RENS OTTENS

HIGH STRENGTH THIN GLASS *AS* STIFF STRUCTURAL FABRIC

TU Delft

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Master of Science thesis

A feasibility study of tensioning a thin, rectangular, chemically strengthened, flat glass sheet into a forced anticlastic surface with a stretchable composite connection, that remains capable of transferring the applied tensile load.

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DATE

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ABSTRACT

Creating smooth, double curved glass façades from thin glass offers highly curved and complex shaped architecture that is less heavy and still transparent compared to conventionally used hot- or cold bent glass. Although bigger curvatures can be achieved with hot bent glass, it requires non-reusable moulds in the fabrication process, whereas cold bent glass does not. This can lower investment costs. This is especially interesting for high strength thin glass, because high curvatures are easily reached by the elastic (cold) bending technique.

To bend flat glass into a double curved shape, the glass can be twisted, resulting in two curvatures in the opposite direction (anticlastic). The technique that is currently used to twist glass is based on a metastable position which depends on the capability of sustaining compressive forces. The thinner the glass, the earlier compressive stresses cause a buckling phenomenon. The radius of the anticlastic curvature reached with the current technique depends therefore on the thickness of the glass.

Replacing conventional glass by high strength thin glass results in a single bent curvature, instead of an anticlastic curvature. Considering the high amount of prestress, high strength thin glass is capable of transferring high tensile stresses and an alternative twisting technique might be more appropriate, that is based on a high tensile stress capability, instead of a low compressive stress capacity. This research explores the great potentials of high strength thin glass by applying an alternative technique that adds tension to the twisting, which in this research is referred to as 'three-dimensional tensioning technique'.

This study starts by analysing differences in material- and mechanical properties between high strength thin glass and the familiar glass (thicker and less tempered Soda-Lime-Silicate glass) commonly used as a construction material. Currently, the twisting technique that is used appears to be insufficient because of strong membrane behaviour in the high strength thin glass.

Structural performance of high strength thin glass is tested for pure in-plane tensile strength. In this experimental analysis a non-standard test method is used and compared with currently used methods for materials that have ductile or brittle mechanical behaviour.

Several connection methods are illustrated that enable an anticlastic curvature. From a SWOT-analysis it is concluded that the connection needs to be characterized by a discontinuous elastic modulus, or stiffness, along the edge surface, that is able to transfer high tension, yet is strainable to fill the gap-tolerance when creating a hypar (hyperbolic paraboloid) surface.

In this research an optimisation is carried out of a side supported glass element based on an FE-analysis that shows the capability of high strength thin glass used as tensile membrane structure.

PREFACE

This research is written in order to obtain the MSc degree in Architecture, Urbanism and Building Sciences with a specialization track in Building Technology. During the study I have developed my engineering skills, in order to create sustainable architecture accomplished by using innovative building technologies.

Although I am not a structural-, nor a material engineer, I have broadened my knowledge in the field of structural mechanics and material science by researching chemically strengthened thin glass during the research project. With a BSc in Architecture as academic foundation, I had mostly performed design studies until last year.

Before I started with graduating, I fulfilled an internship of almost half a year at Octatube in Delft, The Netherlands. Octatube is a design and build company with an emphasis on advanced applications of glass and steel. During the period I gained knowledge about design, engineering, transportation and installation of building structures, components, materials and details.

At the end of the internship I got familiar with the cold bending technique of glass. Additionally, the Glass & Transparency Research Group at the TU Delft focuses on the development of innovative glass solutions for the Built Environment. Therefore I recognised added value in combining science with practical experience and decided to start a graduation internship. With this first, extensive and individual research project of an unused building material, I have contributed in the development of innovative building concepts, components and/or knowledge for building science and Octatube.

In this graduation project, I tried to think as an architect and perform research as an engineer. The aspects that come along with the technology to double curve thin glass for a building implementation made me rack my brain. Balancing between the disciplines Architecture and Engineering is extremely interesting, in which I gained experience. After this research project, I can say that I am just at the beginning of understanding building technology. It is a mix of solving problems in many fields of science. In this case, developing a useful architectural product from a thin, flat glass sheet material.

The research described in this thesis is interesting for anyone who likes to develop new building products within the glass façade industry. A new type of structural glass application is created, which is based on lightweight tensile fabric structures. High strength thin glass applied as a fabric is challenging, but allows us to make transparent, curved, tent-like structures.

During this research I have been helped by many people, whom made small or large contributions to accomplish my graduation project. First of all, I would like to thank my mentors Marcel Bilow and Fred Veer, who helped me get back on my feet. From the moment they took over the guiding process, I started to have fun again with the project. I would like to thank Christian Louter for letting me doing the tests in the lab and the people who technically made this happen: Kees Baardolf and Paul Vermeulen. I would like to thank Peter Eigenraam for his support with the numerical simulations. The last person from the TU Delft, whom I would like to thank is Ad Straub from the graduation committee for taking the time to read my thesis and listen to my presentations.

I would like to thank everybody who I have worked with or gave me a great time during the months I spent at Octatube. I would especially like to thank my external mentor, Marcel Haasnoot, for his guidance, faith in me, and positiveness he gave during the process.

In my personal environment, I would like to thank my family, friends and roommates who have contributed for proof-reading, commenting, but above all the mental support they gave during the research. Furthermore, every contact I made in Delft during the years in university have been very valuable to me and contributed to the person who I have become. Last, but not least, I would like to thank my parents, who gave me unconditional mental and financial support and created the possibility for me to study. They always have faith in me and gave the opportunity to develop myself.

Rens Ottens, TU Delft, January 2018

00

INTRODUCTION
OF HIGH STRENGTH THIN GLASS.

What makes this material so exceptional? What possibilities are interesting to discover?

01. Current application high strength thin glass

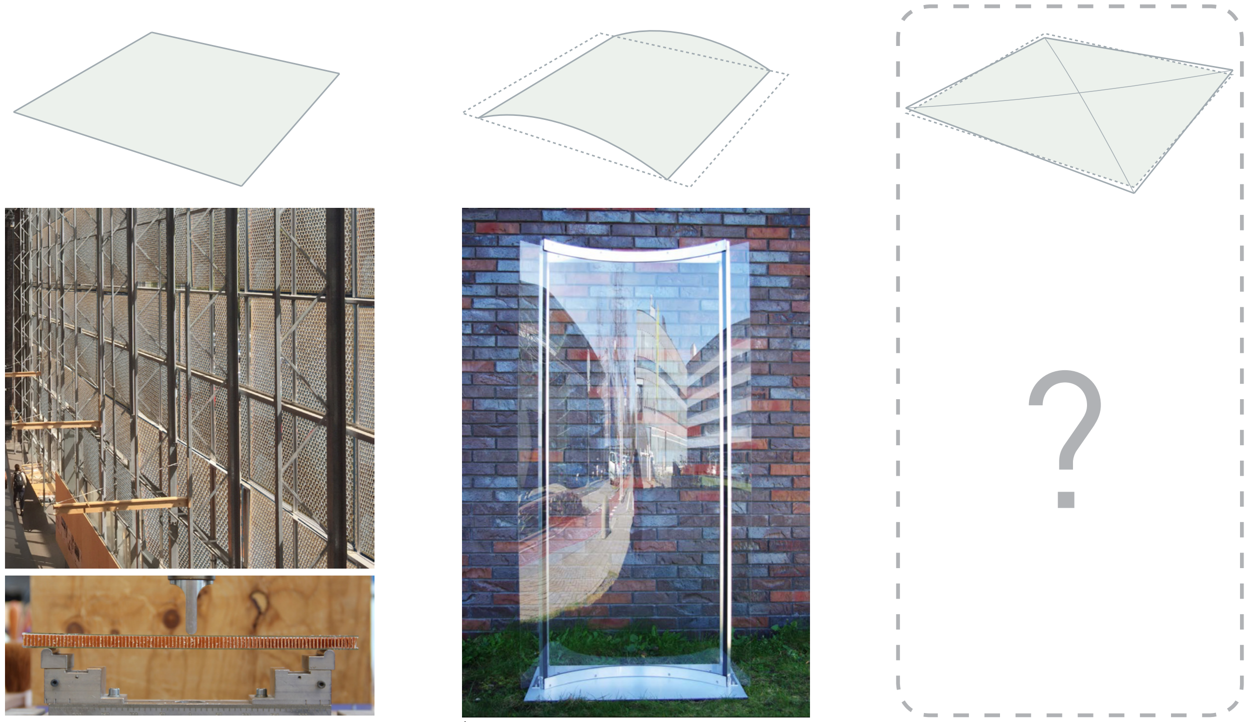
a. Smartphone
b. Tablet
c. Flexible phone

High strength thin glass

High strength thin glass is a material that has gained a lot of popularity in consumer electronics. Devices such as smart phones and tablets becoming thinner, more lightweight and sometimes even curved or flexible. The intensive use of these electronic devices ask for high strength, scratch resistance and a durable screen. Glass manufacturers such as Corning and AGC therefore brought thin glass that has been chemically strengthened to the market. Gorilla Glass and Leoflex are examples of glass products with low thickness and high strength (Corning, 2017; AGC, 2017). Manufacturers show animations of thin glass that can bend almost 180 degrees.

Possibilities

The fact that high strength thin glass is lightweight and flexible makes it in addition for the consumer electronic market, also an interesting product for the architectural market, because it can possibly be used in lightweight and/or curved façades. Several students from the TU Delft used these exceptional mechanical properties of chemically strengthened thin glass and implemented it into architectural products that contain enough stiffness for a



a b c

02. Potential applications architectural market

a. HST glass sandwich construction by I. Van Der Weijde

b. Single bent HST glass by C. Simoen

c. Double bent HST glass, Knowlegde gap

façade application. Van Der Weijde (2017) saw the potential of using the high strength of the glass and researched a sandwich construction creating a lightweight façade. The substrate is made of a honeycomb material. Simoen (2016) noticed the easiness to cold bend the thin sheet into a single curved surface to increase stiffness and creating a curved facade.

Research gap

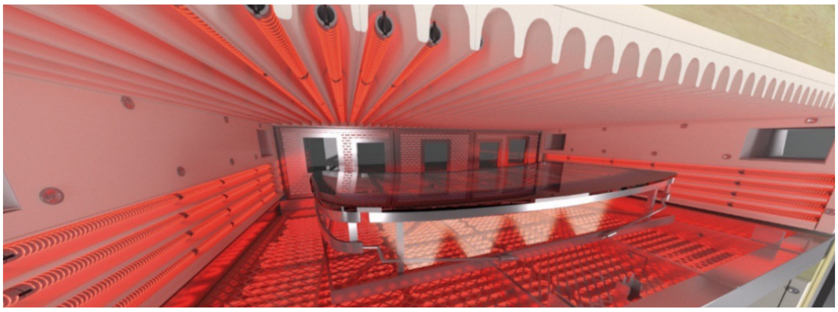
To create geometrically complex façades, by using cold bent technology, flat glass can cold bent into single curved surfaces, but perhaps also into double curved surfaces. However, this type of application has not been researched yet with high strength thin glass. Because of this knowledge gap, this research project dives into the feasibility of double curved cold bent high strength thin glass.

01

RESEARCH DEFINITION
OF A FEASIBILITY STUDY

OF COLD BENDING A FLAT SHEET OF HIGH STRENGTH THIN GLASS INTO AN ANTICLASTIC CURVED SURFACE BY INDUCING TWISTING OF THE GLASS THROUGH TENSION.

What is lacking in the current state-of-the-art? What value adds the proposed technology to the building science?



a

b

03. Hot bent glass

a. Bending via mould and temperature

b. Dome structure

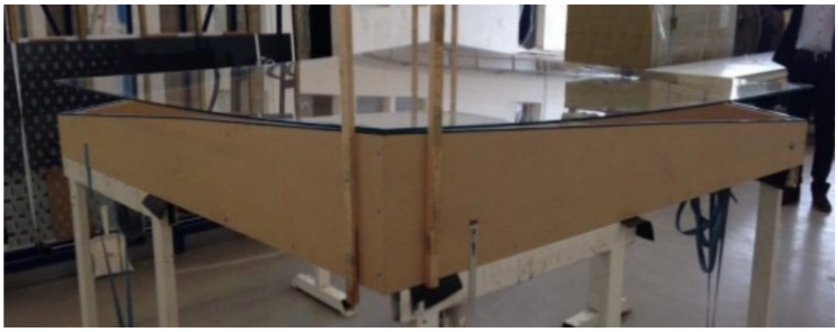
1.1 STATE-OF-THE-ART

Conventional curved glass façades are made of hot bent glass or cold bent glass.

Hot bent glass uses a mould and an oven to deform the glass, either into a single or a double curvature (fig. 3a). A double curved shape can be both in the same direction, creating a dome structure (fig. 3b), as well as a double curvature that consists out of two curvatures in the opposite direction, which is called an anticlastic or hypar surface.

Cold bent glass uses only load to deform the glass, either into a single or a double curvature. The double curvature can only consists out of two curvatures in the opposite direction, (Neugebauer, 2013). To create this shape, a certain cold twist technique is applied (fig. 4).

A cold twisted glass pane in thicker Soda Lime Silicate (SLS) glass is limited to a certain double curvature that can be related to a buckling or wrinkling mechanism and therefore is dependent on the thickness of the glass plate. The concept of this technique is that the forces creates a counter wised bending moment along the edges that create an anticlastic surface which is a double


a


b

04. Cold bent glass

a. Flat glass
b. Bending via mould and load (hypar surface)

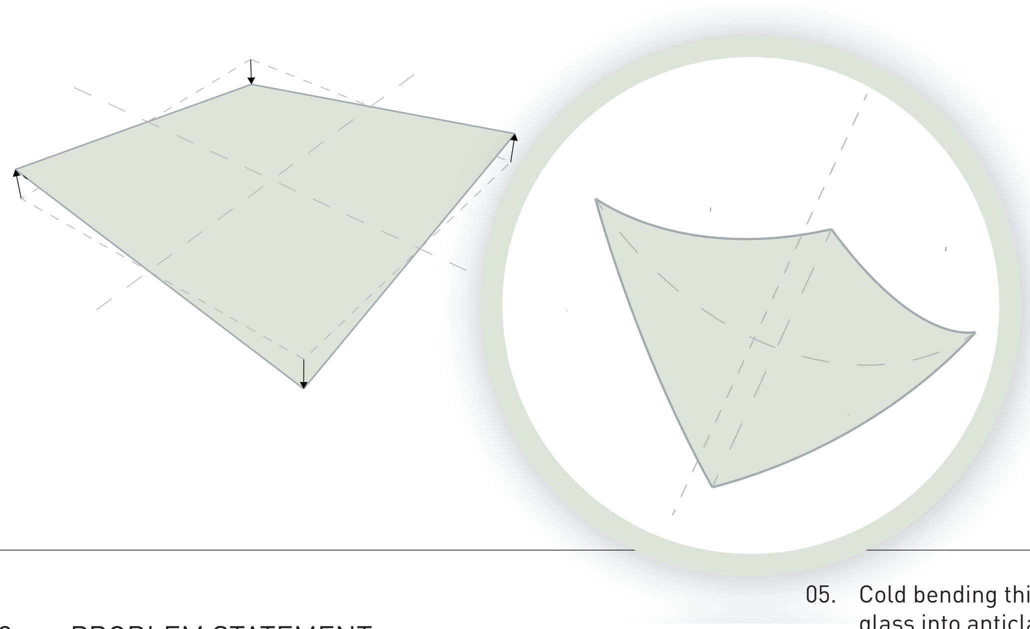
curvature in the opposite direction (Staaks, 2003).

A thicker pane needs a higher externally applied load to deform it to an anticlastic surface. Configuring such panels into a structure and a heavy dimensioned construction is necessary to hold it in the desired shape.

Double bending thin glass into an anticlastic shape by using the current cold twisting technique, would suggest that this is impossible. The concept of this technique is that the forces create a counter wised bending moment along the edges that create an anticlastic surface which is a double curvature in the opposite direction (Galuppi, 2014)).

However, thin glass can be bent very easily. Single bending can create a mechanism that provides more panel stiffness, which it would not have in a flat form (Weber, 2009). Twisted glass, provide even more stiffness, because of having one curvature in each direction.

Research into a more appropriate technology to double curve thin glass might result into transparent building envelopes, that are complex shaped, but less heavy and easier compared to current cold bent glass façades.



05. Cold bending thin glass into anticlastic shape

Buckling phenomena

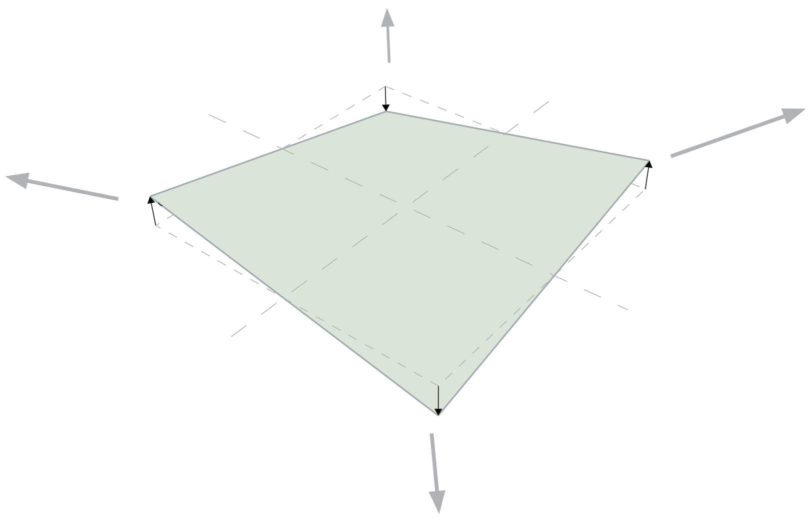
1.2 PROBLEM STATEMENT

"Applying the cold twisting technique to a thin, flat glass plate results in a single curved shape instead of a double bent shape, because of a lack to sustain compressive stresses." (fig. 5)

By decreasing the thickness of glass, the structural behaviour acts differently than conventional thicker glass. Cold twisting glass is based on the assumption that glass deforms according to the first order plate theory. However, this assumption is no longer valid because the glass deforms non-linearly as a membrane (Spitzhuttl, 2014). According to the membrane theory, no bending moments can be transferred, but can solely sustain in-plane tension.

1.3 RESEARCH QUESTION

Failure occurs in tension first, but respecting the structural behaviour of thin glass in combination with the high strength of the chemical strengthening, tension is the only way to create a hyperbolic paraboloid surface. Therefore the hypothesis is that a cold bent double anticlastic curved surface still can be made by adding tension to the twisting (fig. 6). According to this assumption the following research question is formulated:



06. Adding tension to the twisting

Because of high tensile strength

"To what extent is it possible to curve a flat sheet of thin glass into a double anticlastic bent surface by adding tension to the currently used cold twisting technique?"

The three-dimensional (3D) tensioning technique that is identified in this research to create double anticlastic, cold curved, high strength thin glass, asks for research to validate the in-plane tensile strength. Research is also required on the needed tension force to change the glass from a flat to an anticlastic shape and on the capability of glass of being forced into an anticlastic surface by tension. Last, but not least, it also asks for a connection that enables the creation of this anticlastic surface.

1.4 SCOPE

The threat that comes along with tensioning a material is creep. Creep is a time-dependent deformation that accumulates as a result of long-term stress. A mechanical failure mode that is not considered in this research, but is critical for glass. This is an extensive research topic and a research on its own.

Safety is another important aspect that is relevant when implementing this glass into a building structure and sudden failure occurs. This research will purely include the technique that enables the anticlastic geometry. An outlook of some conceptual applications with proposed safety considerations will be shown,

but no detailed or validated safe glass structure.
To summarize, the scope of this research is to deliver a proof-of-concept of cold bending thin glass into a double anticlastic curvature. The connection is not fully technically validated, but gives enough clarity on the concept.

1.5 OBJECTIVE

Three dimensionally tensioning high strength flat thin glass to an anticlastic surface adds value to building science by:

- Giving insight into the potential of the researched glass in tensile structures, more than in compressive structures.

- Showing its true tensile strength.

- Showing an unexplored (in-plane) tensioning and stiffening method for thin glass, instead of adding (global) out-of-plane stiffness to the glass.

- Proposing a more powerful technique to create extremely curved and geometrically complex shaped glass structures.

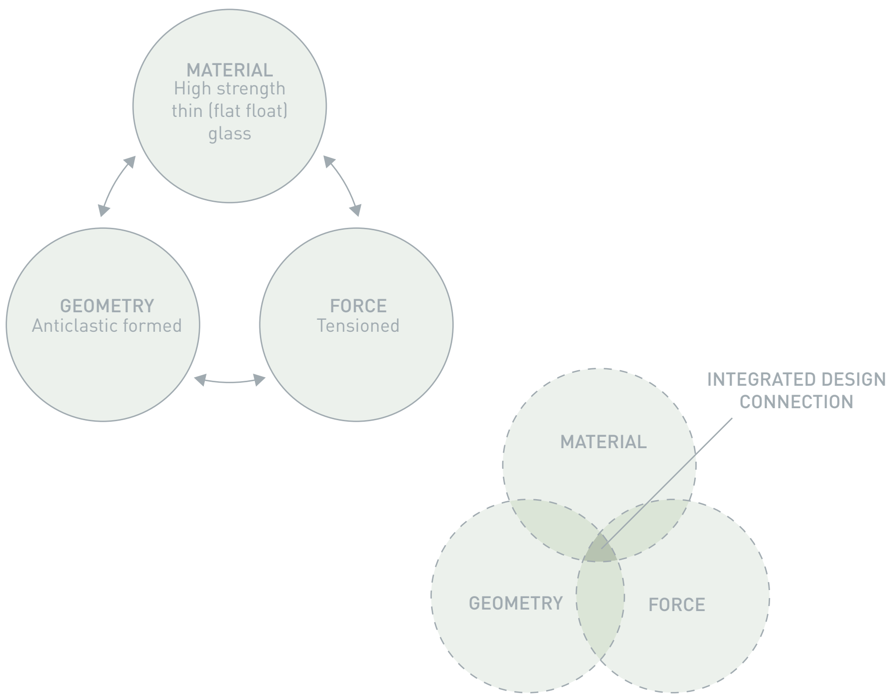
- Showing several connection methods that can or cannot enable an anticlastic shape.

1.6 RELEVANCE

The proposed 3D-tensioning technique to curve high strength thin glass into an anticlastic shape bring:

- A lightweight alternative to the familiar anticlastic structures.
- A lightweight alternative to the familiar curved or any other heavy soda lime silicate glass constructions.
- A tensile glass structure that has never been seen in Architecture.

Possibilities arisen by accomplishing a tent structure made of glass fabrics can lead to spectacular designs, fully pre-fabricated, with lightweight foundation, short construction time on-site, which are easy to assemble and as well to disassemble and bringing possibilities for mobile applications.



