case studies and also on the knowledge developed on the initial phases of this research I selected possible alternatives of moving a thin glass façade panel.

As for the supports alternatives, not all of the proposed solutions are ideal regarding all aspects, the choice between them is dependent in the desired final shape and also on the supports.

The first alternative for movement is the translation of one of the edges of the panel inwards, forcing it to buckle.

This solution is interesting in many aspects, it evidently shows in the façade the change of shape of the panel and the qualities of the material while making use of only one actuator in the edge. Also, it produces single curved shapes, which give stability to the panel.

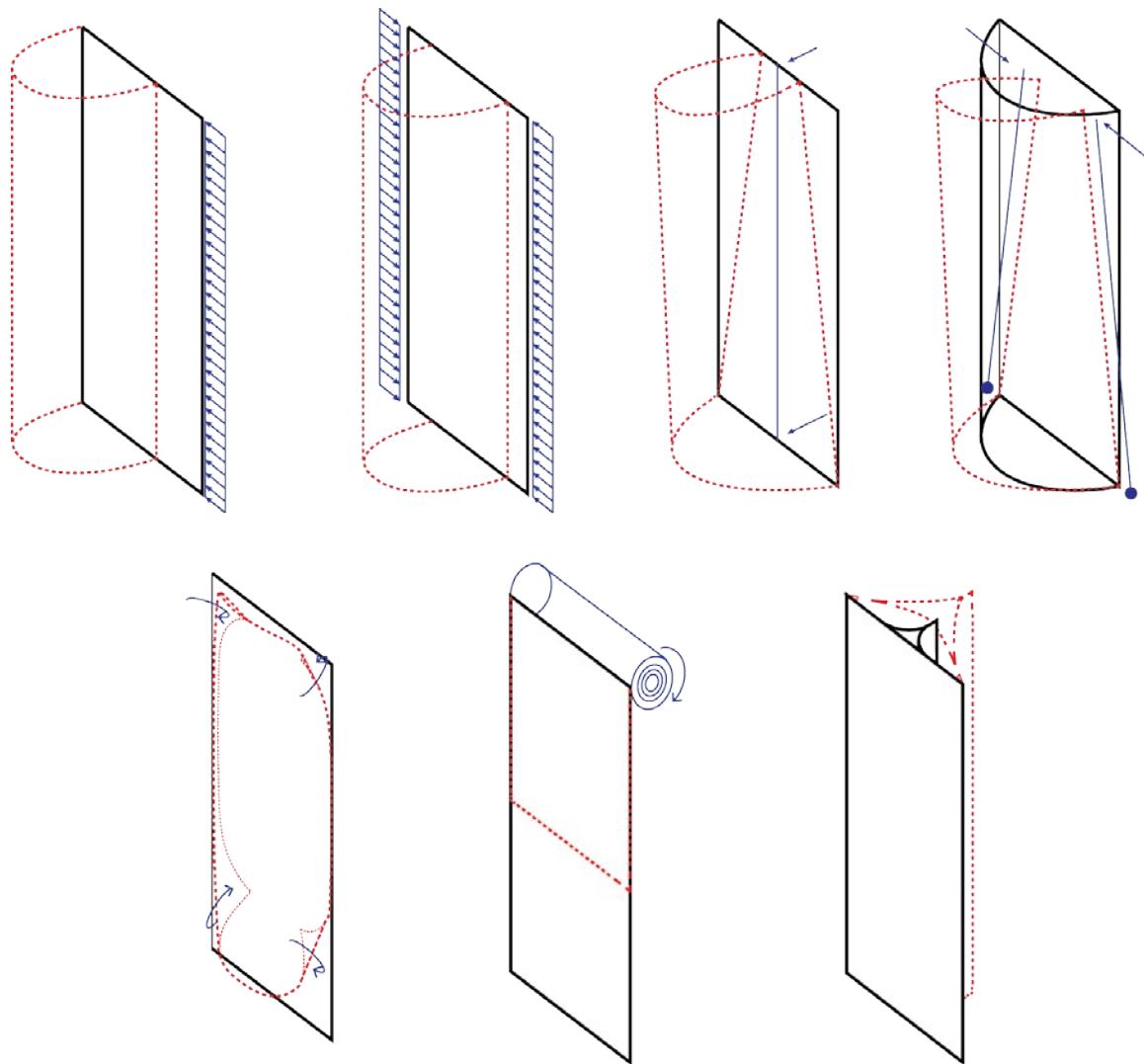


Figure 86-Movement solutions based on potential use of thin glass developed in Chapter 5.

The second solution consists on the translation of two opposed edges of the panel inwards, also forcing it to buckle. Compared to the first solution it has the disadvantage of having two actuators.

The choice for this type of solution would be one that has the necessity of opening the panel in both sides independently; this could be due to aesthetical or technical aspects (such as ventilation).

The third solution presents a similar result of the previous one. It consists on placing a bar in the center of the panel; this element has two functions: to control the movement of the panel and to protect the panel against wind forces.

This idea came from the results of the numerical simulations presented in the previous chapter, which showed that the bending of the panel, by itself, could be susceptible to wind forces against it.

In this case, the bar controls the shape of the panel, which behaves symmetrically with the bar as the symmetry axis. The bar would have two actuators,

achieving similar results to the previous solution. However, there could be the possibility of the bar actuators to create an asymmetrical shape by one of them moving further than the other one.

For the fourth solution, the edges are also used to activate the panel; however, instead of translating the edges rotate having one of the vertices as the center of rotation.

This alternative also works with two actuators and the buckling of the panel. However, this alternative shows a certain constraints regarding the change of height of the panel, so that the supports have to be able to afford this tolerance.

The fifth alternative relates to using point supports to the panel. Instead of having the movement by translating the whole edge, the panel adapts by translating points on its surface.

The result is similar to the previous option, however, there is more freedom to the edges to bend allowing different final shapes to the panel.

However, in this case, the number of actuators is equal to the number of point connections, which can be a disadvantage to this type of solution.

The sixth solution differs from the previous ones by moving the vertices of the panel. In this case the vertices of the panel could bend inwards or outwards, in a similar way as a sheet of paper.

One possible disadvantage of this solution is that if the movement is too subtle it may be difficult to be visualized, missing the factor of valorizing the façade and the material. Otherwise if evident this type of movement is very surprising considering a material such as glass.

Another factor to consider is that the bending itself does not collaborate much with the stiffness of the panel, which would have to be compensated by its supports. In addition, the overlapping of bending lines could become an issue regarding double curvature and generation of peak stresses on the edges.

The seventh solution is also very different from the previous ones. It is based on the capacity of thin glass to bend, and also on the manufacturing of ultra-thin glass.

It consists on rolling the glass, in a similar way of a window blind system. This could result in interesting results in a façade. In this case it is fundamental to consider the thickness of the glass to be used as it determines the minimum bending radius.

Another important factor to consider is that in a façade, the glass is submitted to external conditions which leave residues in its surface; by rolling and unrolling the sheets, it is necessary to be aware of that avoiding the scratching and damage of the glass surface.

The last alternative is related to the geometry exploration described in chapter 3. This is a more general alternative, which consists in an alteration of the initial geometry by the movement of one of the edges.

In this case, the panel's complexity is increased, as other factors, such as surface contact and special supports might be necessary. In the other hand the stiffness of the panel is not only guaranteed by the movement, but by its geometry, which can be considered an advantage.

All these movement possibilities are very dependent on the type of support of the panel. This is further explored on the next section.

7.4. Degrees of Freedom

It is possible to identify movement by dividing it in translation and rotation, one being linear movement and the other related to the change of orientation according to an axis. Each of these can be related to the three dimensional axes and therefore, "the ability of an object to move around in space is therefore defined by a maximum of six degrees of freedom." [25].

This section has the objective of exploring the relation between the type of support and the movement of the panel.

Depending on the design of the support, a certain movement and geometry is possible. This relation is mostly based on the degrees of freedom the supports and detailing of the panel allow.

To describe the relation between supports and movement each of the movements described in the previous section will be discussed according to the number of supports and degrees of freedom.

This analysis does not have the objective of describing all the possible solutions between support and movement, as this would not be feasible for this research; the intention is to analyze the relation between movement, supports and degrees of freedom and what are the consequences of increasing or decreasing the quantity of these last two parameters.

The method to perform these studies is by a FEM model simulation, all concepts (unless mentioned) use the same panel dimensions (3000 x 1750 mm) and thickness (1.1mm) of panel. The choice of the type of degree of freedom and number of supports to be analyzed in each panel is dependent on its particular configuration, generally they were selected in a way to allow for the configuration of a façade panel.

Unless stated, the stress results presented are taken from the top layer of the panel, and correspond to the first principal stresses as tensile stresses are more significant to these simulations.

The description of the degrees of freedom and

movement is based on the Cartesian axis on the configuration presented in Figure 87.

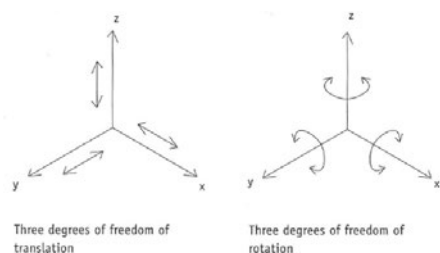


Figure 87-Degrees of freedom and its reference cartesian axes.

7.4.1. One edge translation

This movement was presented as the first solution in the previous section, it consists on the translation of one of the edges of the panel in the x axis on the direction of the other edge, using a prescribed displacement load of 500mm, forcing the panel to buckle.

In the case of this movement, it is interesting to compare its behavior of the panel according to the number of degrees of freedom of the supports by changing them from one to two; first allowing only for translation and then adding rotation.

In addition, the number of supports was also compared to see the behavior of the panel by using two or three supports.

The Table 11 shows the results of the analysis of this movement with these different combinations.

By first looking at the geometry of the panel, it is possible to see that when there is a single degree of freedom (translation) the panel keeps the initial inclination on the edges, while with two degrees of freedom, the curvature of the geometry is homogeneous as the edges can rotate adapting to the movement of the panel.

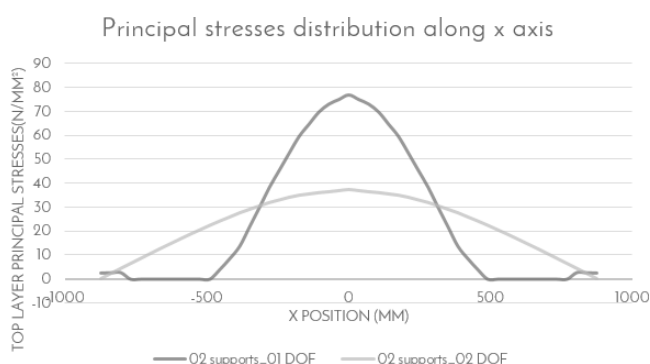


Chart 6-Principal stress distribution along the plate at the top surface of the panel for two supports configuration according to the number of degrees of freedom.

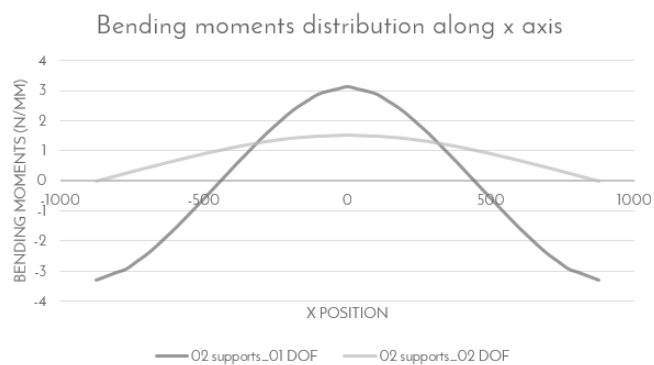


Chart 7-Bending moments distribution along x axis for two supports configuration according to the number of degrees of freedom.

This is also reflected in the stress distribution and bending moments generated in the panel. In Chart 6 and Chart 7, it is possible to see that comparison. The stresses and bending moments when allowing one degree of freedom are two times higher than those when the supports allow for two.

It is also evident on the bending moments chart the difference of behavior on the edge of the panel, while the one degree of freedom option shows concentration of bending moments on the edge, using two degrees of freedom the moments at the same point go to zero. This difference would be also visible in the stress distribution by plotting the stress diagram of the bottom layer of the panel.

The number of supports, and their position also plays a significant role in the final geometry. In this case another line support was added in the middle of the panel.

By using 3 supports instead of two it is already possible to see the potential of this idea; the increasing on the number of supports increases the number of sinus shapes in the panel. However, this also generates a higher stress concentration as the increasing number of supports reduces the radius of each curve.

Again, by adding a degree of freedom (rotation) the shape is different, as well as the stresses that are reduced and more distributed (Chart 8). The same happens for the bending moments, which show that the high difference of stress on the edges of the panel is also present in the comparison using three supports (Chart 9).

One edge translation

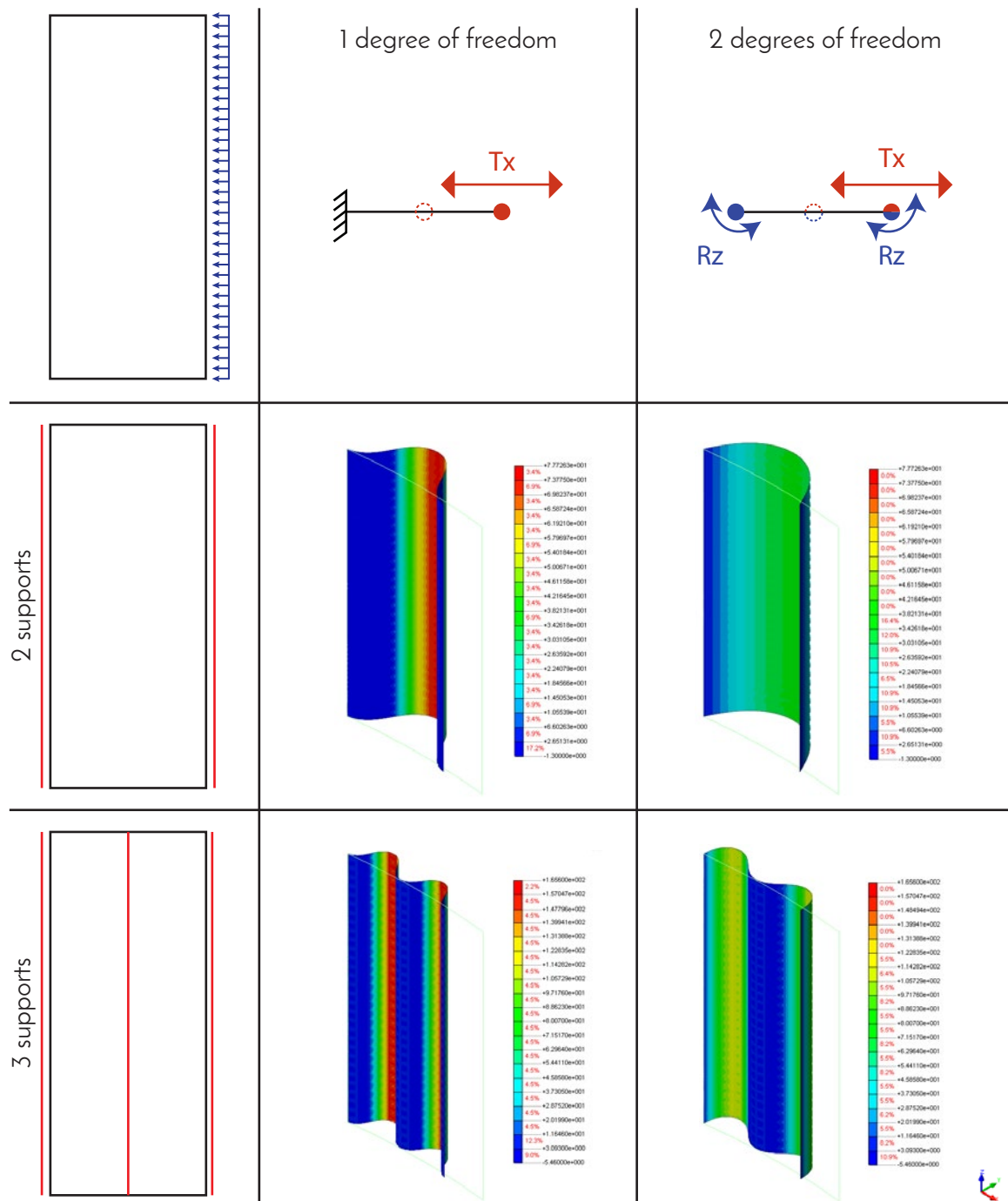


Table 11-One edge translation geometry and stress distribution according to number of supports and degrees of freedom.

Principal stresses distribution along x axis

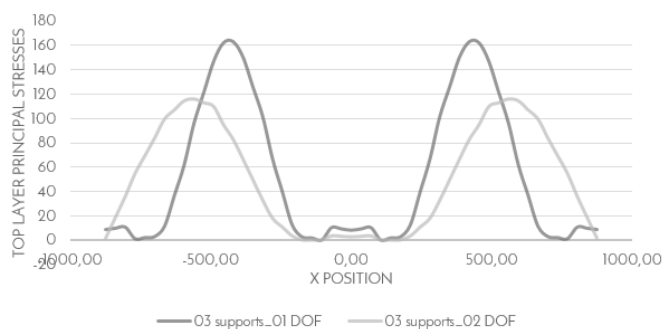


Chart 8-Principal stress distribution along the plate at the top surface of the panel for three supports configuration according to the number of degrees of freedom.

Bending moments distribution along x axis

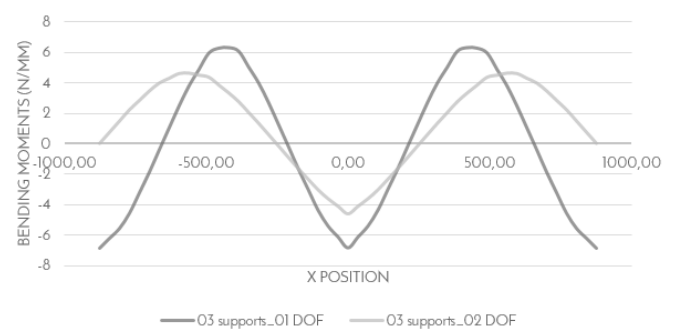


Chart 9-Bending moments distribution along x axis for three supports configuration according to the number of degrees of freedom.

A short conclusion from this movement analysis is that by increasing the degrees of freedom of the supports, the stresses are lower and better distributed along the glass surface and also on the edges (which are the most vulnerable part), as the supports can adapt better to the glass deformation.

7.4.2. Two edges translation

This alternative is very similar to the previous one, the difference is that the movement of the panel is made by translating two edges of the panels inwards instead of only one. The load used to simulate this movement was the same as in the previous example; in this case it was divided by the two edges.

The Table 12 shows that the results of this movement are very similar to the previous one, even the stresses are the same – due to the fact that the displacement magnitude was divided by the two edges. The difference lays on the final position of the panel, which has openings on both sides instead of just one.

Two edges translation

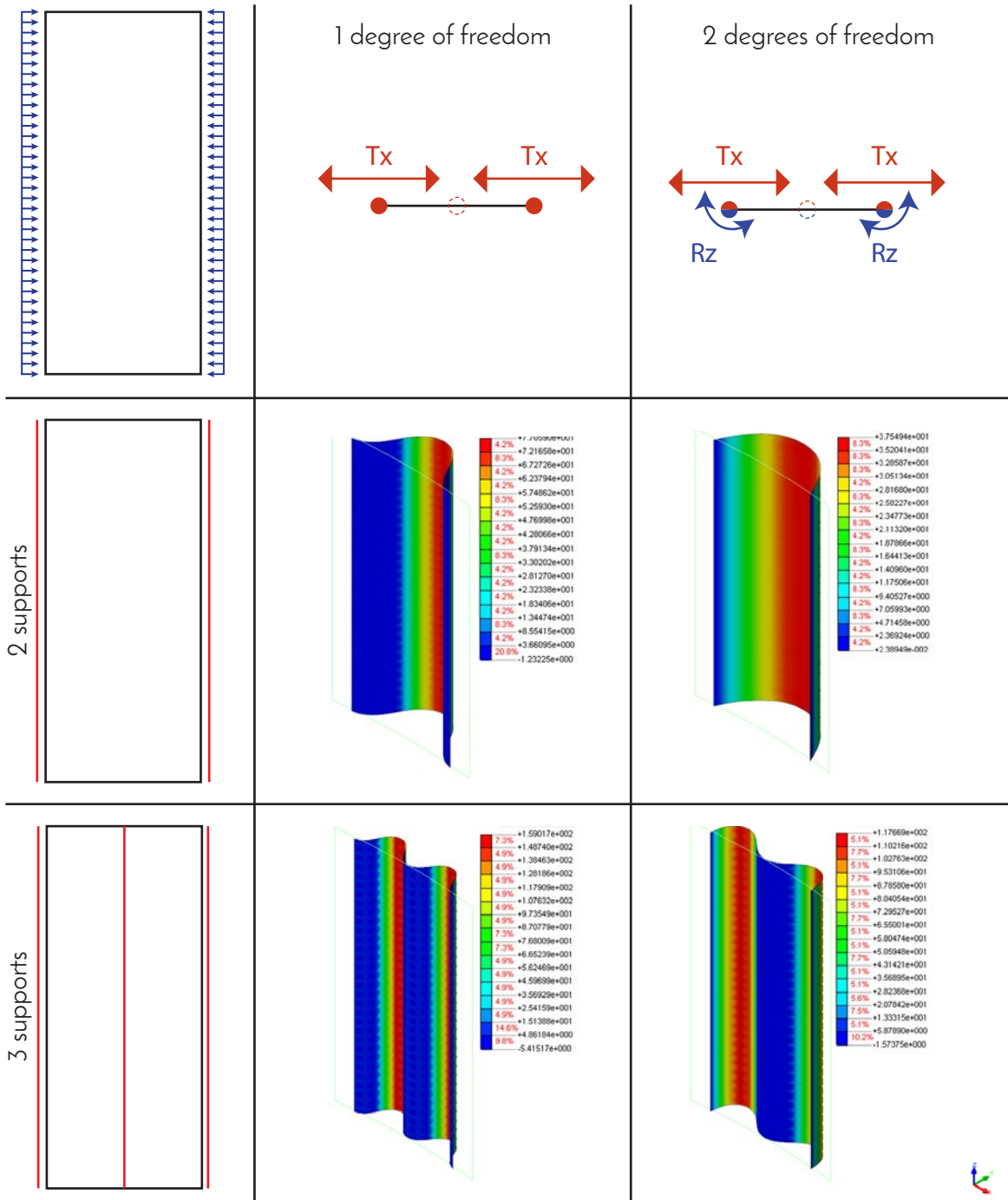


Table 12-Two edge translation geometry and stress distribution according to number of supports and degrees of freedom.

To give another example of this type of movement a new simulation was made by moving the upper and lower edges instead. In this case the initial size of the panel was also changed; the width was reduced to 1250mm and the height was kept at 3000mm.

The displacement of the edges was also increased to 500 mm on each side, to accentuate the final geometry.

Table 13 shows the results of this other alternative.

As expected, the resulting shapes are very similar to the previous ones, but on the vertical direction. The charts 8 to 11 also show very similar patterns as the previous movement analysis.

Two edges translation -short edges variant

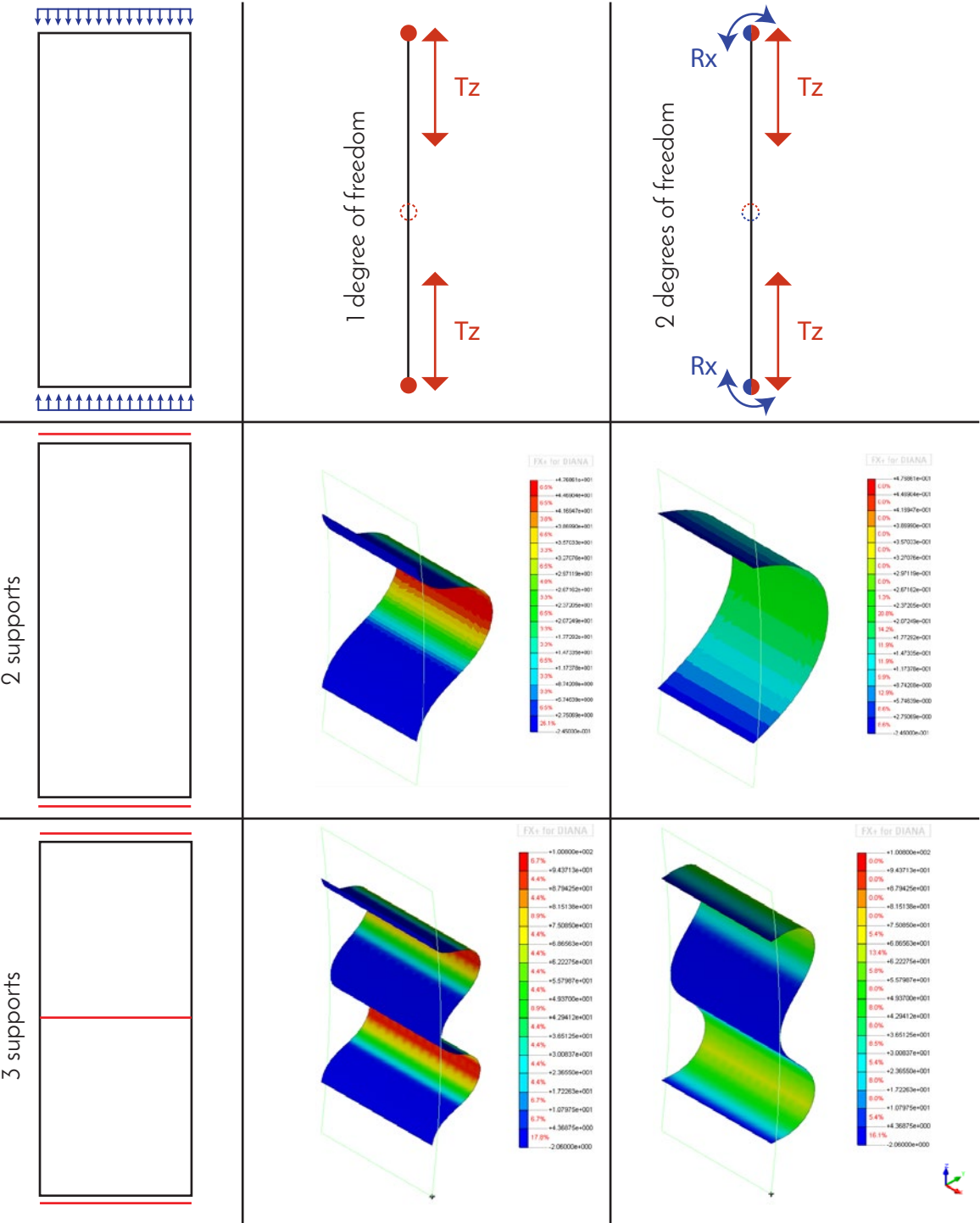


Table 13-Two edge translation short edges variant geometry and stress distribution according to number of supports and degrees of freedom.

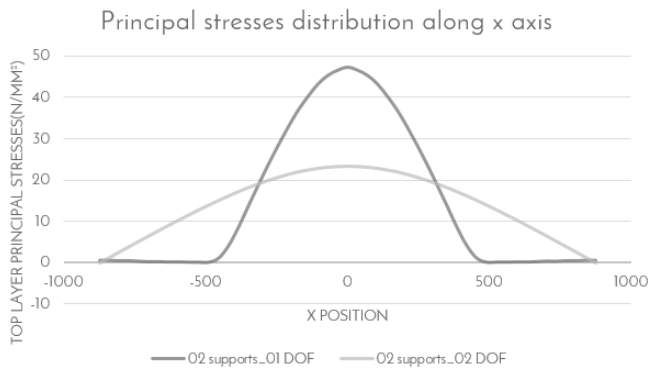


Chart 10-Principal stress distribution along the plate at the top surface of the panel for two supports configuration according to the number of degrees of freedom.

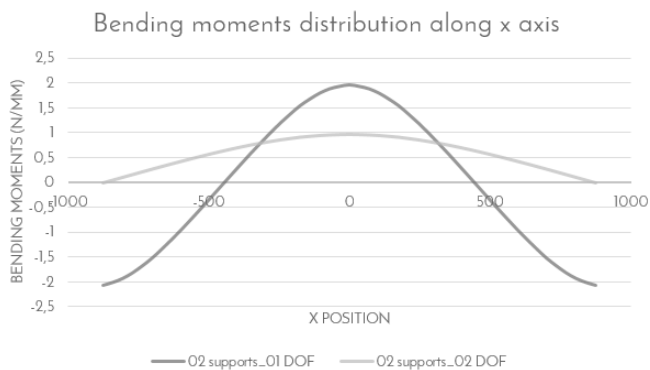


Chart 11-Bending moments distribution along x axis for two supports configuration according to the number of degrees of freedom.

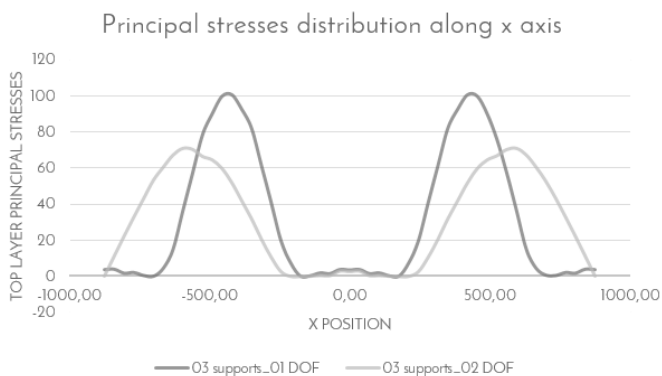


Chart 12-Principal stress distribution along the plate at the top surface of the panel for three supports configuration according to the number of degrees of freedom.