07. Basic Appoach of the Research

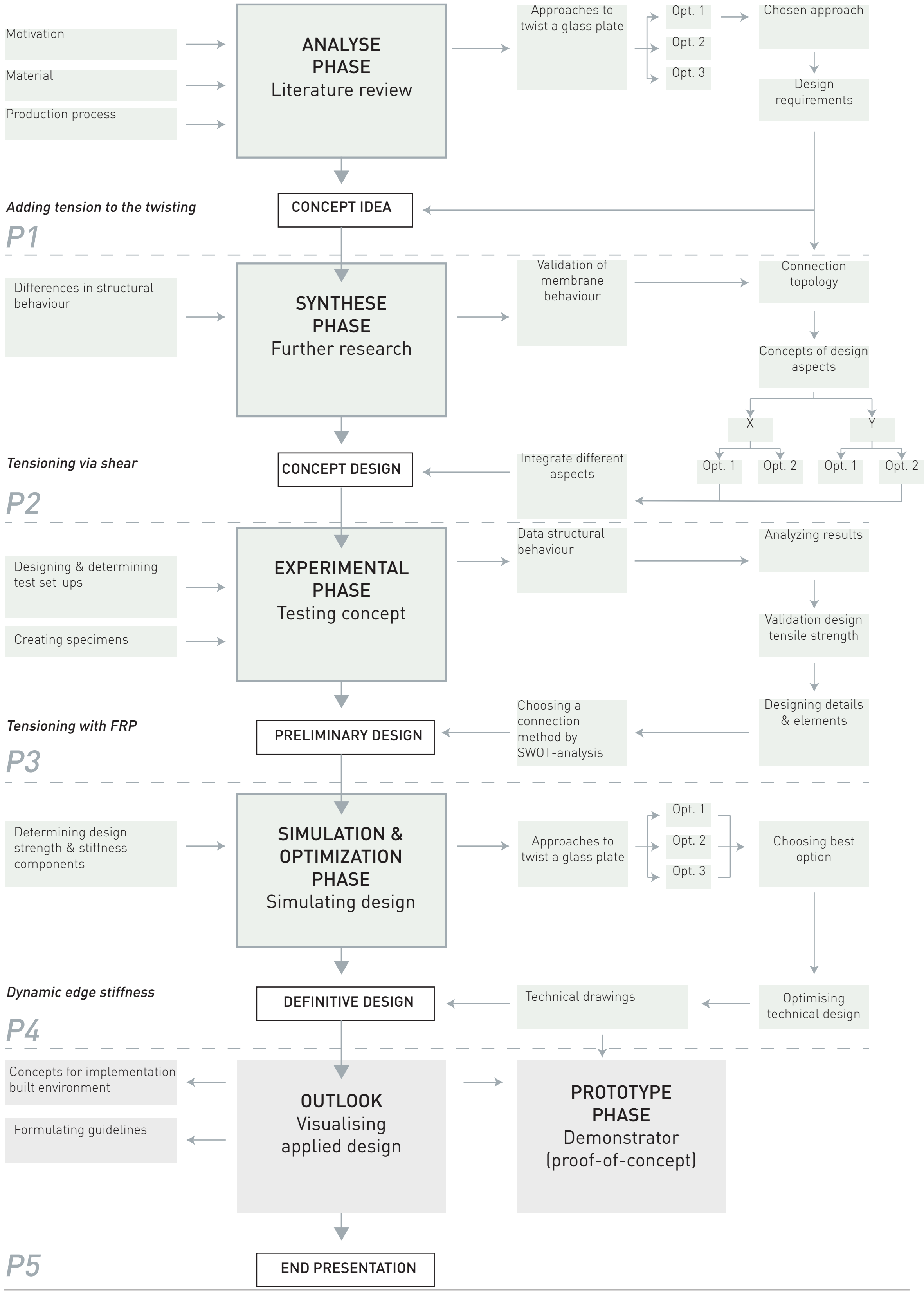
a. Three scientifical subjects

b. structural design concept

1.7 APPROACH & METHODOLOGY

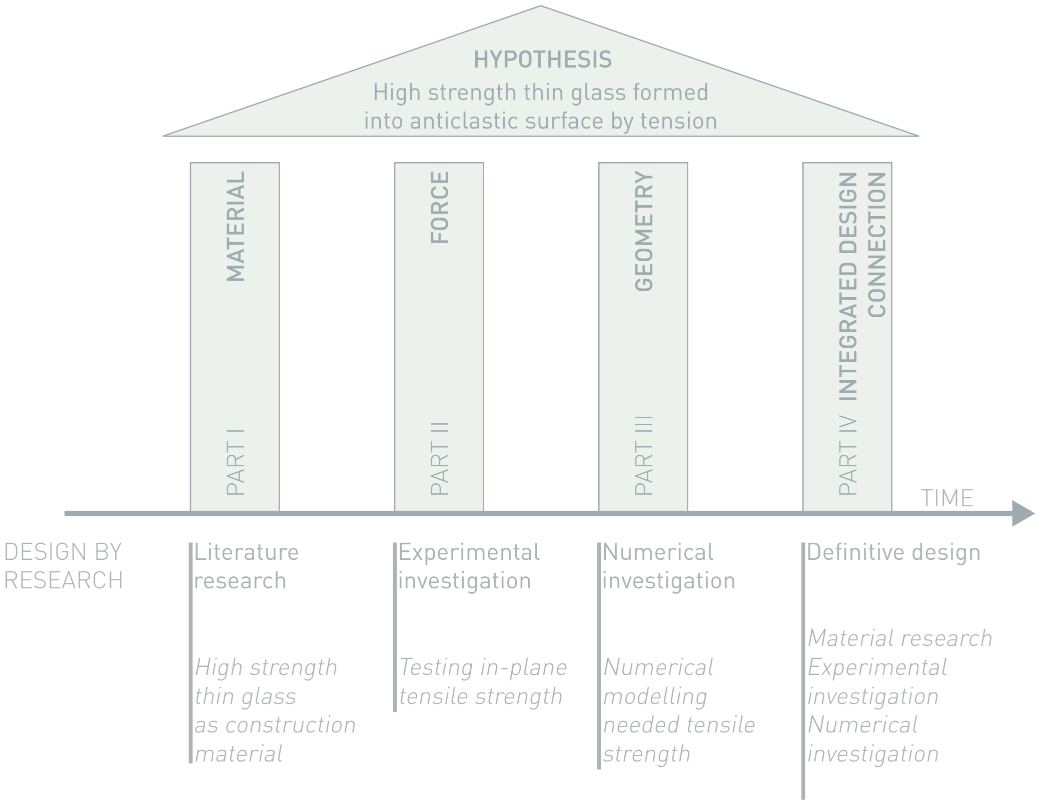
In the MSc in Building Technology, the scientific contribution lies in the application of a technique. In this research the aim to give a potential structural design concept for architectural thin glass is most important. The concept in this case is a cold, double bent thin glass plate.

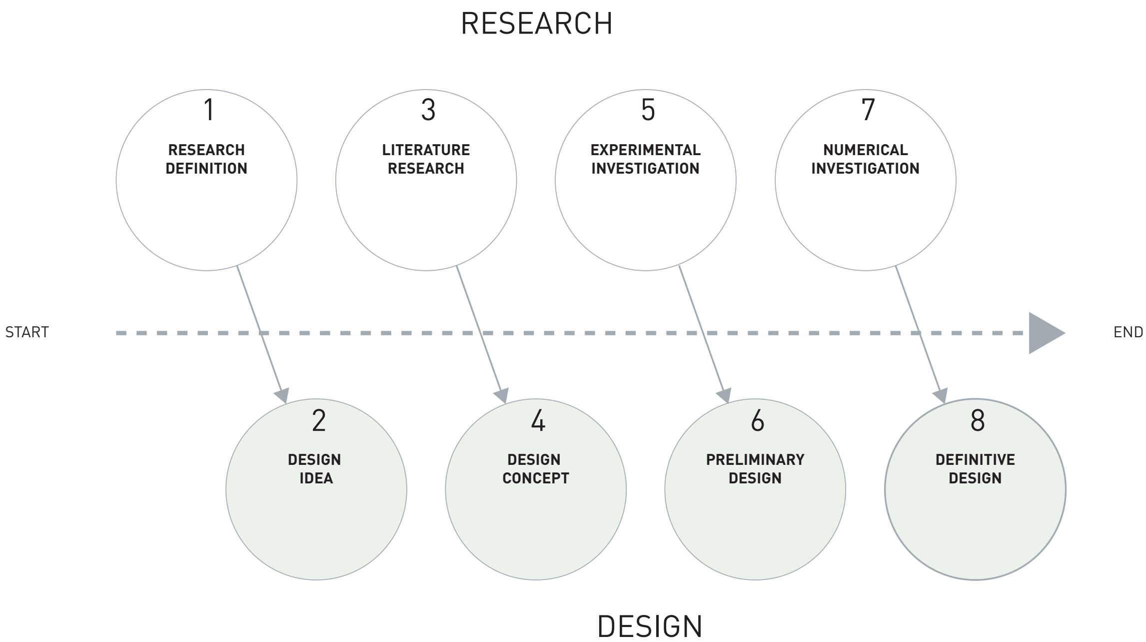
To answer the research question three interdisciplinary subjects need to be clarified in order to develop a structural design. All three are important and related to each other (fig. 7a). Together they form the knowledge package which enables the design (fig. 7b). This design-by-research approach eventually gives sufficient information to validate the hypothesis (fig. 8 & 9).



08. Detailed Approach of the Research

Design by Research





09. Methodology of the Research

a. Hypothesis stands on four pillars

b. Design followed by research in steps

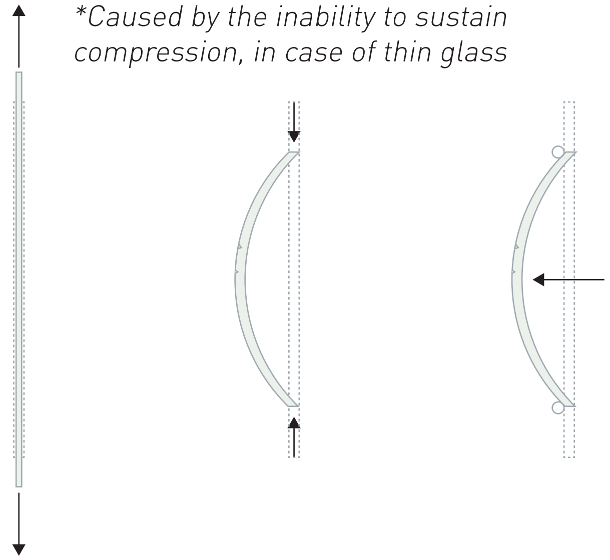
02

DESIGN IDEA
OF APPLYING HIGH STRENGTH THIN GLASS IN A TENSILE STRUCTURE.

What kind of structures can be made?

Brittle materials fail because of tensile stresses*.

**Caused by the inability to sustain compression, in case of thin glass*



10. Deformations that create (bending) tensile stresses

a. elongation

b. buckling

c. bending

A well-known statement in the field of material research is that brittle materials fail because of tensile stresses. Internal stresses caused by a deformation from:

1. a tension force parallel to the normal plane that create an elongation of the material (pure tensile stress)

2. a compression force parallel to the normal plane that create buckling (bending tensile stress)

3. or a force perpendicular to the normal plane that create bending (bending tensile stress)

Current glass structures are built on the idea that glass resist compression better than tension. Large deformations created by an external applied load, causes elongation, buckling or bending of the material and therefore tensile stresses that contribute to the growth of cracks (fig. 10). Compression closes the crack, neglecting the effects of the Poisson ratio (Anongba, 2018), and will therefor have a small contribution to any crack growth, hence the strength of the material.

Glass has a compressive strength of 1000 MPa (Saint-Gobain, 2018). A column will mainly loaded by compression, and if it

11. Four point structure design by Frei Otto
Kassel, 1955

is thick enough can built out of glass. Structural integrity, and buckling, of a glass column are critical factors that need to take care of (Oikonomopoulou, 2018).

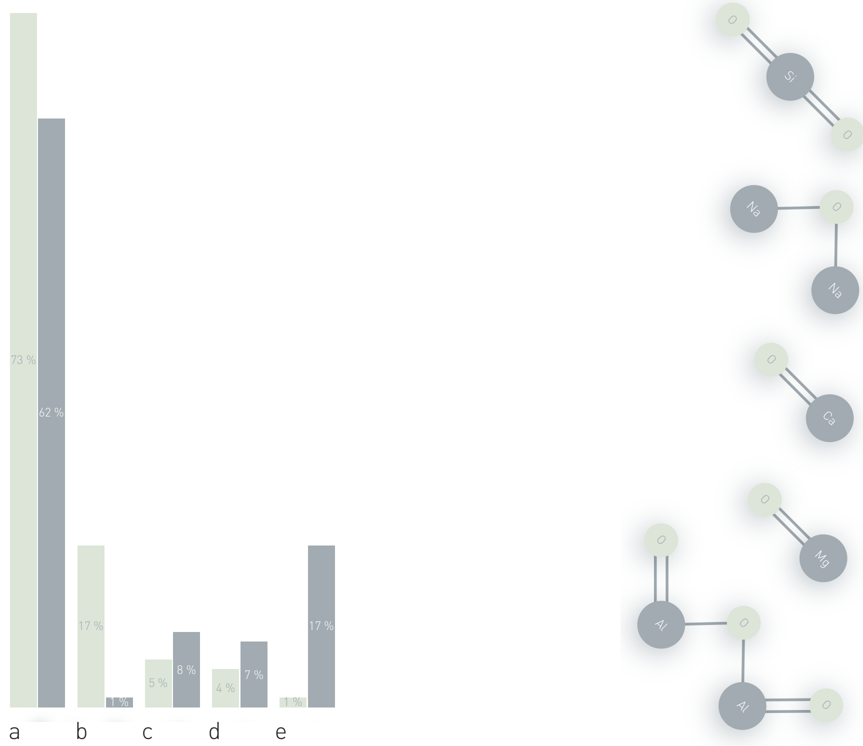
Thin glass will failure in compression dominated structures, because of lack of enough thickness. With the strengthening method of thin glass by an ion-exchange the surface layers have an increased compressive zone. This prestressing results in a tensile strength also up to 1000 MPa according to manufacturers. Assuming these highly increased strength of the surface layers for thin flat shaped glass, it would almost suggest to apply thin glass into tensile -, instead of compressive (form-active) structures (Nikolaou, 2015; Bagger, 2010).

Imagining the possibilities of tensile membrane glass structures. Easily deformable high strength thin glass sheets can be used as an alternative material for conventional textile or plastic fabric structures we use to know from Frei Otto (fig. 11). Only know we do not have a stretchable material, but a very stiff one instead. Extreme double curved anticlastic shaped architecture can be made from glass with the concept of using high strength thin glass as a stiff structural fabric. However, cold twisting flat glass into an anticlastic surface by tension brings lots of challenges with it to enable such a shape.

03

LITERATURE RESEARCH
OF HIGH STRENGTH THIN GLASS
AS A CONSTRUCTION MATERIAL.

Why does it called thin glass and why has it high strength? How can high strength thin glass being applied as a construction material?



12. **Chemical composition of glass**

Differences between SLS and AS glass in %
a. Silicon dioxide (Silica Sand)
b. Sodium oxide (Soda)
c. Calcium oxide (Lime)
d. Magnesium oxide (Magnesia)
e. Aluminium oxide (Alumina)

3.1 PROPERTIES

Composition

Glass is composed out of raw materials such as sand, potash, or rather soda, and lime (fig. 12). A transparent and fragile building material that reacts immediately and is sensitive to improper treatment, but when used carefully, it possesses inestimable advantages (Weller, 2009).

When glass as building material is used, it is predominantly soda-lime silicate (SLS) glass. A mass-produced glass that consist of approximately 70% silicon dioxide, i.e. quartz sand determines the basic structure of the glass. Because quartz sand has a very high melting point of 1700 C, Sodium and Alkali fluxes are mixed to lower this and added to improve the hardness and chemical resistance of the glass (Weller, 2009).

For thin glass mostly a different type of mixture is used with a higher amount of Alumina and Boric acid and less Sodium and Silica. Yet some Sodium is needed for the later ion-exchange. Because of the higher fraction of Alumina it is called Aluminosilicate (AS) glass (Simoen, 2016).

Property	Symbol	SLS* Value	AS** Value	Unit
Density	ρ	2500	2480	kg/m^3
Modulus of Elasticity	E	70000	76700	N/mm^2
Poisson's ratio	ν	0.23	0.21	-
Shear Modulus	G	29300		N/mm^2
Average coefficient of thermal expansion	α	9	4.6	$10^{-6} K^{-1}$
Average refractive index in the visible spectrum	η	1.52	1.51	-

13. Physical properties of glass

*Soda Lime Silicate

**Aluminosilicate

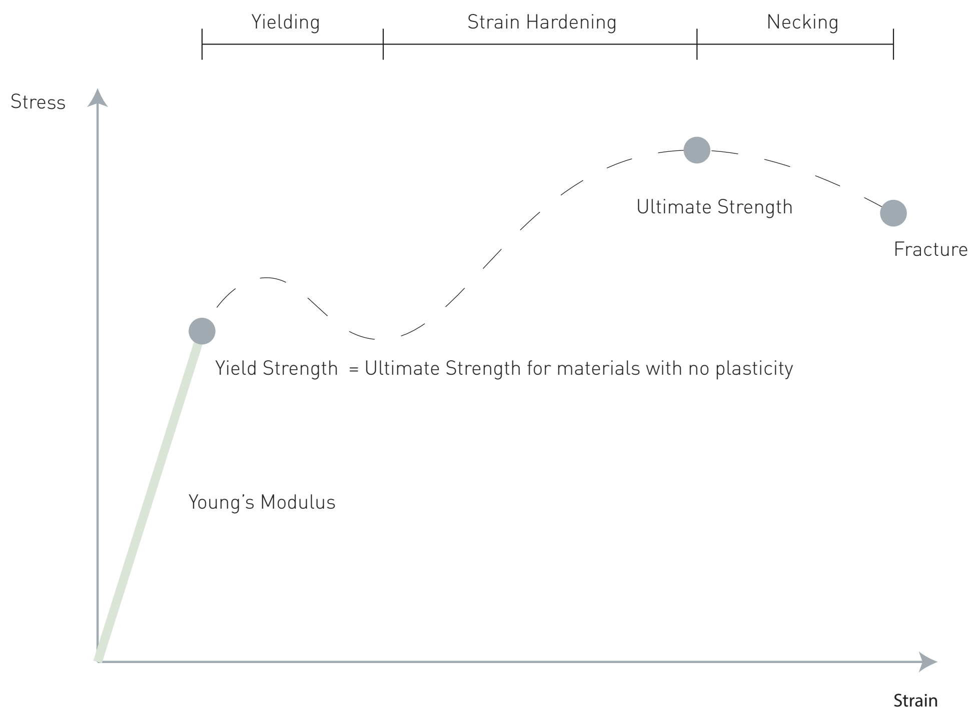
Characteristics

Glass can be best characterised by high transparency and fragility. Because of the high transparency it is a beloved building material, yet needs to be treated real carefully because of its fragility. It transparency is due to atomic structure that is incapable of absorbing the light, which results that light can pass through unhindered (Weller, 2009).

Mechanical behaviour

The brittleness of the material lead to immediate breakage and can be explained by a high amount of silicate in the material composition, which is the reason the material is called fragile. On the contrary it is silicate that gives glass its strength and hardness. These properties exhibit corrosion and chemical resistance, which gives silicate glasses the capability of being a long-term durability building material. Because of the hardness a redistribution of stresses by plastic deformation cannot occur without breakage, and therefore has a low capability of transferring loads via tension. The tensile strength of the glass mixture can be assumed to be a fraction of the theoretically 6500 to 8000 N/mm2. In contrast to this, the compression strength is very high and lies between 400 and 900 N/mm2 (Weller, 2009).

AS glass possesses almost the same physical properties as SLS glass (fig. 13).This means that both glasses also have the same mechanical behaviour. Thin glass often called flexible, because it can heavily bent, but both glasses possesses the same material stiffness, that is called Young's Modulus or modulus of elasticity. This is a relationship between the stress sigma caused by external loading F to a cross sectional area A and the strain (fig. 14).



14. Mechanical behaviour brittle material

According Hooke's Law (dotted line is for ductile material)

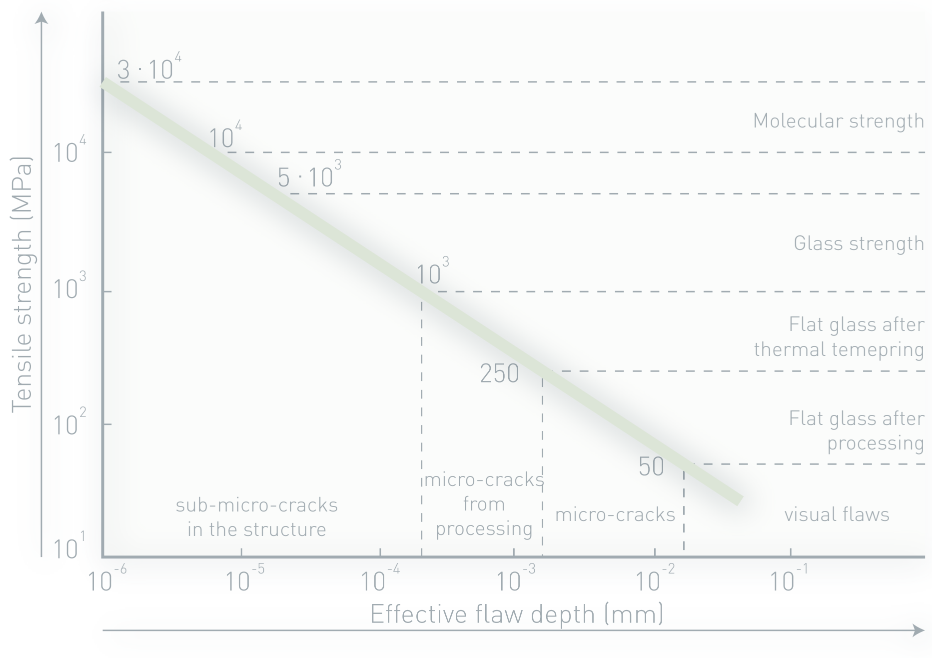
The thinner the material, the less bending stiffness it possesses, which mean transverse load to the surface will be transferred as in-plane stresses instead of out of plane stresses. Because of the deflection it is able to transfer transverse load. Bending glass so heavily makes it interesting to study how the strength is related to the thickness and therefore its structural behaviour. A higher deformation suggest lower internal stress development and/or higher yield strength.

Surface flaws

Just like any other brittle material, the tension strength depends on flaws on the surface and becomes a critical factor in the load-carrying capacity of the glass. Surface flaws, notches and cracks are most of the time hardly able to see to the naked eye (Zijlstra, 1968).

The larger the amount of surface flaws, the lower the strength of the glass. Also the depth of a flaw, decreases the tensile strength (fig. 15).