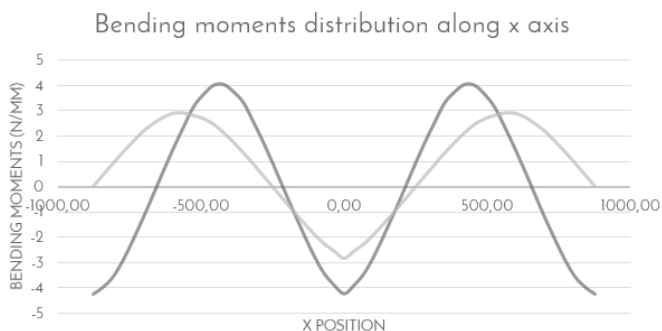


Chart 13-Bending moments distribution along x axis for three supports configuration according to the number of degrees of freedom.

Therefore, the same conclusions as the previous analysis are valid: when allowing rotation on the supports, the stresses on the glass are lower and better distributed, as well as less concentrated on the edges as the supports can follow the movement of the glass plate.

7.4.3. Central bar movement

This movement consists on moving the panel not from its edges but from its center, by using a vertical bar as actuator.

The bar has two functions, moving the panel and stiffening it in its center. The bar is moved by two different points, allowing it to assume an inclined position, creating interesting results in the glass.

Considering this alternative, the investigation was focused on analyzing the difference between the type of supports (full edge or point supports) and different degrees of freedom (translation or translation and rotation).

In this simulation the bar was displaced 500mm on the y direction. The supports were simulating always allowing for translation on the x direction so that the movement of the bar engages their movement.

The Table 14 shows the comparison between points and edge supports in relation to one or two degrees of freedom.

It is possible to see that in both cases the shape of the panel is more stable when rotation is also allowed. The stress distribution also shows similar results to the previous items (7.4.1 and 7.4.2), when only one degree of freedom is present there is more stress concentration in the panel.

As the points supports alternative shows a different geometry along the panel, and therefore different stress distribution, the analysis of bending moments and stress distribution was analyzed by making two sections on the panel, one through the line of the supports and the other through its middle line.

The Chart 14 shows the comparison of the stress distribution along the panel for the point supports along the supporting line, with one and two degrees of freedom.

Central bar movement - symmetric

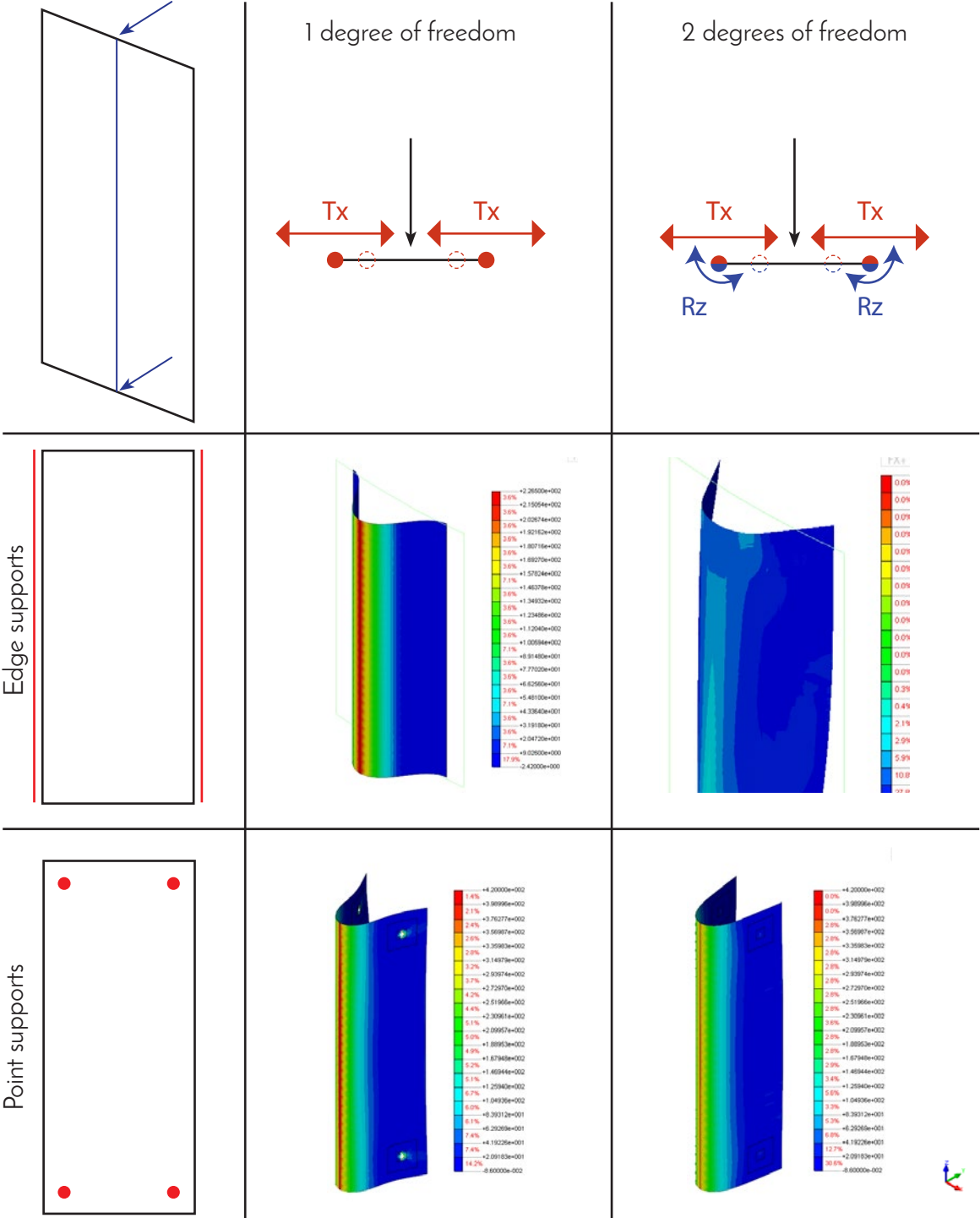


Table 14-Central bar movement geometry and stress distribution according to number of supports and degrees of freedom.

Principal stresses distribution along x axis

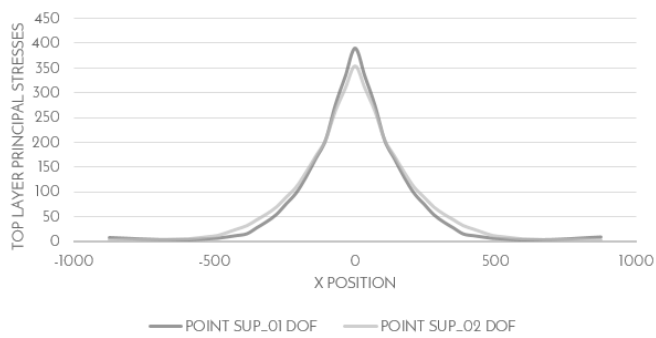


Chart 14-Principal stress distribution in the middle line at the top surface of the panel for point supports configuration according to the number of degrees of freedom.

Although in the position of the bar (the middle of the panel), the stresses are very similar, those at the point connections are ten times higher if the rotation of the support is not allowed; the same happens for the bending moments (Chart 15), which are much higher with only one degree of freedom allowed.

Bending moments distribution along x axis

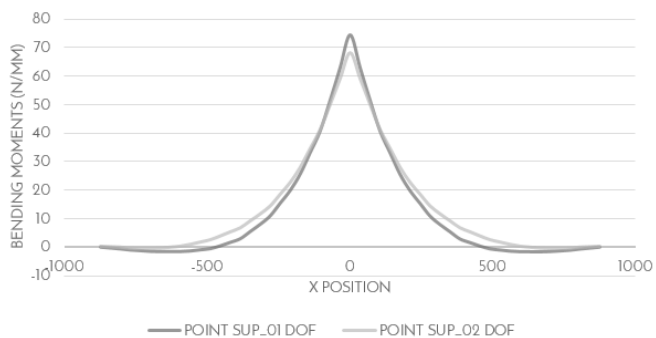


Chart 15-Bending moments distribution along x axis in the middle line of the panel for point supports configuration according to the number of degrees of freedom.

On the other hand, when sectioning in the middle of the panel, where there are no supports, the stress distribution and bending moments are very similar, as is the geometry (Table 14).

Principal stresses distribution along x axis

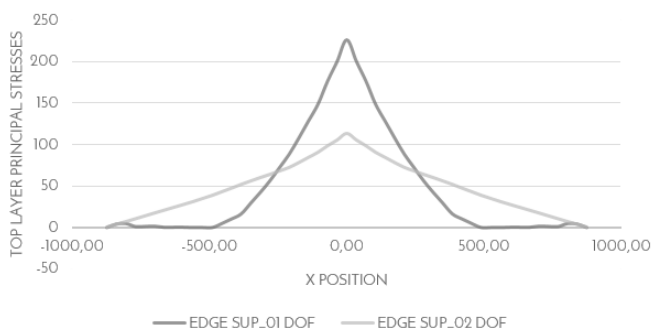


Chart 16-Principal stress distribution in the middle line at the top surface of the panel for edge supports configuration according to the number of degrees of freedom.

The Chart 16 shows the same comparison for the

edge supports. In this case, the results show the same pattern as in the previous analyzes, when translation only creates much more stress in the middle and edges of the panel, which is very clear by the bending moments diagram (Chart 17).

Bending moments distribution along x axis

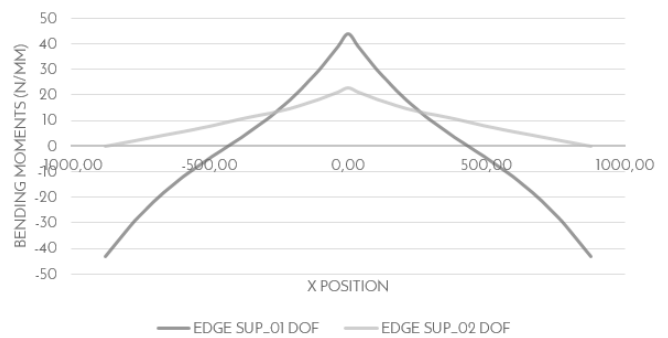


Chart 17-Bending moments distribution along x axis in the middle line of the panel for edge supports configuration according to the number of degrees of freedom.

In this case, both sections (middle and point support line) show the same behavior as the panel has the same pattern of stress distribution along all its surface.

It is also interesting to compare the results of point and edge supports. The results allowing two degrees of freedom were selected for this selection as they showed lower stress.

The Chart 18 shows the comparison of the section through the middle of the panel. Both stress and bending moments charts (Chart 18 and Chart 19) show the same pattern, a homogeneous distribution with its maximum value in the center (bar position) for the edge supports; and a very accentuated pattern also towards the center (with three times higher maximum stress) for the point supports.

Principal stresses distribution along x axis

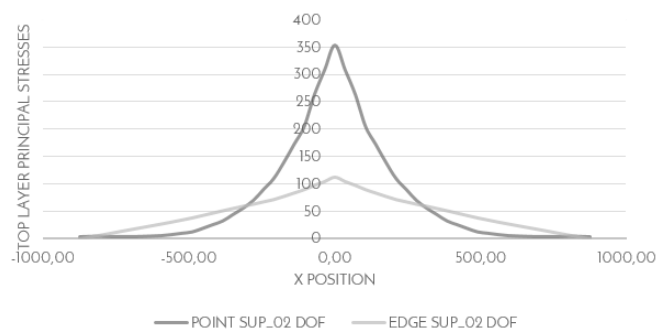


Chart 18-Principal stress distribution comparison of point and edge supports in the middle line at the top surface of the panel according to the number of degrees of freedom.

Bending moments distribution along x axis

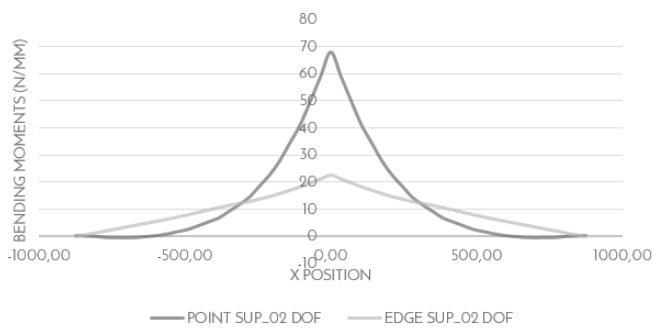


Chart 19-Bending moments distribution comparison of point and edge supports along x axis in the middle line of the panel according to the number of degrees of freedom.

By comparing the section on the line of point supports the difference between these two options becomes even more evident (Chart 20 and Chart 21).

Generally, the stress and bending moments have the same overall pattern as the previous section, however the peak stresses due to the point supports become evident in both charts.

Principal stresses distribution along x axis

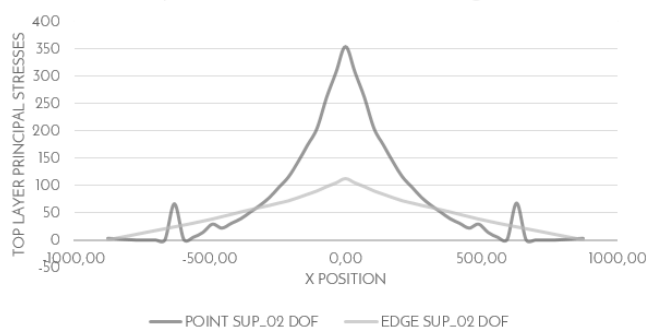


Chart 20-Principal stress distribution comparison of point and edge supports in the middle line at the top surface of the panel according to the number of degrees of freedom.

Bending moments distribution along x axis

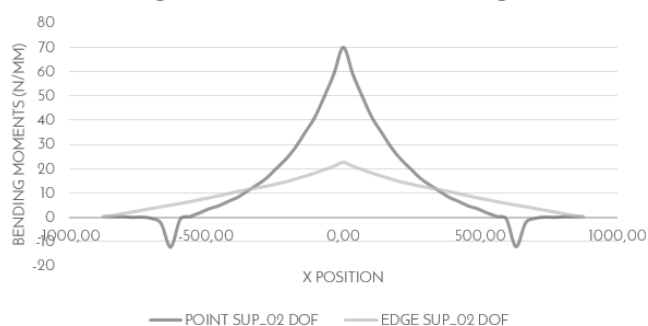


Chart 21-Bending moments distribution of point and edge supports along x axis comparison in the middle line of the panel according to the number of degrees of freedom.

Considering that this movement solution also allows for an asymmetric position, it is important to investigate it. In this case, the edges of the panel can assume an inclined position to allow for the

asymmetrical shape.

Thus, the rotation of the bar on the y axis, as well as the translation of the panel edges on the z axis are to be investigated; as when the edge assumes this new position, its vertices have to translate vertically to keep its dimension. (insert explanative figure for this - reference previous).

This analysis also compares the difference of the behavior of the panel between edge and point supports.

However, the number of degrees of freedom compared is two three and four; so it is possible to compare to the previous studied configuration (without the addition of new degrees of freedom) and to evaluate the difference of allowing or not the translation on the z axis.

The first option consists of allowing translation along the x axis and rotation around the z axis (as the previous analysis). The second one adds the rotation around the y axis. The third option also includes the translation on the z axis to the allowed degrees of freedom.

The third configuration described turned to be a challenge to be modelled in the simulation software, as allowing translation on the z direction interfered on the stability of the model and led to non-convergences.

The solution was to add a hinge in one of the vertices of the edge supports and on two of the point supports. In this way the other vertices or points were free to translate on the z axis.

The asymmetric movement was simulated by initially moving the bar 350 mm in the y direction (this value had to be reduced from the one on the previous analysis due to non-convergences on the simulation) and the adding a displacement of 120 mm to one of its vertices.

The Table 15 shows the results of this comparison.

By looking at the different resulting geometries, it is possible to see that the difference between the two and the three degrees of freedom options is very small, virtually none. The geometry only changes when a new degree of freedom is allowed.

Central bar movement - asymmetric

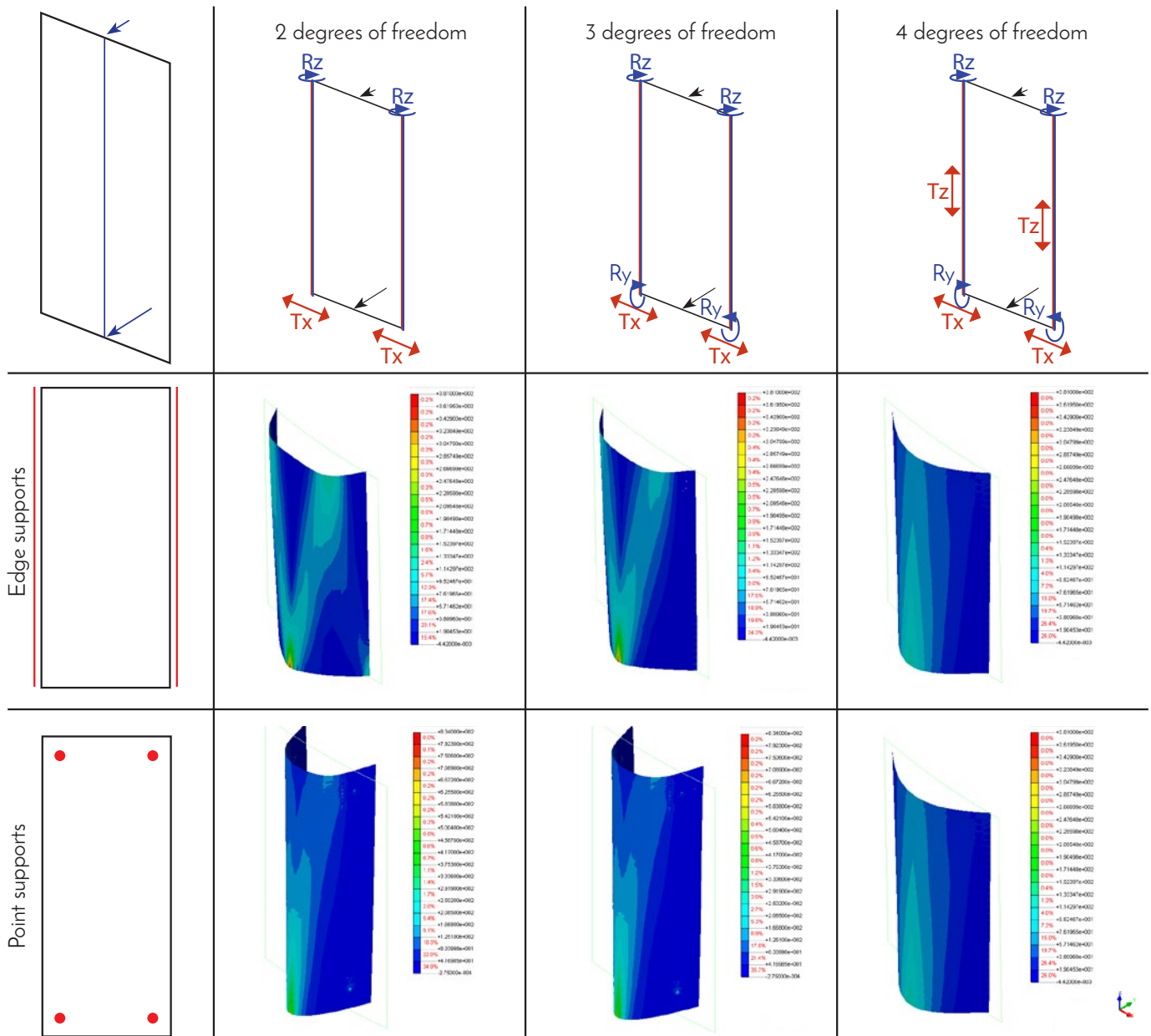


Table 15-Central bar asymmetric movement geometry and stress distribution according to number of supports and degrees of freedom.

The radius on the top edge of the panel is larger, while the lower one is smaller as it is the edge that is moved forward by the bar.

This happens because by allowing rotation on the y axis without the translation on the z axis, the supports do not have their movement capacity increased. When allowing the translation on z direction, the supports become then free to rotate in higher magnitudes around the y axis.

The stress distribution and bending moments analysis confirm this logic. As the panel has an asymmetric geometry, five different sections were made to analyze the different stresses along the panel.

As for the edge supports for the stress distribution the

two and three degrees of freedom options present a similar pattern, with a V shaped peak stresses with the peak at the bottom of the panel. While the four degree of freedom option shows a linear growth of the stress in the middle of the panel towards the bottom.

In this analysis, due to the amount of analyzed sections, only the bending moments diagrams are presented, as they can summarize better the stress distribution on both (top and bottom) surfaces of the panel.

The Chart 22 shows the comparison of the bending moments for the top edge of the panel for edge supports according to the different degrees of freedom.

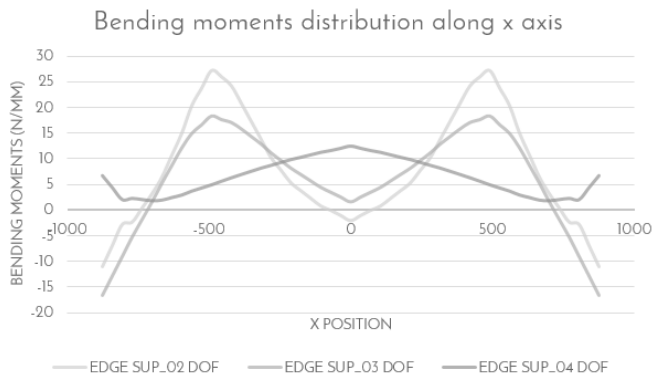


Chart 22-Bending moments distribution along x axis in the top edge of the panel for edge supports configuration according to the number of degrees of freedom.

While the two and three degrees of freedom alternatives follow a similar pattern (with higher bending moments for the first one) the four degrees of freedom option shows a very different configuration, with lower moments than the other two.

By looking at this edge in Table 15 this difference is visible, the first two options present a flatter line in the middle area of the panel, due to the different radii; when the curvature of the edge changes there are peak stresses.

The four degree of freedom option pattern is different, with the bending moments peak on the bar position.

The Chart 23 shows the same comparison on the top point support line position. However, as this alternative does not include the point supports the patterns are very similar to those at the top edge.

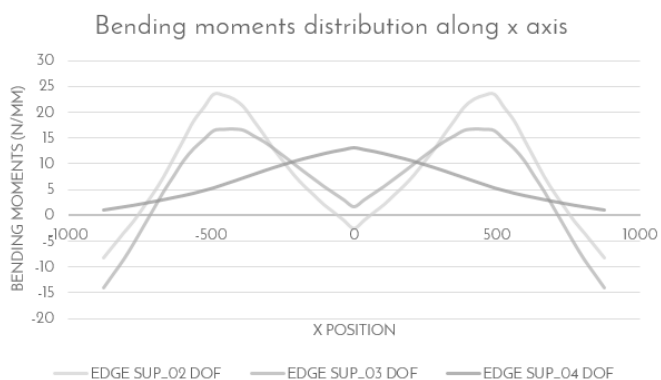


Chart 23-Bending moments distribution along x axis in the top point support line of the panel for edge supports configuration according to the number of degrees of freedom.

The Chart 24 presents the comparison at the middle of the panel. This shows the transition of the stress distribution in the two and three degrees of freedom options; at this point the two lines of the V pattern are closer to each other and their magnitude is reduced

to a similar level of the four degree of freedom options.

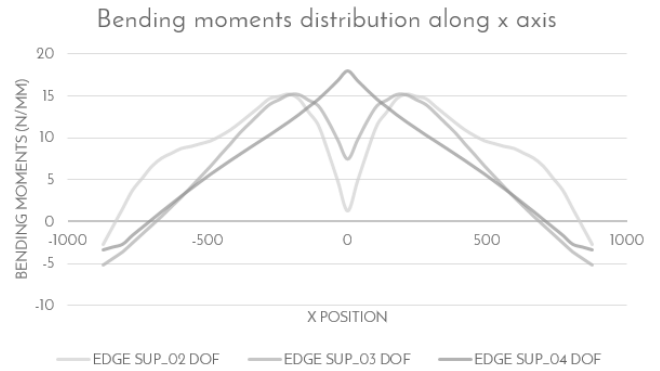


Chart 24-Bending moments distribution along x axis in the middle of the panel for edge supports configuration according to the number of degrees of freedom.

The Chart 25 illustrates this comparison at the bottom supports line. Again the point supports are not present in this option, however it is interesting to see the distribution of the bending moments in this area.

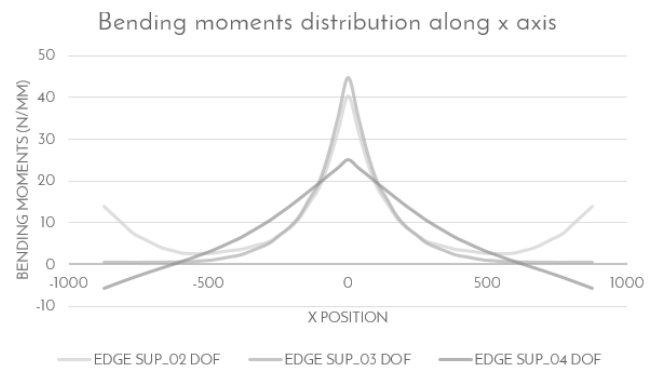


Chart 25-Bending moments distribution along x axis in the lowpoint support line of the panel for edge supports configuration according to the number of degrees of freedom.

At this section the peak bending moments of all alternatives are concentrated in the bar position. The two and three degrees of freedom options present again a very similar distribution, with a higher maximum value than the other option.

This chart also shows a difference of the bending moments at the edges of the three alternatives. While the two degrees of freedom option has tension in this area the four degrees of freedom alternative has compression, while the remaining one has very little bending moments on the edges.

The Chart 26 shows the same comparison for the bottom edge of the panel. The distribution of bending moments is much similar to that of the previous chart (Chart 25) but with a higher magnitude of values.

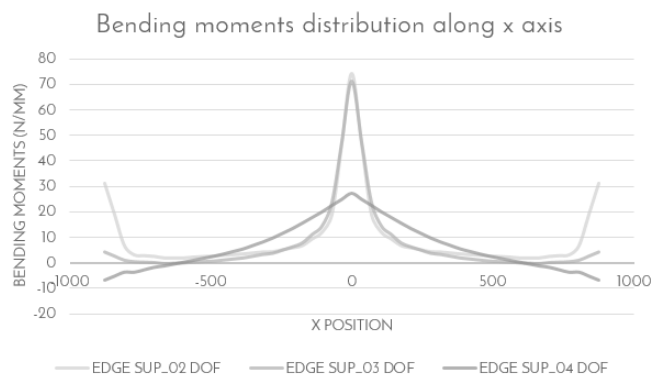


Chart 26-Bending moments distribution along x axis in the bottom edge of the panel for edge supports configuration according to the number of degrees of freedom.

By analysing the Table 15 for the point supports configuration, it is possible to see that the stress patterns and geometries are similar to those of the edge supports.

The main difference in this case is the position of the panel in relation to its initial position; in this case the panel is not aligned to its initial position anymore, but part of it goes back as well. This is because in this case the panel pivots around the point supports and not its edges.

Another difference is related to the four degrees of freedom option, where by allowing translation of the supports on the z direction the edges of the panel were bended in the middle.

The Chart 27 illustrates the bending moments distribution for the top edge of the panel. In this case the two and three degrees of freedom options have almost equal values. It is possible to identify that all solutions follow the same pattern, with peaks closer to the position of the edges.

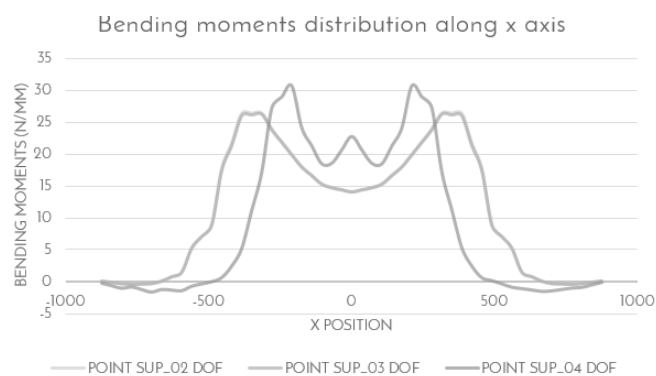


Chart 27-Bending moments distribution along x axis in the top edge of the panel for point supports configuration according to the number of degrees of freedom.

As in the previous analysis the two and three degree of freedom options stress distribution follows a V pattern, as the four degree of freedom a more

linear pattern increasing towards the bottom.

This is already visible in this chart as the peak moments for the first two alternatives are on the sides and the four degree of freedom option shows a peak stress at the position of the bar.

The Chart 28 represents the line of the top supports.

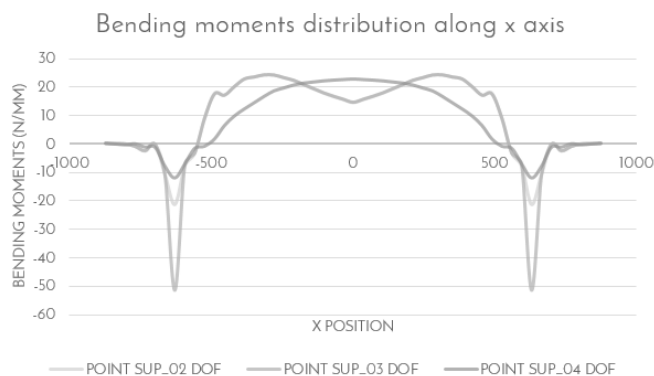


Chart 28-Bending moments distribution along x axis in the top point support line of the panel for point supports configuration according to the number of degrees of freedom.

As for the previous chart the lines of the two first alternatives are very similar; however, in this case, it is visible that the bending moments in the supports are much different.

The three degree of freedom option presents a much higher magnitude than the other two; a possible explanation for that is that as it can rotate, but not translate in the z direction stresses accumulate around the support.

The center of the diagram also shows a difference between the options. While the first two have higher stresses around the bar, the four degree of freedom option presents a homogeneous distribution in this area.

The Chart 29 illustrates the bending moments in the middle of the panel.

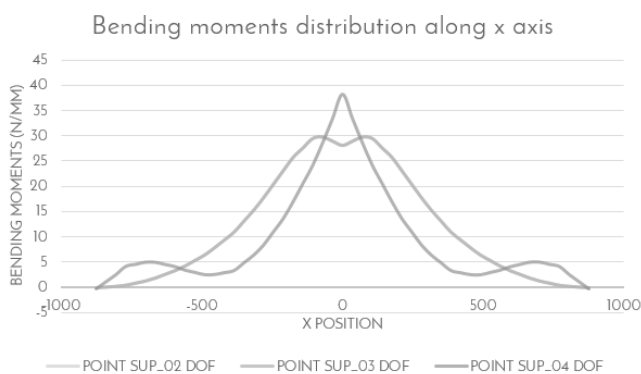


Chart 29-Bending moments distribution along x axis in the middle of the panel for point supports configuration according to the number of degrees of freedom.

Again the two and three degree of freedom options have similar values, their bending moment distribution goes from almost zero in the edges to almost reaching its peak in the middle (this is the bottom area of the V pattern).

As for the four degree of freedom option the peak moments are in the middle, however the edges also show some variation as this is the area that bends due to the vertical translation of the supports.

The Chart 30 shows the bending moments for the bottom supports line. As of on the other diagrams the two and three degrees of freedom options have similar values.

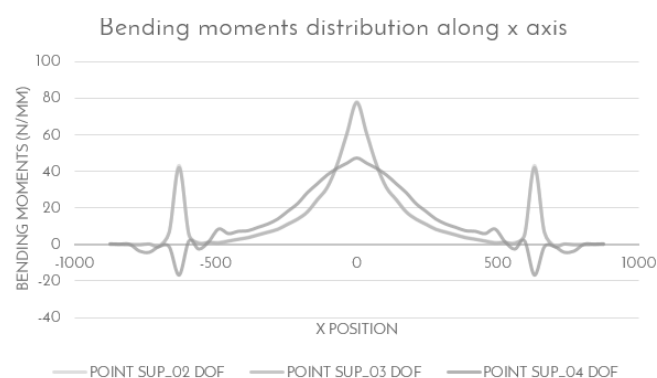


Chart 30-Bending moments distribution along x axis in the low point support line of the panel for point supports configuration according to the number of degrees of freedom.

It is interesting to observe that the four degree of freedom option presents compression on the supports while the other two present tension. A possible explanation for this is the fact that on the four degrees of freedom option these supports are translating, while on the other options this movement is constrained and the panel is pushing these areas.

The Chart 31 presents the bending moments at the bottom edge of the panel. In this point all alternatives reach its higher stresses and moments.

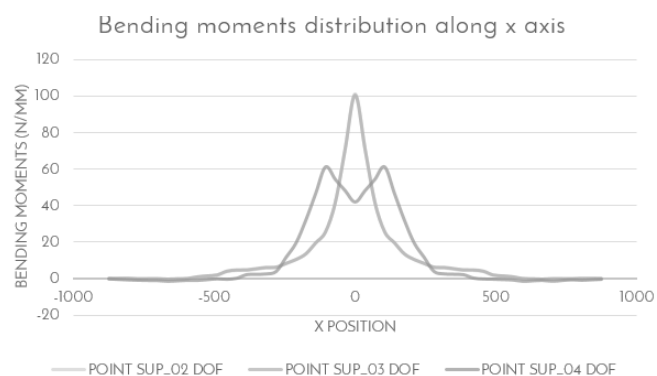


Chart 31-Bending moments distribution along x axis in the bottom edge of the panel for point supports configuration according to the number of degrees of freedom.

For the two and three degrees of freedom options this peak stress is located in the same position as the bar as this is the point that is provoking the asymmetric geometry in the whole panel.

The four degree of freedom option shows concentration of moments next to the bar. As the bar cannot deform, the areas of panel around it accumulate stresses as the edges of the panel bend.

After analyzing edge and point support in the asymmetric configuration of the panel it is also possible to compare the results of both solutions between each other. For this comparison I selected both options considering four degrees of freedom.

The Chart 32 to Chart 36 show the five sections of the panel, comparing the bending moments of each of them.

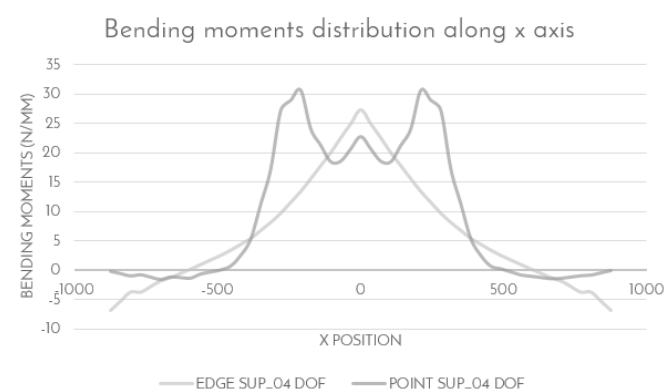


Chart 32-Bending moments distribution comparison of point and edge supports along x axis in the top edge of the panel according to the number of degrees of freedom.

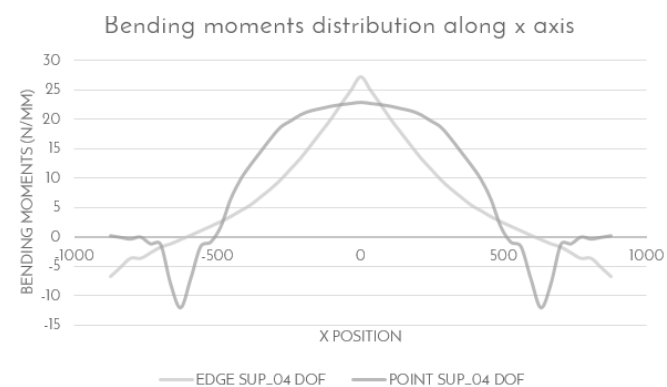


Chart 33-Bending moments distribution comparison of point and edge supports along x axis in the top support line of the panel according to the number of degrees of freedom.

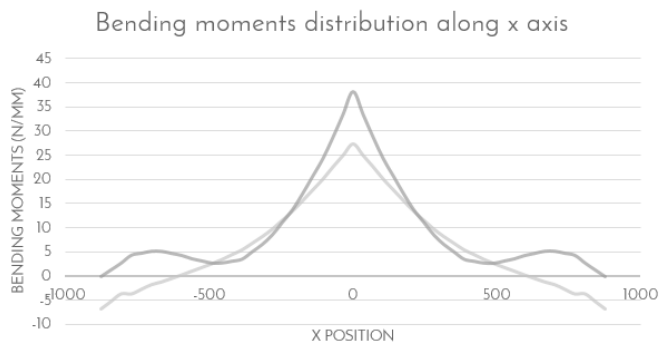


Chart 34-Bending moments distribution comparison of point and edge supports along x axis in the middle of the panel according to the number of degrees of freedom.

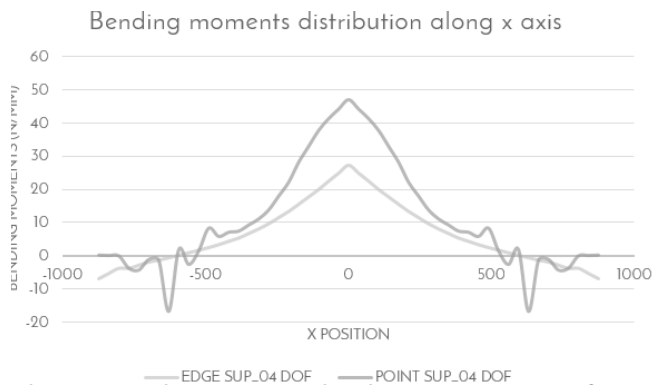


Chart 35-Bending moments distribution comparison of point and edge supports along x axis in the bottom support line of the panel according to the number of degrees of freedom.

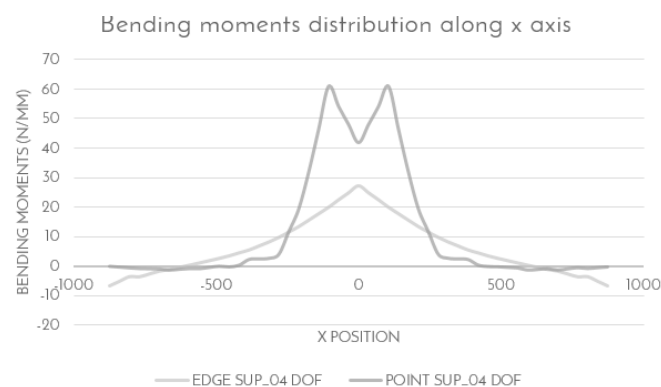


Chart 36-Bending moments distribution comparison of point and edge supports along x axis in the low edge of the panel according to the number of degrees of freedom.

In all of them it is clear that the moments are lower on the alternative that consider edge supports. It is also visible that the edge support option has a more constant stress distribution, with peaks only at the bar position.

Another common difference between the two alternatives is the edge moments. While they are almost zero for the point supports options for the edge support there is always a concentration of bending moments.

After this series of analyses, the relation of movement, type of supports and degrees of freedom comes clear in this case.

Both analysis showed better results for edge supports, which presented lower and more homogeneous stress than point supports.

Also it was shown the dependence on understanding the requirements of the movement to be able to define the necessary degrees of freedom for the support. A very clear example of this is the analysis of the asymmetric bending with only two or three degrees of freedom, in that case, the addition of the third degree of freedom did not cause much effect on the overall results, as the supports were constrained to move vertically,

7.4.4. Two edges rotation

This movement consists not on actuating the panel by translation but by rotation to induce its buckling.

In this case the three different support options were explored. The first by placing edge supports on the edges of the panel, a second one by taking these linear supports inside the panel to avoid stress concentration on the edges, and a third one by using point supports in the panel (at the same position of the vertices of the second option).

In both cases, while the lower vertex of the support act as hinges the support rotates inwards creating movement on the panel. Thus, as for the degrees of freedom, the hinges (lower vertex of the support) is a pinned support allowing for rotation only.

Considering that the expected geometric result is similar than the previous simulation, four degrees of freedom is the minimum allowed for the top of the supports on this case, in order not to repeat the same process and conclusions as in the previous analysis.

Therefore, the degrees of freedom allowed for the top vertex are translation in x and y direction and rotation around the y and z axis.

However, the remaining two degrees of freedom are also dependent on each other, by allowing rotation around the x axis without translation in y axis the panel does not change position and vice versa. *

Thus, in this particular movement analysis the comparison is constrained to the different supports only.

The Table 16 shows the resulting geometry and stress distribution for this comparison.

*Versions of this movement allowing three, five and six degrees of freedom were tested to confirm.

To evaluate the stresses and bending moments of the panel three different areas of the panel were analyzed, the top and bottom edges and the middle.

The Chart 37 and Chart 38 show the stresses and bending moments for the top edge of the panel, the one with a smaller radius.

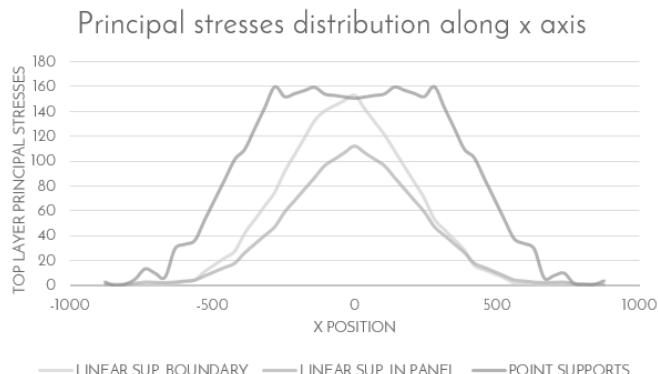


Chart 37-Principal stress distribution in the top edge at the top surface of the panel for according to the support configuration.

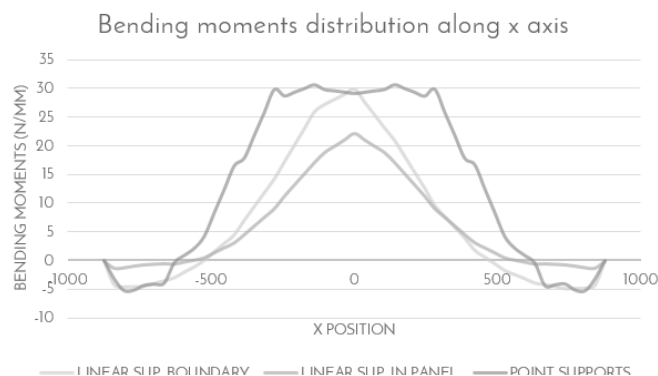


Chart 38-Bending moments distribution in the top edge at the top surface of the panel for according to the support configuration.

Two edges rotation

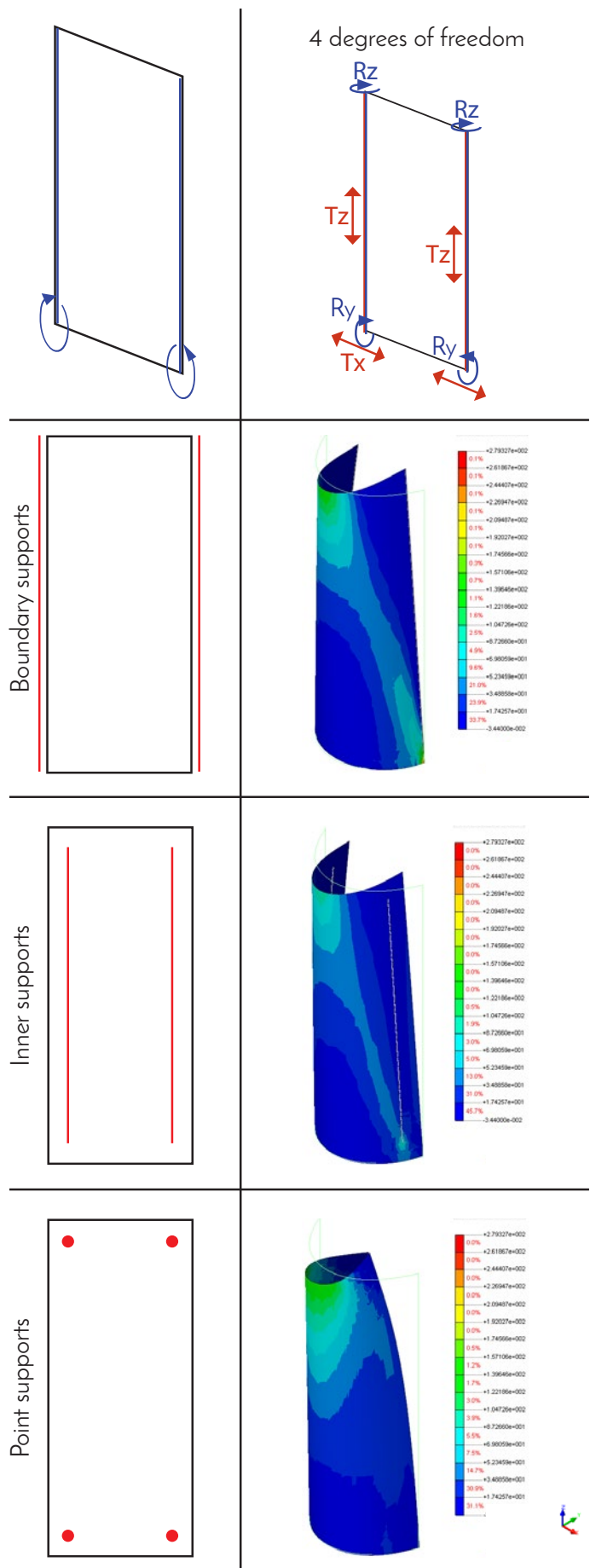


Table 16-Two edge rotation movement geometry and stress distribution according to number of supports and degrees of freedom.

Both charts show a very similar pattern, meaning that the stresses on the top surface of the glass are prevailing in this case.

All support options show an increasing of stresses and bending moments in the middle of the panel. Both the linear supports options present a single peak stress are in the center of the panel, while the point supports option shows overall higher stresses, but no concentration.

On the bending moments chart is possible to see that close to the edges of the panel there is also a difference between the options.

Although on all options the bending moments at the edge is zero, this chart shows the difference of the stresses on the bottom surface, where tension is present in this area. The point supports show higher bending moments, but it is visible that the boundary line supports also have high stress in this area.

The Chart 39 illustrates the same comparison for the stresses on the top surface in the middle of the panel. In these chart all supports show different patterns.

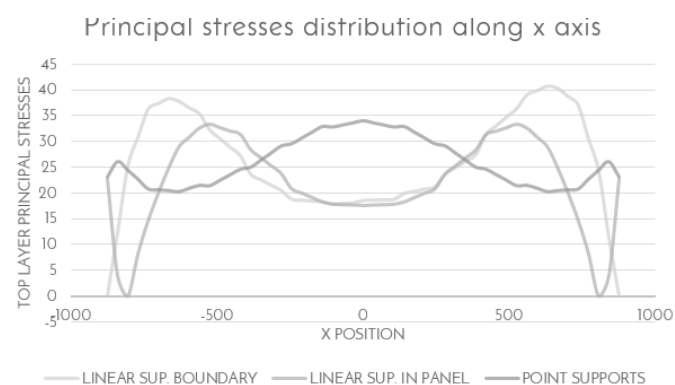


Chart 39-Principal stress distribution in the middle of the panel at the top surface of the panel for according to the support configuration.

The overall diagram for both line support options show the same V shaped pattern that was present in the previous analysis. In this case the difference between them is the stress distribution on the edges.

While the boundary linear support shows no stress on the edges, the inner linear supports have peak stresses on this area. The same happens for the point supports, which, for the center of the panel, have higher stresses both for the edges and middle of the panel.

The bending moments () show a different scenario for the edges of the panel, that in all support options this area presents almost no bending moments.

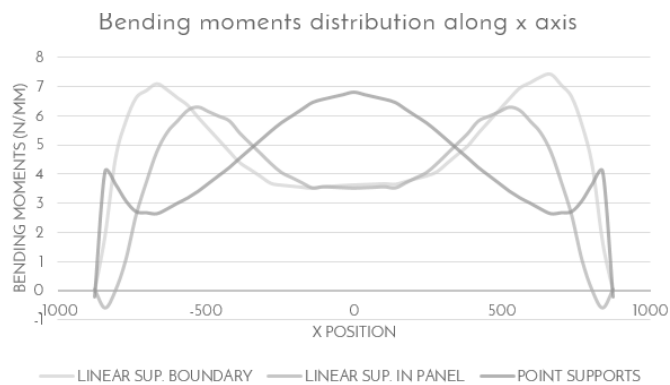


Chart 40-Bending moments distribution in the top edge at the top surface of the panel for according to the support configuration.

For the bottom edge of the panel, the stresses and bending moments show very similar patterns. (Chart 41 and Chart 42).

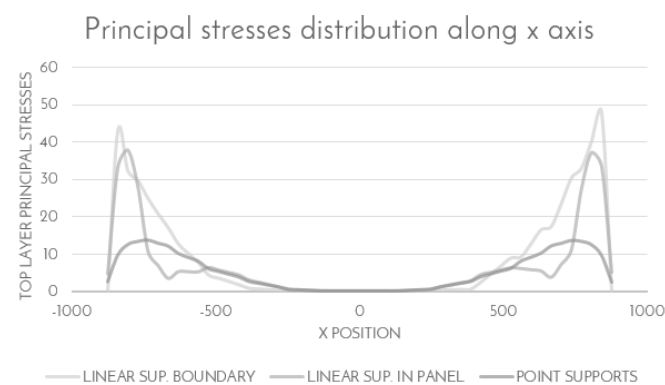


Chart 41-Principal stress distribution in the bottom edge at the top surface of the panel for according to the support configuration.

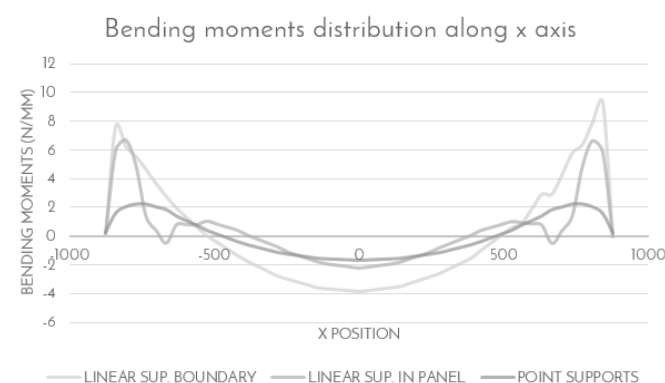


Chart 42-Bending moments distribution in the bottom edge at the top surface of the panel for according to the support configuration.

The point supports show very little stresses and moments compared to the other two options, which have high peaks closer to the edges of the panel.

It is possible to conclude that for this movement, the point supports showed a more homogeneous stress distribution along the panel, with values similar to the linear support in the panel.

The linear support at the edge of the panel was the one that showed higher peak stresses mainly closer to the edges which is the more sensitive are of the panel.

Generally, it is possible to conclude from this movement analysis, that the type of support has to be analyzed specifically to each movement and degrees of freedom.

Although in this case the difference of using less or more degrees of freedom was not visible on the geometry, their definition is very connected to the type of movement desired, if to allow the movement a minimum number of degrees of freedom is necessary, increasing them may not change the general behavior of the panel.

7.4.5. Corner bending

This movement consists on the bending of the corners of the panel (Figure 88).

By considering the panel initially flat, this movement would allow for the ventilation through the corners of the panel, which can be increased or decreased according to the amount of bending.

Due to the complexity of the model and the constraints of the FEM simulation software, it was not possible to simulate this movement.

Therefore, I developed sketches to try to understand the consequences of this movement for the glass panel.



Figure 88-Corner bending movement scheme.

The vertices of the panel are fixed to a mechanism that pushes them inwards. This makes these vertices bend, in a single radius curvature.

This rotation is mainly constrained by the width of the panel, as the curvature on the edges should not overlap, due to the accumulation of stresses.

The areas with peak stresses on this panel are those where the corner of the panel starts bending, at that point the stresses which were zero (as there was no curvature) increase according to the thickness of the panel and the bending radius. On Appendix 03, the equivalent stress according to the bending radius is presented.

In the case of this movement the panel could be either supported by its edges (partially) or by point supports inside the panel. However, the supports are fixed to one position, and there is no variation on the degrees of freedom as none is allowed.

By supporting the panel by its edges it is expected a stress concentration where the bending line meets the edge support (Figure 89). While when using point supports in the surface of the panel this should not occur.

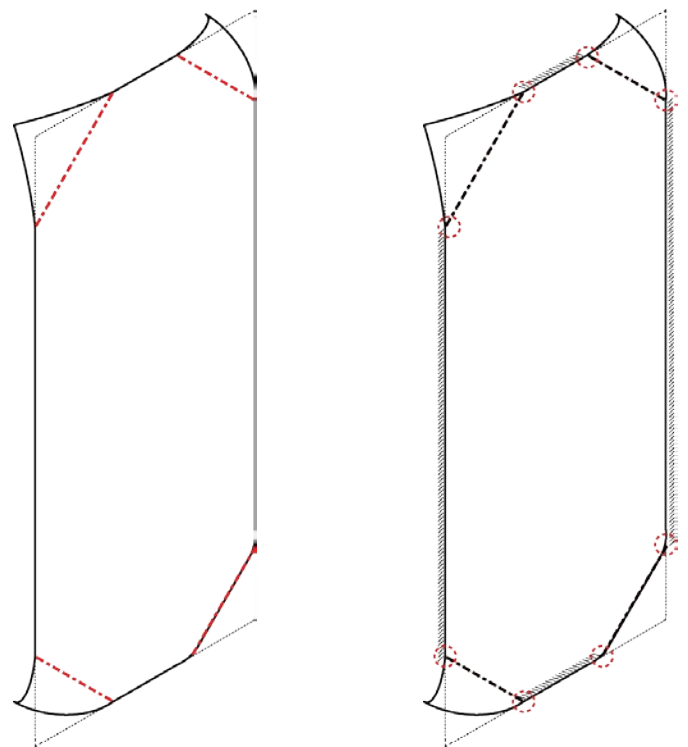


Figure 89-(left) Initial bending lines. (right) Stress concentration when the lines meet the edge support.

In the case of point supports it is expected that the entire edge, as it is not supported, of the panel bends instead on only the corners (Figure 90).

This behavior can be simulated by bending a sheet of paper by its four edges at the same time.

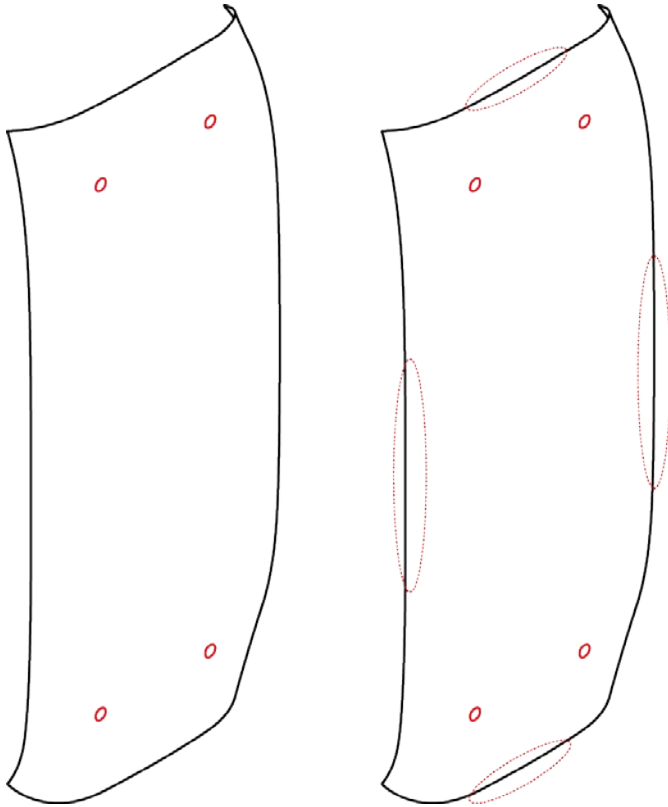


Figure 90-Point support scheme and areas concentrating bending moments on the edges of the panel.

Considering this, also for the point supports, there will be bending moments concentrated in the edges.

In conclusion, although not possible to simulate in the FEM modeling in the range of this research, this movement is very intriguing as it shows a behavior for glass that is unexpected.

The different support possibilities present different constraints and behavior for the glass panel. If the bending of the corners is controlled to a certain limit, the option of using partial edge supports can be more promising, as it gives an overall more stability to the panel.

7.4.6. Rolling glass

This movement consists on having a flat glass pane that can be rolled on its top edge. Allowing for it to be opened in the bottom.

This case, as the previous one, was not possible to be simulated on the FEM analysis due to its complexity.

Therefore, I developed sketches on the stress

distribution in relation to its supports and degrees of freedom.

This movement is a very particular case where there are few options to explore.

The top edge of the panel is fixed to the mechanism which rolls it.

While the other edges of the panel have just to allow for vertical translation as there is no other movement involved in this case.

The panel could be supported by its edges either on the bottom or on its sides. If in both cases the vertical translation is allowed, there is no stress accumulation in this areas.

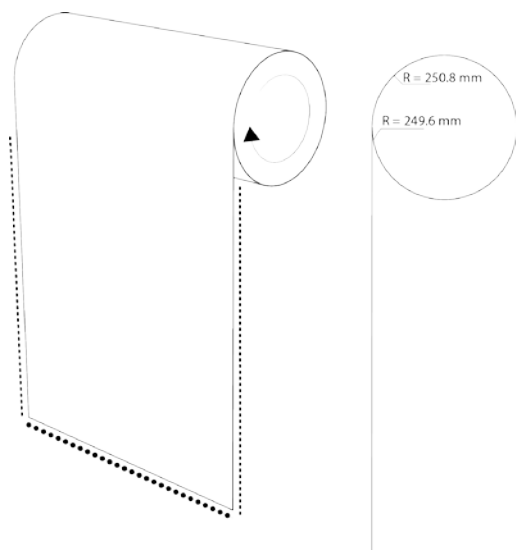


Figure 91-Rolling glass movement scheme with possible support solutions. To the right the different radii to make the rolling possible.

The panel would only start to be under stresses when it starts to roll, these stresses would be proportional to the radius of the rolling. As presented in Appendix O3, the growth of the stress on the glass by bending follows an exponential curve as the bending radius is reduced.

In this case this is what is expected on this movement, the panel remains unstressed on the areas which are flat, and when rolled the stresses start to appear (as compression on the bottom surface and tension on the top).

Due to the thickness of the panel, the successive rolling movements have different radii. As close to the axis of rotation the smaller the radius and higher is the stress, following an exponential pattern.

The Chart 43 shows a sketch of a vertical section in the center of the panel illustrating this situation. In the chart it is possible to see the increasing of the stresses when the bending starts. In this case a 250 mm radius was simulated. As the difference in the radius inside the roll is too small (from 251 to 249 mm) the exponential pattern is not visible.