Higher strength by better surface quality of the glass can be obtained by different production techniques and strengthening methods, discussed in the following paragraphs.



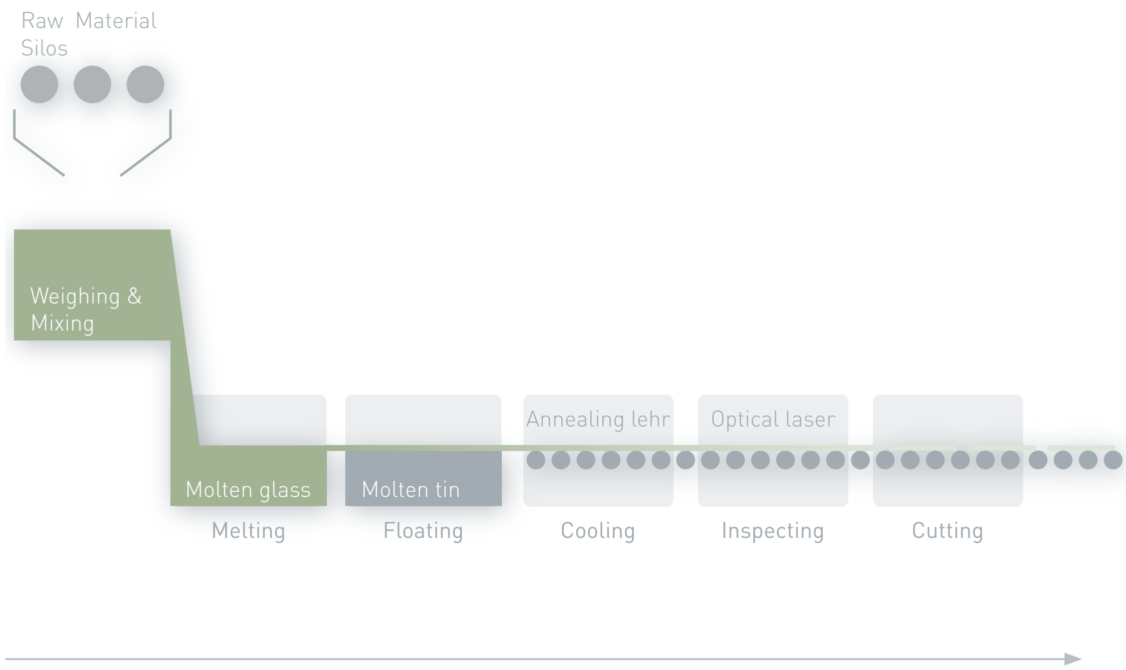
15. Influence of flaws

At different levels

3.2 MANUFACTURING PROCESSES

In the 19th century glass became a material that began industrialised and widely applied in buildings. However full industrialisation of window glass started in the early 20th century, when the concept of vertically drawn glass out of a molten material was invented by Emile Fourcault (1901). Soon, the vertically drawn glass was developed more economically by turning the process into a horizontal one by Libbey Owens (1903-05). Later advantages of both processes were combined into the Pittsburgh drawing process (Schittich, 1999).

Today, Soda Lime Silicate glass is brought to a molten state and floats on a horizontal bath of molten thin. The velocity of the rollers ensures the thickness of the glass (fig. 16). The higher the speed, the thinner the glass. The production line is called a micro-float process when the thickness of the glass are under the 4mm (Hundevad 2014). Under the 3mm it is called thin glass and to produce the glass in the desired flat formation becomes more difficult, yet it is possible down to thicknesses of 0.52mm (Lambert, 2013).



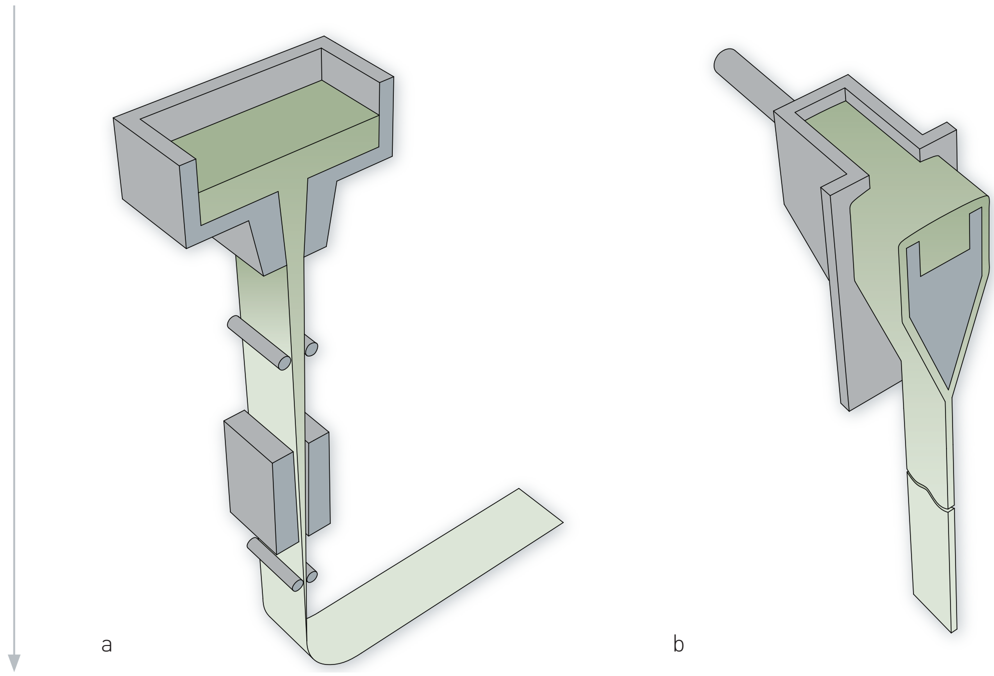
16. Horizontal production process

Float-line

Instead to produce it horizontally, super thin glass can be realised in a production line that moves vertically, such as the down-drawn process or the fusion overflow process (fig. 17). In the fusion overflow process the molten glass is held in V-shaped bath and flows over on both sides and later fused together vertically. This results in a decreased chance of any impurities or distortion at the surface, because there is only air and no tin side to cool or solidify the glass (Lambert, 2013).

Tolerances for the nominal thickness of float glass are ± 0.1mm. Vertically drawn thin glass ribbons can be made up to thicknesses of 0,025mm (25μm). It is called ultra-thin glass if it is between 25μm to 100μm (Schneider, 2015).

Because of economical reasons for a realistic architectural thin glass product, only glass produced by a horizontal float line will be analysed. In this scenario only Leoflex from the manufacturer AGC is known. Other manufacturers that produce (ultra) thin glass vertically, such as Gorilla Glass from Corning or AS 87 eco glass of Schott will not be researched therefore.



17. Vertical production process

a. Down-drawn

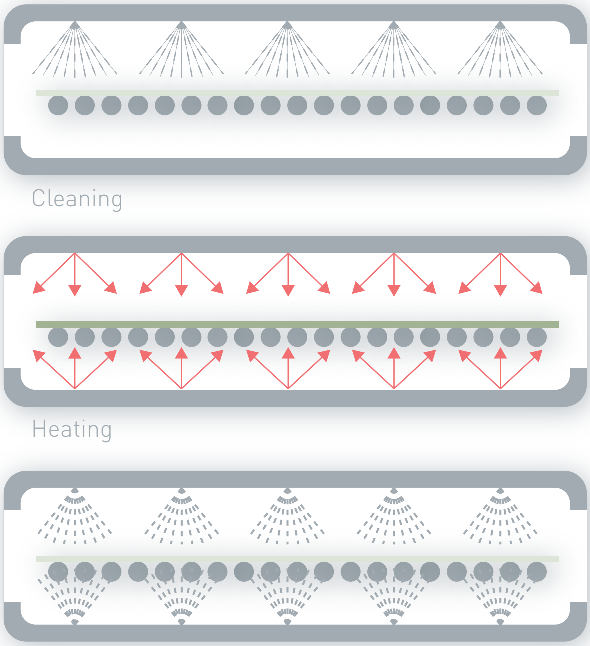
b. Fusion overflow

3.3 STRENGTHENING METHOD

Thermal tempering

By thermally tempering the cooling is controlled with air and tin that effectively strengthen the glass and protect it against over stressing in the form of bending and flexure while used as construction material (Abramov, 2010). The thermal tempering process also needs rollers though to give the glass an equally divided surface compression zone by moving the glass back and forth in an oven (fig. 18). This process, however, is limited to thicknesses down to 2.8 mm with standard tempering equipment.

Thin glass would deform during this heating and cooling and it is favourable not to make use of any roller supports due to the strong non-linearity within the cooling process. Modern equipment such as air cushions instead of roller supports are able to produce heat-strengthened glass with thicknesses down to 1.8 mm. However quenching by air is not yet available for fully tempering (Scheider, 2015). The difference between fully tempering and heat-strengthening is time in which the panel is cooling. If it is less quickly as with fully tempering, the stress built up inside is also less and results also in less resistance to bending or tension (Wurm, 2007).



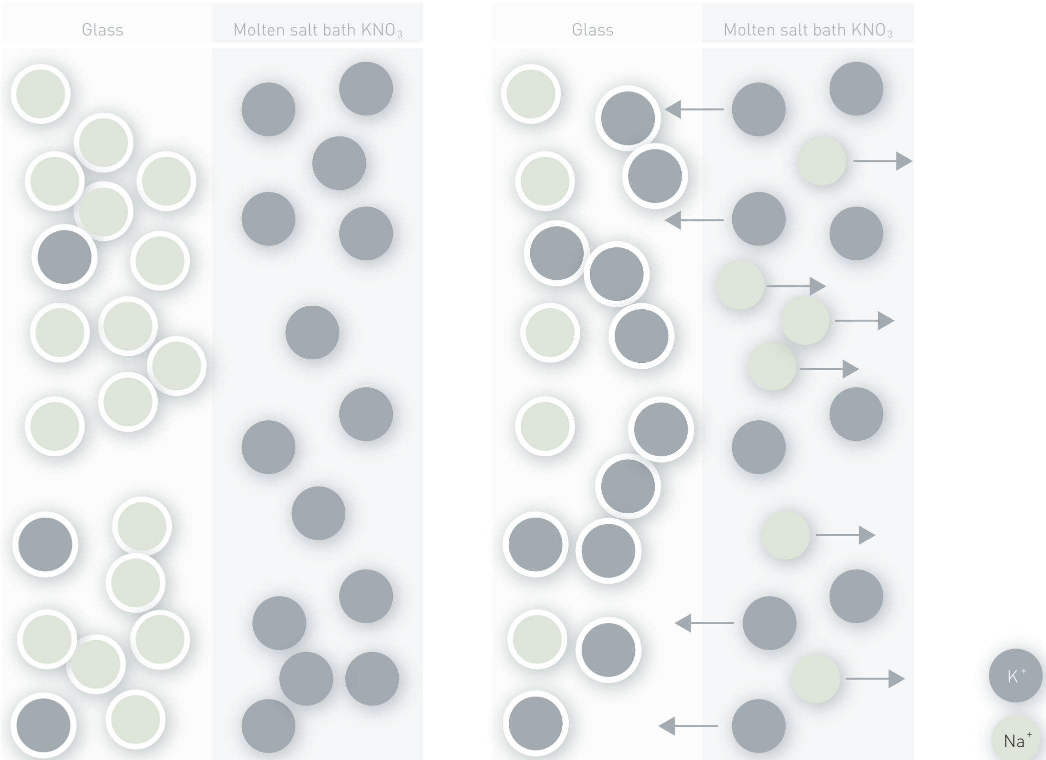
18. Thermal tempering

In an oven

Chemical strengthening

The thinner the glass, the higher the chances of any impurities or distortions when it gets tempered thermally. Thin glass would not have a good homogeneity nor optical quality after thermal tempering process as with a chemical toughening process (Hundevad, 2014). Unlike air-tempering process, there are no rollers needed to move the glass for equally surface compression, because the glass is placed vertically in a molten bath of salt (Corning, 2007). The optical quality of the glass is the same as before the chemical strengthening and there is no visible 'strain-pattern', like in thermal tempered glass when lightening is slightly polarised (Gy, 2008).

The difference of chemical strengthening and thermal tempering is that the glass increases its surface compression by ion exchange for relatively heavier potassium ions (fig. 19). This process, originally proposed by Kistler in 1962, of "crowding" or "stuffing" is submersed in a bath of molten salt, where the temperature of the bath causes the smaller sodium ions to leave the glass (Kistler, 1962).



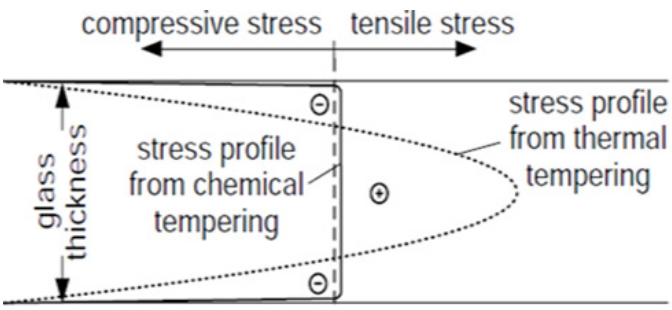
19. Chemical strengthening

In a salt bath

The effect of the ion exchange is only possible when alkali silicate glasses are used. The presence of Feldsper (Al2O3) in alkali-aluminosilicate glass allows a faster and better diffusion of the alkali-ions, so that is why this material is often chosen for making thin glass (Schneider, 2015).

The compression zone or depth of layer (DOL) is limited to a very thin layer. Any dropping, knocking or bruising have high risk of penetration, because the surface flaws penetrating through the thin compression layer and can lead instantly to failure of the glass (Zijlstra, 1968). This makes chemically strengthened glass makes unreliable or unpredictable as a construction material.

Temperature and composition of the salt bath and time the glass has left in the salt bath can influence the value of the created compressive stresses (CS) and DOL. The DOL is mostly deeper when higher temperatures are reached. The longer it is in the bath, the higher the DOL. Before the glass goes into the bath with a temperature of 400 degrees Celsius it needs to pre-heated. Over tempering can happen if the temperature is too high or the glass has left too long in the molten bath of salt and causes excessive tensile stresses within the glass (Corning, 2007).



a

Prestressing method	Value in MPa [N/mm^2]
Annealed	45
Heat-strengthened	70
Fully tempered	120
Chemically strengthened	750-1000*

b

20. Prestressing

a. Difference stress patterns between thermal and chemical tempering

b. Characteristic tensile bending strength

* Depends on time, temperature and composition salt bath and type of glass (AS glass)

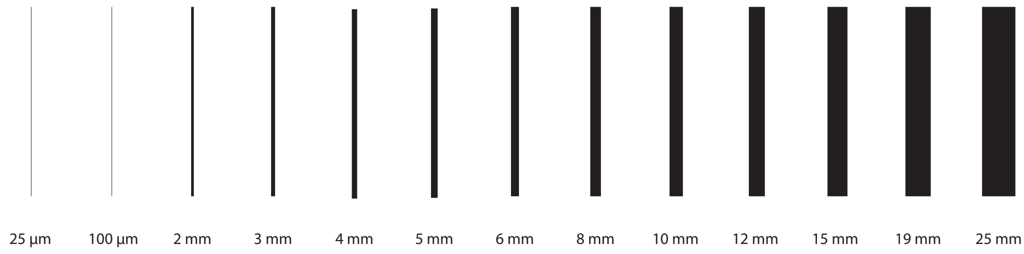
If the strengthening process has offset parameters of temperature and/or time, the glass has a low strength. Compared to the heat strengthening method, maximum surface stresses of 981MPa when a alkali-alumino-silicate glass is used and 250MPa when soda-lime-silicate glass is used (Overend, 2013).

3.4 MECHANICAL PROCESSING

Cutting before strengthening

The cutting can be done by scratching the glass with a glazier's diamond or rolling it with a tungsten carbide roller for every thickness of the glass (fig. 21). By bending the panel exactly where the scratched line is made, the glass splits by the generated tension. Both created surfaces of the cut shall have damages such as crumbled and cross micro cracks (Veer, 2011).

The width of the panes from the float-line production is 3.21m and usually cut into standard lengths of 6m also know as "jumbo" format, which fit in the oven for thermal tempering (Veer, 2001). For the micro-float line the sizes are smaller for the basic product, because of the limited size of the salt bath (1.5m x 1.8m) that needs to be used for the ion-exchange, explained in paragraph tempering.



21. Available thicknesses

(ultra) thin - thick

Most cut glass needs an edge treatment to reduce made micro cracks by grinding and polishing. These mostly invisible damages for the naked eye can be so large that even after edge treatment micro cracks may remain. This appearance of hidden damage have big influence on the strength of the glass elements (Veer, 2011).

Cutting after strengthening

Once glass get reinforced by thermal tempering, it needs to be cut before this process. Otherwise, the high elastic energy stored within the pane is too high and will result in fragmentation after cutting (Scheider, 2015).

The advantage of chemically strengthened glass is that it can be cut before and after strengthening, but ion-exchanged glass makes is difficult to cut in with conventional mechanical equipment as described for float glass. The major effort required to cut the glass can lead to contamination from edge chips and edge defects that result in a weakened edge (Abramov, 2010).

Due to the thin compression zone and the low elastic energy stored, the glass strength at the edges is reduced and can be compared with annealed glass. Instead of looking to the visible scratch track, the depth of the invisible median subsurface crack induced by the scratching needs careful attention, because this is the responsible factor of the glass strength after cutting (Scheider, 2015).

In the past years a laser based cutting technique has been developed that enables full separation of the strengthened glass sheets. Although the level of ion-exchange is high, a nearly "flaw-free" edge is created with strengths of 500 MPa in the compression surface and a central tension range of 26MPa by using optimal ion exchange conditions and laser cutting parameters matched with the velocity of the crack tip (Abramov, 2010).

3.5 SAFETY

Breakage pattern

If glass structures are not laminated, the fracture strength of glass equals its ultimate strength. If glass is reinforced with glass and other ductile materials that can be laminated with the structural element, the strength after fracture is enhanced to a stronger and safer system, because it can last longer after breakage. This structural integrity after fracture of one or more panes is different depending on the built up elastic energy stored within a pane (Overend, 2013).

Glass is strengthened either thermally or chemically, this added energy in the form of stored elastic strain contributes to prevent fracture and fragmentation. Prior to this, the fracture topography is different. When the crack-tip intensity factor equals the fracture toughness, the crack will grow. So residual stress pattern has effect on the fracture of the glass (Jiang, 2017).

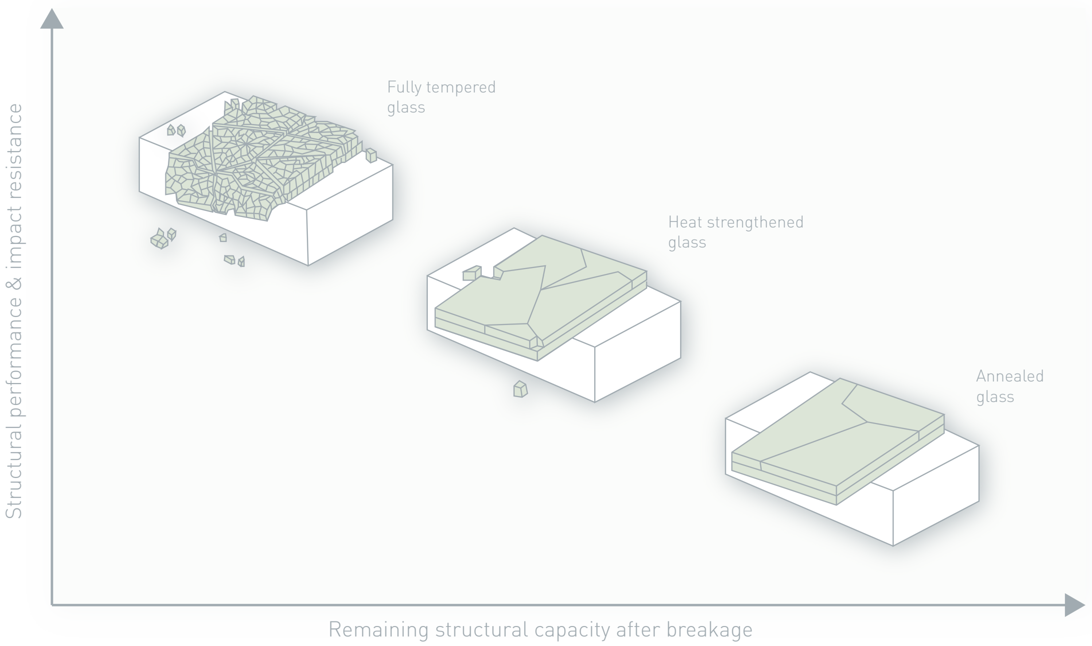
The glass breakage pattern is often compared to a measurement of indication for the absolute stress level of the glass surface. Additionally, the thickness of glass is also of influence. Thickness and the absolute stress level forms the total elastic energy stored within the glass and exhibits a non-linear relation with the fracture pattern (Lee, 2012).

However for thin thermal tempered glass the relation of stored energy contained in the glass and structural capacity after breakage behaves differently. Thin glass spends more stored energy to generate a new fracture surface and stores less energy for the second cracking as compared to thick glasses (Schneider, 2015).

Lamination

To enhance the safety of a glass structure, different polymer interlayers can be used to bond different glass panels together in a structural application. In this laminate the interlayer provides shear coupling between the glass panels that in case of fracture adheres the interlayer to the glass (Overend, 2013).

Laminating panes is done in an autoclave under pressure and heat. Different polymer interlayers can be used, and are mostly thermoplastic. Before putting the translucent interlayer in an autoclave, it is attached to the panes. During the consilidation process in the autoclave heat and pressure cures the thermoplastic to form an adhesive mechanical bond to both panes with transparent characteristics (Ungureanu, 2011).



22. Glass & Lamination

Breakage behaviour of a glass laminate with different levels of prestressing

Different interlayers

Glass is considered as "safety glass" when the pieces of glass after failure are still bonded to the interlayer and cannot hurt people. A widely used interlayer is transparent polyvinyl butyral (PVB) which is a thermoplast and originally developed for safe car glazing (Delincé, 2008). This functional product started to develop for building industry, where the interlayer sometimes benefits for structural application if its stiffer, such as an ionomer and one of the best-known is SentryGlas® Plus (SGP).

If structures need to construct lighter, a higher density polymer such as SGP could be used which result in a more monolithic structural behaviour of the laminate. Approximately 30% less glass is used by using a stiffer interlayer, such as SGP, instead of PVB. Also thinner glass would benefit strength if an ionomer interlayer is used. A sufficient interlayer reaches a high shear transfer coefficient (Bennison, 2008).

The combination of thinner glass and thicker polymer interlayer is the optimum way to achieve weight reduction, because higher interlayer to glass ratio have demonstrated strong weight reduction. For thin glass stiff polymer laminates the highest weight reduction is achieved by a interlayer to glass ratio of 7.41 (Shitanoki, 2013).

Property	PVB	SGP	Units
Volumetric weight (density)	1070	950	kg/m^3
Elastic modulus	18	300	N/mm^2
Tensile strength	+20	34.5	N/mm^2
Deformation at breakage	+250	400	%

23. Glass & Lamination

Physical properties of most used interlayer material

Also thermoset epoxy polymer interlayers, like Ethylene Vinyl Acetate (EVA) can be used, next to thermoplastic interlayers (Overend, 2013). A difference between the thermoplast/ionomer and thermoset interlayers is the production technique. Epoxies can consolidate at room temperature. The infusion process of the epoxy and harder is at liquid state and needs to be completed secure and fast.

Different glasses

Because glass breaks in different ways, combining mechanical properties of different prestressed panes can make significant improvements of the integrity of the structure. While fully tempered glass is stronger than heat-strengthened glass, the bending stiffness of the laminate after breakage is higher for heat-strengthened glass. This is explained by the bigger pieces of glass fragmentation (fig. 22).

Chemically strengthened glass has many factors that influence the built up residual stress pattern. Fact is that relatively high elastic stored energy is built up during the prestressing. It is recommended to know how each chemically strengthened monolithic glass plane will fracture, before laminating.

Additions to the interlayers

Next to glass reinforced glass, the addition of fibre reinforced polymers rods or metal plates embedded in the interlayer of laminated glass increases the post-breakage strength of a glass structure. This embedded reinforcement will carry the tensile forces after breakage and result in a higher residual stress capacity (Louter, 2007 & 2009).

SentryGlas is used as intermediary between glass and the reinforcement rods and plates. Despite fracture and failing of brittle materials, fracture strength is not the ultimate strength of the structure. This type of reinforcement in laminated glass beams shows a plastic deformation that can occur in which stress is retransferred in a more efficient way. Extensive research on this topic is provided by C. Louter (Louter, 2011).

24. Cold bent glass, by Octatube

Van Gogh Museum Amsterdam, 2015

3.6 CURVED GLASS

Plastic deformation

For hot bent glass a mould is used and annealed placed glass is carefully heated and formed beyond the weakening point in plastic state. Either in a vertical process the hanging glass is pushed to the developable curvature or in horizontal process one side is clamped and the glass curves by its own weight. Cooling slowly the glass product slowly, result in no internal bending stresses (Neugebauer, 2014).

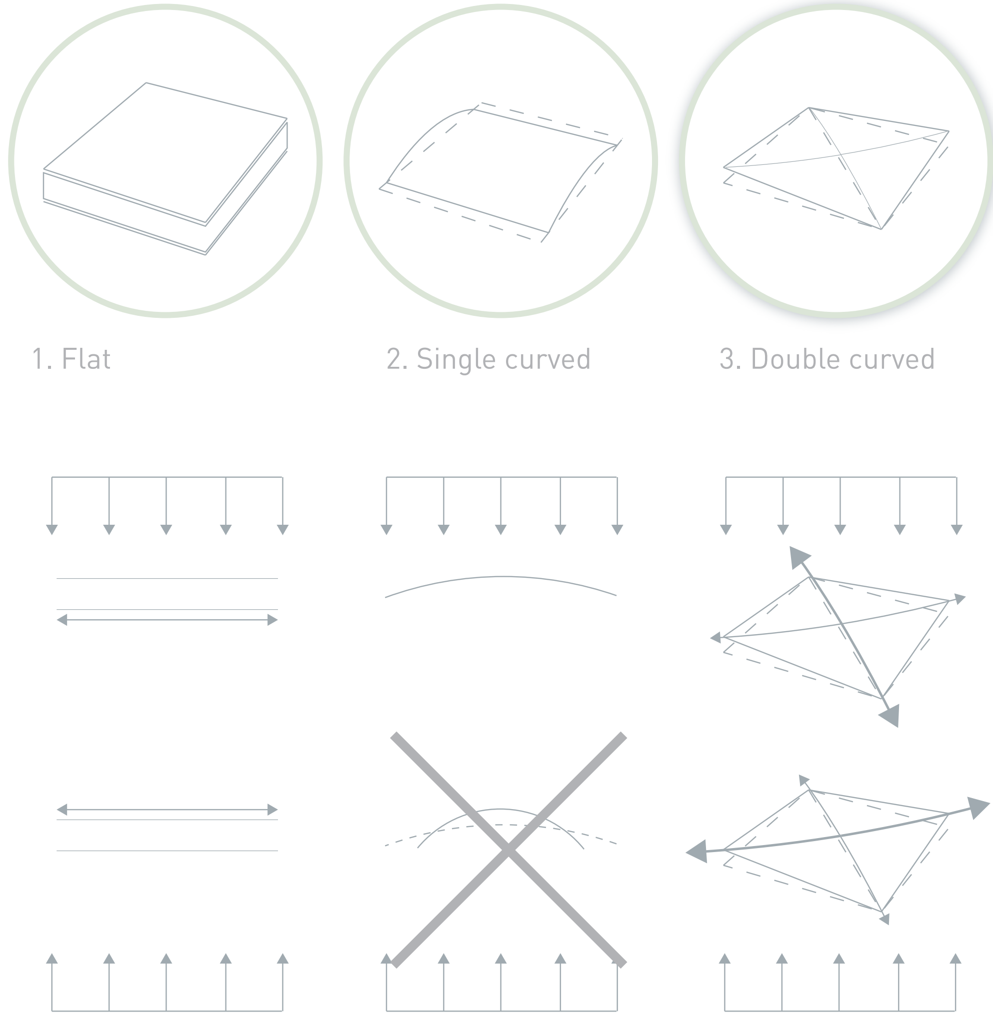
Elastic strain single curvature

Glass also can be single and double cold bent, cold twisted, but only if its been strengthened. By prestressing glass, higher values of tension and shear stresses can successfully be transferred without failure of the glass during bending. Higher surface strength, means a higher capacity of transferring tensile stresses, resulting in higher bending radii (Schneider, 2015). Because of these high elastic energy, safety becomes a much bigger issue, because of the released energy in case of failure. Therefore lamination in cold bent glass applications is even more needed than usual.

To increase more shear coupling within the laminate, it can be heated up a little to plastically deform the interlayer. Heating the laminate while bending is necessary for most curved glass façade projects in order to realise sufficient bending radii (Belis, 2007). The end product results in a curved laminate that structurally almost behaves similar as glass that had been curved before laminating (Galuppi, 2014).

In the case of the "two step" cold bending, the glass panes are first elastically bent over a jig before laminating in the autoclave. The created curvature is partially held by the cohesion due to the interlayer. Because shear transfers are becoming really high, a stiff interlayer is desired. Not only the glass arrives in a pre-bent state at the building site, also tighter bending radii are possible due to the use of thinner glass and higher quality if its drawn vertically (Fildhuth, 2014).

Instead of using a substructure to held the pane in a curvature, the transparent interlayer is equally distributing its load to the both glass surface. While engineering the desired curvature of the laminate, there should be taken an elastic springback into account, directly after releasing from the jig. Also by relaxation of the laminate that depends on time and temperature, the bent laminate want to spring back to its original state (Fildhuth, 2014).



25. Stiffness & stability

Adding material or geometry to sustain (wind) load

3.7 STRUCTURAL BEHAVIOUR

Applying cold anticlastic curved high strength thin, flat glass by as a building product or construction material, it needs to withstand loads perpendicular to the pane. By anticlastic curving the flat plate it is able to transfer loads from both sides with same internal stresses. The same can be said for a sandwich construction. On the contrary for single curved glass, only one side is able to transfer the perpendicular load sufficient. With that noted, twisting high strength thin glass as a tensile membrane results in an application with the purest approach to the material, considering its structural behaviour as a membrane and its high tensile strength.

Deformation plate elements

Small deflection theory (plate)

Usually the structural behaviour of glass plates are compared to the behaviour of linear elements as earlier discussed. However, this will implicate that solely the (classical) plate theory has to be considered in case of a deformation. This theory is a development by many scientists, but it was Kirchhoff that contributed the most of how we interpret fundamental assumptions of linear, elastic, small-deflection theory for the bending of thin plates (Ventsel and Krauthammer, 2001) H1. This theory only describes first order elastic mechanical behaviour of plates. The theory is only sufficient if the following can be assumed:

1. *The material of the plate is elastic, homogeneous, and isotropic.*

2. *The plate is initially flat.*

3. *The deflection (the normal component of the displacement vector) of the mid plane is small compared with the thickness of the plate. The slope of the deflected surface is therefore very small and the square of the slope is negligible quantity in comparison with unity.*

4. *The straight lines, initially normal to the middle plane before bending, remain straight and normal to the middle surface during the deformation, and the length of such length is not altered. This means that the vertical shear strains gamma xz and gamma yz are negligible and the normal strain Elips z may also be omitted. This as the "hypothesis of straight normals".*

5. *The stress normal to the middle plane, sigma z, is small compared with the other stress components and may be neglected in the stress-strain relations.*

6. *Since the displacements of a plate are small, it is assumed that the middle surface remains unstrained after bending.*

Only point 1 and 2 are valid, given the huge deformations of thin glass. Apparently the glass in this research behaves structurally more as a membrane than a "beam". To validate this the conditions of the large defection theory has to be known.

Large deflection theory (membrane)

To identified how to consider chemically strengthened thin aluminosilicate glass then, it can be compared to a membrane that must satisfy the following conditions (Ventel and Krauthammer, 2001) H13:

1. *The boundaries are free from transverse shear forces and moments. Loads applied to the boundaries must lie in planes tangent to the middle surface.*

2. *The normal displacements and rotations at the edges are unconstrained: that is, these edges can displace freely in the direction of the normal to the middle surface.*

3. *A membrane must have smoothly varying, continuous surface.*

4. *The components of the surface and edge loads must also be smooth and continuous functions of the coordinates.*

To verify these conditions numerical experiments needs to be simulated. If a membrane (read thin glass) is unable to sustain compressive loads, the material might be more appropriate to use it in tensioned structures. Therefore the tensile strength needs to be analysed. The bending strength is known obtained from the Bend Tests, but is a derivative tensile strength of the deformation behaviour by bending sufficient enough?

3.8 CONCLUSION

Micro-floatline

Using the horizontal production float-line process with a high velocity of the rollers thin glass can be mass produced with thickness below the conventional thinnest 4mm. The thinnest glass that is available now is from AGC, called Leoflex Architectural glass and can be 0.55mm. In order to give this thin glass an increased tensile strength, only chemically strengthening technique is possible. Therefore the thickness is a limited factor when prestressing is desired.

Chemical strengthening

Instead of prestressing glass using the oven, a salt bath can be used that enables an ion-exchange which stuff the surfaces by replacing smaller ions for bigger ones. The thickness now is not a limiting factor, although the size of the glass sheet is depending on the size of the salt bath (which is currently smaller than the used jumbo panels of 3m by 6m). The biggest squared chemically strengthened glass pane can be 1.5m by 1.5m. Ion-exchange alkali-aluminosilicate strengthened glass can be 8 times tougher than thermal tempered soda-lime-silicate glass. This increased strength and low thickness of the glass is the reason why it is often called high strength thin glass.

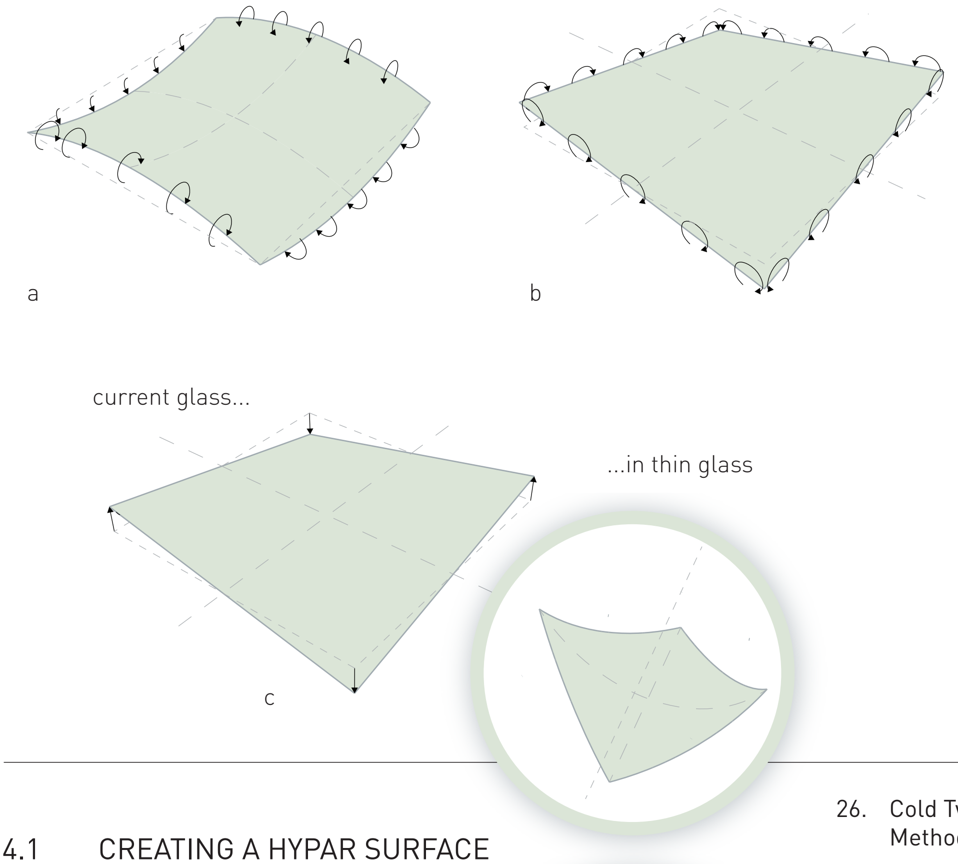
High strength thin glass as construction material

To use high strength thin glass as construction material, higher structural performance and impact resistance can be expected compared to fully tempered glass. But the remaining structural capacity after breakage is the same as annealed glass and therefore high strength thin glass definitely needs to be laminated to prevent injuries than can occur because of the large and sharp pieces of broken glass. Further research is performed that determines the true and safe design tensile strength of high strength thin glass.

04

DESIGN CONCEPT
OF TRANSFERRING TENSION VIA AN ADHESIVE.

How could tension load being applied to the glass plate?

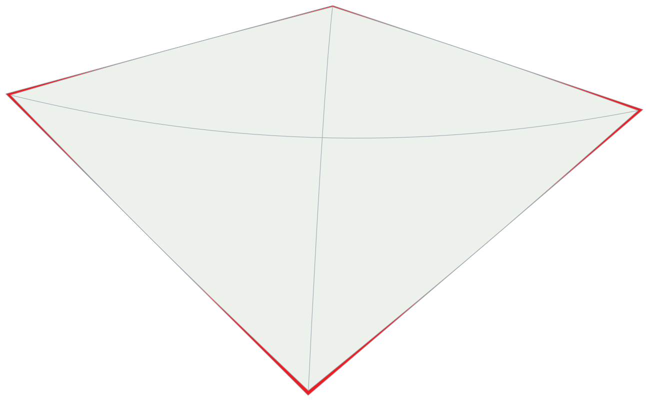


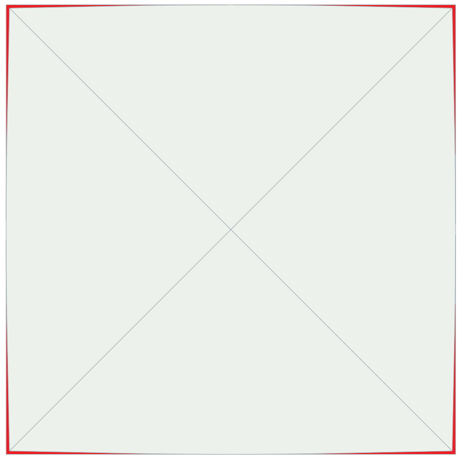
26. Cold Twisting Methods

a. Bending moment
b. Torsional moment
c. Nadai

4.1 CREATING A HYPAR SURFACE

There are two ways to create a so called hypar surface. The first way is to load the surface along the edges with a constant bending moment in the opposite direction (fig. 26a). The second way is to load the surface along the edges with a constant torsional moment in the opposite direction (fig. 26b). This one is usually applied in the current cold bent technology, but then created with a different type of loading. Instead of a constant torsional moment, four external point loads are used to create similar desired double curvature (fig. 26c). Considering the conventional glass plates this technique is sufficient enough for application in the built environment, although limited to a certain translation in Z-direction. The reason for this does not depend on the used material, but on its thickness. The torsion stress generated by the four point loads are forced to flow along the edges around the glass plate. This shear cannot be transferred through membranes, at least very limited to unnoticeable. Meaning that thinner glass will not get the desired double curvature of a hyper surface.
So to create a hypar surface with thin glass, the introduced conventional forced displacement dZ does not only needs to be





Red: created gap compared to a perfectly made squared hypar

27. Twisting glass & geometry made

a. 3D view

b. Top view

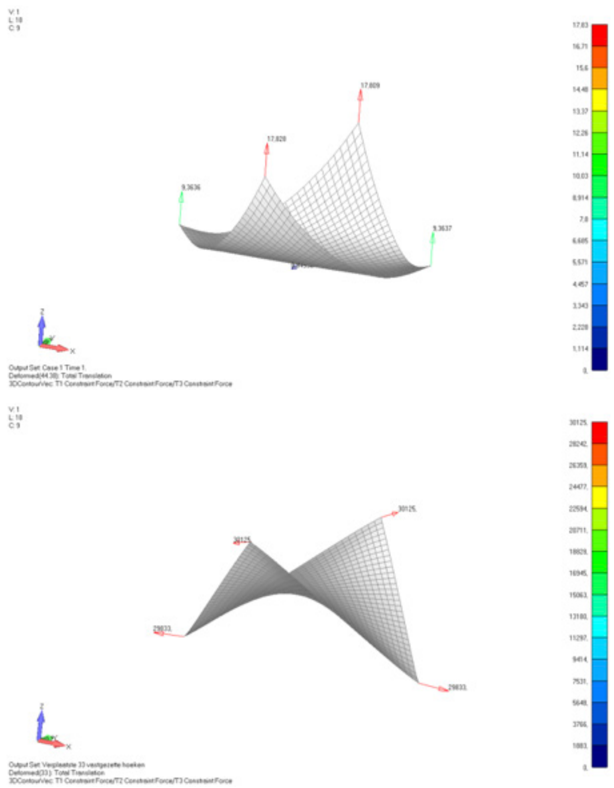
constrained in Z-direction, but also in X- and Y-direction. Nor the bending or the tension stress are relevant, in contrast to the needed in-plane tension load.

4.2 LIMITATIONS & CHALLENGES

Current anticlastic formed glass limitations

The current maximum anticlastic shaped surface is limited to a metastable configuration. The plate may suddenly buckle towards the asymmetric configuration. With thicker plates this type of internal stresses can be neglected, but as the translation in Z-direction will be bigger, membrane stresses will occur and increase significantly when the deformation of the plate become much bigger than its thickness.

With the twisting of the plate tension and compression zones will be created. When the tension increases above the ultimate tensile strength, the glass will failure. When compressive normal forces gets too big it will cause instability to the plate and buckles to a second buckling mode instead of failure. It might be that the changed deformation of a singular shaped cylinder still has too big tension zones and in the end lead to breakage of the glass plate. Interesting to analyse is the difference of these tension and compression zones with thin glass. Probably the plate support fails, when supported only in Z-direction.



28. Cold Twisting Thin Glass with FeMAP

a. Only Z-support

b. Adding tension

Present anticlastic formed thin glass limitations

The interesting thing of the constrains in this research investigated material is that there might be more extremely curved (anticlastic) hypar surfaces possible out of glass. New fields of research aspects regarding the geometry are:

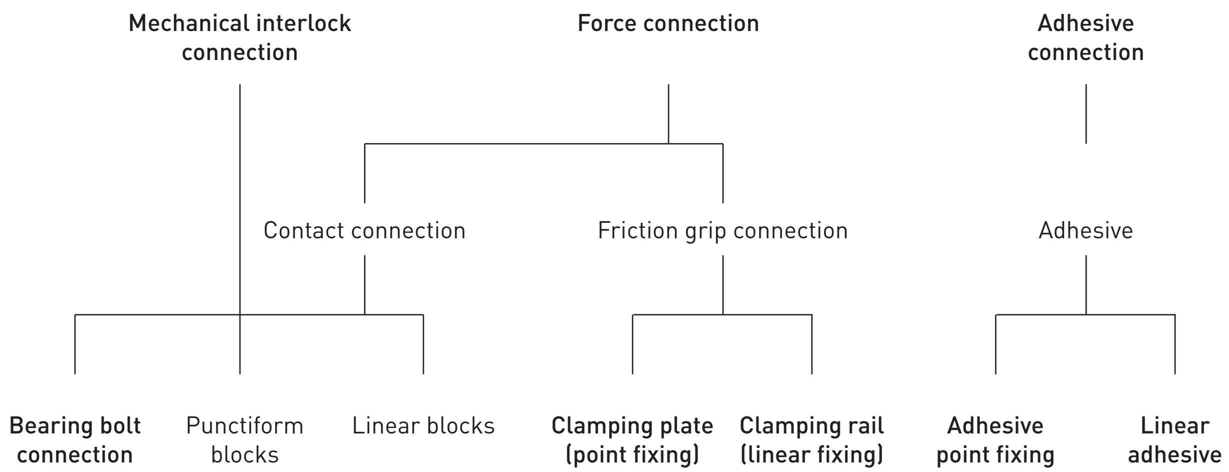
1. Created surface when twisting a geometric non-linear thin plate. Is it still a hypar?

2. The maximum geometrical possibly anticlastic surface that can be created, which is related to the maximum tensile strength of the glass.

3. The minimum translation in Z-direction needs to have an acceptable deformation when it gets loaded by its dead load and wind load. The anticlastic surface might benefit from three-directional cold twisting compared to a solely tensioned flat thin plate.