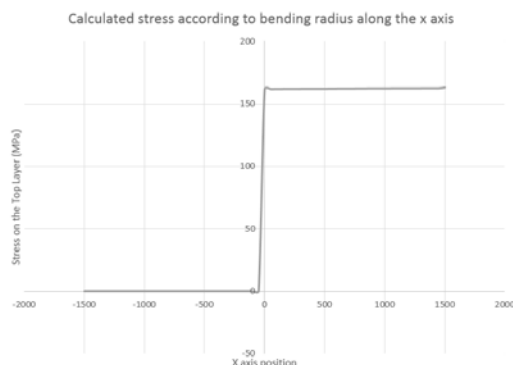


Chart 43-Bending moments distribution comparison of point and edge supports along x axis in the low edge of the panel according to the number of degrees of freedom.

It is possible to conclude that due to the increase of stress in the beginning of the bending an edge support on the side of the panel could concentrate stresses on that area. While a support on the bottom edge could avoid this problem.

7.4.7. Geometry deformation

The last movement to be studied is the geometry deformation. As mentioned in 7.3, this movement concept was inspired by the exploration of geometries developed in Chapter 3.

During that phase of the research physical models were developed in order to explore different geometries. In this process a particular configuration of glass panels could have its geometry changed and adapt between different applications. The triangular shape, in a flat and bent position was studied as a column, beam and single layer flat panel (items 3.1.1 and 3.1.2.1).

The Figure 92 and Figure 93 show the physical study model for this geometry. By connecting all stripes of acrylic together, they would assume a bent position; when pushing one of the edges of the geometry perpendicularly, they would assume a flat position.

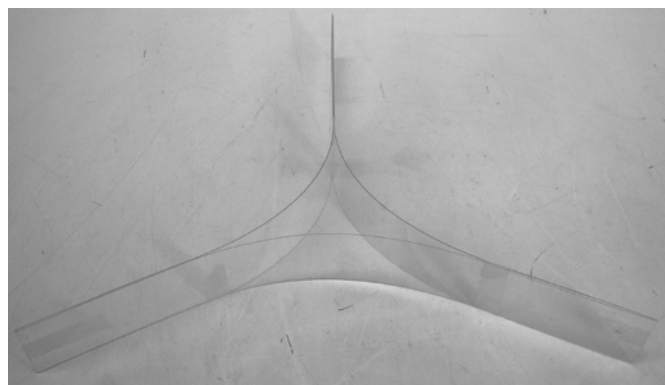


Figure 92-Study model in initial position.

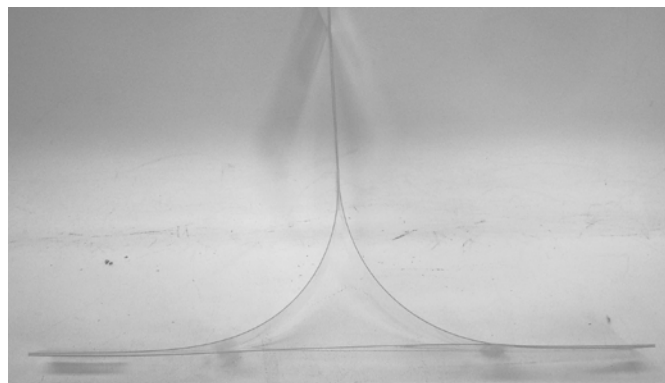


Figure 93-Study model in flat position.

Therefore, this geometry was selected as an examples to perform the study of the geometry deformation movement.

This movement consists of supporting two edges of the triangular geometry, while translating the other edge on the y axis (300 m). The panel size used for this movement analysis was of 3000x1250 as the initial geometry of the panel is flat.

In the FEM model the surface contact was not considered due to the limitations of software.

To analyze the relation to supports and degrees of freedom in this movement, a similar configuration to the first movement analysis was made as both movements consist on the bending based on two edge supports.

However, in this case, a third support is not a feasible option (without considering the actuated edge). Thus, different support types are proposed.

This analysis compares edge supports with linear supports displaced from the edges, attached to the surface of the glass; allowing for one (translation x axis) or two (translation x axis and rotation around z axis) degrees of freedom.

Geometry deformation

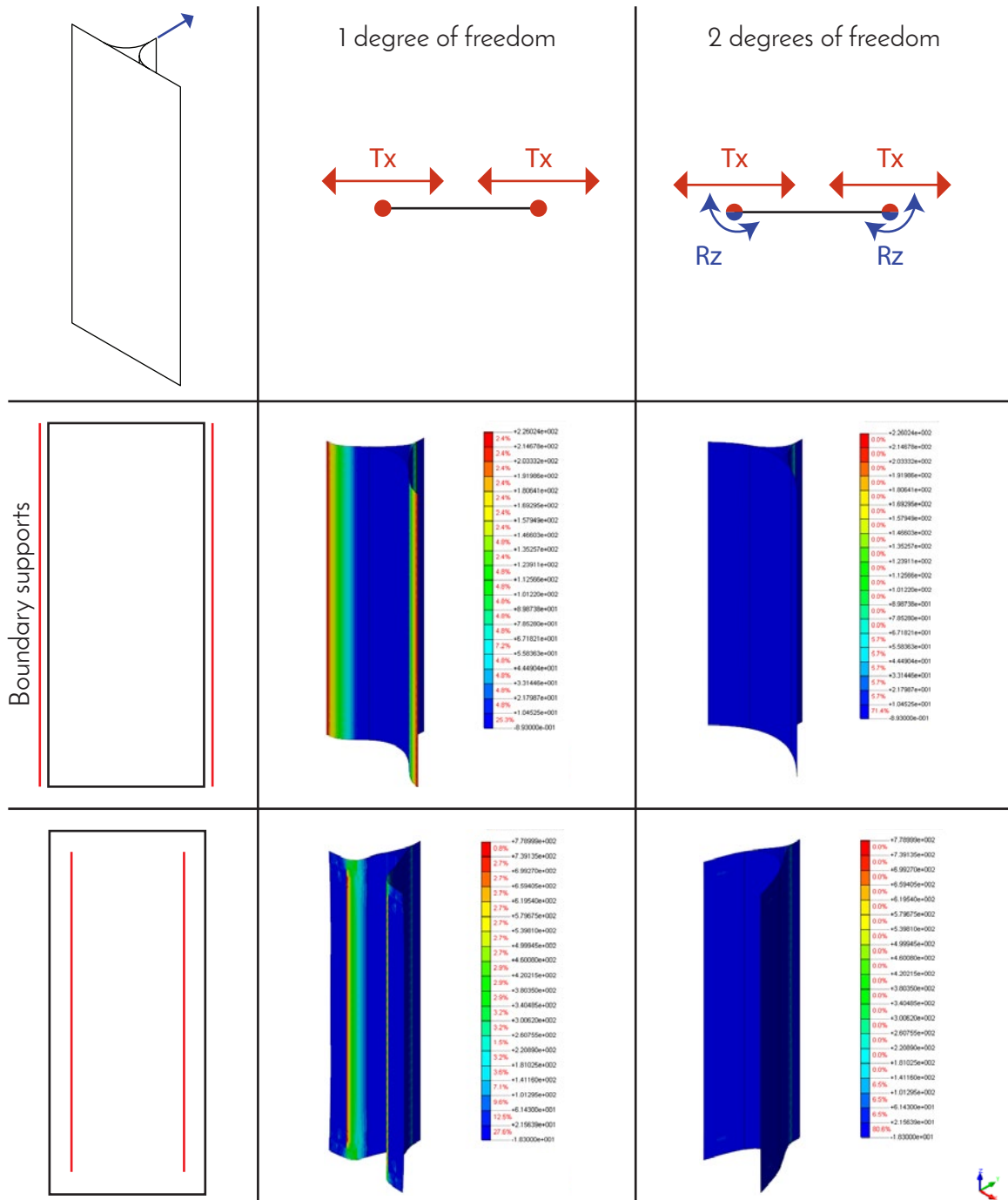


Table 17-Geometry deformation movement geometry and stress distribution according to number of supports and degrees of freedom.

The Table 17 shows the results of this comparison with the stress distribution on all panels.

As the panel is symmetrical in both directions, only the middle section of the front panel (as it is the one with more bending) was selected to make the comparisons.

In Table 17 it is possible to see that the stress distribution in the panel is not continuous. In the boundary supports for one degree of freedom figure it is possible to see in the highlighted area this issue.

A possible reason for this is the local element axis direction on the simulation, which is not the same for all elements of this specific case. Although this was tried to be manually changed, the alterations on the file made the simulation not possible. However, for the other areas of the panel, by selecting the principal stresses on the panel, the results are valid.

Also in this movement analysis, top and bottom surfaces stresses charts were plotted, as the bending moments diagram would be influenced by the element axis direction.

The Chart 44 shows the comparison for the stress for the boundary support for one and two degrees of freedom; for the top layer of the panel.

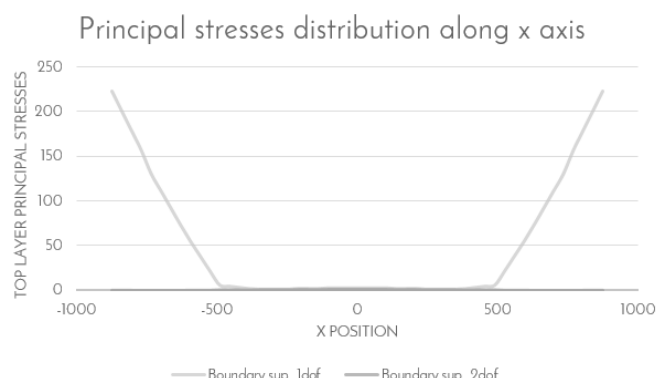


Chart 44-Principal stress distribution in the middle of the panel at the top surface for according to the support configuration.

In this case the difference between both degree of freedom solutions is very big, while with two degrees of freedom there is almost only compression on the panel, with one degree of freedom there is a high concentration of tensile stresses on the edges of the panel, as they are resisting the bending.

The Chart 45 shows the same comparison for the bottom layer of the panel.

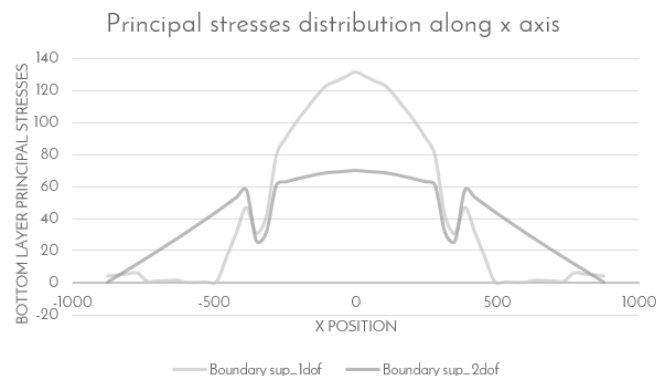


Chart 45-Principal stress distribution in the middle of the panel at the bottom surface for according to the support configuration.

In this case it is possible to see a similar pattern for both solutions. The main difference is the magnitude of stresses. The one degree of freedom option shows a much higher concentrated amount of stress in the center of the panel, while for two degrees of freedom this is more dispersed.

In both lines it is possible to see that the stresses go down at one moment; those are the areas in which the front panel is joined to the back panels, changing its stress distribution.

The Chart 46 shows the comparisons relative to the

second support alternative, that of inner surface linear supports. This chart shows the stress distribution for the top surface of the glass.

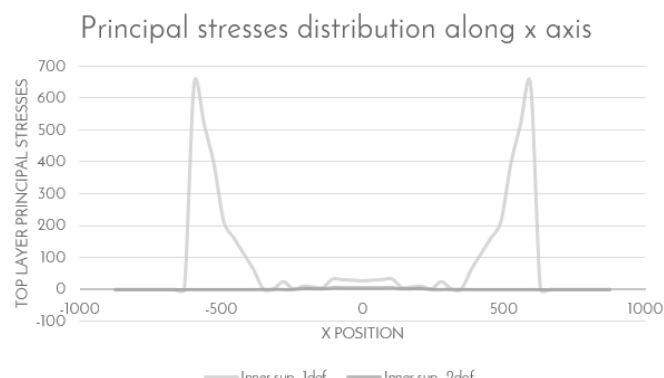


Chart 46-Principal stress distribution in the middle of the panel at the top surface for according to the support configuration.

Again, for the two degrees of freedom option there is a predominance of compression, while for the 1 degree of freedom option, there is a very high peak stress at the points where the support points are located, as this part of the panel is constrained for rotation. This peak is also high due to the fact that in this option the panel pivots around the supports and its inner radius is much smaller than the previous support alternative (tablex).

The Chart 47 shows the same comparison for the bottom layer of the panel. Again, the conclusions can be the same as for the other support alternative, with the one degree of freedom option presenting much higher peak stresses.

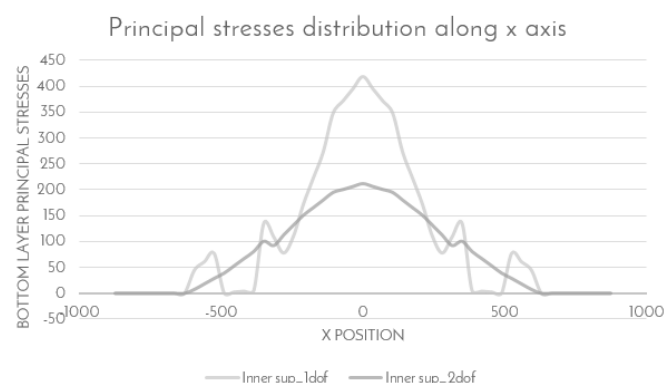


Chart 47-Principal stress distribution in the middle of the panel at the bottom surface for according to the support configuration.

The last two charts compare both support alternatives stress distribution for both the top and the bottom surface of the glass panel.

For both charts (Chart 48 and Chart 49) it is clear that the stress distribution is much higher in this case

for the supports placed inside the panel.

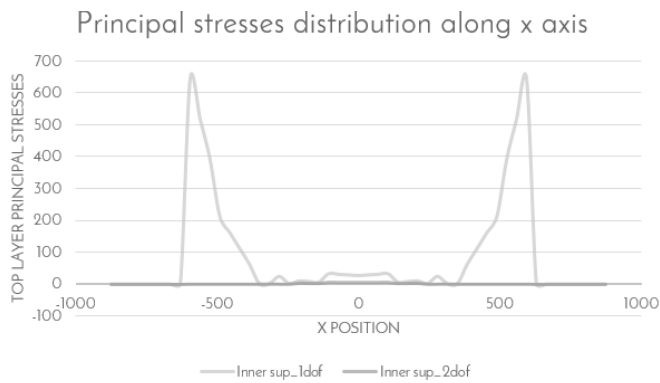


Chart 48-Comparison of the principal stress distribution in the middle of the panel at the top surface for the different support configuration.

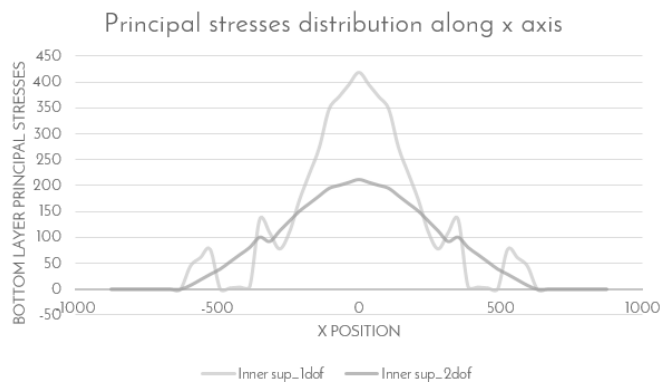


Chart 49-Comparison of the principal stress distribution in the middle of the panel at the bottom surface for the different support configuration.

Although in this simulation most of the graphs do not show a continuous result, the contrast of values between the different solutions make it possible to make a few conclusions.

It is possible to conclude from this movement analysis that the options with two degrees of freedom are more adequate for this case, as they follow the movement proposed for the panel, as they are able to follow the rotation of the glass.

A particularity from this analysis is the difference of the position of the supports to the final geometry of the panel. Although their distance was only of 200mm, the impact of this was visible in the deformation of the panel, which became much higher.

7.5.Conclusions

In this chapter different options to move and support a thin glass panel were presented.

However, there is a clear relation between these two

characteristics of an adaptive panel. To study this relation, between movement and supports, each of the proposed movements were analyzed, using different supports strategies.

In addition, these studies introduce the necessity of understanding the degrees of freedom allowed by the support, a relation that proved to be very important to be analyzed.

Although each of the movement had its particularities, after looking at each of them it is possible to draw important conclusions.

The number of degrees of freedom allowed by the supports is very closely related to the desired movement of the panel.

In general, by analyzing all studied movements, it can be said that if the number of degrees of freedom is lower than the necessary, stress concentration may occur in parts of the panel. If there are more degrees of freedom than necessary, initially there might be no difference in the panel besides an unnecessary increase of complexity on the support design; or there is also the possibility that the movement becomes unpredictable due to the excess of freedom.

After these conclusions, it is possible to better understand a few phases of the development of a thin glass adaptive panel design.

The first step to understand its movement, and the necessities of the building which can be answered by that solution.

As the type of movement is defined, it is possible to design the supports with the adequate degrees of freedom to allow for that movement.

After this process it is possible to simulate if the geometry achieved is according to the desired, if not, the type of movement, or type of support has to be reviewed and the process can be repeated.

To better understand these strategies the next chapter covers the development of the final product of this research.

THIN GLASS ADAPTIVE FAÇADE PANEL

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.

8.1.Introduction

In the previous chapters a general overview was given related to thin glass and adaptive structures, followed by model studies exploring the possibilities of using this material in an adaptive façade panel.

In the following sections, the knowledge developed in the previous chapters will be translated into a design of the façade panel.

At first, the design challenges and criteria are defined to the development of potential design strategies. Then, these design strategies are analyzed and one of them is selected for further development.

The selected design strategy is then further analyzed according to the supports and degrees of freedom conclusions developed in the previous chapter.

This is followed by the detailing of this design into a double skin façade panel. After this, propositions for design alternatives are made as recommendations, according to additional parameters related to the panel.

8.2.8.2 Design challenges/ criteria

To develop possible alternatives for the design of the adaptive panel I first looked into the ideal characteristics for it, in other words the criteria with which start to develop the panel.

The first criterion is the search for transparency. As a glass façade panel one of the main objectives is to create a transparent barrier to the environment, allowing the user of the building to see the outside.

The second criterion was to try to reduce the vibration of the panel regarding wind loads. The deformation of the panel by itself is not a problem regarding its integrity (considering that it does not reach its limit states), but its movement may generate noise and disturb the user of the building. This means that the panel has to be designed in a way that the curvature generated in the panel stiffens it, increasing its resistance to wind loads.

The third and fourth criterion regard the adaptiveness.

The first of them relates to the creation of a visual effect. Using thin glass in a façade is a new development and it should be visible and possible to differentiate from common glass.

The second is the technical aspect of the adaptiveness; as it would be interesting to have an adaptive façade panel not only for aesthetical reasons, but also that helped in other aspects if possible. As described before, there are many different applications to which adaptiveness can be a solution; considering this research I have constrained them mainly to ventilation, and therefore this criterion relates to this factor.

The fifth criterion is the feasibility of the façade panel. This regards the degrees of freedom of the supports and also the actuators. In general, the simpler the better and the less number of actuators is also an advantage for reducing the complexity of activating the whole system.

8.3.Potential design strategies

After creating the criteria, I developed potential solutions, based both in the initial geometrical exploration described in chapter 3 and also on the potential use of thin glass in the case studies developed in Chapter 5. From these ideas, I selected four of them to be further analyzed to see which is the one that has more potential regarding the object of this study and the constraints of this research.

8.3.1.Triangle

The first potential design strategy is based on the thin glass column design presented in chapter 3 and studied in item 7.4.7. This concept consists of three layers of thin glass laminated together forming a triangular shape.

In this way, by pushing one of the edges it is possible to make a flat and stiff thin glass panel, this would be the standard position of the panel. To allow movement this same edge is pushed backwards or forward, making the other edges move in the direction of each other, opening both sides of the panel.

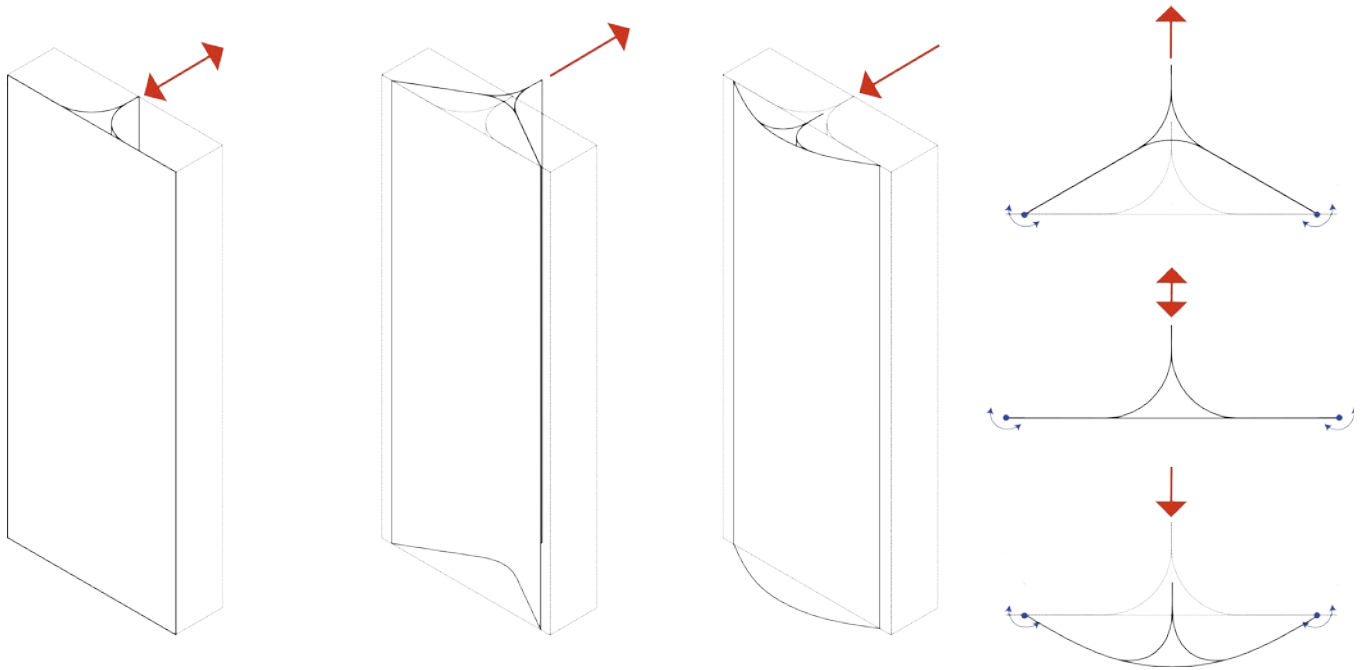


Figure 94-Movement scheme for triangle potential design strategy.

Although there were some issues with the FEM modeling of this panel, this solution is still very appealing, and shows much potential. Therefore, I decided to explore it further in this item to better understand it.

As analyzed in item 7.4.7, considering this movement of the panel, the most feasible solution for the supports would be to have them at the edges allowing for two degrees of freedom (translation on the x direction and rotation around the z axis).

Although this solution is composed most of glass, and directly there would be very few visual obstructions (vertical actuator and edges) this panel has a visual constraint considering its depth.

This is due to its geometry being based on the bending of two panels perpendicular to another. In order to not have high stresses on these two panels, the bending radius has to be higher, and therefore the panel becomes deeper.

Considering a bending radius of 300 mm, the depth of the panel would be at least 350mm as there is still the need to extend these panels to the back to attach the actuator. In addition, the actuator would push back to move the panel, leaving the overall needed depth for this panel of around 500mm, which is large dimension for a façade panel

Thus, this panel would have to be probably placed in between floors with mechanisms on the top and bottom.

These factors could be considered an issue regarding the transparency of the panel.

In order to simulate this scenario, a visualization was made to better understand the effect of these factors in the transparency of the panel. In Figure 95 it is possible to see this panel in an urban environment.



Figure 95-Interior view of the panel.

In addition to the mechanisms it is possible to see the result of the reflections on the glass due to the accumulation of layers.

After analyzing the transparency of the panel, the stress generation due to the initial bending and due to wind forces was analyzed.

This simulation was made with the final initial geometry of the panel, as in item 7.4.7, the stress of bending the plates to their initial position is not present in the simulations. Considering the hand calculation method presented in item 6.3.2, and

in Appendix O3 the bending stresses for a 1.1mm panel at 300 mm radius are of 135 MPa; therefore, a radius of 400 mm was considered to reduce this initial stress to approximately 100MPa.

As mentioned, the same issues regarding the FEM modeling of this panel are also present in this simulation. While simulating the movement of the panel outwards there was no contact surfaces determined, so they went through one another at one point, therefore the amount of translation of the actuator in this direction was reduced to 180mm.

The Figure 96 shows the stress results for the bending of this solution. The maximum stresses are 78N/mm^2 for the inwards movement and 42N/mm^2 for the outward movement.

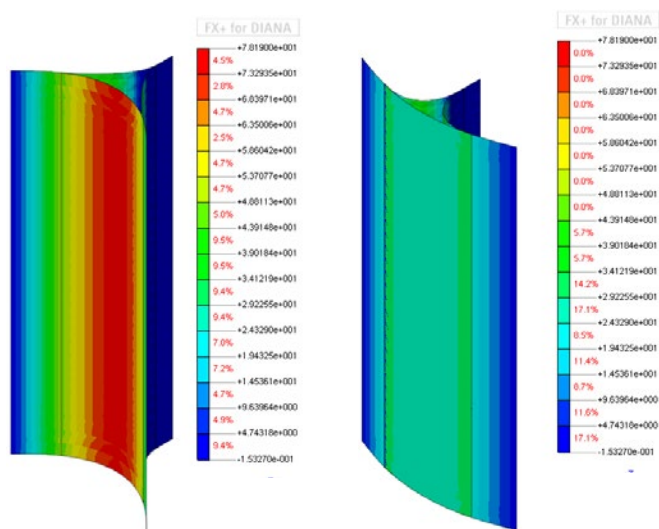


Figure 96-Stress distribution generated by the movement of the panel.

As for the wind loads, the contact of the surfaces is fundamental to determine the resistance of the panel. Again this simulation failed, as the contact between the surfaces could not be simulated (Figure 97).

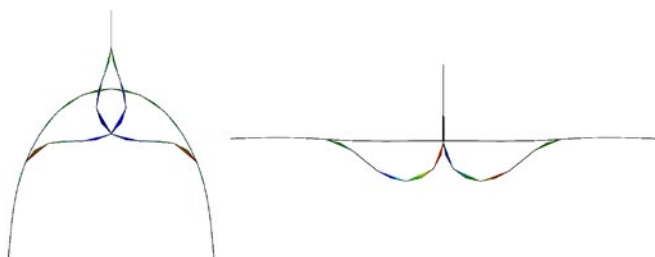


Figure 97-Geometric results of the wind pressure simulation due to the lack of surface contact configuration.

After looking into the stresses and wind resistance of this design, the adaptiveness characteristics have also to be taken into consideration.

Considering ventilation, in the closed position the panel would serve as the external barrier against wind and rain. The different types of movement (out or in the building) proposed by this panel solution have different ventilation outcomes.

When the panel is moved in the building, small openings are created on its lateral edges, allowing for ventilation without completely exposing the cavity; which could be useful for winter, when ventilation is desired but the thermal buffering of the cavity is also important. When the panel move out of the building, the same small openings on the sides are created, however this time, the middle part of the cavity also moves outwards and allows for air flow increasing the ventilation in the cavity.

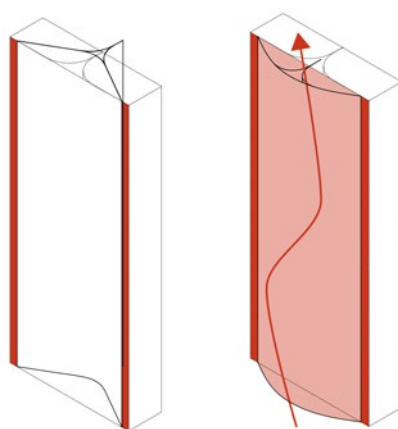


Figure 98-Ventilation scheme for triangular panel.

As for the visual effect in the façade, different visualizations were made to simulate how this panel would affect the identity of the building.

As the initial position of this panel is flat the façade would look as a usual glass façade. However, with the movement created it would be possible to create a surprising effect of a common glass façade that can move.

Regarding the feasibility of this option a major constraint is the lamination of the glass. For this concept to work the three layers of glass would have to be laminated to each other partially and also together, which might be not feasible or very complicated.

An option to this could be on using adhesives, however, it could also be a complicated task as the surfaces would have to be bonded one at a time, while already bending the glass.

As for the actuators and supports, this panel is feasible as it uses edge supports and the actuator could work on rails pushing the panel back and forth.