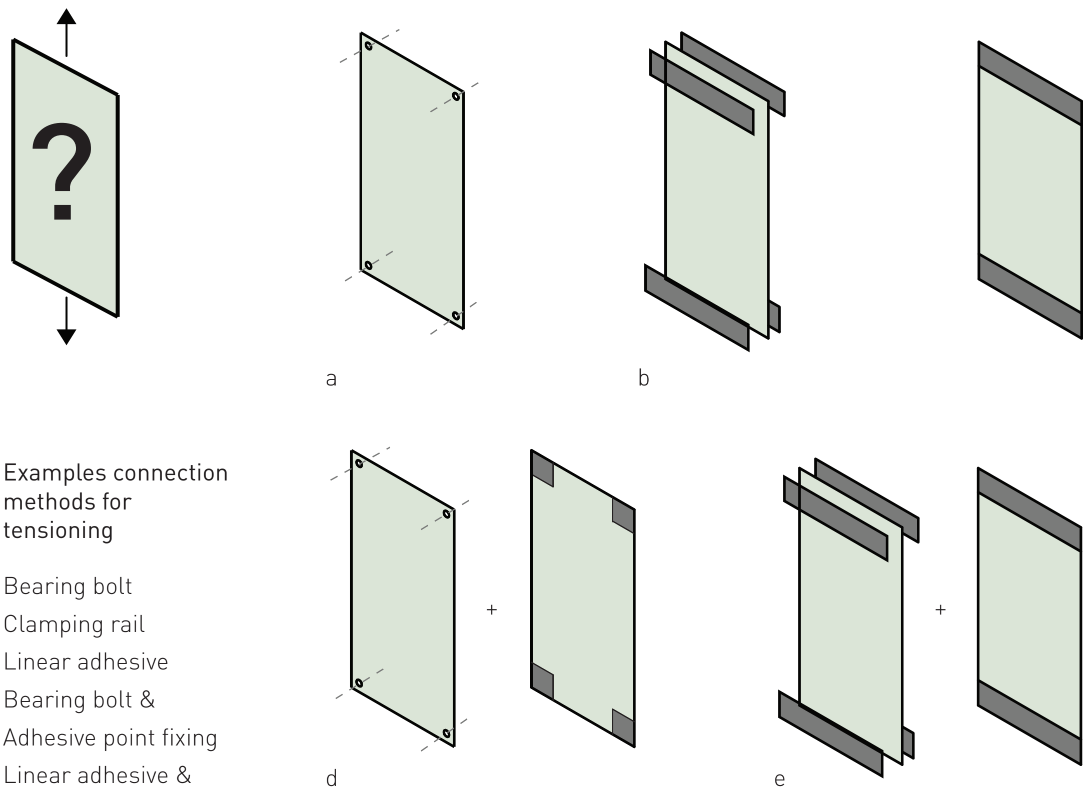
4. Awareness of possible new type of wrinkling effect and resonance effects that often occur in tensile structures.

4.3 INTRODUCING TENSION IN A FLAT SHEET



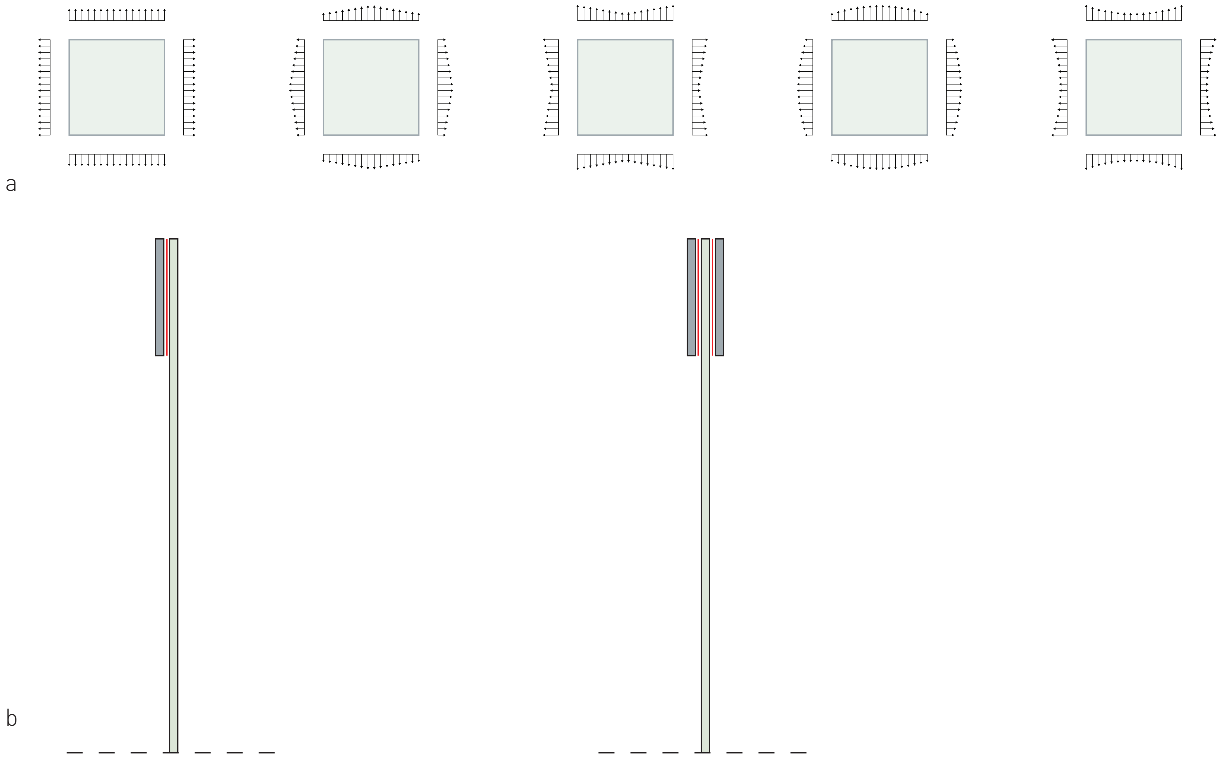
29. Connection topology

to load a flat sheet of glass



30. Examples connection methods for tensioning

Bearing bolt
Clamping rail
Linear adhesive
Bearing bolt &
Adhesive point fixing
Linear adhesive &
Clamping plate/rail



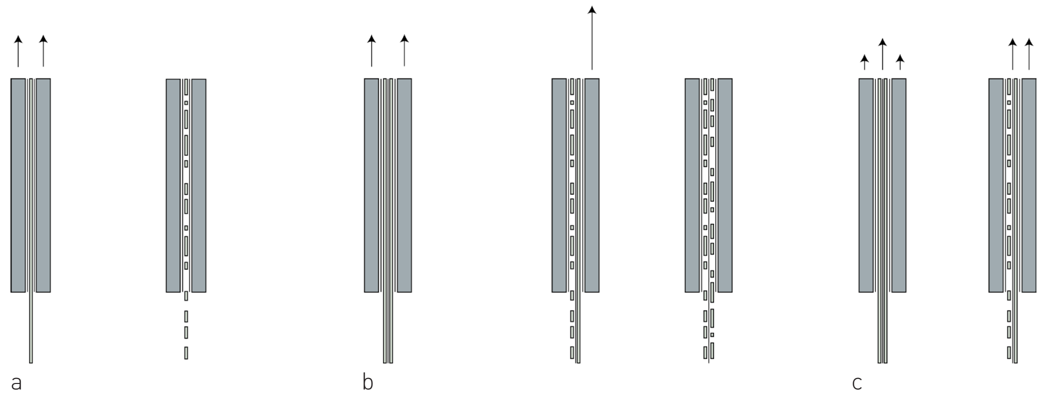
31. Applied tension
a. Top view
b. Cross section

Adding tension to the twisting

Current technology to cold bend glass into an anticlastic curvature can be explained by loading the surface along the edges with a constant torsional moment in the opposite direction that result in a metastable situation of the buckling phenomena (Galuppi, 2014). Creating such a hypar shape is based on the idea that the pane can resists compression and a little tension.

Replacing this glass with conventional thicknesses for thin glass with high strength a metastable configuration is not possible, because of a lack to sustain compression. However, thin glass can have exceptional high tensile strength when it is chemically strengthened. Therefore adding tension to the twisting might result in the desired hypar shape.

Because of the membrane behaviour of thin glass it is desired to add tension in the same direction of the normal plane of the glass plate and at minimal distance. The connection method therefore can be best accomplished with an adhesive.



32. Breakage behaviour

a. Single layered glass

b. Double layered glass

c. Double layered glass with extra insert

Adhesive & material that is attached

Due to the forced hypar shape, displacements in the corners result in the highest tensile stresses. Therefore to maximise the hypar shape, this applied tension needs to be divided along the edges. The connection must be a material that also needs to deform in the same way as the glass. Also to make a perfectly squared panel in the bent configuration the connection material needs to stretch and capable of transferring the tension. If the glass only needs to be two-dimensional tensioned this is not necessary.

Adhesive becomes critical

The adhesive connection becomes a critical joint that determines the tensile strength of the glass. By laminating the glass, safety can be ensured in case of breakage. Further research within the in-plane tensile strength of chemically strengthened glass is needed to determine the adhesive that is sufficient to transfer tension forces to the pane. Loading the glass this way mechanical properties of the adhesive needs to be engineered to withstand tensile stress larger than that of the glass. Hence, the connection needs to be stronger than the tensile strength of the glass.

4.4 CONCLUSION

The applied tension at both sides induces shear all around the edges of the glass plate that gives a favourable uniform in-plane stress distribution. Next to the use of an adhesive, hybrid connections are possible using an adhesive as well as a clamping bolted connection through holes in the glass plate. Just clamping, without the use of an adhesive, but do apply tension through a hole will generate stresses within the thin glass that cause direct failure.

05

EXPERIMENTAL INVESTIGATION OF THE IN-PLANE TENSILE STRENGTH OF CHEMICALLY STRENGTHENED GLASS.

What maximum design stress can be used for a safe implementation of tensioned high strength thin glass?

5.1 DETERMINING TENSILE DESIGN STRENGTH

Ideally, both bending tensile strength and tensile strength should be the same, but there are differences. Especially when the geometry of specimen behaves non-linear. Chemically strengthened, thin aluminosilicate glass deforms with the same load significantly more. When the strength of this thin glass is tested, large deflection theory must be considered - as discussed in chapter three, paragraph 7 - when analysing the flexural strength. The stress versus the load plot is nonlinear and the small deflection theory can predict stresses that are two or more times higher than the stress has to be considered because of its flexibility, otherwise extremely high strength value will be measured.

By pure in-plane tensioning, the tension will be produced uniform across the whole cross section. While obtaining the tensile strength by bending, peak stresses will be created at the top surface. The initial of crack motion is in the tensile area of the specimen. By bending the specimen, it will failure eventually at the tension area first. While implementing glass as structural fabric, specimens need to tested in pure tension. These values can strongly differ between two situations. Peak stresses are produced at the connection where the tension to the specimen is introduced. By doing this a certain surface area can be calculated. Also the connection that transfer the tension to the glass can be dimensioned.

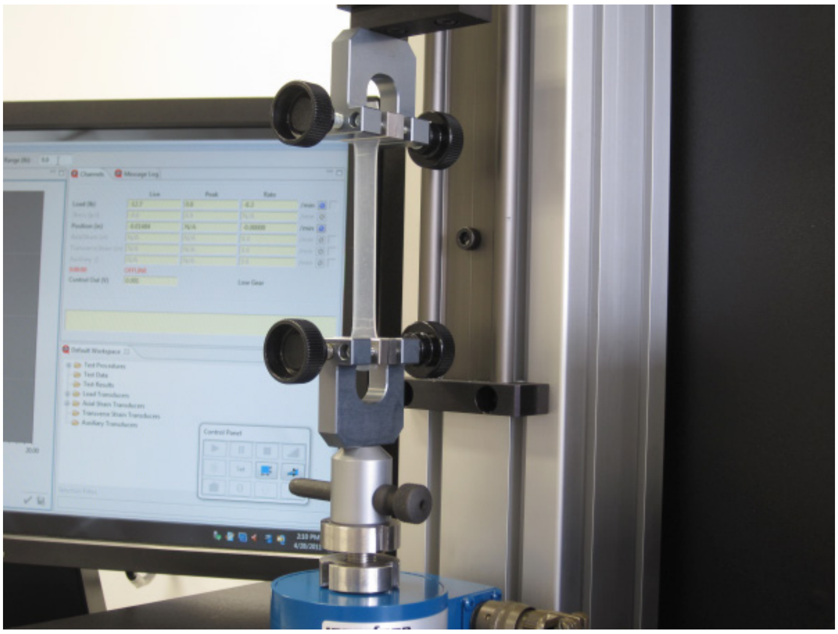
5.2 TEST METHODS

Standard test methods for ductile materials

The standard test method for uniaxial tension (and compression) test are explained in ASTM E8/E8M-13. Specimen materials such as steel, aluminium and fibre reinforced polymers can placed directly within the standard grip section of a UTM's crosshead (fig. 33). Straight alignment is important for uniaxial tests. The machine displaces at a constant rate and records the displacement as well as the resulting load. Next to the displacement of the crossheads, there can be several strain gages placed directly on the specimen. Engineering strain can be calculated as:

$$\varepsilon_e = \frac{\Delta L}{L_0}$$

Where ΔL is the measured displacement and L_0 initial sample length along a single axis. Engineering stress can be calculated as:



33. Pull-out test

Plastic specimen

$$\sigma_e = \frac{P}{A_o}$$

Where P is the applied load and A_o is the initial cross sectional area of the sample normal to the loading direction. Specimens have typically two shoulders and a gauge section in between. See figure.

The shoulder are large so that this area can be gripped. In between the cross-sectional area reduces to the middle, such that failure occur near the middle. The stress-strain curve can be made from the recorded load and displacement. See figure for a stress-strain curve of a typical ductile tested specimen. Initially the material behaves in a linear elastic manner and will deform to its original shape when unloading. This is the ratio of the engineering stress to the engineering strain in the axis, or Young's modulus.

$$\mathrm{E} = \frac{\sigma_e}{\varepsilon_e}$$

The elastic modulus E characterises the stiffness of a material in units of force per unit area (N/mm2, or MPa). Under the linear curve is the elastic strain energy of the material. At a certain strain, the material deforms nonlinear or plastic and becomes irrecoverable when unloading. Glass does not have this ductile behaviour.

Standard test methods for brittle materials

Because glass is a brittle material it is not as simple as with ductile materials to cut it so easily in a typical tensile testing specimen. Next to that it cannot be gripped such easy within the crossheads. Still the tensile strength of glass is known and can be performed on a UTM. Current testing capabilties are:

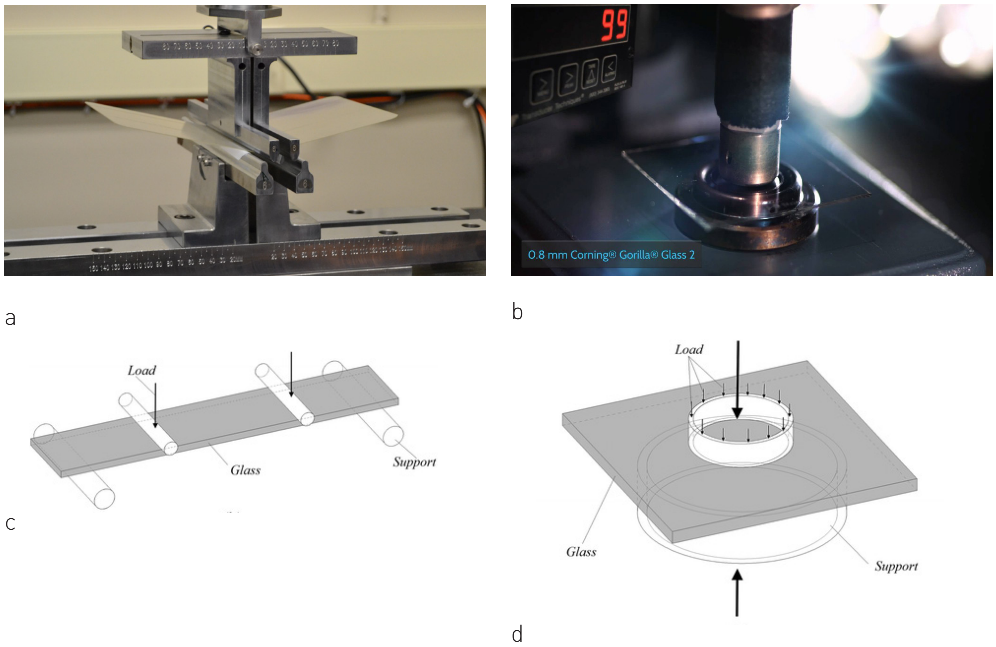
Four Point Bend Test	(4PB)
Three Point Bend Test	(3PB)
Two Point Bend Test	(2PB)
Identation and Scratch	
Ring on Ring	(ROR)
Abraded Ring on Ring	(AROR)
Device Drop (electronics)	
Pendulum Impact Test	
Ball Drop	

To test the bending strength of glass, standard test methods are developed. Applying a single or double external point load transverse to the pane will create bending stresses. Compression stresses in the surface where the load is applied en tensile stresses in the surface at the other side. As explained earlier flaws at the surface will close by compression and open by tension. The three point bending test, only one flaw is tested to a peak load. To test a whole flaw population, the four point bending test is better.

The maximum stress at failure on the tension side of the bended specimen is also called the flexural strength. The flexural strength can be derived from the maximum load at failure.

However, this considers only the beam theory. Because of the large deformation of thin glass, there will be significant end forces developed at the supports that affects the flexural stresses in a beam. The formula therefore must be corrected with the La Grange term. The ratio L/h also can be lowered to lower the membrane behaviour.

Having the thin glass specimen in the flexural test arrangements, the bending will cause a maximum tensile stress only in the surface area of the specimen. Note that this is not the true tensile strength of the material. The difference between the bending tensile strength and the true tensile strength is that a flexural load create a non-uniform stress distribution, while a tensile load creates a uniform stress distribution. A three-point flexural strength can be significant higher than its tensile strength. Because in this research the glass will be loaded by a tension load and not a bending load, the true tensile strength is of importance instead of the bending tensile strength.



34. Tensile testing methods

a. ROR test

b. 4PB Test

c. Principle ROR test

d. Principle 4PB test

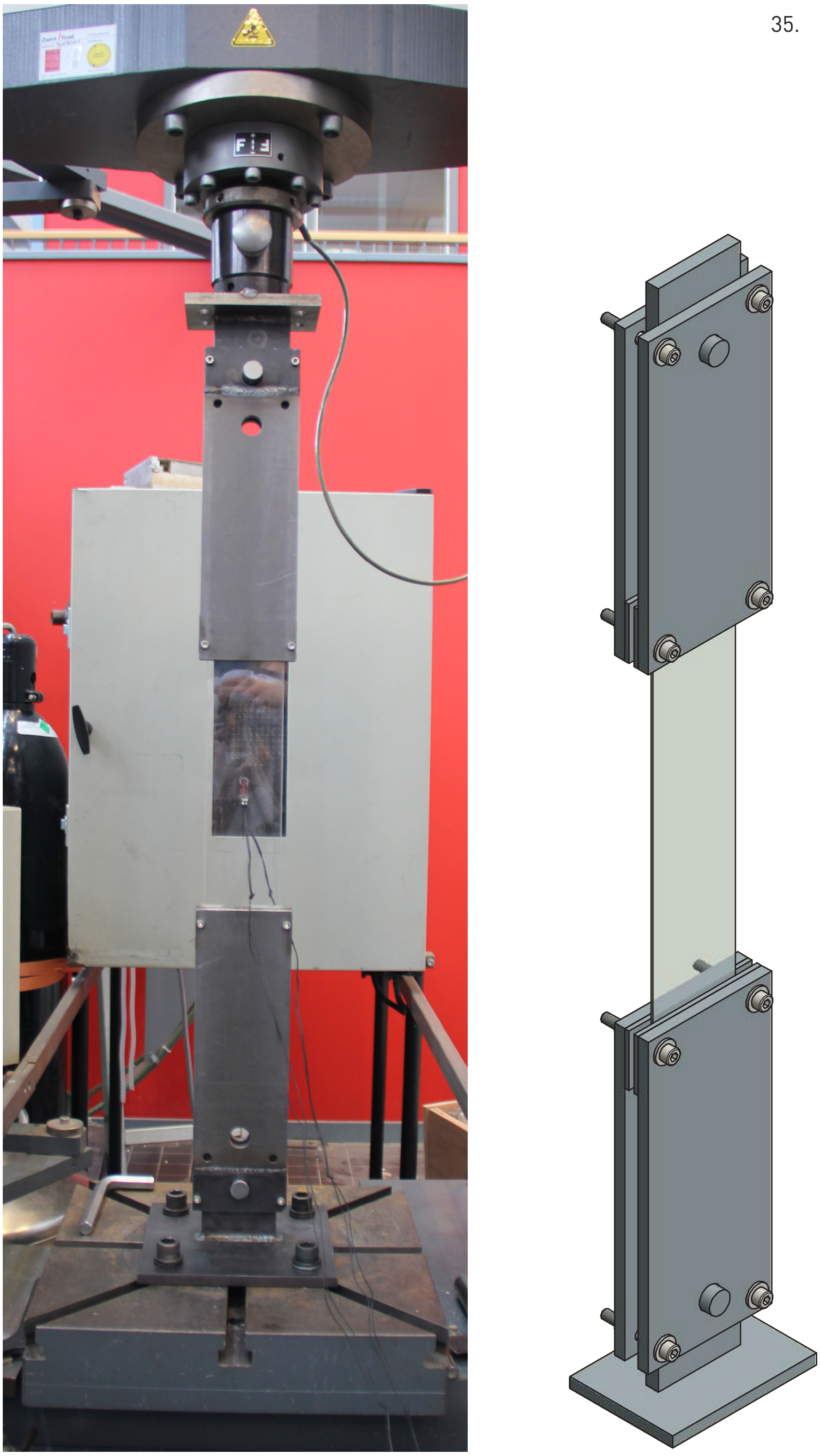
By tempering glass the flexural strength increases. To evaluate the strength of a panel the ROR test or coaxial double ring test is mostly been used.

Surface flaws that are invisible to the naked eye can be the beginning of a crack, assisted by humidity. But usually the development of cracks appears, after a projectile such as a rock hits the glass. Impact loads can be simulated by the pendulum impact test.

Conclusion

Giving the uncertainties of membrane behaviour and the need of the true tensile strength of high strength thin glass, this research investigates an alternative test method for the current standard ones.

Creating a uniform tensile stress pattern in the glass can be done via a substructure, but makes it complex. This non-standard test method needs to be as simple as possible and reproducible in a consistent manner.