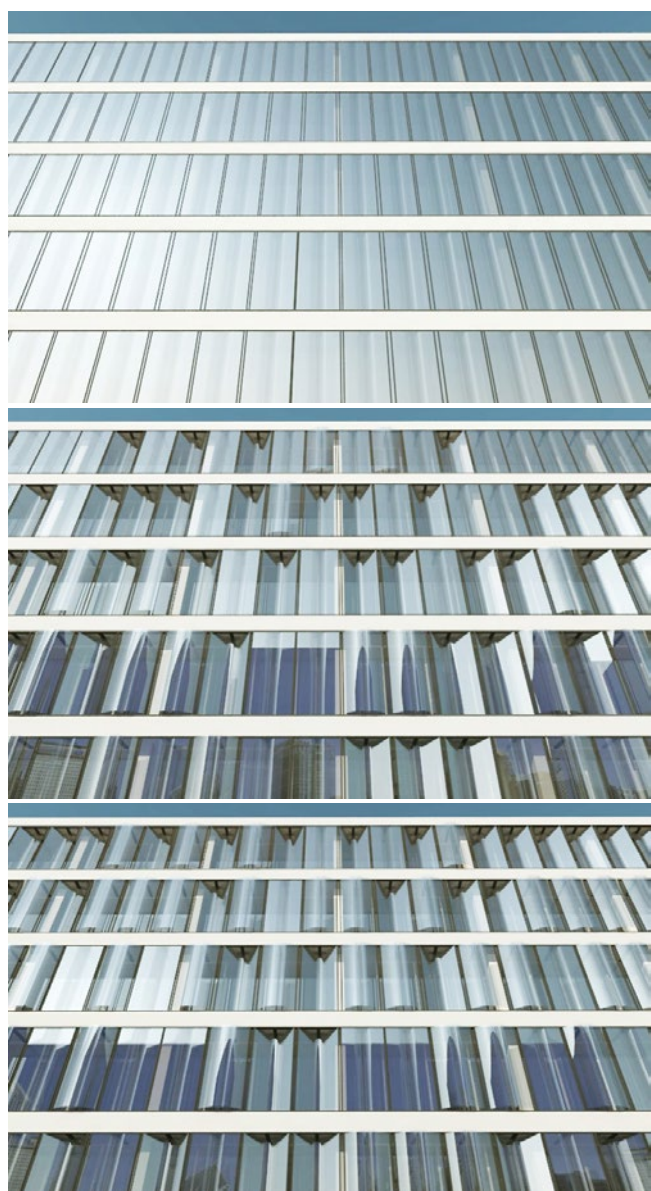


Figure 99-Visual Effect for the Triangular shaped panel.

8.3.2. Central bar movement

The second design strategy was based on the movement studied on item 7.4.3.

This design strategy consists in having a thin glass pane which is by a vertical bar that pushes the glass pane outwards increasing its curvature.

The glass is connected to the frame by four points, which are out of the edges to avoid the generation of peak stresses in these areas. Each of these points is connected to a support that can move in the frame in the x direction. This option was simulated in item 7.4.3.

According to the movement of the bar, the supporting points translate on the x direction opening or closing the panel according to the necessities of the building.

As the bar is supported by two different actuators, it can assume inclined positions, allowing for different curvatures in the top and bottom layer of the glass, increasing the stiffness of the surface. In this case it is also necessary to allow for the vertical movement of the supports.

In addition, the actuator works as a support against wind loads, avoiding the buckling of the panel.

This configuration allows for an almost unobstructed view of the outside, as the only direct visible barrier would be the actuator and the supports. To better understand this effect a visualization was made to simulate this scenario. (Figure 100).



Figure 100-Interior view of the panel.

Considering the stiffness of the panel, a new simulation, with better detailing for the supports (using four degrees of freedom), was made to verify the bending stresses caused by the initial bending and its resistance to wind forces. The initial bending position consisted on translating the bar in 500mm on the y direction and the increased bending on adding 135mm on the lower vertex of the bar. The wind pressure tested was of 1KN/m^2 .

It is possible to see in Figure 102 that both for the initial bending and the increased bending stresses are under 250 N/mm^2 . This is also true when these panels are under wind loads. Still, the simulation stopped converging at approximately 0.25KN/m^2 for both cases. In the table the stresses for the point connections are not present, as they were modeled as lines with only one node touching the surface of the glass the stresses were very concentrated and did not allow to show the stress distribution in the other areas of the panel.

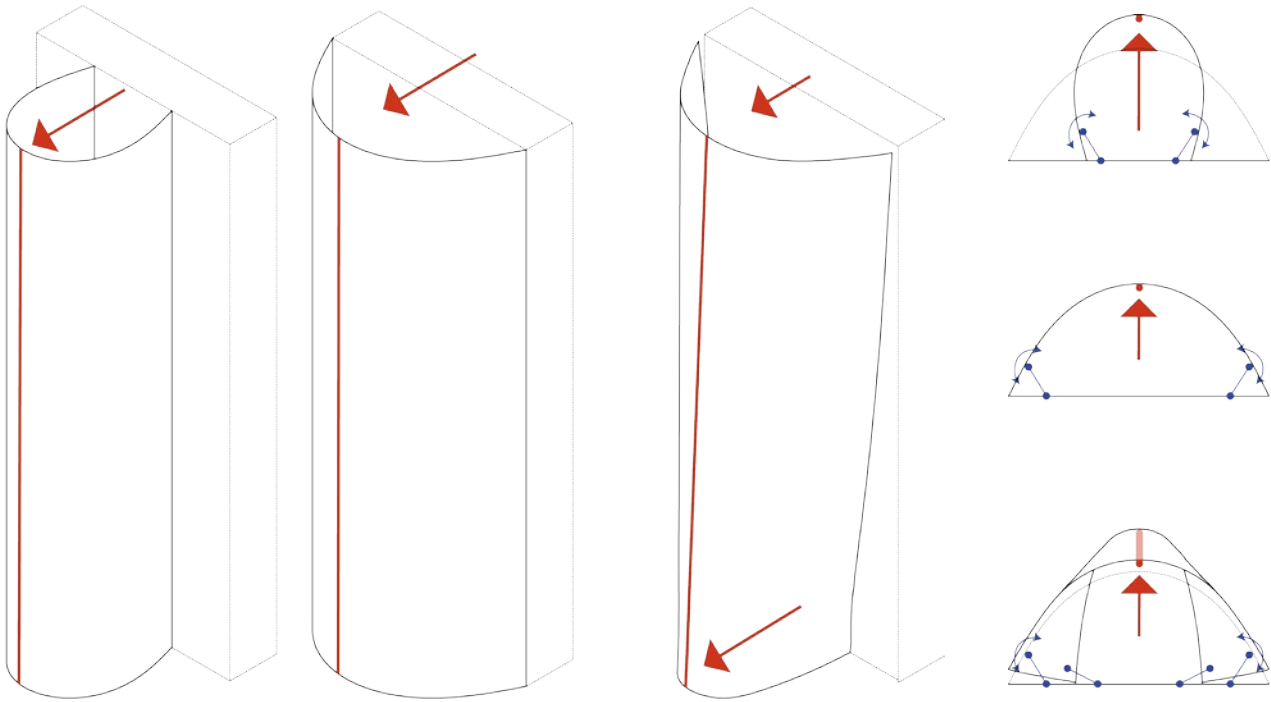


Figure 101-Movement scheme for central bar potential design strategy.

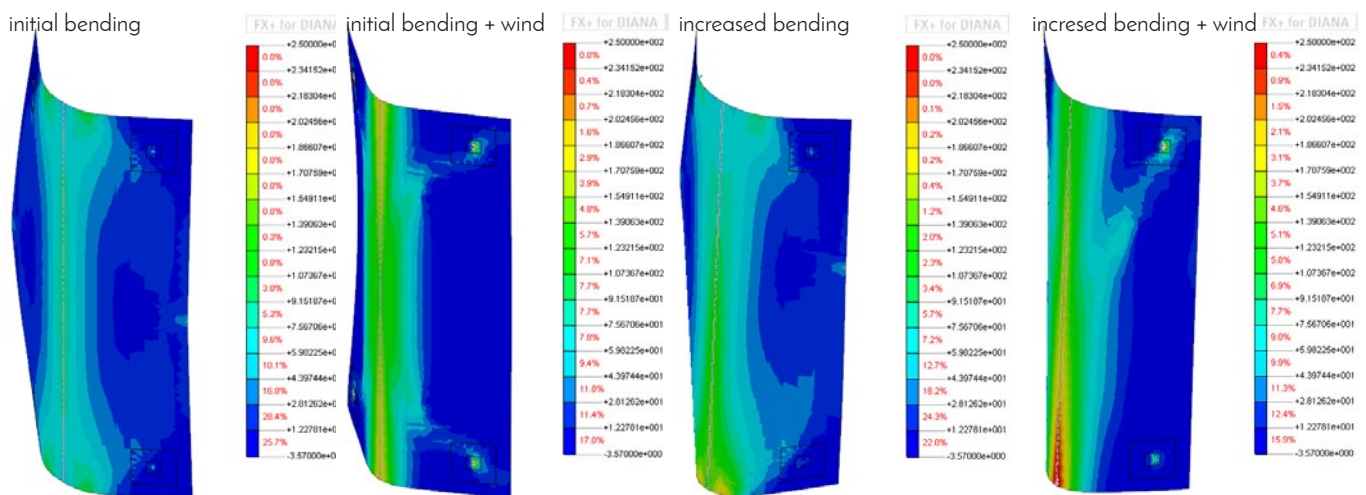


Figure 102-Stress distribution generated by the movement of the panel and wind pressure

After analyzing the stiffness of the panel, the factors regarding adaptiveness, ventilation and visual effect, were studied.

As for the previous example, the movement of the panel generates openings on its sides, that are directly opened to the outside. The increasing of the bending of the panel increases these openings, allowing for direct ventilation of the cavity. In addition, as the curvature increases the middle of the panel moves forward, which also allows for indirect ventilation of the middle of the panel. This is valid for both symmetrical and asymmetrical positions.

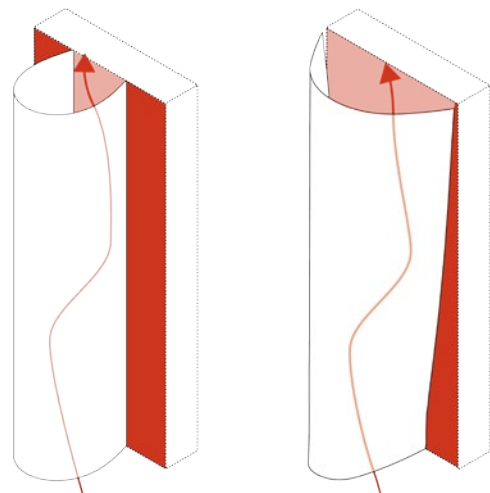


Figure 103-Ventilation scheme for central bar potential design strategy.

As for the visual effect in the façade, visualizations were developed to see this effect.

As the initial position of this panel is curved, it already creates an unusual façade. With the movement of these panels, this effect is increased, giving it a unique identity.

Regarding the feasibility of this panel, the detailing and movement of this solution seems feasible, the challenge lays in the definitions of the connections to allow the points to move together with the central bar.



Figure 104-Visual Effect for the Central bar movement shaped panel.

8.3.3.Sinus

The third option was developed after the movement studies developed in item 7.4.1 and 7.4.2

This design strategy consists on moving the panel by translating its two edges, and using three supports, the result is a series of sinus shapes, which resemble a curtain. As demonstrated, this option could work vertically or horizontally.

This panel would be moved by a single actuator in one of the sides of the glass panel; this forcing the panel to buckling. However, the panel is attached to its frame in specific points, so the buckling is controlled to the sinus shape. These points move together with the glass panel as it is pushed by the actuator, keeping the controlled buckling behavior and increasing the stiffness of the panel.

This option also offers an unobstructed view, besides for the actuator and the support points (or lines). In the visualization (Figure 105) it is possible to see another effect, that of the reflections caused by the sinus shapes, which may be considered as a visual barrier to the outside.



Figure 105-Interior view of the panel.

To better understand this movement, a new simulation was made, simulating the initial position and the open position, and the impact of wind in this panel.

In addition, two different plate sizes were used to see the effect of reduction of general width in the plate. The standard size of 1750x3000mm is compared to the 1500x3000mm size. The simulation of the initial bending consists on bending this plates to the width of 1250mm, and the increased bending consists on translating the edge for more 250 mm.

In the Figure 107 and Figure 108 it is possible to see that for both cases the initial bending stresses arrive already at around 300N/mm^2 for the wider version. Stresses which are easily increased in by moving the panel to around 340N/mm^2 in the same case.

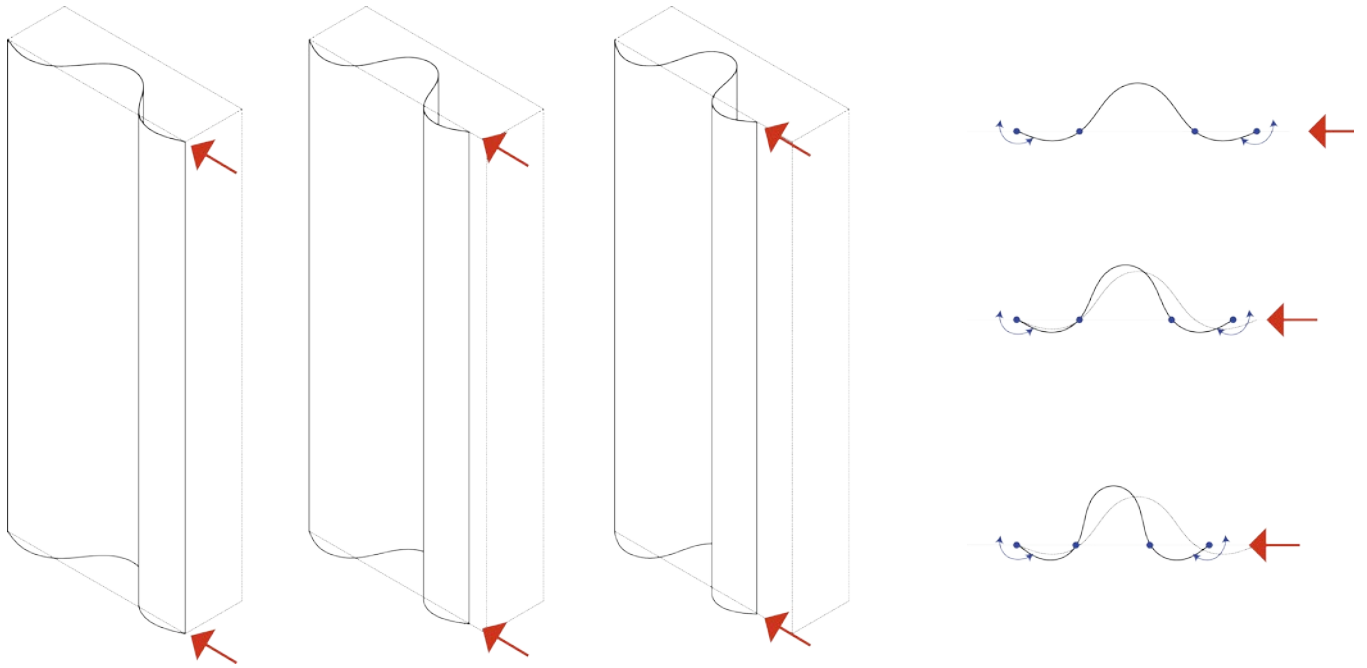


Figure 106-Movement scheme for sinus potential design strategy.

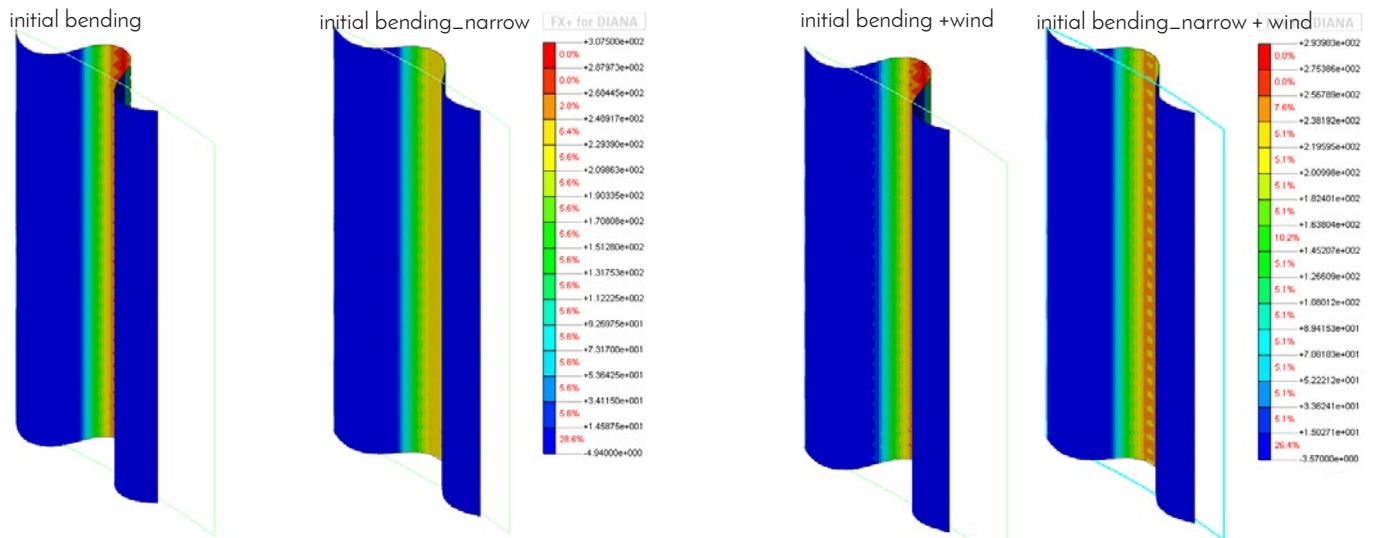


Figure 107-Stress distribution. Initial bending and initial bending with wind pressure.

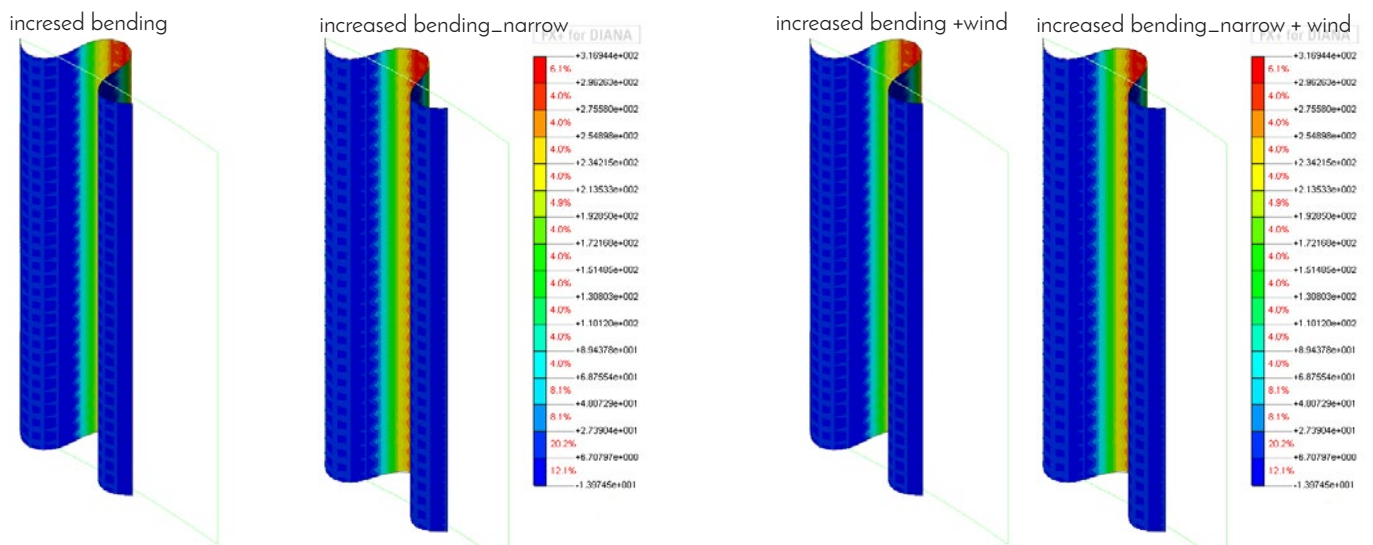


Figure 108-Stress distribution. Increased bending and increased bending with wind pressure.

An advantage of this is the wind resistance as an arc or parabola the panel is very vulnerable to wind forces, if the radius of curvature is reduced and the whole panel works in a sinus shape it becomes much more stiff.

It is visible in the figures that when the wind makes pressure on the surface the stress is reduced, as the radius is reduced as well. However, in this case this is true only for the top surface, by looking into the tensile stresses of the bottom surface of the panel at the same moment, they increase as the wind starts stretching these areas for the compression of the others.

As for the ventilation effects proportioned by this panel it is very similar to the previous cases, when the translation of the edge creates an opening on the side which allow for direct ventilation. This effect could be increased by using two actuators, one in each side of the panel, allowing for the creation of two openings (as the previous options).

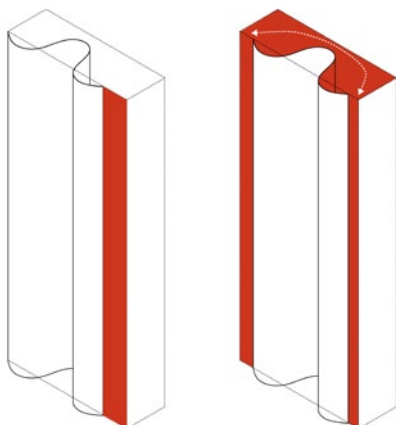


Figure 109-Ventilation scheme for sinus panel.

The visual effect of using this panel was also simulated by visualizations. Also in this solution, the initial geometry of the panel is unusual, creating already an interesting effect. In the case of this panel, as the movement is limited by the high stresses already present on the initial geometry the visual effect due to the movement of the panels is compromised.

As for the feasibility of the panel, the bending of the panel to the initial position can be seen as an obstacle, due to the force necessary to put it in position. Another challenge, which is feasible, is the movement of the supports, that need to follow the glass movement by the actuator.

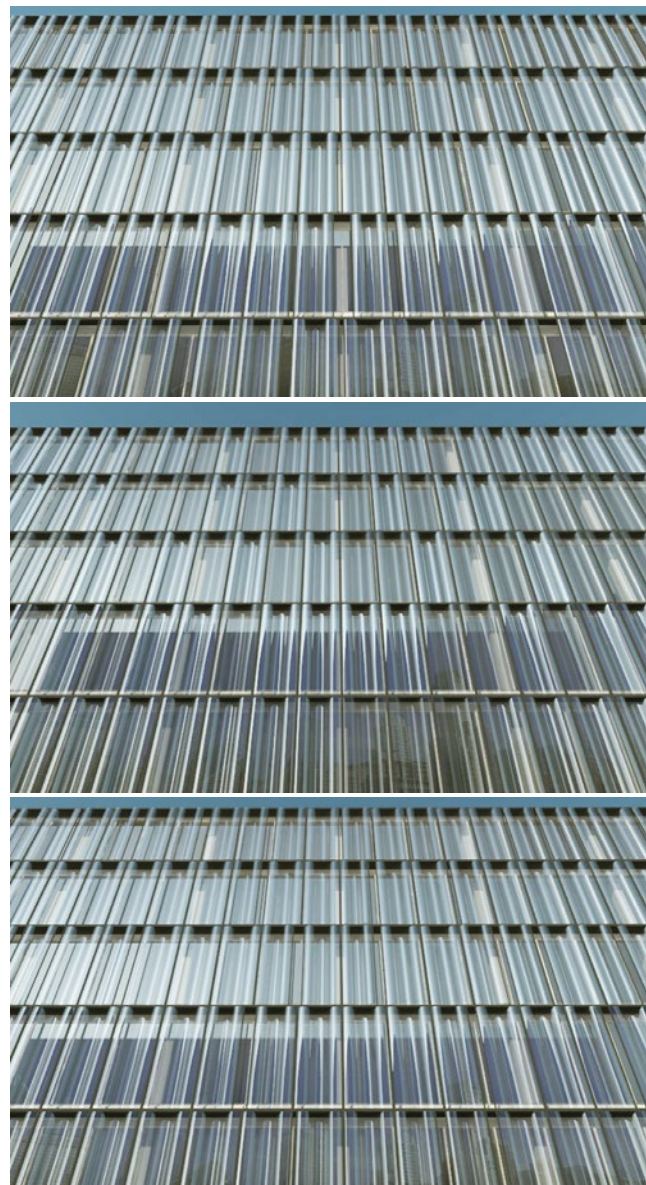


Figure 110-Visual Effect for the Central bar movement shaped panel.

8.3.4. Corner bending

The fourth and last potential design strategy is also based on the potential use of thin glass in the case studies and on the movement study presented on item 7.4.5.

It consists of a flat panel that adapts by pulling its corners inwards, this also creates curvature in these specific areas, stiffening the panel.

This panel is supported by all edges, but only partially, as the corners are left free to rotate inwards.

The actuator would be in the middle of the panel, connected to each of the edges by cables; which are then pulled by the actuator, pulling the edges of the panel inwards and allowing its movement.

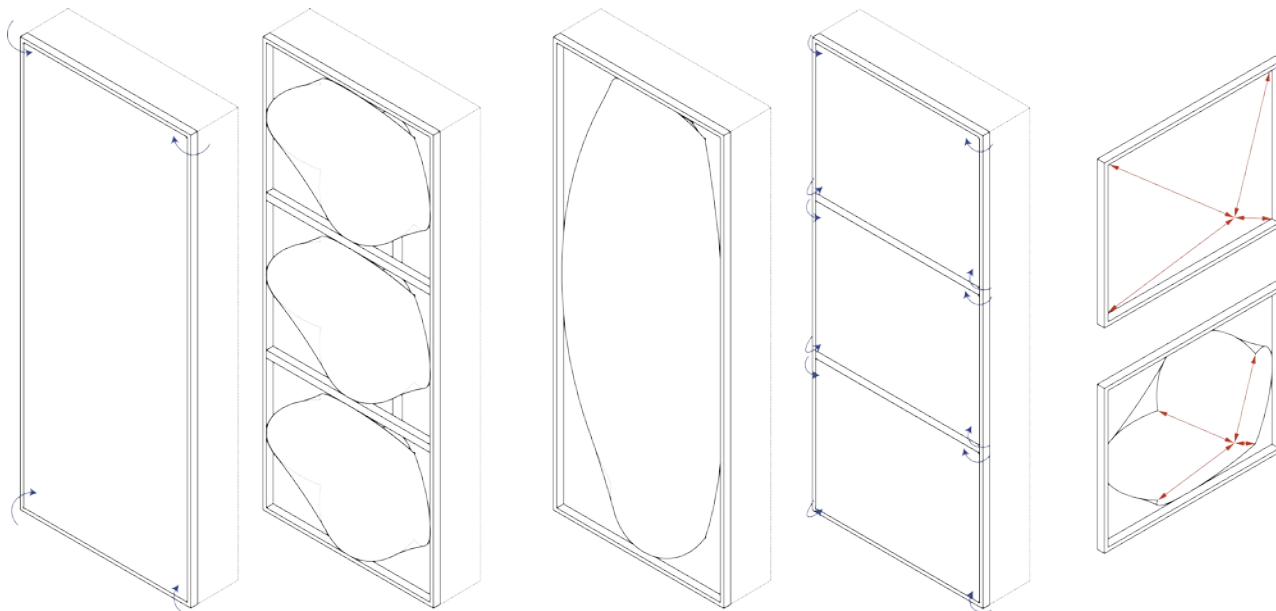


Figure 111-Movement scheme for sinus potential design strategy.

However, this strategy (of actuating the panel) also implies in an obstruction of the view to the outside, by the cables, the actuator and the supporting structure. This was simulated in a visualization. (Figure 112)

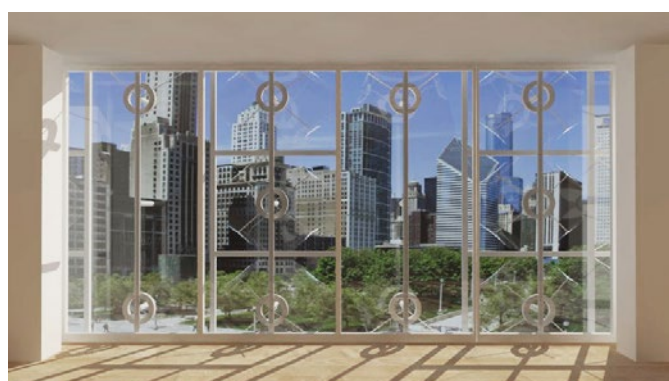


Figure 112-Interior view of the panel.

An alternative to this would be the lamination of bimetal stripes to these edges (presented in item 4.4.2), being they the actuators and answering to the changes in the weather and bending according to the change of temperature. (Figure 113).

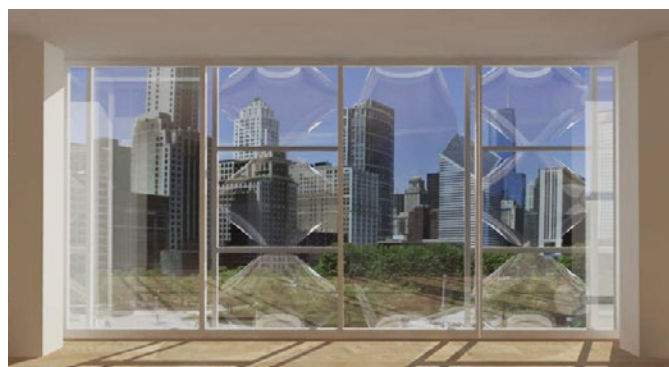


Figure 113-Interior view of the panel without obstructions.

In both visualizations, there is the presence of smaller elements, this option was considered to be an alternative to increase the stiffness of the panels due to the wind loads.

The stresses generated by this bending could not be calculated due to software limitations (as mentioned in item 7.4.5). These stresses would be dependent to the radius of the bending defined by the actuator, being it a cable or the metal strip. However, it was possible to simulate the wind pressure, for the partially supported edges configuration.

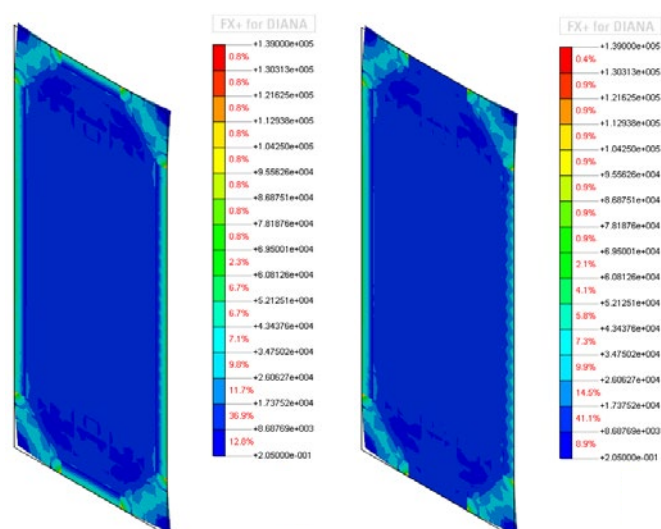


Figure 114-(Left) Clamped edges under wind forces. (Right) Pinned edges under wind forces.

In the Figure 114 it is possible to see the high stress concentration on the edges. An interesting effect is that only by the wind forces, the edges of the panel would already move, meaning that maybe they

should be fixed to avoid this vibration. An interesting fact is that the assumptions made on item 7.4.5 proved to be right in this wind simulation, besides the edges high stresses, there are areas of peak stresses on the points where the transition between the fixed and free parts of the edge.

As for the ventilation, this panel provides a different outcome. When open, there are openings both in the bottom and on the top of the panel, making it possible for the generation of a stack effect, moving the hot air more efficiently. (Figure 115).

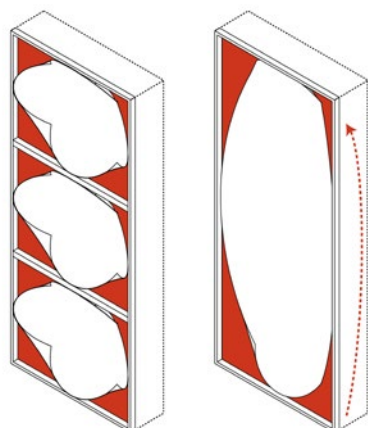


Figure 115-Ventilation scheme for corner bending panel.

The visual effect in the façade would also be very intriguing. As the initial position of the panel is flat, and its edges move, a surprising effect is achieved as that is a movement that is not expected from glass. Figure 116 shows a visualization as an example of this effect.

Still, the detailing of this panel is a major challenge to its feasibility. The attachment of its vertices to cables could be difficult and the use of bimetal strips would imply on a deeper research on how would this material behave attached to glass.

Another challenge is the stiffness of the panel, as a flat panel the wind loads push it, concentration tensile stresses on its edges. Adding curvature to the initial state would make it difficult to bend the edges without creating double curvature. An option would be to reduce the size of the panels, dividing it in smaller panes, which could be more stiff, but the supporting frames could obstruct the views, as seen on Figure 112.



Figure 116-Visual Effect for the Central bar movement shaped panel.

8.3.5. Analysis of selected strategy

After studying each of the potential design strategies according to the developed criteria it is possible to affirm that the central bar movement was the one that better attended them.

The triangular panel design proposal had an advantage related to its stiffness, which was guaranteed by its geometry and not its bending, which reduced the stresses on the glass. Another positive factor was its ventilation that, due to the different movements proposed had two different settings which could attend distinct necessities. Also its visual effect on the façade was interesting, creating surprise by an unexpected movement.

However, considering transparency, the superposition of panels in different curvatures generated an excess of reflections; besides that, the necessity of including the mechanism inside the floor to floor height due to its depth also affected this factor. The depth of the panel could also affect its implementation in a building by taking much of floor area, or creating a cavity excessively wide.

In addition, the assemblage of this geometry is a challenge in itself, due to the necessity of laminating or gluing the panels together while having them already bent.

As for the sinus design proposal, its stiffness was also an advantage, however to achieve such a geometry, the initial bending stresses were so high that very few movement was possible, compromising its visual effect and ventilation. Also this could become an obstacle related to the production of the panel, as the panel would have to be bent and fixed in the frame with high stresses.

As for the solutions of the corner bending, the feasibility of the panel was a major constraint, together with its stiffness. A possible solution by using a central actuator would also imply in a big obstruction of the views. However, this possibility brings a very exciting visual effect and unusual movement for glass, the development of a feasible option (by using bimetal parts on the corners) was out of the range of this research.

The selected design proposal, the central bar movement, shoed a good balance between the different criteria, with main advantages being its transparency, visual effect and feasibility. The stiffness of the panel should be improved, as in its bending there was concentration of stresses in the edges due to the "folding" of the panel and also due to its wind resistance behavior.

8.4. Design proposal

After analyzing the selected design strategy, I started the further development of the solution.

The first step was to analyze what were it could be improved. The answer was on the supports. On item 7.4.3 a comparison between point supports and edge supports for this movement was made, with edge supports showing a much better result. In the development of the potential design strategies, the

point solution was tested again in a better modeled simulation, but the results were very similar to those of before

Therefore, to increase the structural performance of the panel, edge supports are to be adopted instead of points supports.

After selecting the type of supports, the detailing of the panel started, to understand further the next step on to developing the thin glass adaptive panel.

As the movement and support strategy were already defined, the degrees of freedom necessary for the desired movement to happen were analyzed; this was the basis for the development of the detailing strategy of the panel.

The principle of this concept is the movement of the vertical bar in the middle of the panel, which forces it to change its radius.

The movement of the bar happens only perpendicular to the panel, in the y axis, generated by its two actuators. These actuators may move symmetrically or asymmetrically, creating an arch shape or a conical one respectively.

According to this movement, the radius of the panel changes. For this to happen it is necessary that the vertical edges of the panel are allowed to translate in the x axis, and also to rotate around the z axis in order to follow the change of radii.

The second position to consider is when the panel moves asymmetrically. In this case the panel assumes a conical shape, and its vertical edges assume an inclined position. Considering this, it is necessary that the supports also allow for rotation around the y axis and translation also in the z direction.

Therefore, four degrees of freedom have to be integrated in the supports of the panel for it to behave in the desired manner. This configuration was already tested and compared to other configurations of degrees of freedom; the results presented on item 7.4.3 showed the importance to adequate the supports to this configuration.

Therefore, the development of the detailing of the panel was made to achieve the four degrees of freedom described.

8.4.1.Detailing concepts

The detailing process was started by looking into each of the degrees of freedom described before and translating it into an element in the design of the panel, this was developed in a way to better understand the possibilities of supporting and moving the panel, a rough sketch to be further developed.

The first degree of freedom to be analyzed was the translation of the supports on the x axis, so the glass panel can change its radius according to the movement of the central bar.

This movement is the fundamental one to the panel to work. However, there was the challenge of choosing a solution that would prevent the panel to get stuck at one point.

After studying different possibilities, the one that seemed more suitable was using a rail and a set of wheels for each of the vertices of the supports.

Also the direction in which to place these wheels had to be decided in a way that it would help on the stability of the panel. Thus, the wheel system was selected to be in a set of four wheels per vertex, so that the wheels would give stability to each other both vertically and horizontally.

These set of wheels would be V wheels, for stability and would be rolling on a rail made of a profile with a V insert made to aid on the rolling.

The wheels would be connected by a plate bended in a U shape which would serve both as a connector for the wheels between each other, but also between the wheels and the remaining parts.

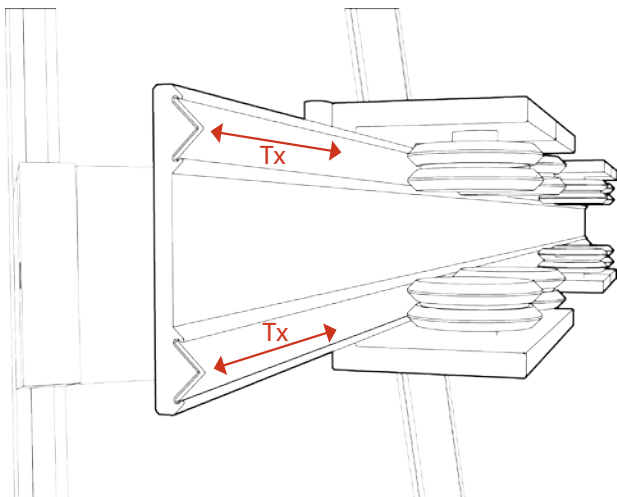


Figure 117-Rail and wheel system.

The second degree of freedom to be taken in consideration was the rotation around the y axis, this movement together with the previous one, would already allow the panel to move symmetrically.

The solution for this degree of freedom was a simple hinge, with part of it connected to the U shaped profile described above and the second one connected to the other parts of the system.

The addition of the remaining two degrees of freedom allows for the asymmetric movement.

The third degree of freedom considered was the rotation around the y axis. This was allowed by connecting a plate to the other part of the hinge mentioned in the previous step. This plate was then connected to a pivot that was connected to the edge profile connector.

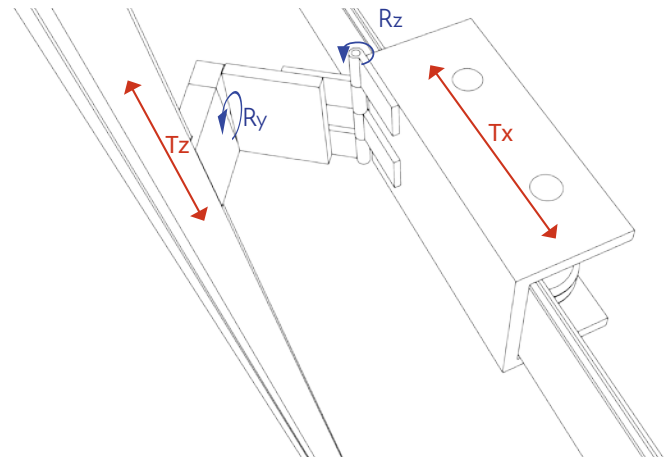


Figure 118-Hinge and pivot system allowing for rotation.

The edge profile connector was the part of this system that allowed the fourth degree of freedom, the translation in the z axis. This was made by not constraining the edge profile of the panel, in a way that this profile could slide vertically in the connector.

In this case the connections for the top and bottom of the panel were different, the connection from the bottom part of the panel would not allow the sliding of the edge profile of the glass, otherwise there would be not vertical constrain and the glass plate would be only constrained vertically by the central bar, loading the actuator.

This set of solutions could solve each of the degrees of freedom, individually. However, after analyzing if the system would work as a whole, this proved to be wrong.

Although there were no issues regarding the

movement of the panel symmetrically, the asymmetric position was not possible.

This was due to the fact that when the edge would rotate around the pivot the connectors from the top and from the bottom of the panel would not align.

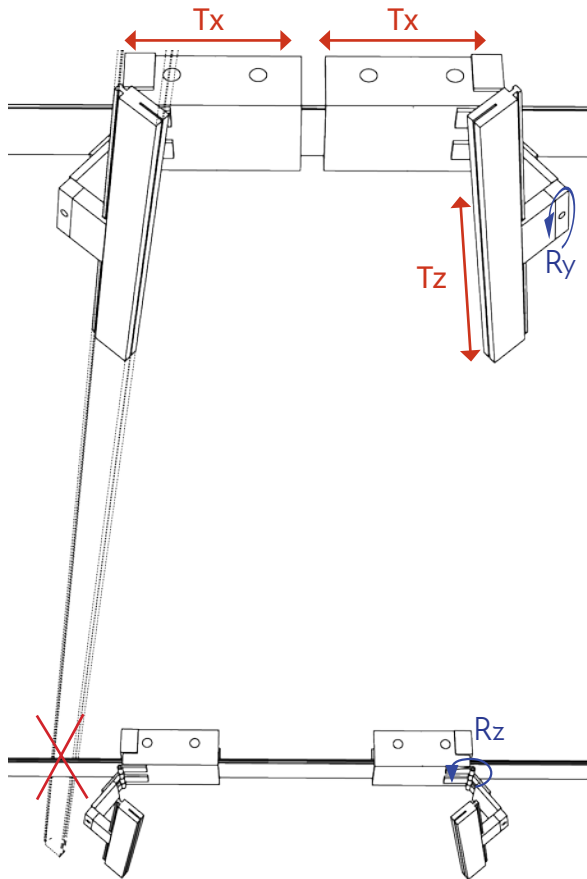


Figure 119-Overview of the system with alignment issue.

A short conclusion from this first design is that it is not possible to design by following the degrees of freedom individually, as for the movement to work they need to work together. Therefore, in the design process there is the need to review if there is any interference between the different parts of the panel.

After analyzing the first solution and identifying the problematic areas, the design of the panel was updated.

At the same time, other parts of the panel started to be defined as well.

The actuator had to be specified. One of the important factors in this case is the opening stroke, which is the distance the actuator can operate. Considering that in the initial bending position, the center of the panel is displaced 500mm from the alignment of the edges. In a symmetrical position this

can be increased to 700mm.

The initial assumption was to try to find an actuator which had a stroke of 700mm. However, the actual displacement the actuator needs to cover is of 200mm only. Thus, it was defined that the actuator would be connected to a 500mm bar which would be connected to the vertical bar to move the panel; this would be the initial position of the panel. The actuator would then move the connection bar for the panel to be opened.

Another factor to be detailed was the connection between the bar and the panel. As the bar pushes the glass and the radius of the glass is decreasing, it is important to protect the glass surface from the edges of the bar.

The solution for this challenge was on changing the geometry of the bar, to half circle, bonded to the glass on its edge and then the sides of it to be sealed with silicone, also helping on the connection between the materials.

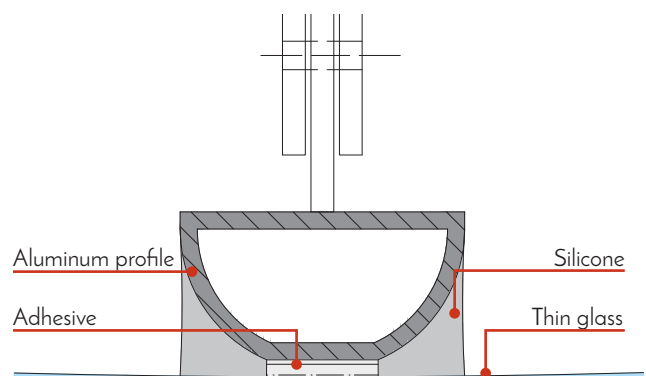


Figure 120-Connection between the bar and thin glass.

The wheel system was kept as before, with an addition of a spring that would be initially compact and then would be stretched when the wheels moved, helping to keep them in position.

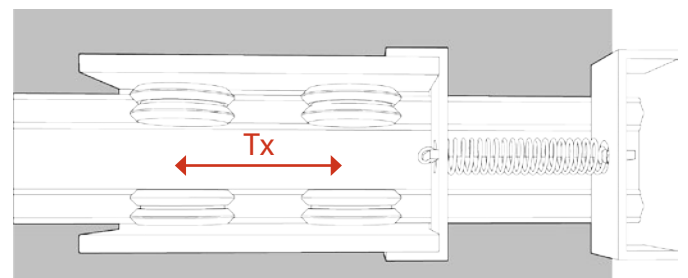


Figure 121-Rail system with stabilizing spring.

However, the rest of the system was updated. By looking for a simple solution that could allow for the other degrees of freedom, a double ball joint system

was selected.

This concept would work with two ball joints connected by a tube. One of the ball joints would be connected to the U shaped plate (that was connected to the wheels), while the other ball joint would be connected directly to the surface of the glass. While the edges of the panel would be protected by an edge profile.

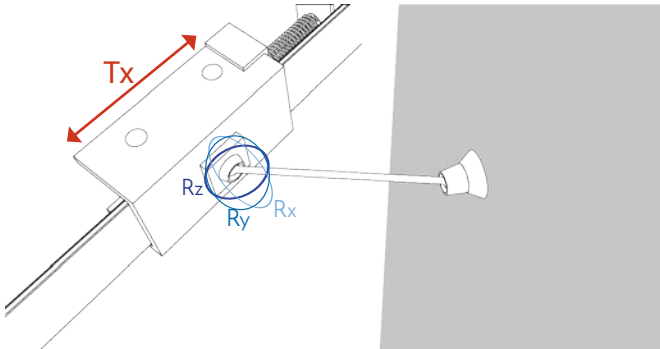


Figure 122-Ball joints connection.

Again, after reviewing this system, there was also an issue. By using ball joints in all connections, the vertical loads of the panel were not supported, thus, the panel would just move down by gravity, leaving the actuator as the only vertical constraint. This could be solved by using a hinge instead of the ball joint connected to the wheel system, however, I decided to review the whole system again and update it to find a more suitable and elegant solution.

After discussing the previous design with my mentors, we decided to change the rail position to above and below the panel, in a way to support the gravitational loads directly.

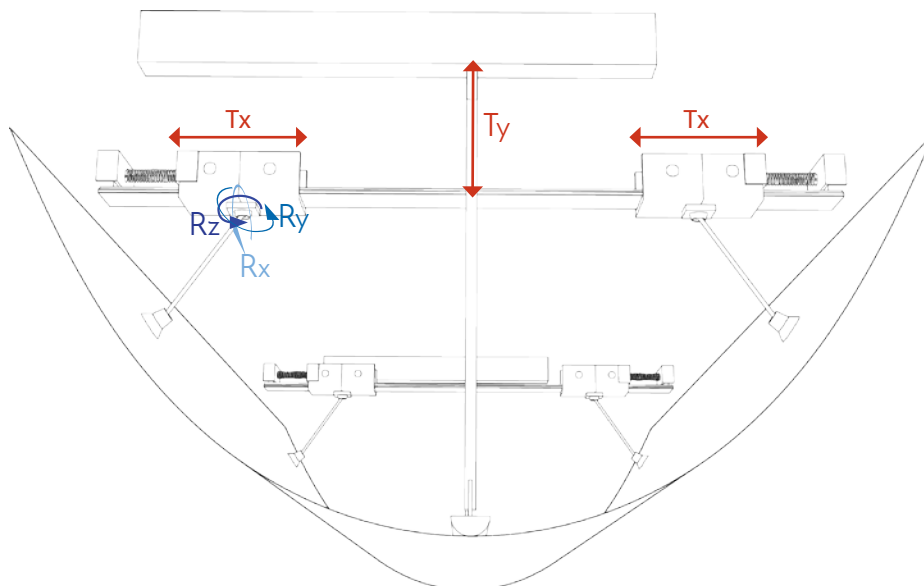


Figure 123-Overview of the second detailing concept.

This decision implied in a review of the whole system. I decided to start again, looking at all design parts, and trying to find a better solution to them.

The first part of the system to change was the wheels. Instead of four wheels per vertex, this number was changed to one.

The wheel was now placed vertically, acting as a moving pendulum. By using this strategy, the translation in the x axis, and the rotation around the y axis are allowed by the wheel.

The axis of this wheel is fixed to a U bend plate, which is the connection point for the remaining parts.

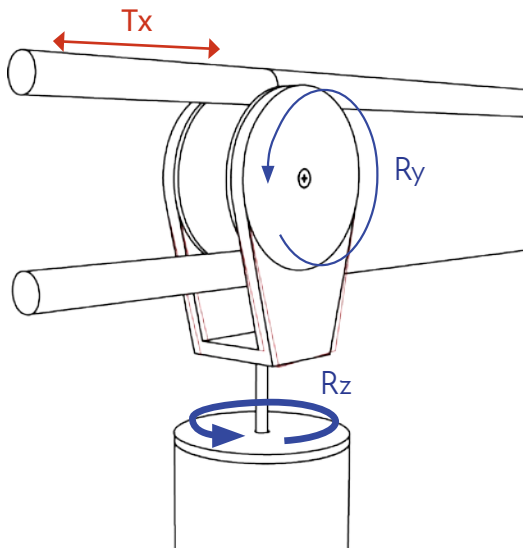


Figure 124-Wheel solution as a pendulum.

Fixed to this plate is an elevator bolt (a long bolt with a large flat head). This bolt serves as a vertical tolerance regulator during the assemblage of the panel. This bolt is also connected, but not fixed, to the top of the edge profile of the panel, which can rotate around it, allowing for the rotation on the z axis.



Figure 125-Elevator bolt example.

Also to allow for this rotation, the glass edge profile of the panel was made round. This shape not only allows for rotation, but guarantees a singular moment of inertia independent of the rotation of the panel.

To connect the bolt to the profile, while still allowing

for rotation, a connector was needed. In this case this was made by a cap. This cap is connected to the round profile by a thread.

In the assemblage of the panel, the bolt is inserted through the cap which is then connected to the glass edge profile.

However, there is still need to accommodate the translation of the edge in the z axis. To do so, a spring is placed in between the cap and the bolt; as the bolt is not fixed to the cap, when the profile needs to translate up and down the spring is compressed and part of the bolt gets out of the cap. (Figure 126).

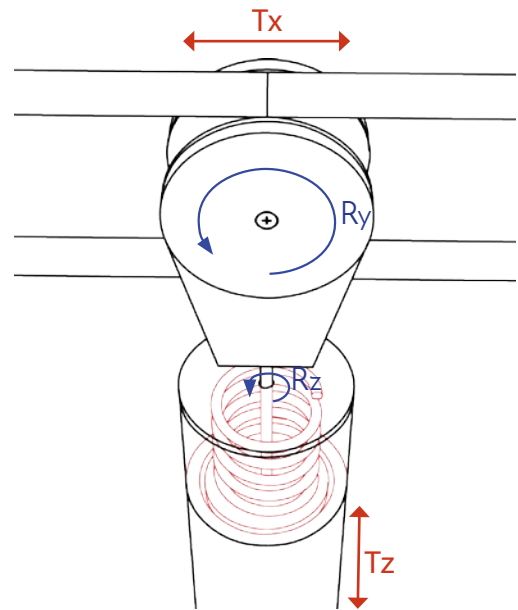


Figure 126-Spring inside the profile cap allowing for vertical translation.

By repeating the same solution in all sides of the panel, it was possible to attend to all the degrees of freedom together. Due to this reason this solution was then selected to be taken one step further, to a component analysis.

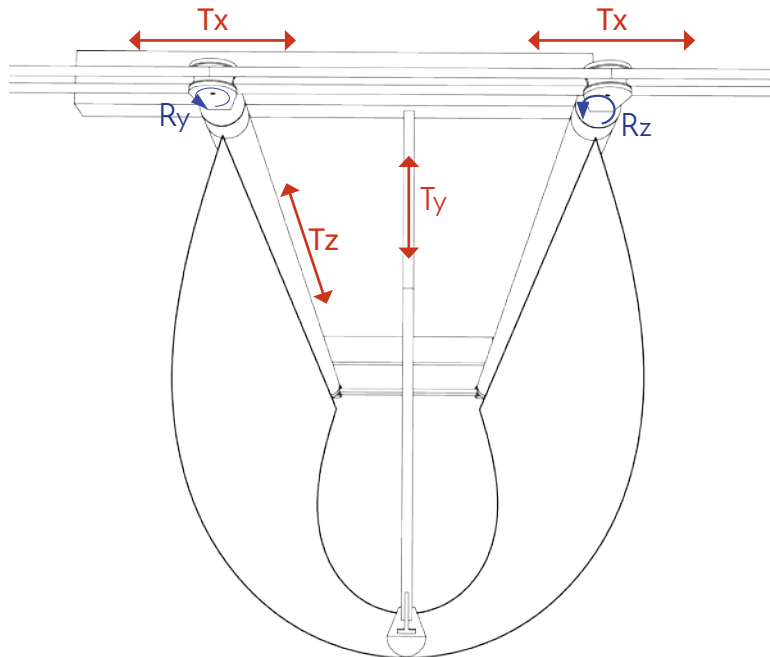


Figure 127-Overview of third detailing concept.

8.4.2.Components development

After defining the overall system to move the panel, each of its parts was analyzed to understand them better and be able to develop a final design.

The first element to be analyzed individually was the edge profile of the glass. As described in the previous item, it was initially made round to be able to pivot around the bolt.

However, by better analyzing its functions, it could be difficult to use this shape.

The edge profile of the glass has to clamp the thin glass panel at the same time as having enough area to bond it. To create a clamp, two different parts are needed (not necessarily two profiles, as one could be bent to shape) and to be fixed together. To do this in a circular shape, the most efficient way would be to clamp it in the middle, or it two different parts.

However, by having a small round profile (trying to keep it around 50 mm), that had to accommodate a fixture (bolt or screw) and area for bonding the glass pane was very difficult.

To overcome this obstacle, I first looked into different ways to clamp and bond this edge to the profile.

I first looked into different combinations of L profiles, as in one of its faces it would be possible to bond the

glass to one of its faces and to clamp the profiles on the other.

I tested two different configurations, a T shaped and a L shaped with one profile on the other. These solutions seemed to work well in the profile, but the pivoting of this shapes seemed to be challenging.

Another solution was to associate L profiles with a square profile, creating a similar shape but giving more area for the rotation of the edge.

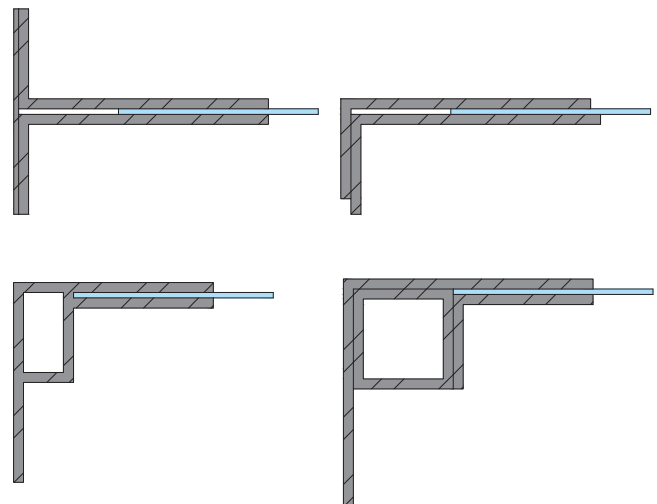


Figure 128-Profile Alternatives.

Still, these seemed to be adaptations that could work, but not ideally to the design. Thus, I decided to develop an alternative, by designing a profile that would suit the design in a better way.

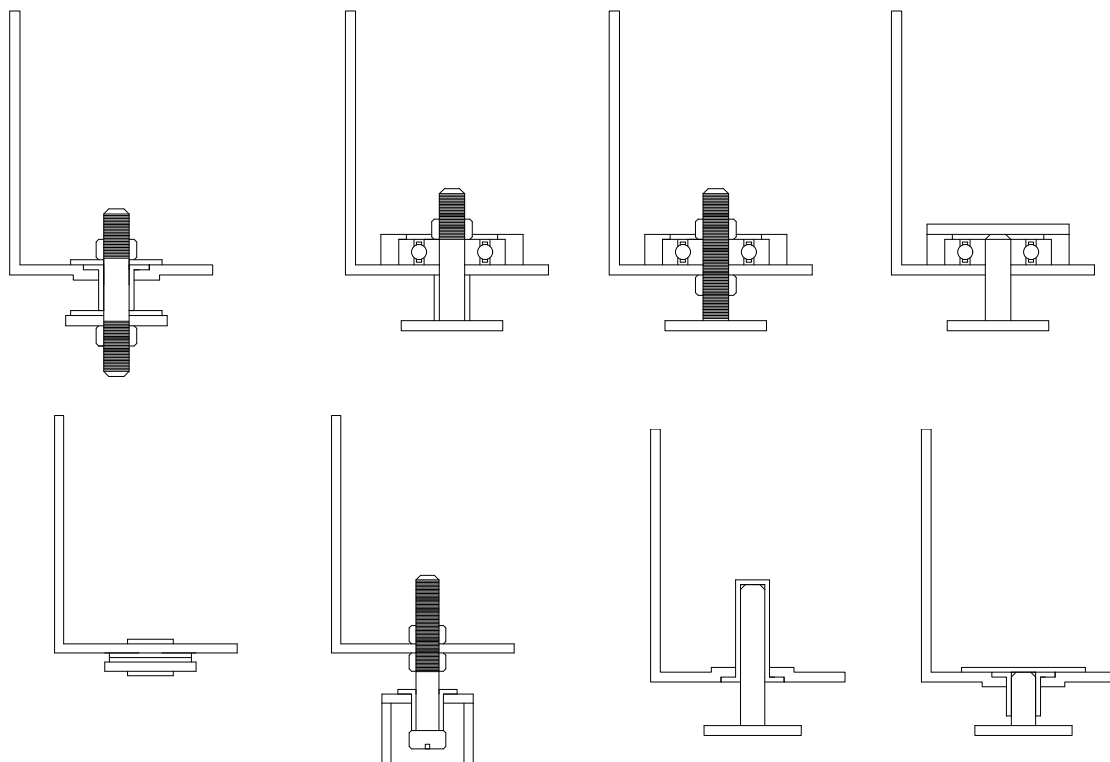


Figure 129-Different pivot alternatives studied.

The next step was to analyze the rotation system. To do so I researched many different possibilities, by using roller bearings, bushings, pivots. It is possible to see these different concepts on Figure 129. Yet, none of them seem to work as well as the system described in the end of the previous system, so I decided to keep the elevator bolt together with the spring.

Still, a small change was made in the previous configuration. The spring is no longer present in all of the support edges, but just on the bottom ones. This has the objective of supporting the panel by the bottom, and using the top support as a hinge. When the support needs to translate vertically, its top is fixed and the spring is compressed in the bottom so the bolt can be extended.

The next step was to look in the wheel system.

The wheel was previously put in between two round rails, but this configuration would not work in the way it was proposed. The idea was to avoid that the wheel could “jump” off the rail due to wind forces, however, by placing two rails touching the wheel it cannot move. This was simply resolved by moving one of the edges five millimeters away from the wheel.