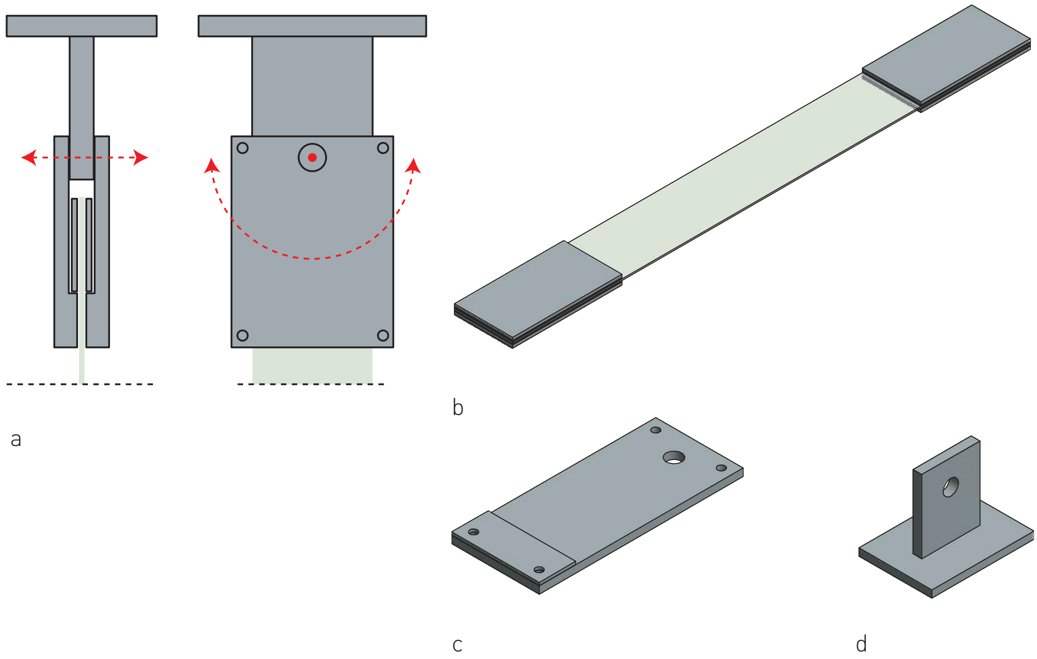


a b

35. Pull-out test setup at room temperature

a. photograph of the pull-out test setup.

b. schematic presentation of close-up p.ull-out test setup with a pull-out specimen that is clamped in a costum made steel sub-structure that can be mounted on the testing machine.



36. Pull-out test setup

a. Movement

b. Glass specimen with glued alumium strips

c. Costum-made steel structure clamping part

d. Costum-made steel structure feet part

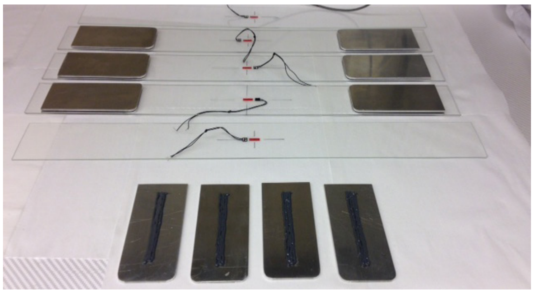
5.3 EXPERIMENT PULL-OUT TEST

To determine the tensile strength a non-standard test set-up is used (fig. 35). A distinction can be made of the steel construction (fig. 36c&d) and the glass specimen with glued aluminium strips (fig. 36b). Several other set-ups were considered. To get grip on what happens in the specimen itself strain gages are needed on the specimen.

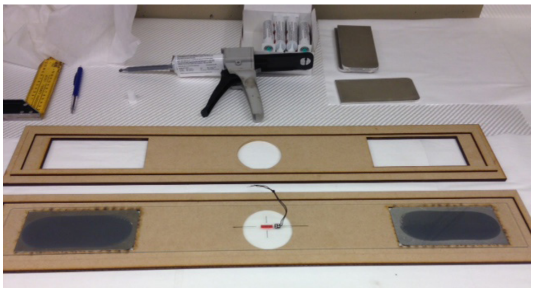
Design pull-out test setup

The glass used for this tensile test is chemically strengthened float glass manufactured by AGC. The exact CS, DOL and CS are not certified and therefore not given by the manufacturer. All samples have a length of 710mm, width of 80mm and a thickness of 2mm.

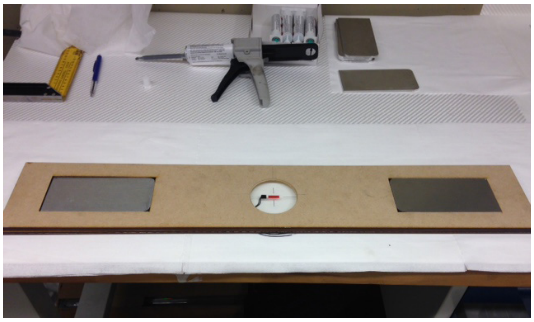
Four samples are made with aluminium strips for determining the tensile strength. With the structural adhesive Acrylite 300 the aluminium plates are attached to the glass. The two component epoxy has a work life of 1.5 hours and a handling strength of 4 to 6 hours at room temperature. The adhesive is first applied to



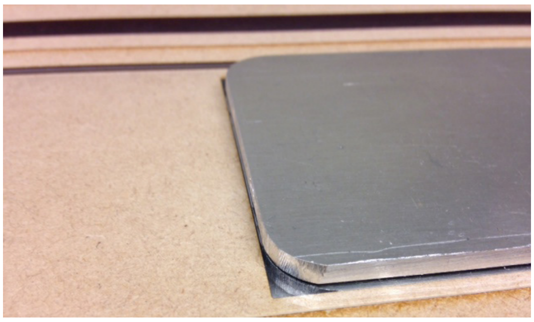
a



b



c



d

37. Preparing the specimen

a. Applying epoxy on alumium

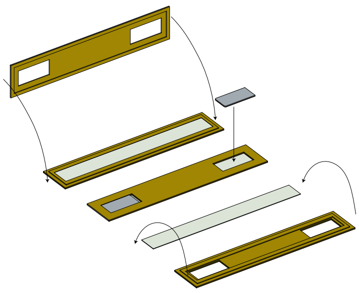
b. Using one part of the mould

c. Using both parts of the mould

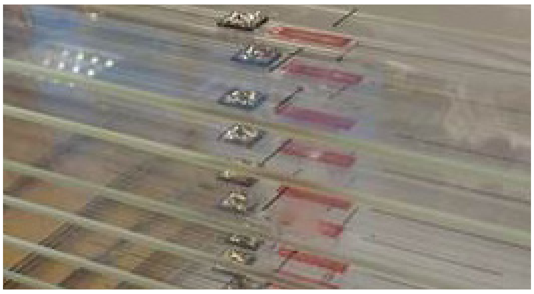
c. Nadai

the aluminium strips, each time with the same amount and area, after degreasing with ethanol and then to the cleaned glass.
Glass specimen and glued alumium strips

The glass and strips are placed in a mould to be sure of right positions of the strips. Because the work life is quite long, the strip will not directly keeps the position as it is attached and will move by any little force. Therefore removing the mould from the glass with glued strips need to be done carefully to prevent from any little displacements or after the adhesive have been cured. When cured the prepared samples can be controlled of correct alignment by placing it back into the mould. The other side now is also provided with a strain gauge to filter any strain caused by bending (fig. 37).

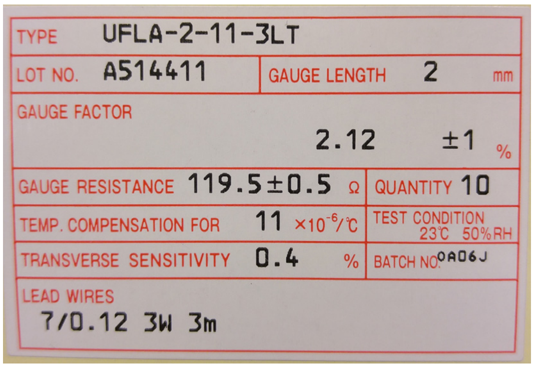


The strips have rounded edges to prevent high stress concentrations in case the adhesive would had covered the whole surface. However while applying the adhesive, the area already have rounded edges when the aluminium strip were compressed to the glass by a glue clamp. Instead of the meant area of 70mm x 150mm, the area where via shear within the adhesive glass can be tensioned is reduced to the red outline (fig. 39).



a

b



c

d

38. Applying strain gauges

a. Strain gauges glued on glass specimens

b. Used adhesive

c. Used strain gauges

d. Applying wires

Strain gauges

The specimens that are used were already equipped with a strain gauge at one side right in the middle (fig. 38a). This was meant for a bending test to measure the strain until failure. Now the remaining specimens are used for a non-standard test method in which stresses caused by bending are undesired. The sub-structure that grips the specimen is designed such that there are only in-plane stresses are going to be developed when tensioning the specimen. To validate this actually happens, a strain gauge also will be glued with CN adhesive (fig. 38b) at the opposite side of the already placed strain gauge (fig. 38d).

The strain gauges used are manufactured by Tokyo Sokki Kenkyyujo Co., Ltd., type FLA-10-11 (fig. 38c). All data of electronically resistance has been gathered via a 24-Bit Universal Analog Input NI 9219, manufactured by National Instruments. This device has four analogue channels that can be used at the same time which in this case are two; one per strain gauge. This record data in the form of MP3 can be made visual by software developed by TU Delft (see figure). Any difference noted can be seen directly in the display and means undesired bending in the specimen.

Steel sub-structure

Lots of ideas felt off, because of the limitation of the maximum space (length) that can be used in the test machine. Also less use of extra material is mostly better, because any added material can cause impurities in the desired and unknown tensile strength of glass.

To tension the glass, claws of steel are made, however the surface that loads the aluminium strip needs to be 100% parallel with the attached strip onto the glass for accurate and pure tension within the pane. Therefore after welding two RVS strips, the smaller one that will load the aluminium strip is milled.

After milling the wholes are drilled. For exact location, a centre line is used. Before drilling a big hole, a smaller hole is drilled. The structure can rotate the specimen such that it will load the tension in-plane. For more information see appendix C.

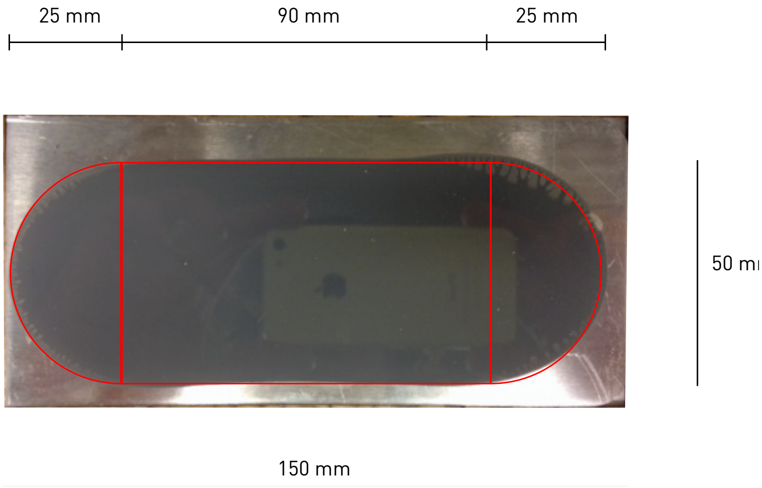
Expectation

The stress that can be developed in case of full capacity tensioning of the test machine is 100 kN. From the bending tests, the maximum tensile stress of chemically strengthened glass is 750 MPa based of the technical information given by AGC's Leoflex architectural glass (see appendices). The cross section of the specimen is 80 mm by 2 mm, so 160 mm2. The maximum force then can be calculated by multiplying the cross section A with the maximum tensile stress.

$$F_{\max} = A \cdot \sigma_{\max}$$

When filled in the equation the maximum theoretical force that can be applied to the glass specimen is 120 kN. That is 20 kN above the capacity of the testing machine. But because of the connection that is needed to test the specimen on its in-plane tensile strength, the glass will fail below the theoretical tensile strength, because of the high peak stresses that will be created right around the connection where the tension will be transferred from the sub-structure to the glass.

The adhesive will transfer the tension from the designed sub-structure to the glass via shear. The shear strength of Araldite 300 is 20 N/mm maximum. Meaning that the maximum tension force of 120 kN needs to transfer by the adhesive at a certain area



a

b $$A_{real} = length\ \text{rectangle}\ x\ width\ \text{rectangle} + \pi r^2$$

39. Cold Twisting Methods

a. Real surface adhesive

b. Formula calculating real surface

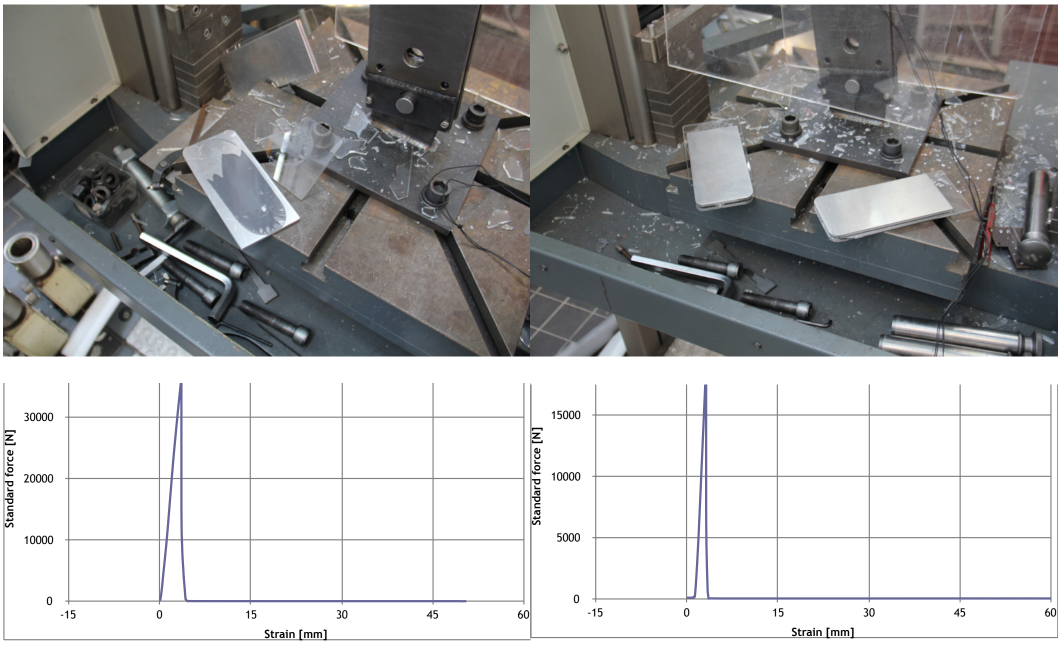
where it does not fail on its shear strength. The minimum total area that is required can be calculate as follows:

$$A_{\min} = \frac{F_{\max}}{\sigma_{\max}}$$

The minimum area of adhesive is then 6000 mm2. Because the sub-structure is designed such that the tension force can be introduced at both sides and ends of the specimen, so four times 1500 mm2. The actual used area however is bigger and can be read from the picture taken when preparing the specimen (fig. 39).

That brings a total capacity of more than four times the actual area needed. This is done in case of one side will failure, the other area could carry the load by itself with a safety factor of 2.

The smaller the area, the higher the peak stresses will be, but a glued area on the edges is more risky because of the surface flaws creating by cutting the glass and combined with the tension onto the surface of the glass result in a tearing failure. This is avoided by enough space around the glue and the edge of the specimen.



a

b

40. Results pull-out test

a. Specimen #1

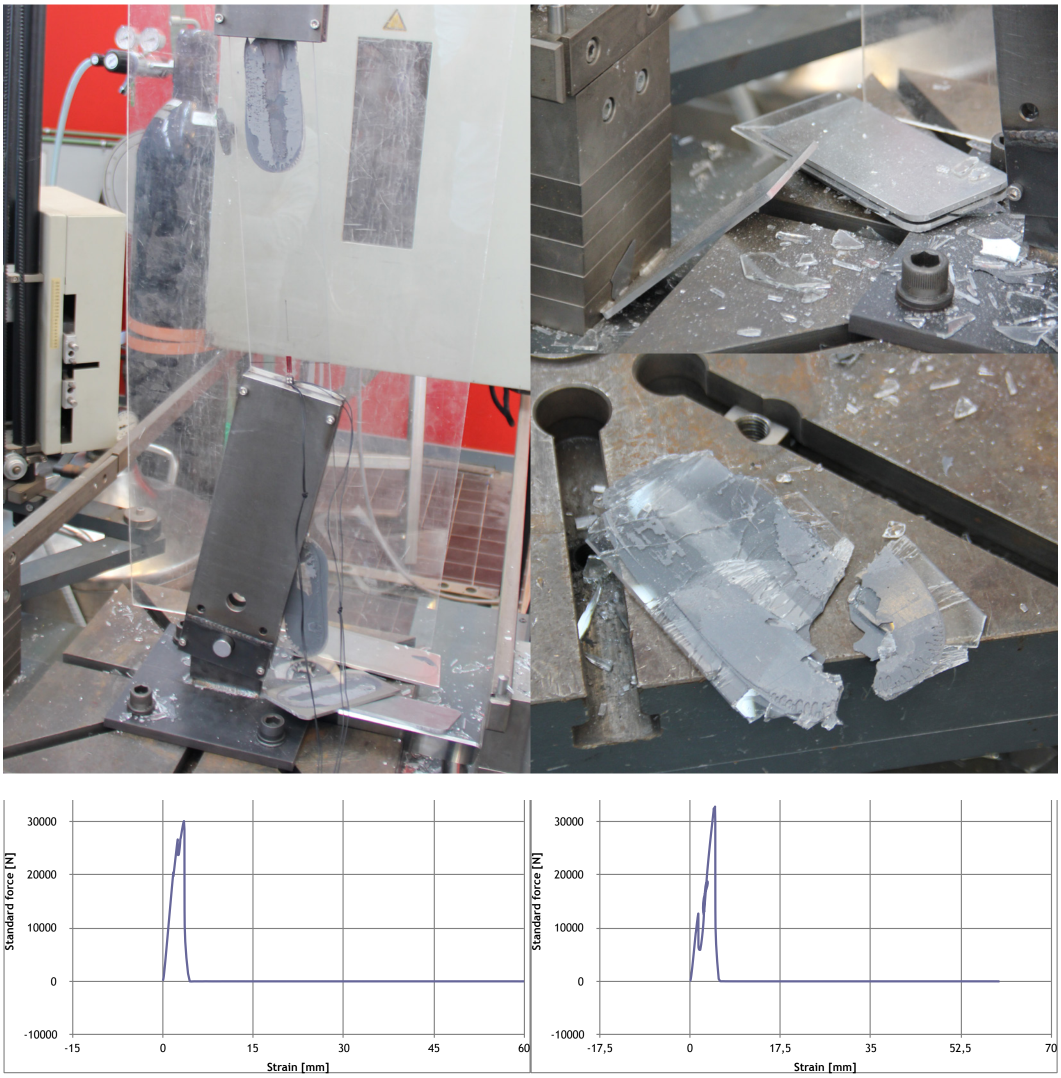
b. Specimen #2

Results

From the four pull-out test that are performed, three are above 30 kN. Given that the specimen has a width of 80 mm and a thickness of 2 mm, a minimum tensile stress of 225 MPa is created until failure. Only the second specimen failures with almost half of the other reached tensile strength. Another fact that can be seen in the diagrams is that the function does not behave constant linear over time, exactly when the failure occurred at one side of a glued aluminium plate.

The released aluminium plates indicate a proper adhesive connection, yet were not sufficient enough to transfer a tension load equal to the ultimate tensile strength of the chemically strengthened glass. Theoretically this is three times higher, but practically seeing it should be definitely higher than the values that are reached now, because the connection is the weakest part in this design of the test set-up.

Specimen #1 (fig. 40a) reached a tension load of 36 286 N and a strain of 3.570 mm. The strain gauges in the middle however measured a strain of 3.145 mm.



a b

41. Results pull-out test

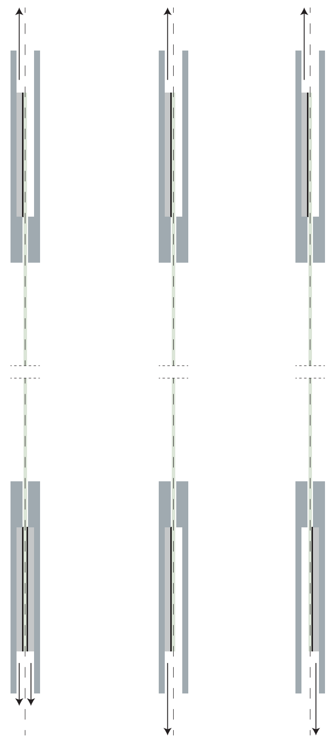
a. Specimen #3

b. Specimen #4

Specimen #2 (fig. 40b) reached a tension load of 19 038 N and a strain of 3.184 mm. The strain gauges in the middle however measured a strain of 1.625 mm.

Specimen #3 (fig. 41a) reached a tension load of 30 164 N and a strain of 3.576 mm. The strain gauges in the middle however measured a strain of 2.620 mm.

Specimen #4 (fig. 41b) reached a tension load of 32 767 N and a strain of 4.923 mm. The strain gauges in the middle however measured a strain of 2.850 mm.



42. Results pull-out test

a. 1/4 aluminum plate failures

b. 2/4 aluminum plate failures same sides

c. 2/4 aluminum plate failures opposite sides

A jump in the diagram can be explained by the failure of the adhesive between the glass specimen and the aluminium plate. Failure of the adhesive at one side does not mean directly a failure of the pull-out test, because the construction still have the ability to make a sufficient grip at the other side, which apparently gave enough grip to even increase the applied load. However, because of the failed adhesive, the aluminium plate felt down to the ground which created a gap between the glass specimen and the construction (fig. 42a). This happened to specimen #1, #3 and #4. The last two specimens however were still able to pull-out further, until also the other side felt off in case of #4. Specimen #3 was special (fig. 42b,c), because at the top as well as the bottom one side felt off before total failure.

According to the measurements of strain gauges at both sides at the middle of the glass specimen it revealed that the strain developed exactly the same at both sides. Meaning that there are no internal bending stress presented, solely in-plane normal tensile stresses at the middle of the specimen.

So the created gap causes an eccentric loading to the glass specimen, and therefor high bending stresses concentrated nearby the glued aluminium plate. Probably because the specimen has such a low thickness, it behaves like a membrane which explains the concentration of the bending stresses. This also means that the adhesive needed to transfer the load by peel stresses instead of shear stresses. The used adhesive is way less stronger in this way which also can be an explanation why the adhesive failed way before the strength-to-failure initially had been calculated. Also the maximum shear stress capacity of the adhesive could have reached way earlier than expected, because the average is calculated while in reality the maximum is higher. Still it is strange, because a safety factor of more than four is taken into account.

A second reason why the specimen failed earlier than expected could be the highly developed concentrated bending stresses in the glass. Relatively existing flaws at the surface teared out more in case of bending than a perfectly made uniform stress distribution when pulled at both sides.

A third reason why the specimen failed earlier than expected is that the strength of the adhesive were reduced because of ageing.

The second specimen was the only one that the adhesive was definitely not the reason why the specimen failed. Although this scenario is desired for all done tests, the ultimate tensile strength of the glass was so low, that probably the glass itself was damaged too much. Any scratch in the surface directly means a decrease in strength of the glass.