The wheel is made out of a roller bearing system that allows it to rotate better while still receiving loads. Through the axis of the wheel, a bolt fixes two spacers next to it. These spacers are then connected to the U shaped plate which is then connected to the

rest of the system.

Another factor to consider was the actuator. The actuator is directly connected to the central bar of the panel, which was located in this position to increase the stiffness of the panel, mainly due to wind loads. While perpendicular loads would not be an issue for this component, as it is designed for it, perpendicular loads can be a serious problem

To face this, the actuator had to be chosen accordingly.

Different types of actuators are available, for instance an option considered was using linear actuators, however, to achieve a stroke of 200mm more 200 mm are necessary of equipment, using more than the depth of the panel. Another type of actuator considered was a chain actuator, as it can have small dimensions, while still being able to have larger strokes. Besides that, a scissor actuator was also considered, due to the necessity of increasing the stiffness against loads in perpendicular directions to the panel. Yet, none of the options have technical specifications concerning lateral loads.

An alternative raised to face this issue was to create a structure that could prevent non-perpendicular loads to reach the actuator. This solution would consist on placing a supporting tube around the tube that connects the actuator to the central bar. In this way, when loads from different

directions reach the vertical bar, the stresses are directed to this outer tube instead of the actuator.

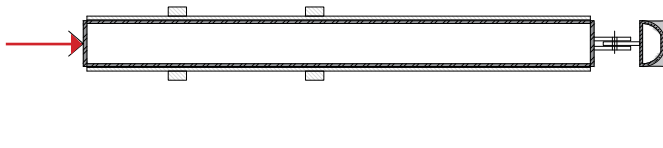


Figure 130-Actuator stabilizer scheme.

Besides the mentioned components another aspect to be taken in consideration is the connection of the panel to the building. The only parts attached to the construction are the rails and the actuator.

Although specific solutions are necessary for an integration to a building design, the principle of the connection should remain the same.

The rails should can be supported only on its ends, as the spam is only of 125mm and the weight of the panel is low.

As for the actuators, they have to be placed in a position in between both rails, their position is dependent on the building in which the panel is installed.

8.5.Final product

The development of each component made it possible to continue the detailing into final products. As for the date of this report the final drawings are not yet finished, as they will be shown in the presentation. The drawings presented here are a preview of the final ensemble of products.

Here, two different details are presented, that of the edge profile of the glass, and the connections to the rail.

To develop a custom extrusion, I looked into

manuals on how to design it, to better understand the constraints of this process.

The profile was developed symmetrically, in a way that only one cross section can be used for making the whole profile.

The development of this extrusion was based on the idea of the tube, which would allow for the pivoting of the panel, together with an extension to allow for the bonding of the glass.

The dimension of the extension was determined by checking the tape manufacturer's datasheet and calculating the necessary width of tape for this case, which is 35mm.

The profile also has to allow for the clamping of the glass, this is done by creating a canal which serves as a 90o screw port. On the outer part of the screw port a line was made to orient the correct axis of the screw.

It is also visible the presence of four screw ports. These are present to allow for the screwing of the cap of the profile.

The cap of this profile is an aluminum cast piece. This was made in this way to be able to create a custom cap for the profile, together with a thread to connect the blocking cap for the bolt.

As it is possible to see on the detail, the top rail and the bottom one are different, this is to create the hinge behavior mentioned in the previous item. Therefore, on the top of the panel the blocking cap is placed closer to the profile cap, avoiding the movement of the elevator bolt; still on the top detail, a low density foam is placed to avoid the contact of the bolt and the cap, for noise and maintenance reasons.

As for the bottom detail, it is possible to see that

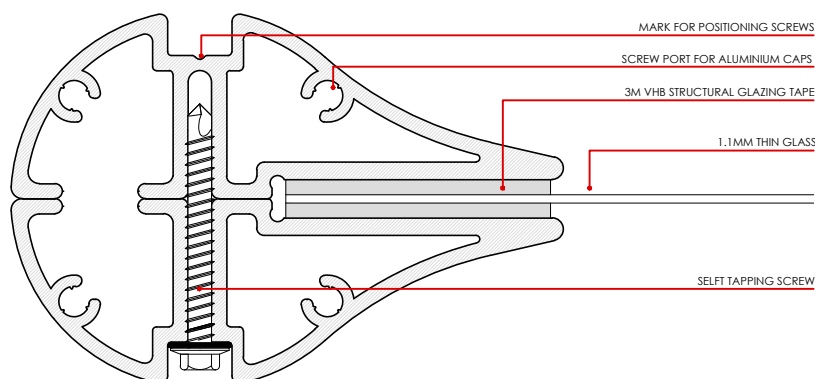


Figure 131-Profile detail in scale 1:1.

the blocking cap is now placed further from the profile, allowing the movement of the elevator bolt, which is stabilized by a spring.

Around the elevator bolt it is possible to see a rubber protector, which has also the function of hiding the bolt giving more uniformity to the connection.

The elevator bolt is then fixed to the U shaped stainless steel section. This fixture has also an additional function of height adjustment for the panel, allowing for a vertical tolerance of 25mm.

The U shaped stainless steel section is then attached to spacers in both sides of the wheels, this was made to create distance between the rails and the u shaped section.

These details already show the translation of the studied degrees of freedom to the design of the panel.

All components used on these details are specified on Appendix 04.

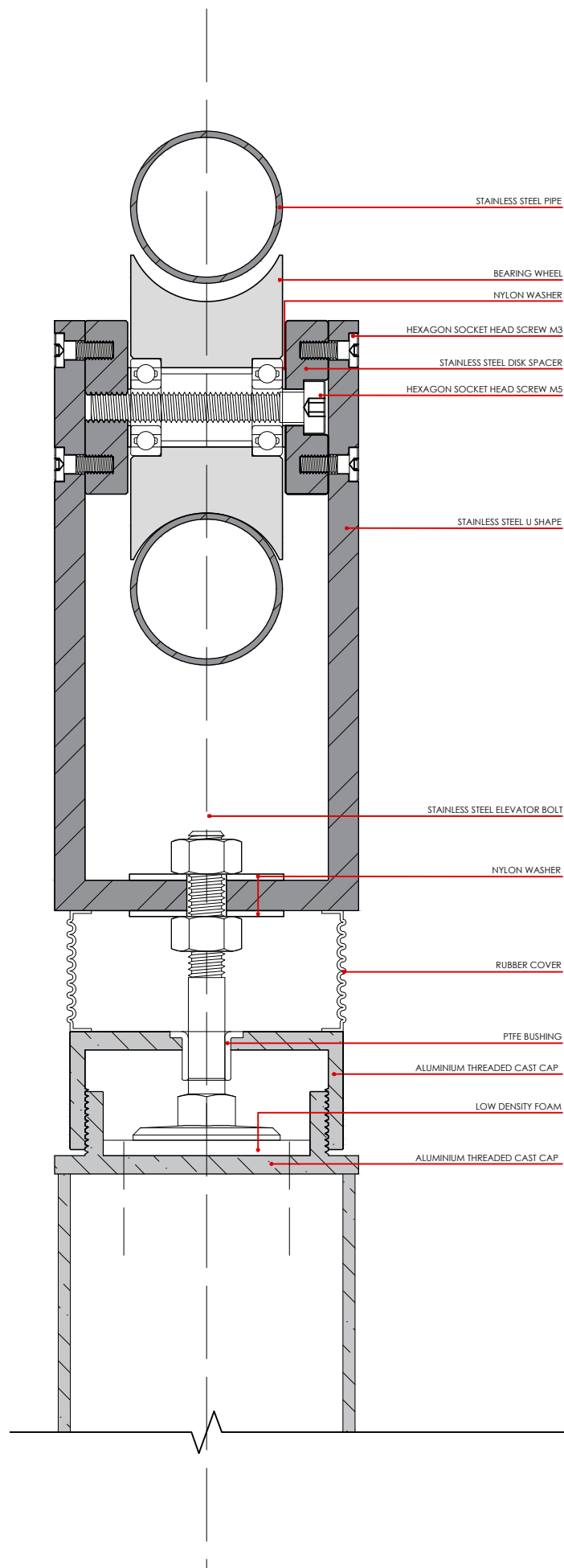


Figure 132-Top rail detail in scale 1:1.

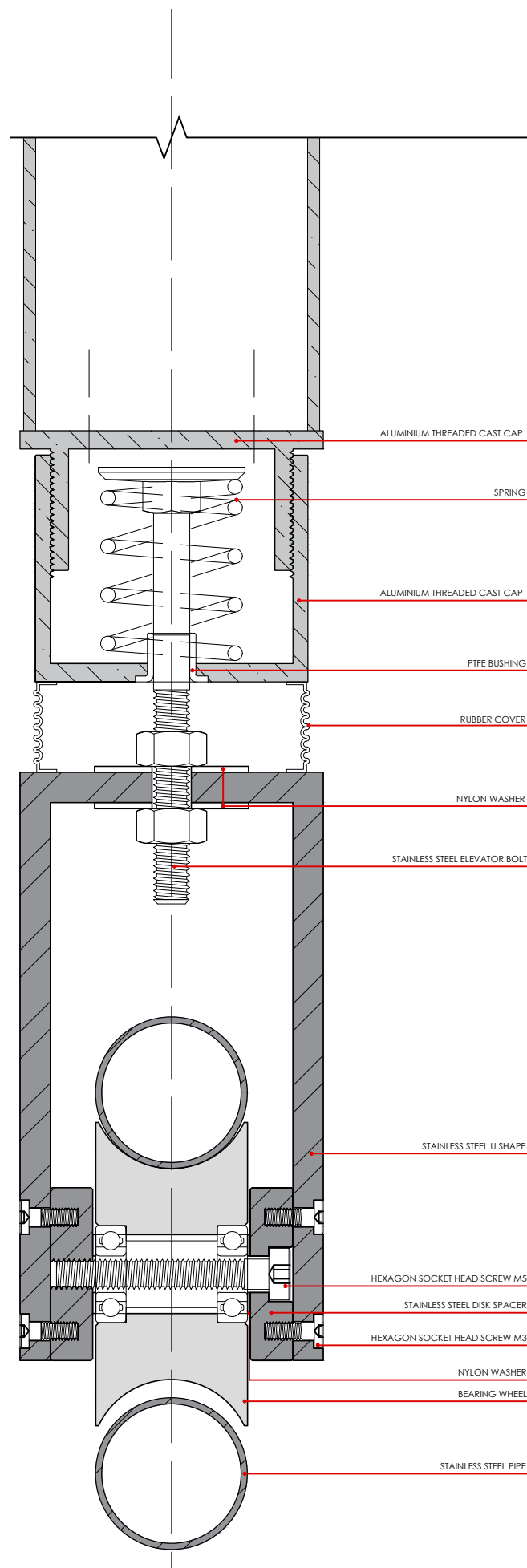


Figure 133- Bottom rail detail in scale 1:1.

CONCLUSIONS

This chapter presents the general conclusions of the research together with the research questions and suggestions for further development

9.1. Initial considerations

Thin glass is a common material for the mobile electronics industry, with its main application as a protector for smartphone screens. This material presents characteristics not commonly associated with glass such as impact resistance, flexibility and lightness.

On the other hand, the construction industry and designers are exploring the limits of designing with glass panes; facing challenges related to the weight of the panels and the use of raw material and energy. These issues are mainly associated with the necessity of using many layers of glass together, for stiffness of the elements and safety.

This research aimed to link these two points, using the characteristics of thin glass to overcome the problems faced on glass design.

Introducing this new glass technology to the in this context follows the history of the development of glass design, which shaped the built environment we experience today.

Nevertheless, using thin glass as an alternative to common glass implies in a reduction of raw material and energy. Besides that, it also reduces the loads in main structures of buildings, reducing the need for structural material. In addition, if used as an alternative to achieve geometries previously executed by hot bending, energy and economic resources are spared.

The challenge faced was on finding applications in the built environment for this new material.

Although many possibilities could be explored, the main characteristic of this material, its flexibility, dictated the focus of this research.

After researching different possibilities, an application showed great potential to use this material as an alternative to glass and also embracing its flexibility: adaptive façade panels.

This defined the research question, which was how to make thin glass panels adaptive.

To answer that question many aspects had to be developed as there is very few research on the use of this material on the built environment.

These aspects were defined as sub questions which started as very broad topics, such as the possible purposes for adapting this panels, until very technical ones, as in how to translate the degrees of freedom into detailing.

The next items on this chapter will cover a summary of the process of answering the research questions, and suggestions for further research based on the findings developed on this one.

9.2. Research Questions

The beginning of this research started as to trying to find a suitable use for thin glass in the built environment.

The first three chapters of this research were dedicated to this introduction to the subject. After looking into the characteristics of glass, thin glass and possibilities of using the later as an alternative to the first, the research gained a direction: adaptive elements.

However, this was still too much broad. To refine this, adaptiveness in the built environment was studied together with trying to apply thin glass in different contexts to understand its potential and constraints (Chapters 4 and 5).

This first part of the research defined its final focus and its main research question:

How can a thin glass double skin facade panel be made adaptive?

In order to answer that question, multiple other factors had to be studied (as there is very few research available on the use of this material on this context), these were then defined in sub questions, from wider to very specific ones, which were studied during the research.

This structure established the development of the research, which aimed to cover these aspects on the best way possible, increasing the knowledge over this material in the built environment.

9.2.1. To what purposes can a thin glass panel be made adaptive?

This question had the objective of understanding the relation between thin glass and adaptive facade panels and mainly why would a thin glass facade panel be made adaptive.

In chapter 4, adaptiveness in the built environment was studied, identifying principles and purposes which would suit the use of thin glass in this context. The conclusion of this chapter was that thin glass in adaptive elements could be used to six different purposes: ventilation, sun protection, sun energy, visual effect, wind load and noise reduction.

Although all these different uses have potential, ventilation and visual effect were selected as the ones to be taken in account for the following of the research.

9.2.2. How does bending influences the stress generation in the thin glass panel?

The second sub question was related to understanding the behavior of this panel under bending, as using its flexibility implies on curving it.

In chapter 6 multiple simulations were developed with the objective of answering this question. As thin glass was not available, acrylic was used in a study model to gain insights, and then these ideas were further developed in FEM simulations.

The computer simulations compared bending for different thicknesses of glass and a clear relation was shown between the bending radius and the thickness of the panel: the stress generation was proportional to the thickness of the material.

It was clear that the more the material would be bent the more the stresses would increase, however the objective was to know how much, to be able to set boundaries to the development of the research, and these simulations presented a good overview.

9.2.3. What are the influences

of bending and thickness on the load resistance of the thin glass panel?

This question was a development of the previous one. Considering that the panel is on a facade context it is important to understand how the bending of the panel relates to its load resistance, if it makes it more susceptible to loads or more resistant to them.

The research for this question was also developed in Chapter 6, applying a wind load to each of the analyzed bent geometries.

The results of the simulations did not correspond to the expected, just one of the three thicknesses did.

Therefore, although this question was explored, there is still room for improvement in this case.

Generally, the bending of the panel did not increase the resistance to wind loads, either the panel maintained its resistance or, as expected with excessive bending, it became unstable very easily.

9.2.4. What are the possibilities of movement for this panel?

As for making a thin glass facade panel adaptive movement is necessary, this question had the objective of identifying ways to do that, taking in consideration the results of the previous questions.

This question was answered in two phases of the research. On chapter 5, by simulating the use of thin glass in multiple case studies and on chapter 7 by further analyzing the types of movement developed before.

From those ideas, seven different movement possibilities were developed and studied, looking into the constraints and potentials for each of them.

9.2.5. How can supports influence the movement and geometry of the thin glass adaptive panel?

Together with movement, the supports also play a fundamental role on making the panel adaptive.

The objective of this question was to relate the support constraints to the movement desired.

Initially, in the same process as the movement possibilities, support possibilities were selected.

Then each movement was analyzed according to different types of supports and degrees of freedom.

I became clear after the analysis that the movement of the panel is highly dependent on the design of the supports.

If the supports are designed with less degrees of freedom necessary for the movement, there is concentration of stresses and geometry deformation. On the other hand, an excess of degrees of freedom can cause unnecessary complexity on the detailing or unpredictable movements.

9.2.6. How to translate the necessary degrees of freedom to the detailing of the panel?

The last sub question refers to the detailing of the panel, on how to bring the theoretical approach of analyzing the degrees of freedom to a design.

In chapter 8, this process was developed step by step in a way to show that only by creating elements answering to each degree of freedom is not a recommended path, as it can create unwanted results.

This method has to consider all degrees of freedom together, in a way that the solution for one movement does not interfere or obstructs the others.

Most of all, considering the thin glass panel, the detailing of the panel and the movement allowance has to be made in a way to make the movement of the glass as unobstructed as possible.

9.2.7. Main research question

After looking into all the sub questions, it is possible to reanalyze the main question and provide its answer.

The development of this research covered the process

of making a thin glass façade panel adaptive, from the material behavior analysis to the considerations into the detailing of the panel.

It is possible to say that only the ensemble of the sub questions creates the knowledge necessary to answer the main proposed question.

In summary, the process to make a thin glass panel adaptive is connected to all factors presented above.

Initially, the identification of the purpose of adaptiveness is fundamental, as it defines the necessities to which the panel has to adapt.

This is necessary for the definition of the initial geometry of the panel and of its movement, according to the limitations of the material.

The movement of the panel has then to be studied, identifying the degrees of freedom needed to allow for it. This process has to be related to the definition of the types of supports.

Finally, after analyzing relation between supports, movement and degrees of freedom it is necessary to translate this into a design.

It was shown that an integral approach is necessary to do so, in order to take in consideration all possible movements of the panel, taking special care for the unobstructed movement of the thin glass panel.

9.3. Suggestions for further development

Regarding the development of the research of thin glass in the built environment there is still much to be done as this subject is still in its first steps.

During the development of this research I identified subjects that are in need of further development and that I would like to leave as a suggestion for future works.

First of all, there is the necessity of studying the properties of this material, related to the build environment, such as pre stress levels on the surface and on the edges, strength, fracture behavior. As this material was developed for the electronics industries, these factors were not studied (or published) with enough data to allow for its use in build applications.

As for the date of this thesis, there is a research currently being developed considering the strength of this material in TU Delft.

A factor that I became much curious about was if there is fatigue present in this material, an aspect which was not yet tested (as glass is not commonly cold bent continuously).

Another factor is the lamination of this material, and how does this affects its properties. This aspect may also be influenced by the movement of the material; a possible study could be on the delamination of thin glass movable components.

An aspect that I consider to be also of great importance, and which was also addressed in this thesis was the behavior of this material under wind loads, and how to make it stiff by curvature (which is challenging due to the limitation of single curvature).

These were general aspects which I think should be covered to provide the fundamentals for further research in this material.

REFLECTION

This chapter presents the reflection of the author concerning the process of the graduation research.

This chapter is a way of looking back and critically analyzing the process chosen for this research, and understand the factors that were developed correctly and those which could be improved.

This research started by looking into a new material, to be used out of its intended application. This was in itself a challenge.

The first major constrain regarding this factor was the lack of information on the subject, mainly on material properties.

This factor led to an extended literature review, as much of the initial months were spent looking for possible reference material.

Another factor that delayed the process was the time taken to define the focus of the research. In my point of view this was due to two main reasons; one of them being the lack on references and the other to be the initial intention of the research which was to create a stiff panel of thin glass.

However, with time, this developed into better understanding the material and focusing the research on adaptive façade panels.

After facing the first challenge of the references, the use of FEM simulation software also proved to be very time consuming, for further research in this area I recommend the research on alternatives to this. I could get access to a plugin from ITKE in Stuttgart that could do that more efficiently in a late phase of the research when learning a new software was not feasible.

The general strategy adopted during the research was of facing each part of it by creating multiple alternatives, and then selecting the most interesting to be further explored. This method proved to be challenging but at the same time rewarding, as many different alternatives have to be explored equally to be comparable, but in the end a good overview of the work is achieved.

Although some phases took much time, the schedule presented on the P2 was mostly accurate until the end of the research.

A challenge faced in the end of the research was the development of the mockup. Although this process started late, other factors also created barriers to it. The first one was the unavailability of workshops for

metal working in the Faculty. Although a very good workshop is present in the faculty of Industrial design, it is inaccessible for students from other studies.

This showed that the mock development should be made with more planning as the unpredictability of events delayed its process.

In answer to that I have already planned its development for the final presentation, after meeting professor Bilow he suggested me to join the Buckylab course building weeks to develop the final mockup, as they have plenty of availability of tools.

Also I believe, that a better planning could have allowed me to get access to other software earlier and study more alternatives in this research.

Overall, I believe that this thesis will help to grow the knowledge over this material, by helping to increase the few studies related to it; and to the possibilities of implementing it on the built environment. It may also inspire other students to explore and research about it.

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Figure 6 - Bundesarchiv, Bild 183-1987-0204-305. Available at: https://en.wikipedia.org/wiki/Bauhaus#/media/File:Bundesarchiv_Bild_183-1987-0204-305,_Dessau,_Bauhaus.jpg.

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>.

Figure 9 - Kraaijvanger architects. Available at: <http://www.kraaijvanger.nl/en/projects/73/temple-de-lamour/>.

Figure 10 - WELLER, B. [6] p.12.

Figure 11 - WELLER, B. [6] p.15.

Figure 12 - WURM, M. [8] p.54.

Figure 13 - WELLER, B. [6] p.17.

Figure 14 - WURM, M. [8] p.66.

Figure 15 - O'CALLAGHAN, J. **The Apple Glass Cube: Version 2.0**. Challenging Glass 3. p60. 2012.

Figure 16 - LOUTER, C. et al. **Reinforced Glass Cantilever Beams**. Glass Processing Days. p434. 2005

Figure 18 - SCHOTT. **Ultra-thin Glass**.

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Figure 19 - KUEFFNER, G. **BRUCHFEST UND HART MÜSSEN SCHEIBEN SEIN**. Frankfurter Allgemeine. April 2012. Available at: <http://www.faz.net/aktuell/technik-motor/smartphone-displays-bruchfest-und-hart-muessen-scheiben-sein-11712180.html#aufmacherBildJumpTarget>. Retrieved in 30 December 2015.

Figure 20 - ALBUS, J. ROBANUS, S. [13] p.9.

Figure 21 - AGC. **AGC Succeeds in Rolling SPOOLTM, a 0.05 mm-thick Sheet Glass**. Press release. May, 2014.

Figure 22 - WURM, M. [8] p.54.

Figure 23 - NEG. **Dinorex™ - The Ultimate Glass for Chemical Strengthening**. Available at: http://www.neg.co.jp/glass_en/O2.html Retrieved in 02 January 2016.

Figure 24 - MEM4WIN Technologies explored in **MEM4WIN project**. Available at: <http://mem4win.eu/index.php?id=86> Retrieved in 05 January 2016.

Figure 25 - AGC 2014 **FIFA World Cup Brazil™ Glass Roof for Player Benches Unveiled**. Available at: <http://www.agc-glass.eu/English/Homepage/News/Press-room/Press-Detail-Page/page.aspx/979?pressitemid=3295>. Retrieved in 05 January 2016.

Figure 27 - HUNDEVAD, J. [19] p.335.

Figure 28 - HUNDEVAD, J. **A movable canopy**. International Conference on Building Envelope Design and Technology. Graz. Advanced Building Skins. 2015. p.324.

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Figure 35 - Corner Magazine. Available at: <http://www.cornermag.com/an-insiders-guide-to-antwerp-part-three-what-to-do/>. Retrieved in: 15 March 2016.

Figure 38 (right) - Spacebuster - Raumlaborberlin, photograph by Alan Tansey. Available at: <http://>

raumlabor.net/spacebuster/. Retrieved in: 26 april 2016.

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Appendix

Appendix 01. Abrisa Technologies specialty glass materials products and specifications technical sheet.



Specialty Glass Materials Products & Specifications

11/15

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/cm³
- 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/mm²
 - Strengthened 674 kgf/mm²
- Fracture Toughness 0.7 MPa m^{0.5}
- Coefficient of Expansion 84.5 x 10⁻⁷/°C (0 °C - 300 °C)

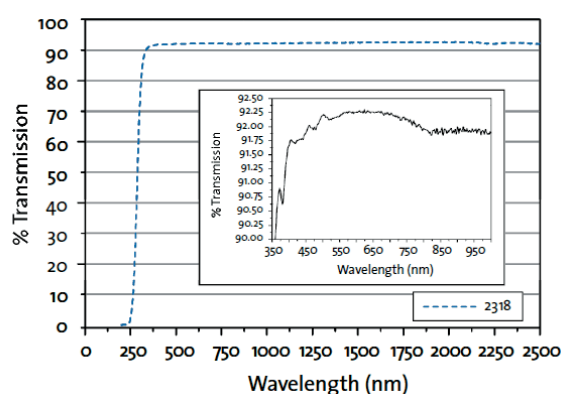
Chemical Strengthening:

- 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/cm2)
HCl - 5%	24 hrs	95	0.04
NH4F:HF - 10%	20 min	20	3.14
HF - 10%	20 min	20	11.96
NaOH - 5%	6 hrs	95	1.10

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

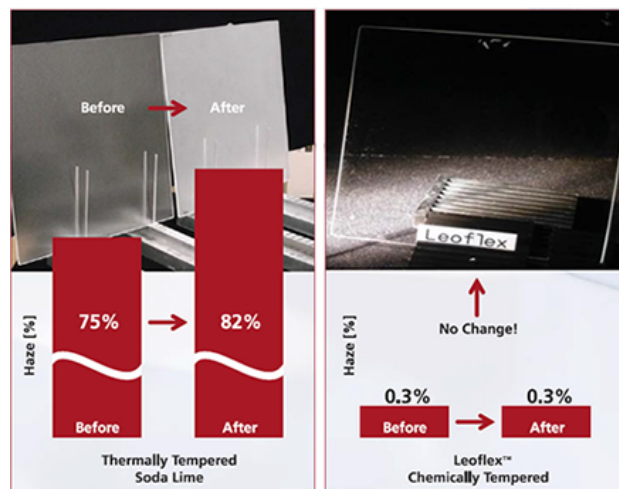
- ✓ 5X tougher than thermally tempered soda lime glass
- ✓ Lightweight
- ✓ Bendable
- ✓ High scratch resistance
- ✓ Outstanding weather resistance
- ✓ High optical clarity
- ✓ High strength compared to soda lime glass

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 ³	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

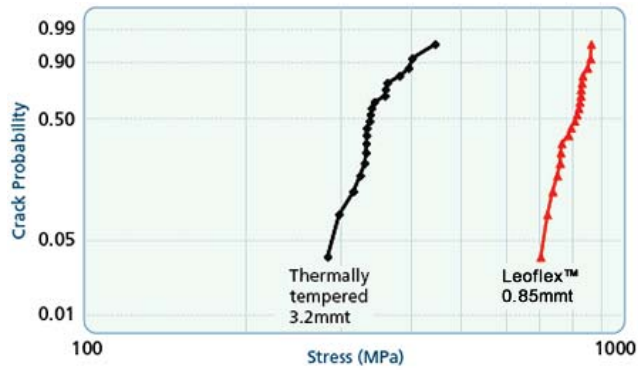
Sizes:

Standard size is 48" x 29".

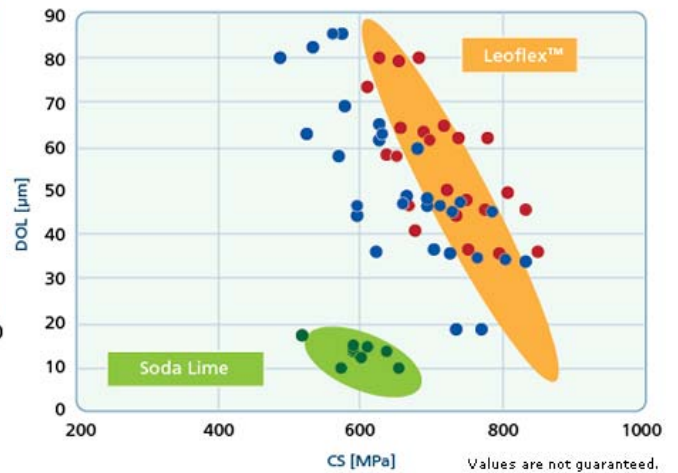
Thermal	CTE	$[10^{-7}](50\sim 200^{\circ}\text{C})$	98	85
	Tg	°C	604	550
	Softening Point	°C	831	733
	Annealing Point	°C	606	554
	Strain Point	°C	556	511
Optical	Refraction Index	Nd	1.51	1.52
	Photoelastic Constant	nm/cm Mpa	28.3	25.6
Electrical	Volume Resistivity	log ($\Omega\cdot\text{cm}$)	8.4	8.5

Custom sizes available.

Toughness Ring-on-Ring Test



Chemical Tempering Performance



Specialty Glass Materials Products & Specifications

11/15

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 λ (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 α (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 ₃ pure	1.516	1.514	1.510
Transmittance τ (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 ϵ'	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 ρ_0 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 ³ *
Young's Modulus E	74 kN/mm ²
Poisson's Ratio	0.215
Shear Modulus	30 kN/mm ²
Knoop Hardness HK _{0.1/20}	
Non-strengthened	534
Strengthened	639
Vickers Hardness HV _{0.2/20}	
Non-strengthened	617
Strengthened	681

*cooled according to DIN

Chemical Strengthening:

Compressive Stress	capable > 900 MPa
Depth of Layer	capable > 50 μm
4-Point Bending Strength	cap. > 800 MPa

Appendix 02. Corning Gorilla Glass for large format applications technical sheet.



Corning® Gorilla® Glass for Large Format Applications

Corning® Gorilla® Glass is Big, Bold, and Beautiful

Corning® Gorilla® Glass is an ideal cover glass for the most innovative large-format displays, including interactive white boards, digital signage, and other large-size public displays. It is elegant, lightweight, and durable enough to resist many real-world events that commonly cause glass damage and failure.

The unique composition of Gorilla Glass allows for a deep layer of high compressive stress created through an ion-exchange process. This compression layer makes the glass exceptionally tough and damage resistant. The composition also helps to prevent the deep chips and scratches that degrade appearance and can cause glass to break.

Additionally, Gorilla Glass is formed using the same proprietary fusion process as all of Corning's high-technology display substrates. This extraordinarily precise, highly-automated process produces glass with exceptionally clean, smooth, flat surfaces and outstanding optical quality.

Gorilla Glass is also remarkably thin and clear, which reduces weight, helps reduce the appearance of parallax, enables more sensitive and accurate touch responses, creates a more precise and professional display, and helps deliver on the promise of high-definition and 3D technologies.

Product Information

Display Screen Diagonal Size

Typical sizes 32 inches to 84 inches

Finished Part Dimensions

Width (max)	2020 mm
Length (max)	1365 mm @ 1 mm thickness 1200 mm @ 2 mm thickness
Thickness (mm)	2.0, 1.5, 1.0, 0.7, 0.55

Viscosity

Softening Point ($10^{7.6}$ poises)	896 °C
Annealing Point ($10^{13.2}$ poises)	627 °C
Strain Point ($10^{14.7}$ poises)	573 °C

Mechanical Properties

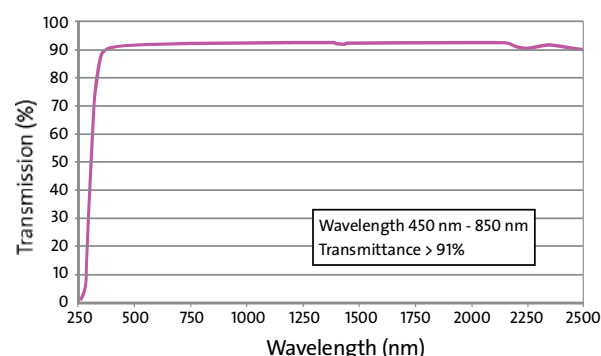
Density	2.39 g/cm ³
Young's Modulus	68.0 GPa
Poisson's Ratio	0.22
Shear Modulus	27.9 GPa
Vickers Hardness (200 g load)	
Un-strengthened	551 kgf/mm ²
Strengthened	654 kgf/mm ²
Fracture Toughness	0.69 MPa m ^{0.5}

Thermal

Coefficient of Expansion (0 °C - 300 °C)	$75.5 \times 10^{-7}/^{\circ}\text{C}$
--	--

Optical

Refractive Index (590 nm)	
Core index (no ion-exchange)	1.50
Compression layer	1.51

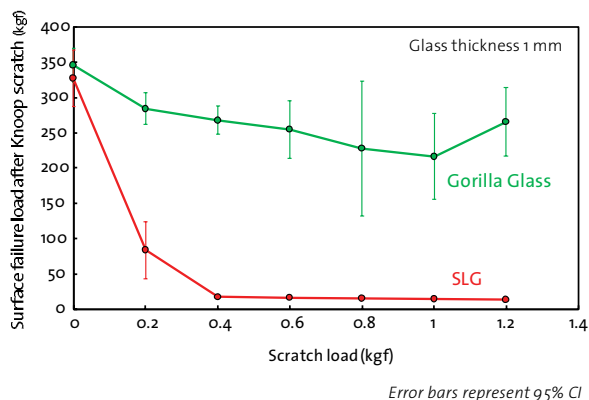


Chemical Strengthening

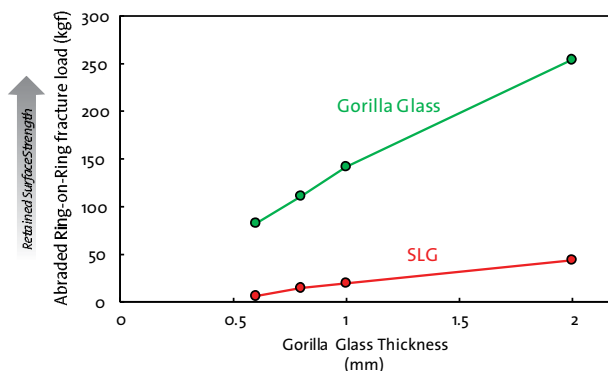
Compressive stress	≥ 650 MPa @ 40 μm DOL
Depth of Layer	≥ 40 μm

Note: Additional surface treatments are available, such as screen printing, optical films, and anti-glare finishes. For more information please contact Corning with your specific requirements.

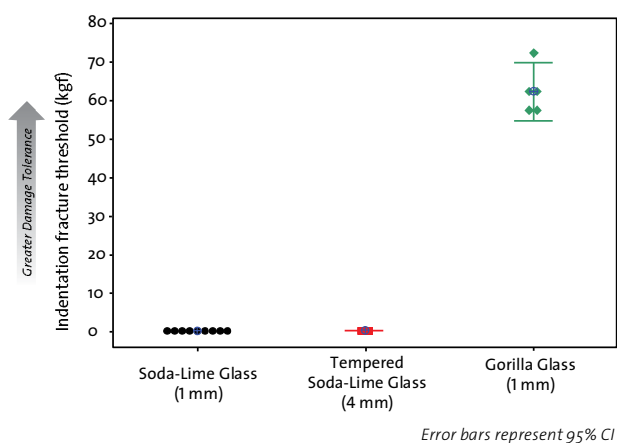
Greater retained strength for Gorilla® Glass after scratch



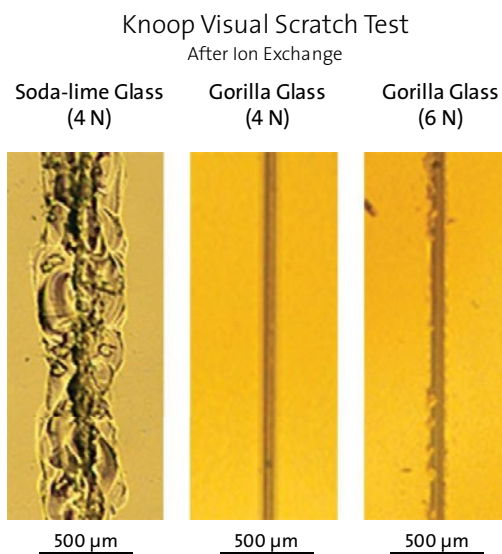
Greater retained strength for Gorilla® Glass enables use of thinner glass



Higher damage resistance for Gorilla® Glass



Scratches are less visible



CORNING

For more information about Corning® Gorilla® Glass:
email: gorillaglass@corning.com
Web: CorningGorillaGlass.com

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September 2015

Appendix 03. Calculated bending stresses

$$\sigma = \frac{E \cdot t}{2 R}$$

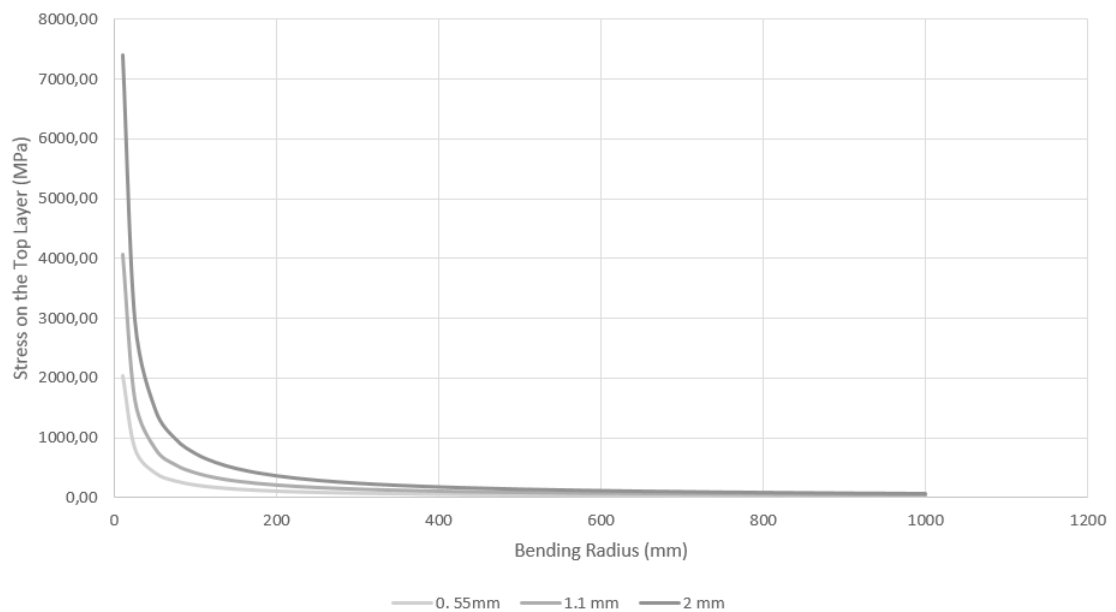
σ = stress on the top surface

E = Young's modulus

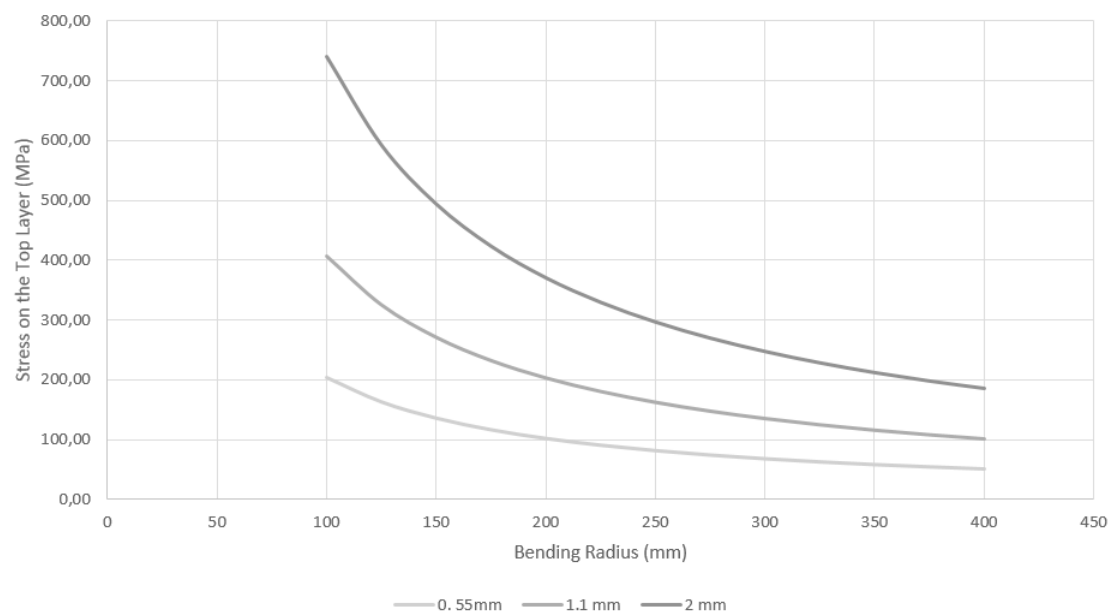
t = thickness

R = Bending radius

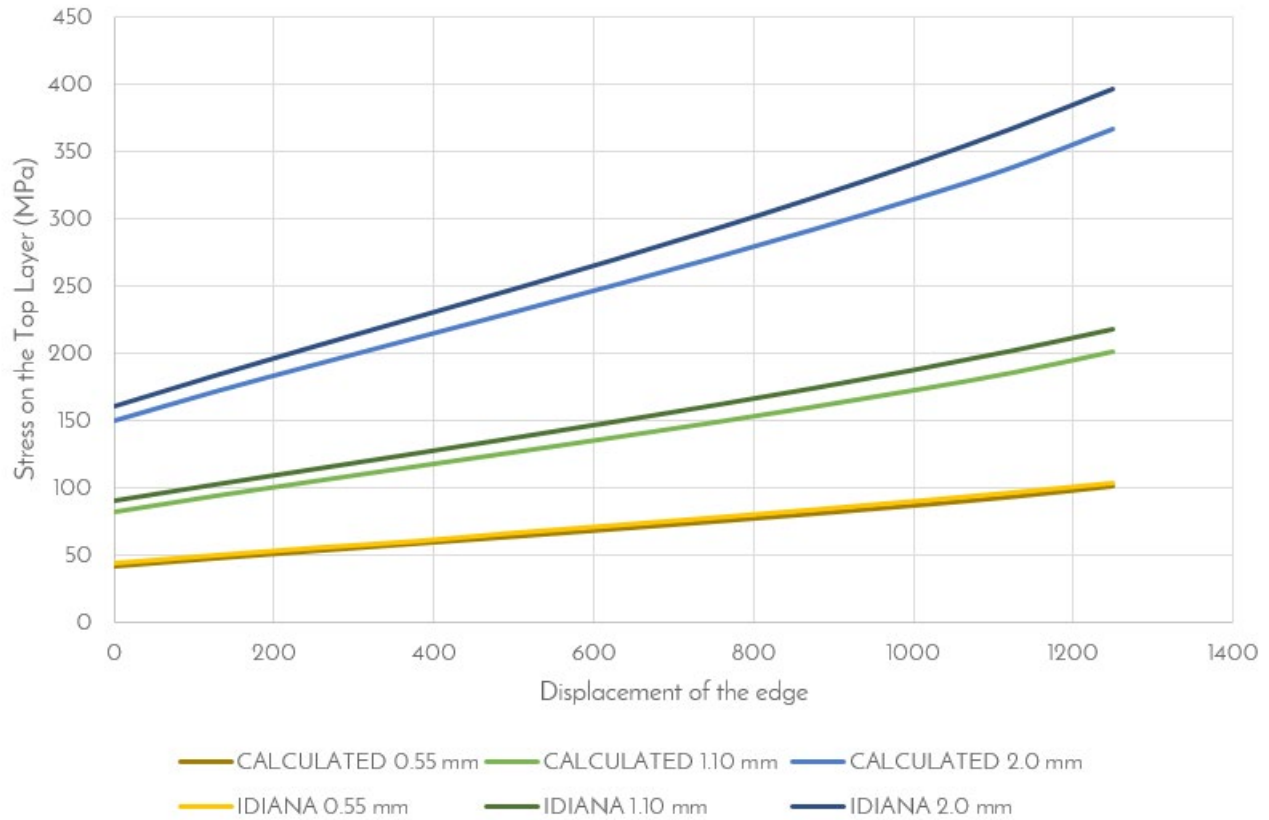
Calculated stress according to bending radius



Calculated stress according to bending radius



Calculated stress X Numerical simulation



DISPLACEMENT (mm)	APPROXIMATE RADIUS (mm)	CALCULATED			IDIANA			DIFFERENCE (%)		
		0.55 mm	1.10 mm	2.0 mm	0.55 mm	1.10 mm	2.0 mm	0.55 mm	1.10 mm	2.0 mm
0	493,42	41,24	82,49	149,97	43,61	90,21	160,49	5,43	8,56	6,55
125	431,93	47,11	94,23	171,32	49,45	102,16	183,10	4,73	7,76	6,43
250	386,75	52,62	105,24	191,34	55,12	113,68	204,83	4,54	7,42	6,59
375	350,79	58,01	116,02	210,95	60,08	125,23	226,17	3,44	7,35	6,73
500	321,02	63,39	126,78	230,51	66,39	136,99	247,47	4,52	7,45	6,85
625	295,64	68,83	137,67	250,31	72,09	148,93	269,21	4,52	7,56	7,02
750	273,44	74,42	148,84	270,62	77,92	161,20	291,78	4,49	7,67	7,25
875	253,63	80,24	160,47	291,77	83,93	174,01	315,32	4,40	7,78	7,47
1000	235,60	86,37	172,75	314,09	90,22	187,56	340,33	4,26	7,90	7,71
1125	218,92	92,95	185,91	338,02	96,89	202,12	367,05	4,06	8,02	7,91
1250	202,00	100,74	201,49	366,34	104,08	218,04	396,19	3,21	7,59	7,53

AVERAGE (%)		
0.55 mm	1.10 mm	2.0 mm
4,33	7,73	7,10
6,38		

Appendix 04. Product Specification

3M™ VHB™ Structural Glazing Tape



3M B23F VHB Structural Glazing Tape Black



3M VHB Structural Glazing Tapes are fully-cured, durable, high performance double-sided pressure sensitive acrylic foam tapes. They are used for attaching glass panels to metal frames in curtain wall systems, commercial windows and doors, skylight and canopy systems replacing commonly used mechanical fasteners, gaskets or structural silicone sealants. Application performance history since 1990 and 3rd party test results demonstrate the outstanding durability, UV resistance and temperature performance of 3M VHB Tape acrylic foam chemistry.

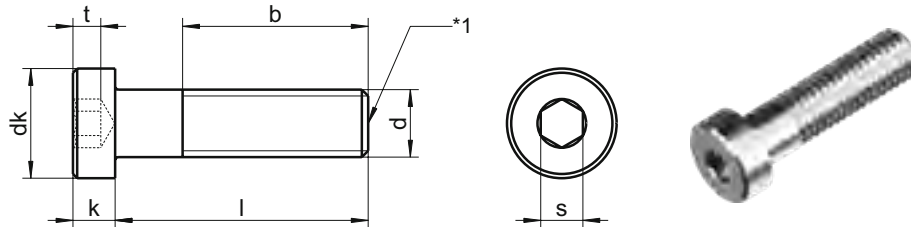
Details

Brand	3M
Size & Packing	15mm x 36 yards 20mm x 36 yards 25mm x 36 yards other sizes available Sold individually
Part Numbers	B23F

DIN 7984

Hexagon socket head cap screws

with low head



dk	5,5	7,0	8,5	10,0	13,0	16,0	18,0	24,0	30,0
k	2,0	2,8	3,5	4,0	5,0	6,0	7,0	9,0	11,0
s	2	2,5	3	4	5	7	8	12	14
t	1,5	2,3	2,7	3,0	3,8	4,5	5,0	5,5	7,5
b	12	14	16	18	22	26	30	38	46
●	2	2,5	3	4	5	7	8	12	14
Length / Ø	M3	M4	M5	M6	M8	M10	M12	M16	M20
5	▲ ●								
6	▲ ●	▲ ●	▲ ●						
8	▲ ●	▲ ●	▲ ●	▲ ●					
10	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●				
12	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●				
14	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●				
16	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●			
20	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●		
25	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	
30	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	
35	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
40	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
45			▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
50			▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
55			▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
60			▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
70			▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
80					▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
90					▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
100					▲ ●	▲ ●	▲ ●	▲ ●	▲ ●
110								▲ ●	▲ ●
120								▲ ●	▲ ●
130								▲ ●	▲ ●
140								▲ ●	▲ ●
150								▲ ●	▲ ●
SU	1000 ≥ 30 500	500	500 ≥ 45 200	500 ≥ 20 200 ≥ 50 100	200 ≥ 40 100 ≥ 50 50	100 ≥ 60 50	50	25	10

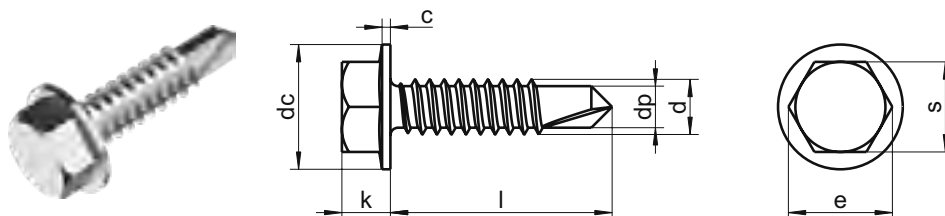
■ A1 / ▲ A2 / ● A4 | SU: Sales unit | All measurements in mm | Other dimensions on request.

Example item no. 7984-2-8X40 DIN 7984 - A2 - M8 - l = 40mm - *1 with flat point acc. to DIN 78

■ Hexagon socket head cap screws with low head and pilot recess can be found as DIN 6912 and with TX as ISO 14580 in this catalogue.

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DIN 7504 K - sim. ISO 15480 Self drilling screws type K hexagon head with flange

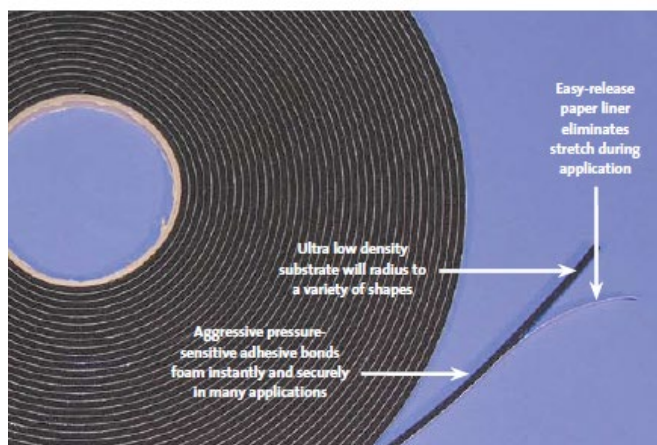


dp	2,8	3,1	3,6	4,1	4,8	5,8
s	5,5	5,5	7	8	8	10
c	0,6	0,6	0,9	0,9	1,0	1,0
k max.	3,45	3,45	4,25	4,45	5,45	6,45
dc max.	8,3	8,3	8,8	10,5	11,0	13,2
e min.	5,96	5,96	7,59	8,71	8,71	10,95
●	5,5	5,5	7	8	8	10
Length / Ø	ST3,5	ST3,9	ST4,2	ST4,8	ST5,5	ST6,3
9,5 (3/8")	▲	▲	▲	▲	▲	
13 (1/2")	▲	▲	▲	▲	▲	
16 (5/8")	▲	▲	▲	▲	▲	
19 (3/4")	▲	▲	▲	▲	▲	▲
22 (7/8")	▲	▲	▲	▲	▲	▲
25 (1")	▲	▲	▲	▲	▲	▲
32 (1 1/4")		▲	▲	▲	▲	▲
35 (1 3/8")		▲	▲	▲	▲	▲
38 (1 1/2")		▲	▲	▲	▲	▲
45 (1 3/4")				▲	▲	▲
50 (2")				▲	▲	▲
60 (2 3/8")					▲	
70 (2 3/4")					▲	
80 (3 1/8")					▲	
90 (3 1/2")					▲	
100 (4")					▲	
110 (4 1/4")					▲	
120 (4 3/4")					▲	
130 (5 1/8")					▲	
SU	1000	1000 ≥ 32 500	1000 ≥ 32 500	500 ≥ 32 200	200	200

■ A1 / ▲ A2 / ● A4 | SU: Sales units | All measurements in mm / inch | Other measurements on request.
Example item no. 7504-2-4,2X38K DIN 7504 - A2 - Ø 4,2mm - l = 38mm - form K

218 Please note that self drilling screws, made of stainless steel are mainly suitable for the processing in aluminium and thin stainless steel sheets.
Self drilling screws, hexagon head with flange DIN 7504 K are available in other dimensions and A4 on request. Self drilling hexagon head screws with flange and EPDM-washers can be found as WS 9165 in this catalogue.

NORSEAL® V310



NORSEAL® V310—Closed-cell polyvinyl foam sealant with pressure-sensitive adhesive on one side.

Features/Benefits:

- Flame retardant closed-cell foam seals out air, light, dust and condensation when compressed 30%.
- Low deflection force causes no distortion of thin-gauge plastics and metals.
- Excellent resistance to weather, fungi and oxidation provides a long sealing life.
- Will not crack under cold temperatures.
- Ultra low density sealant is very conformable, adapts easily to irregular contours and curved surfaces.

NORSEAL® Acrylic Adhesive

The tight bonding adhesive keeps sealant in place during each stage of product assembly. The adhesive is on the non-liner side, keeping slit rolls from falling apart and making installation easier and quicker.

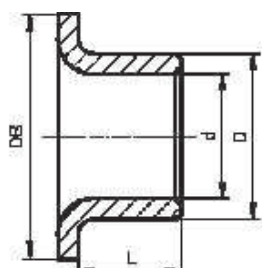
**Please note: NORSEAL® V310 is not recommended as a primary seal in severe exposure.*

Ultra Low Density Foam with Flame Retardency, Suitable for Sealing of Thin-Gauge Metals and Plastics

Typical Applications

- Heating, ventilation and air conditioning system seals
- Telecommunication
- Environmentally controlled rooms
- Refrigeration
- Vending machines
- Lighting
- Electrical outlet switch plates
- Toolbox seals
- Retail weatherstripping
- Appliance seals

SAINT-GOBAIN
PERFORMANCE PLASTICS



PTFE (Teflon® type material) Flange Split Bearings



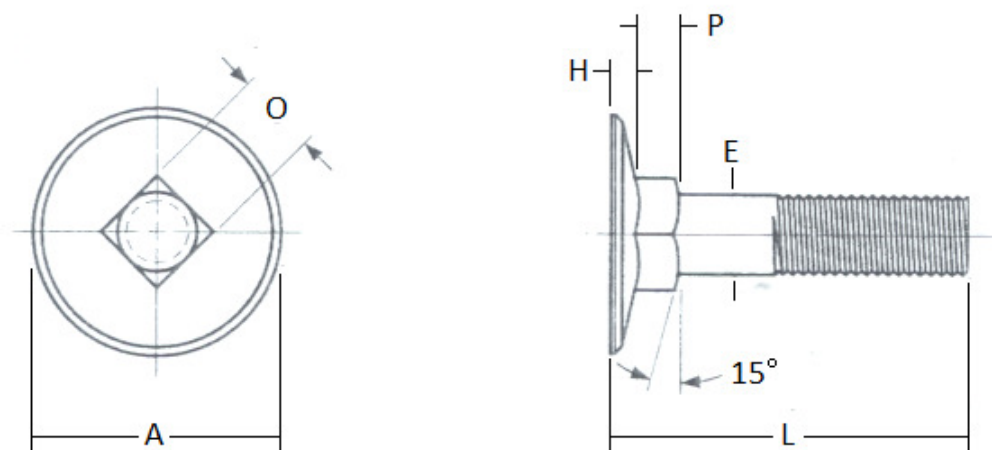
Part No.	d	D	L	DB	Wt. g	Part No.	d	D	L	DB	Wt. g
ST3-4.6x5-7	3	4.6	5.0	7	0.3	ST15-17x17-23	15	17	17.0	23	8.5
ST4-5.6x5-9	4	5.6	5.0	9	0.5	ST16-18x17-24	16	18	17.0	24	9.1
ST5-7x6-10	5	7	6.0	10	0.9	ST18-20x12-26	18	20	12.0	26	6.6
ST6-8x7-12	6	8	7.0	12	1.4	ST20-23x11.5-30	20	23	11.5	30	13.7
ST8-10x5.5-15	8	10	5.5	15	1.9	ST22-25x21.5-33	22	25	21.5	33	21.0
ST8-10x9.5-15	8	10	9.5	15	2.3	ST25-28x26.5-35	25	28	26.5	35	27.3
ST10-12x9-18	10	12	9.0	18	2.9	ST30-34x30-42	30	34	30.0	42	53.3
ST10-12x12-18	10	12	12.0	18	4.0	ST35-39x26-47	35	39	26.0	47	46.0
ST12-14x17-20	12	14	17.0	20	5.6	ST35-39x40-49	35	39	40.0	49	81.4
ST14-16x17-22	14	16	17.0	22	6.2	ST40-44x26-53	40	44	26.0	53	92.0
ST15-17x12-23	15	17	12.0	23	5.0	ST50-55x22-60	50	55	22.0	60	145.8

Part No. = ID - OD x LENGTH - FLANGE OD

Page 1 of 1	Fastenal Product Standard	REV-00
Date: January 15, 2016	FASTENAL	EB.Z

Elevator Bolts, Flat Countersunk Head, Zinc Plated

The information below lists the required dimensional, chemical and physical characteristics of the products in this purchase order. If the order received does not meet these requirements, it may result in a supplier corrective action request, which could jeopardize your status as an approved vendor. Unless otherwise specified, all referenced consensus standards must be adhered to in their entirety.



Nominal Size		E		A			H		O		P	
		Body Diameter		Head Diameter			Head Height		Square Width		Square Depth	
		Max.	Min.	Max. Edge Sharp	Min. Edge Sharp	Min. Edge Flat	Max.	Min.	Max.	Min.	Max.	Min.
#10	0.1900	0.199	0.182	0.790	0.750	0.740	0.082	0.062	0.210	0.185	0.125	0.094
1/4	0.2500	0.260	0.237	1.008	0.969	0.938	0.098	0.078	0.280	0.245	0.219	0.188
5/16	0.3125	0.324	0.298	1.227	1.188	1.157	0.114	0.094	0.342	0.307	0.250	0.219
3/8	0.3750	0.388	0.360	1.352	1.312	1.272	0.145	0.125	0.405	0.368	0.250	0.219
7/16	0.4375	0.452	0.421	1.477	1.438	1.397	0.176	0.156	0.468	0.431	0.281	0.250
1/2	0.5000	0.515	0.483	1.602	1.562	1.522	0.176	0.156	0.530	0.492	0.281	0.250

Specification Requirements:

- Dimensions: ASME B18.5
- Material & Mechanical Property*: ASTM A307A per ASME B18.5
- Thread Requirements: ANSI B1.1, UNC, Class 2A
- Finish: Fe/Zn 3AN per ASTM F1941/F1941M

**90% of tensile load may be accepted, with fracture occurring at the juncture of the head.*

**Note: Fastenal recognizes that the ASTM A307 requirement for these fasteners to be stress relief annealed has been frequently ignored by the industry. This practice is unacceptable and Fastenal requires these products to be produced with full compliance to this standard including stress relief annealing.*