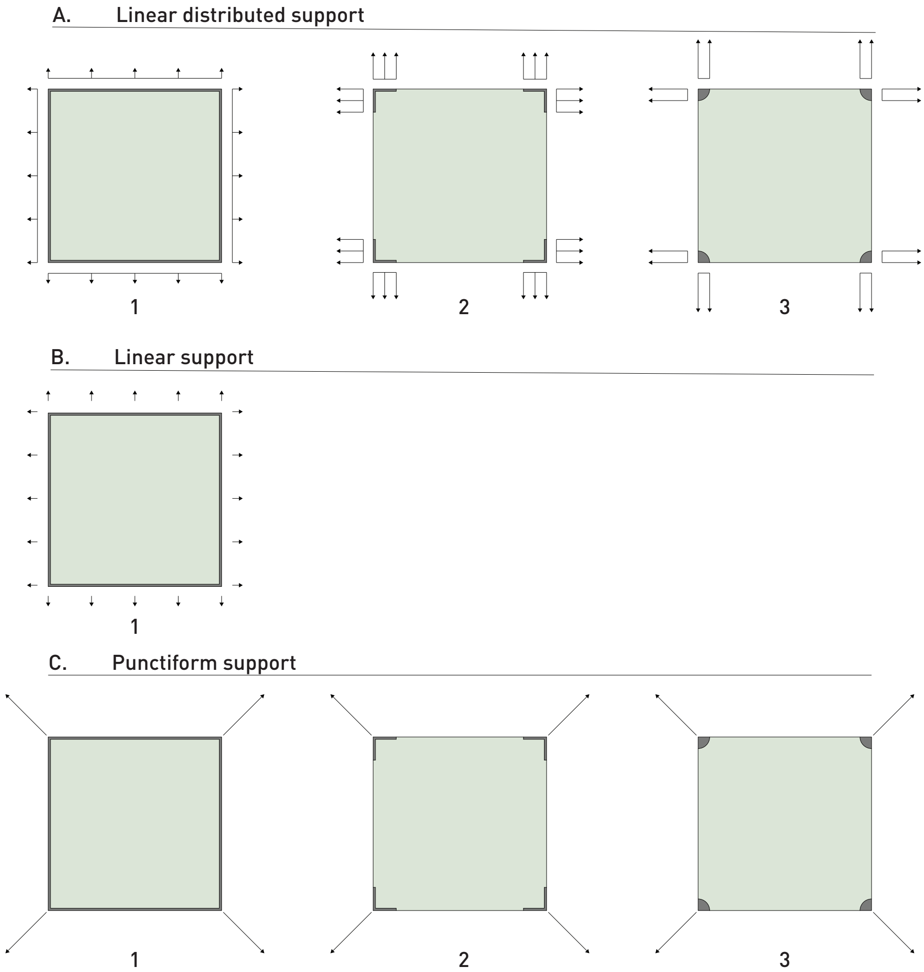
5.4 CONCLUSION

Instead of using the bending tensile strength obtained by a flexural load, a non-standard test method is made that obtains the true tensile strength of chemically strengthened glass. Results from several pull-out tests in the lab showed a tension load can be applied via adhesive that creates stresses above 250MPa. This is a third of the mentioned maximum bending tensile stress of 750MPa form the literature. Although its lower, this result has the same yield strength as structural A36 steel used in the building industry. Of course there need to be taken a design safety factor into account. Therefore a safe design stress of 100MPa will be used for further calculations for tensioning and bending high strength thin glass into an anticlastic surface. Further research is needed what stresses are developed in relation to the bending and the tensioning.

06

PRELIMINARY DESIGN
OF A COMPOSITE EDGE CONNECTION THAT ENABLES THE TENSIONING.

Which connection methods are possible to tension glass?

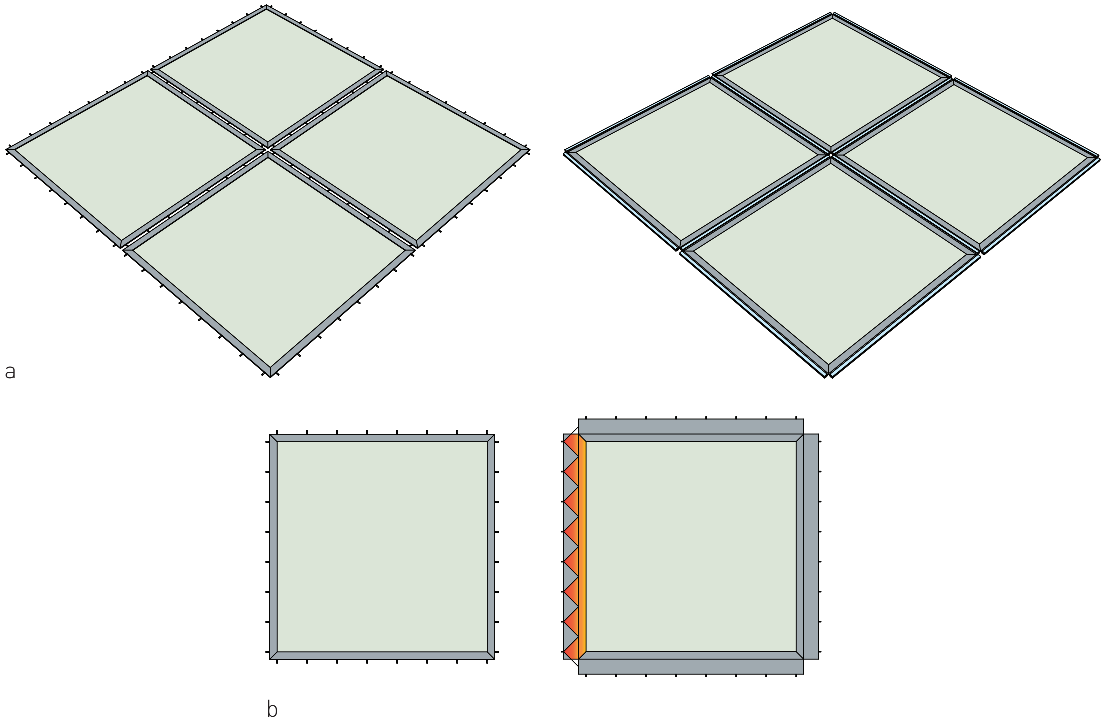


43. Principles to tension glass via adhesive

Support & Grip section (surface adhesive)

6.1 DESIGN OF A CONNECTION

It can be assumed that chemically strengthened glass is capable of transferring a tensile load in-plane via an adhesive. The relevant question then is how and where this adhesive should be applied. To answer this question the support of the glass that give the tension load already can be thought of by designing the principle. Because the support can be linear (distributed) all or partly along the edges (fig. 43), it somehow need to grip. By making several principle designs that could fulfil the explained connection methods, it can give more information about the easiness of fabrication and assembling, structural behaviour and lightweightness of the connection. All these aspects can be decisive how the tensile load as best can be applied.



44. Connection method

a. Panel support 3D view (l) point support (r) distributed support

b. Point support top view (l) without extra material (r) with extra material for equal stress distribution

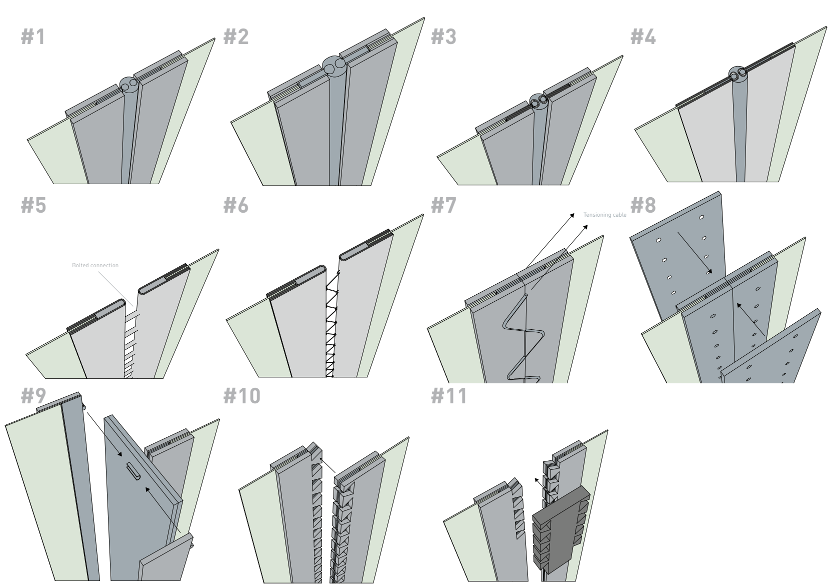
6.2 SWOT ANALYSIS

By logical thinking the amount of possible connection methods can be reduced that should be verified via numerical simulation in order to make the conclusion if the connection is able to cold bend the thin glass into an anticlastic shape. If we compare for example two panel designs with both adhesive all along the edges but one is point supported and the other distribute supported (fig. 44a), then there already can be said something about the structural behaviour that influence the transparency of a configured panel façade.

Because the first panel configuration transfers its tension load via points, the stresses are in the beginning not equal. To have an equal stress distribution within the glass, material is needed for the introduction of the non-uniform stresses between the point supports and the grip section of the adhesive (fig. 44b).

On the other hand, if the second panel configuration is chosen that supports the all along the edge, the connection method is able to transfer the stresses directly uniform and equal divided, but is very hard to fabricate and assemble!

Brainstorming about connection methods in this way can tell a lot about the challenges and potentials of each design. Therefore in



a

STRENGTH	**W**EAKNESS
OPPORTUNITY	**T**HREAT

b

45. Connection analysis

a. Designs

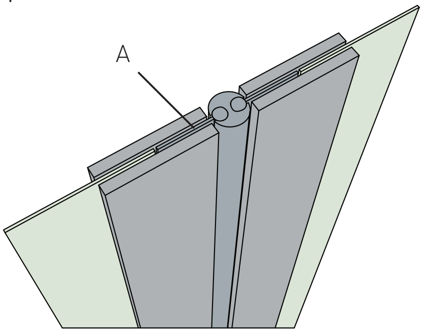
b. Applied SWOT method

this study more than ten connection methods are discussed (fig. 45a) by reviewing the earlier mentioned aspects with the help of a Strength, Weakness, Opportunity and Threat-analysis or SWOT-analysis (fig. 45b).

To analyse which connection methods are best for the design concept, each design will be analysed individually via the SWOT analysis. Negative design aspects are trying to solved in the following connection method, starting with #1. Thereafter a conclusion can be made which connection method or category have the most potential as support structure for the idea of cold bending thin flat glass into a double anticlastic curvature.

SWOT-analysis (#1-#4)

#1



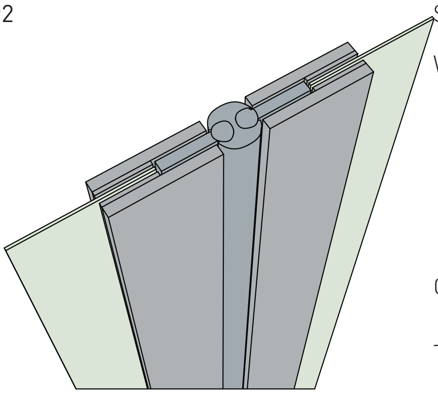
STRENGTH
+ Equally supported at both sides of the glass

WEAKNESS
- High stress concentration part A
- Accuracy needed during fabrication
- Hinge connection that does not create a stiff surface
- Difficult to connect panels with each other in case of side supported

OPPORTUNITY
Part B can be made thicker (#2) or being replaced by a stronger, yet thinner material (#3)

THREAT
Extruded part become to thick

#2



STRENGTH
+ Equally supported at both sides of the glass

WEAKNESS
- By making part A thicker, part B becomes difficult to make
- Even higher accuracy needed during fabrication
- Still hinge connection that does not create a stiff surface
- Still difficult to connect panels with each other in case of side supported

OPPORTUNITY
Extrusion profile can consist of two separated parts (#9)

THREAT
Whole connection becomes to heavy compared to the glass panel itself

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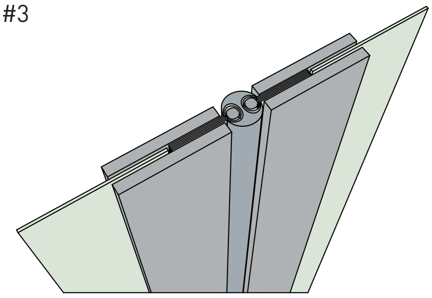
#3



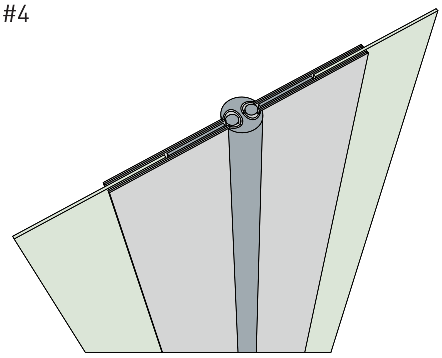
STRENGTH
+ Equally supported at both sides of the glass
+ By replacing A made of steel by C made of FRP creating a stronger, yet thinner part

WEAKNESS
- Still hinge connection that does not create a stiff surface
- Still difficult to connect panels with each other in case of side supported
- Still accuracy needed during fabrication
- And lot of different used materials, which make it complex

OPPORTUNITY
FRP is a high strength-to-weight material, connection might be made totally from FRP (#4)

THREAT
de-lamination FRP can occur at the place of the rod, because of badly designed connection (hinge)

#4

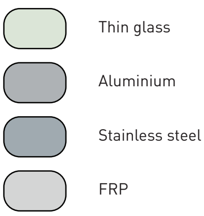


STRENGTH
+ Equally supported at both sides of the glass
+ By replacing glued steel with FRP, a flatter connection (more in-plane stresses)

WEAKNESS
- Still hinge connection and out-of-plane transferring stresses within extrusion profile
- Still accuracy needed during fabrication
- Still difficult to connect panels with each other in case of side supported

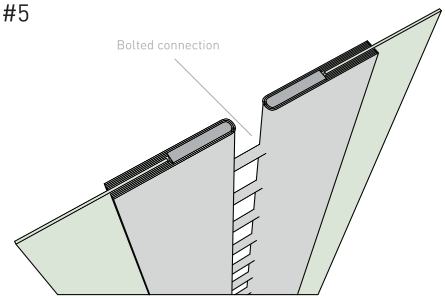
OPPORTUNITY
Get rid of the extrusion profile (#5 - #11)

THREAT
Still de-lamination can occur in the FRP material at the place of the rod
Dry spots after infusion process at the fabrication of FRP and therefor might not equally support the glass



SWOT-analysis (#5-#8)

#5



STRENGTH
+ Equally supported at both sides of the glass
+ FRP used in a better way without the threat of de-lamination
+ Connection can be made rotation-free not difficult to fabricate
+ Space for adjustability

WEAKNESS
- Takes much effort to mounting a panel
- Connection by bolts at the expense of transparency, because of introduced point load

OPPORTUNITY
Replacing bolts by a connection method that counts less individual parts (#6)
Replacing bolts by connection method integrated into the glued parts (#7 - #11)

THREAT
Bolts do no not behave structurally the same as the rest of the panel which result in a different deformation, that can be noticeable

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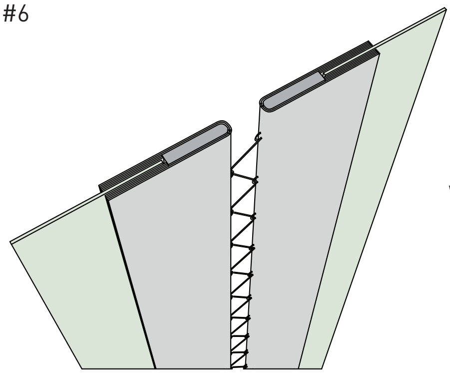
#6



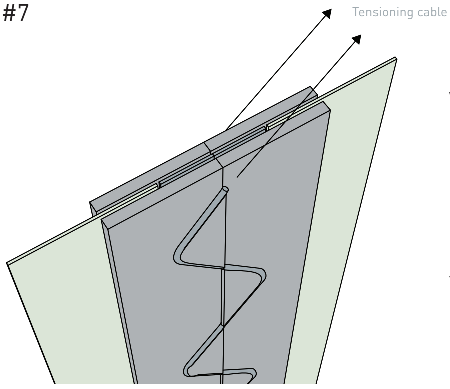
STRENGTH
+ Equally supported at both sides of the glass
+ FRP used in a better way without the threat of de-lamination
+ Connection can be made rotation-free not difficult to fabricate
+ Space for adjustability

WEAKNESS
- Takes much effort to mount a panel
- Connection by rope/cable at the expense of transparency, because of introduced point load
- Hinged connection, less stiffness overall structure

OPPORTUNITY
Moving the connected part to the sides of the panel instead of in between to reduce used space (#7&#8)
Replacing rope/cable by connection method integrated into the glued parts (#10&#11)

THREAT
Easiness of sliding and tensioning a cable in this way is questionable (lots of friction)

#7



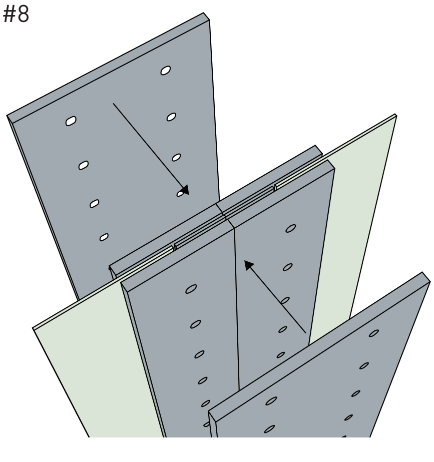
STRENGTH
+ Equally supported at both sides of the glass
+ Less space connection, yet demountable

WEAKNESS
- Transferred stresses moved more out-of-plane
- Strange woodie-ropie construction
- Unequally supported at the connection, takes material for equal distribution of stresses

OPPORTUNITY
Replacing the rope by a more simple construction (#8)

THREAT
Easiness of sliding and tensioning a cable in this way is questionable (lots of friction)

#8



STRENGTH
+ Equally supported at both sides of the glass
+ Less space connection, yet demountable

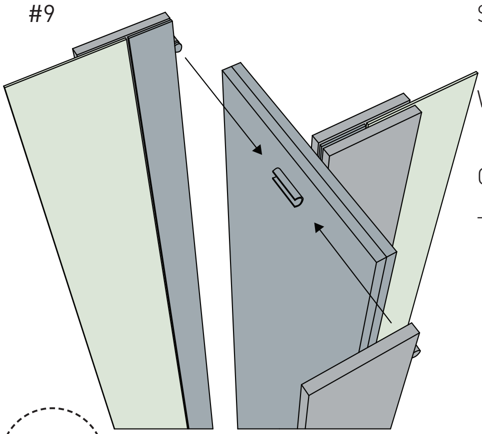
WEAKNESS
- Connection becomes heavy in relation with the glass

OPPORTUNITY
Improving dry connection by less used individual connection parts (#9)

THREAT
Too stiff connection, total different deformation behaviour that blocks the desired anticlastic shape of the glass

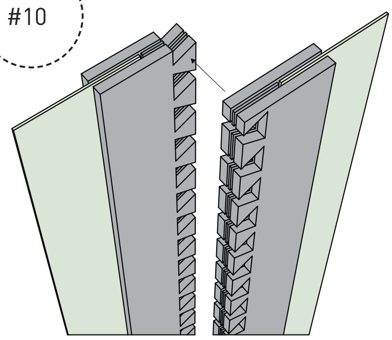
SWOT-analysis (#9-#11)

#9



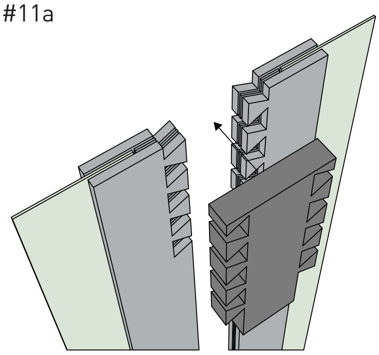
STRENGTH	+	Equally supported at both sides of the glass
	+	Less space connection, yet demountable
WEAKNESS	-	There is a sub-structure created that are conflicting the asked design criteria
OPPORTUNITY		*Integrated connection*
THREAT		*too stiff connection, total different deformation behaviour that blocks the desired anticlastic shape of the glass*

#10

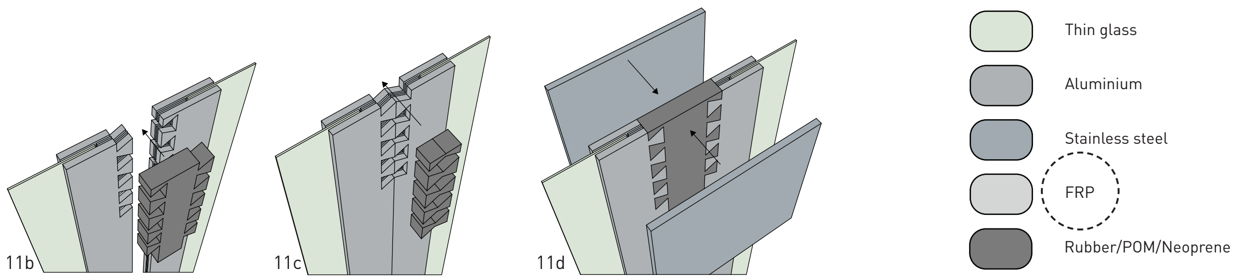


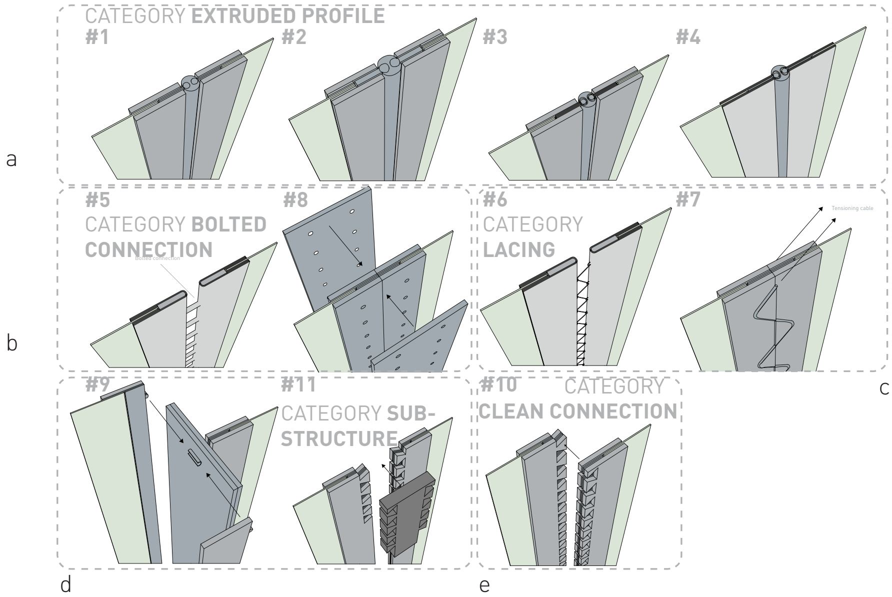
STRENGTH	+	Equally supported at both sides of the glass
	+	Integrated connection
WEAKNESS	-	Connection is too stiff yet, considering the twisting movement that is desired
OPPORTUNITY		*Put something soft between the connection that not give too much friction*
THREAT		*The soft part is not able to transfer the tension force along the edges*

#11a



STRENGTH	+	Equally supported at both sides of the glass
	+	Clean connection
WEAKNESS	-	The need of an extra individual connection material
	-	The paradox the connection needs to be soft, yet with high tensile strength
OPPORTUNITY		Replace the rubber for epoxy reinforced with fibres of glass: FRP and integrate the connection within the glued part
THREAT		When the panel is connected and twisted: what will prevent the "zip" connected panel from fall out of its support?



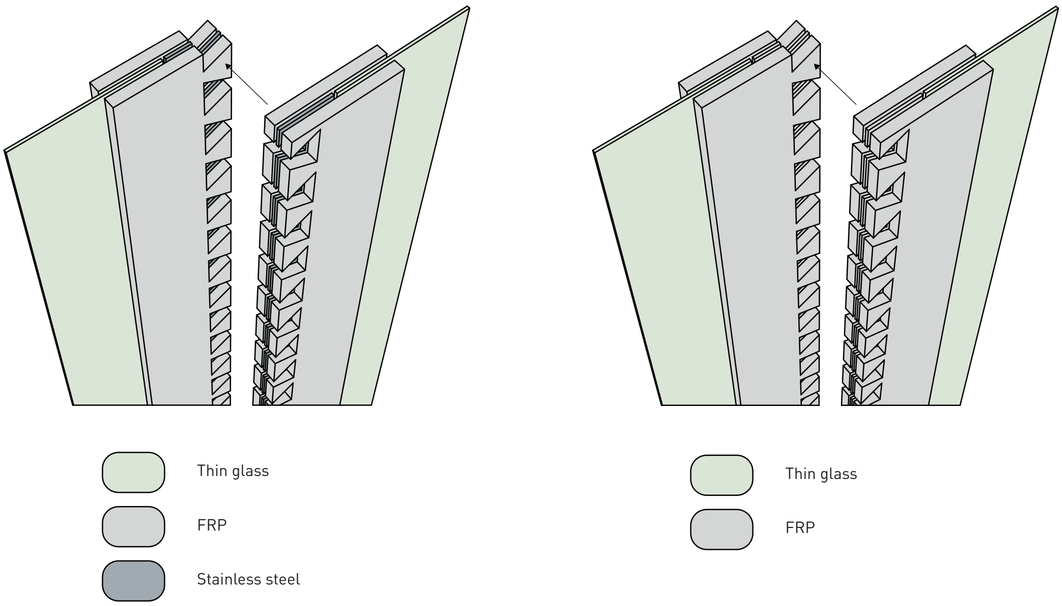


46. Categories type of connection

a. Extruded profile
b. Bolted
c. Lacing
d. Sub structure
e. Clean connection

All connections can be categorised into five different type of connection methods (fig 46). #1 - #4 are all connection that are line supported with an extruded profile. #5 and #8 transfer their tension load through bolts. #6 and #7 are hold together by the technique of lacing. #9 and #11 using a substructure to enable a three-dimensional displacement started from a flat surface. And #10 uses no loose construction material to create a tensile membrane structure. This connection was initially designed with steel material. The joint is a dovetail connection that often can be seen in structures made out of wood. Because several connections also were made out of a fibre reinforced material, the potential of composing the stiffness would also be ideal in the zipped connection method. To discover which kind of stiffness and where the support around the panel is needed, a numerical simulation needs to be made. The design of the support however can be determined now and is visualised in figure 47.

Fibre-reinforced polymer material is composed by a volume of fibres and a volume of a polymer matrix. The stiffness depends ratio between the volume and what kind of fibres and matrix is used, but also the direction of the fibres influence how flexible the composed edge material is going to be. In this case it is wise to pick glass fibre to simulate the same coefficient of expansion as the glass plate itself. Often the composite material have multiple layers with different directions of fibre lay-up. In this research the global stiffness of the cross section only be dealt with to simplify



47. FRP “ZIP” connection

a. With stainless steel insert

b. Totally made from FRP

the calculations. Calculations should verify at which places the elastic modulus or stiffness should be higher or lower to create a double anticlastic curved panel with a maximised twist. To maximise the twist an equal stress distribution of the tensile stresses need to be created by the composed edge material.

6.3 CONCLUSION

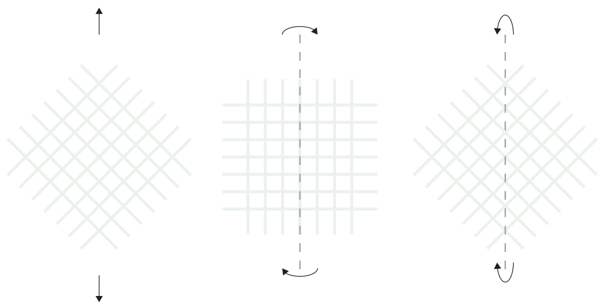
Via a SWOT-analysis several aspects are reviewed from several connection methods. Aspects such as easiness of fabrication and assembling, structural behaviour and lightweightness are reviewed. Eleven connection methods are categorised into five different connection types. From all these type of connection, a clean connection made out of a composite “zip” connection got the most potential one for a definitive design. Further research is needed which stiffness is best along the edges of the glass plate and at which place support is needed to create a cold bend hypar surface of thin glass.

Several gradients concepts will be analysed by starting with a glass plate that is been surrounded with an edge that has a constant E. Analysing different gradient options opens up information which concept will be best to generate an equally devided stress distribution within the glass plate. Such optimisation of E can only be made with composite materials.

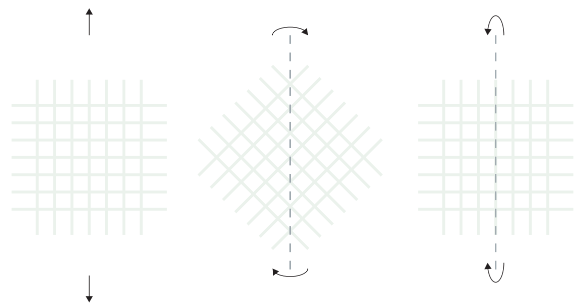
07

NUMERICAL INVESTIGATION OF A DYNAMIC EDGE STIFFNESS THAT ENABLES THE ANTICLASTIC GEOMETRY.

Which gradient of edge stiffness is most effective tensioning glass for maximum cold bend double anticlastic curvature?



a



b

48. Force & Strain of FRP material

a. More strain in low stiffness direction

b. Lower strain in higher stiffness direction

7.1 DETERMINING THE SUPPORT STRUCTURE

As discussed in the previous chapter the edge material is going to be made out of glass fibre-reinforced polymer. The biggest reason for this is that the stiffness of the edge can be composed in such a way the created tensile stresses by the twisting and tensioning are equally divided over the glass plate. This means that the stiffness and the dimensions of the edge now need to be determined to make a definitive design of the dove-tailed frp, thin glass panel that is capable of being treated as a stiff structural fabric.

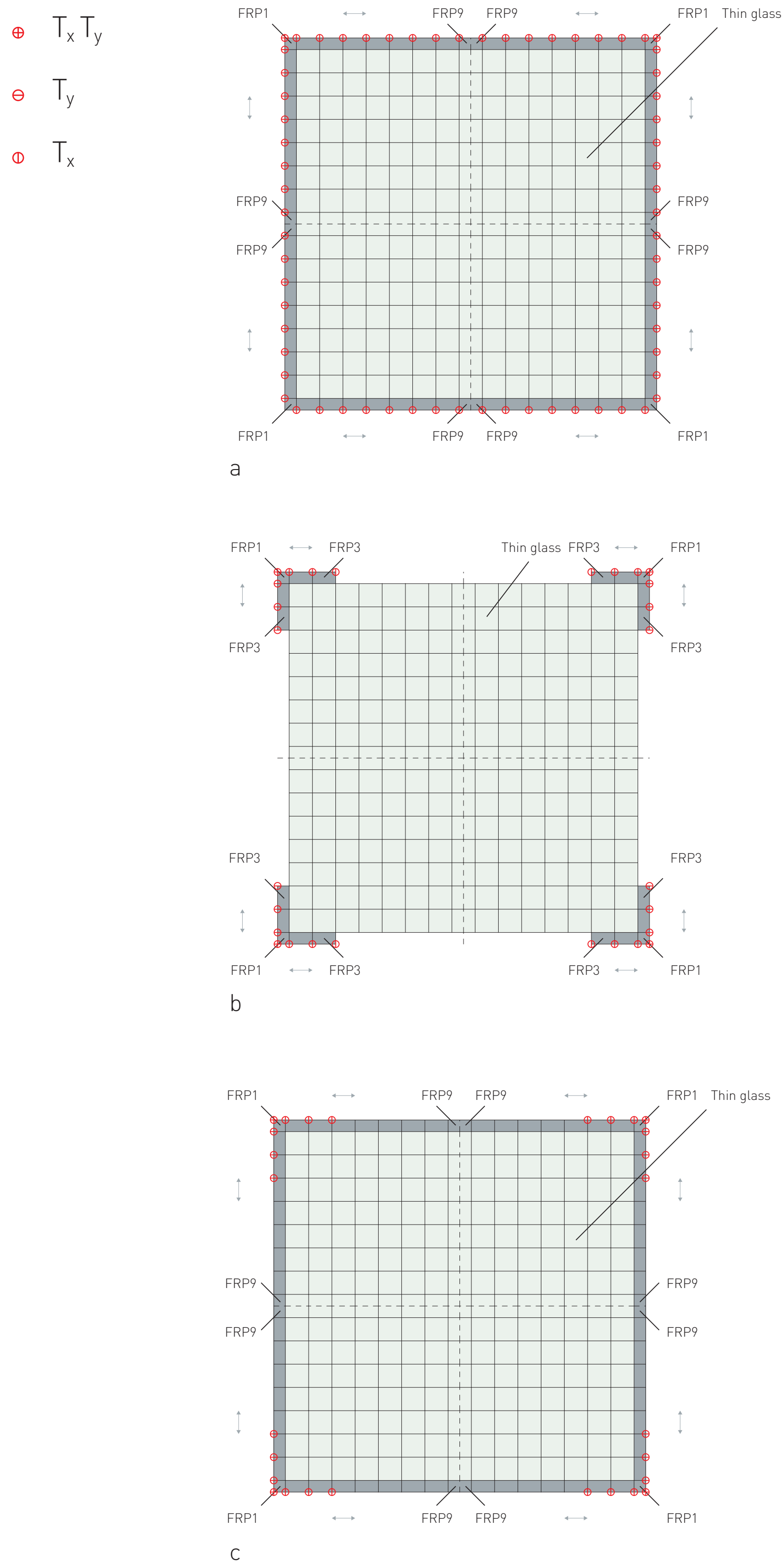
Finding the right stiffness of the edge can tell a lot of how it should be designed. Stiffness depends on thickness of the material, but also in which the direction of the fibres are placed. In figure 48a is showed that tensioning or torsion have lower stiffness and higher strain than the 45 degrees turned fibres in figure 48b. If a combination of is used of both configurations in multiple layers a stiffer composite material can be composed. One layer of fibres and epoxy is equal to approximately 0.25 mm. Starting with an edge thickness of 50 mm, means 200 layers of fibres. In this numerical research three models (fig. 49) are investigated which design and stiffness should adjust best to minimise peak stresses within the glass plate. Five different stiffness gradients

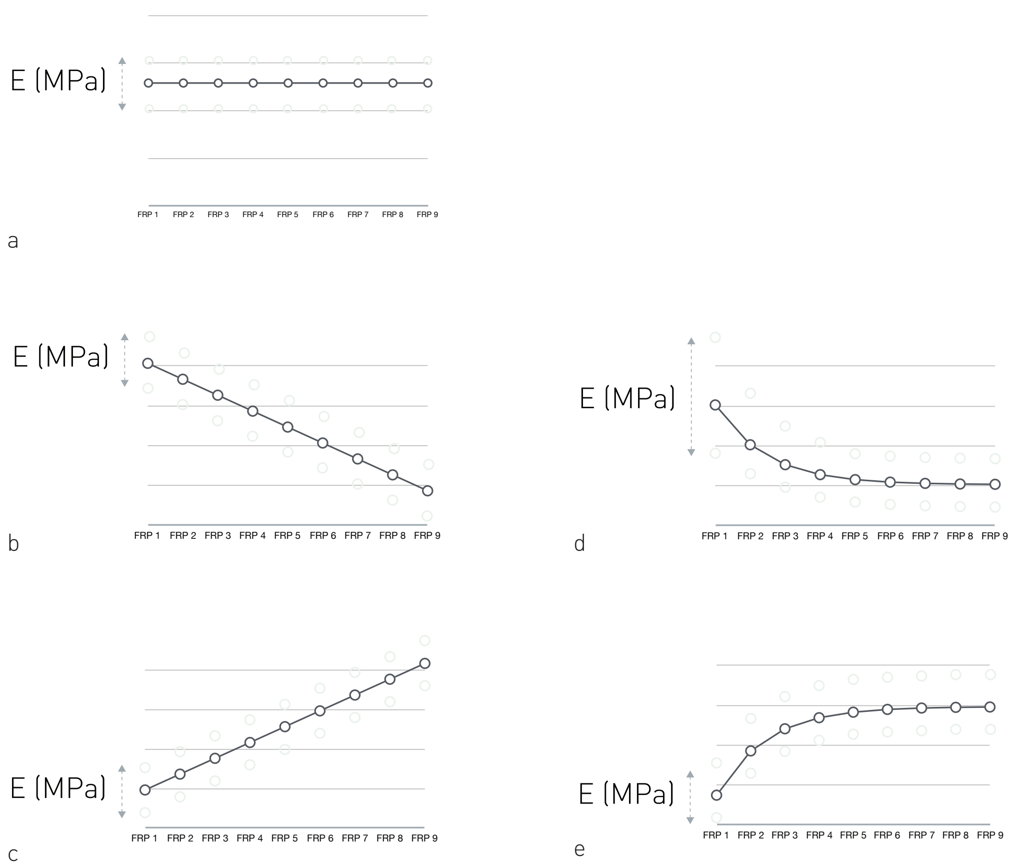
49. Three different analysed models

a. Model I: Twisting from the middle

b. Model II: Twisting from the corners

c. Model III: Twisting from the corners





50. Five different stiffness gradients

a. Constant stiffness

b. Linear decreased stiffness

c. Linear increased stiffness

d. Digressive decreased stiffness

e. Digressive increased stiffness

are applied (fig. 50). Of course writing an algorithm for this case study eventually should come up with more precise answers, but because this is just the start of a new concept to twist glass, all stiffness gradients are numerical modelled on its own to give a fast, yet simple indication what kind of edge design should be considered for a final definitive (concept) design. The finite element programme that is being used is Diana from TNO.

Model I and III are different because of its constraints, although both have covered all glass edges with FRP material. Model II however has reduced FRP edges, but the same constraints as model III. Where model I is twisted from anchored middle points, are model II and III twisted from pinned corner points.

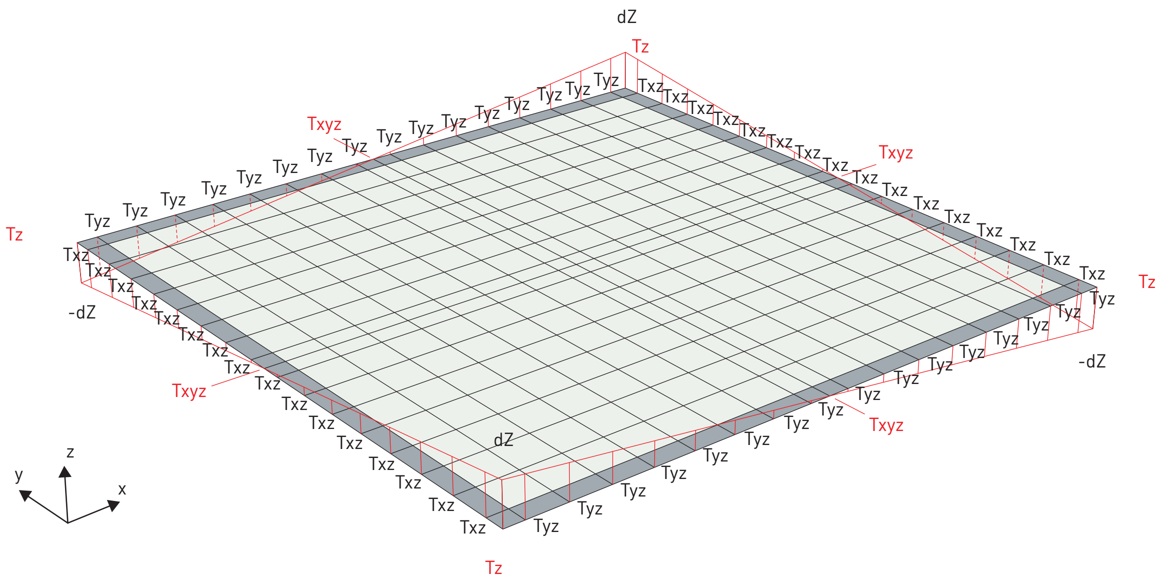
All models have one 0.55 mm glass plate of 1500 mm by 1500 mm and a FRP edge of 50 mm. In total the panel design is 1600 mm by 1600 mm, divided into smaller rectangles. Each rectangle within the grey coloured FRP edge can be changed manually into a different value of elastic modulus or stiffness. The

applied scenarios are showed in figure 50, where FRP 1 is at the corners and FRP 9 at the middle of the composed panel design.
In figure 49 can be seen the three models which are researched. Model I and III are different because of its constraints, although both have covered all glass edges with FRP material. Model II however has reduced FRP edges, but the same constraints as model III. Where model I is twisted from anchored middle points, are model II and III twisted from pinned corner points.

All models have one 0.55 mm glass plate of 1500 mm by 1500 mm and a FRP edge of 50 mm. In total the panel design is 1600 mm by 1600 mm, divided into smaller rectangles. Each rectangle within the grey coloured FRP edge can be changed manually into a different value of elastic modulus or stiffness. The applied scenarios are showed in figure 50, where FRP 1 is at the corners and FRP 9 at the middle of the composed panel design.

Each following paragraph one model is showed with the results of the five differently applied stiffness gradients. The results of the maximum internal S1 cauchy stresses caused by the prescribed displacement are displayed in top view. Because this case study mainly focusses on the feasibility study on the possibility of cold bending a flat sheet of thin glass into a double anticlastic curved surface by adding tension to the twisting via a (G)FRP composite support structure, no loads are applied other than the prescribed displacement. Because the glass is so thin and the edge material is made out of lightweight GFRP, the dead load of the composed panel also is low and have little influence to a change of the developed stress distribution caused by the prescribed displacement. Wind load, however, could change the deformation of the panel strongly, but will be neglected for now.

Because the thin sheet of glass is relatively so thin compared to its size, it shows strong membrane behaviour which mean that the analyses of the numerical simulation should be solved with a non-linear static analysis. Because of this analyses, the calculation is done with iterative steps. By using steps, the prescribed displacement is partitioned. Each model is modelled with a linear prescribed displacement along the edges with a maximum of +/- 100 mm at the corners and always 0 mm at the middle. Most of the times 20 load steps are used, which mean a prescribed displacement of 5 mm each step in Z-direction.



51. Model I
Twisting from the middle: FRP covers all edges of the glass

Input: Constraints and prescribed displacements

7.2 NUMERICAL SIMULATION I

Input

Model I is made out of a single 0.55 mm squared thin sheet of glass covered all along the edges with FRP material with a thickness of 50 mm. In this scenario all four edges are totally supported. The middle point is constrained in all three possible translations. The corners are only supported in Z-direction. A torsional moment at the middle point is applied by giving all points along each edge a linear prescribed displacement in such a way the panel gets twisted.

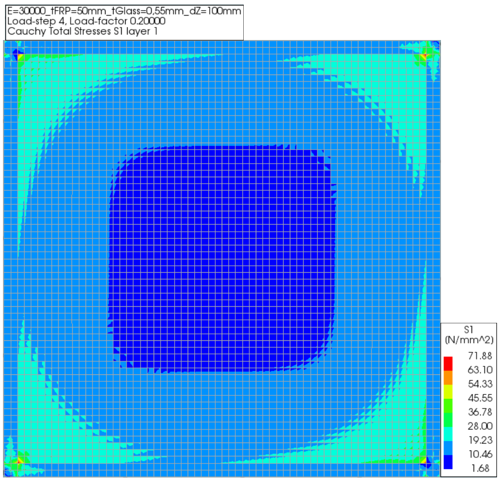
Results & Discussion

A. Constant stiffness

Maximum twist

dZ = 20mm

Twisting model I with a constant edge stiffness show high stress development in the corners.

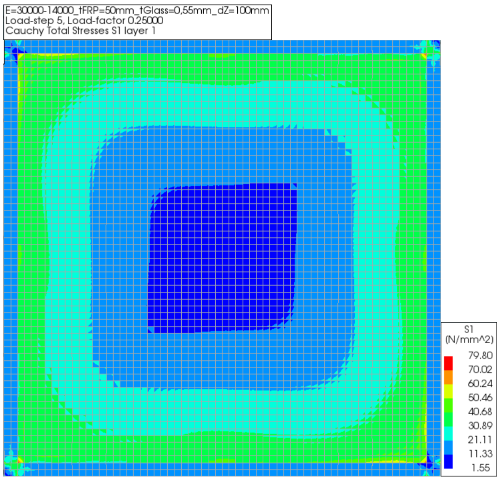


B. Linear decreased stiffness

Maximum twist

dZ = 25mm

By lowering the stiffness in the middle stresses can be transferred further along the edge and eventually into the glass plate. This type of stress development is desired, because it causes a more divided stress distribution within the glass and in the end also a higher possible twist of +/- 25 mm each corner instead of 20 mm.

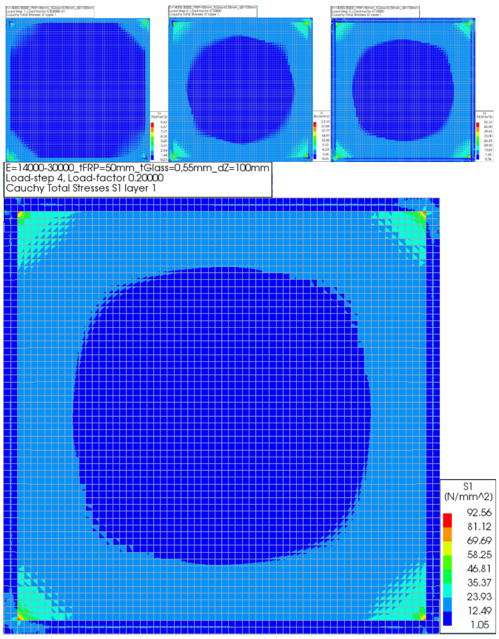


C. Linear increased stiffness

Maximum twist

dZ = 20mm

Now, if this linear stiffness is reversed that instead of the middle, the corner points have lower stiffness, internal stresses in the glass are becoming higher than in the edge and in the end also less twisting is possible.

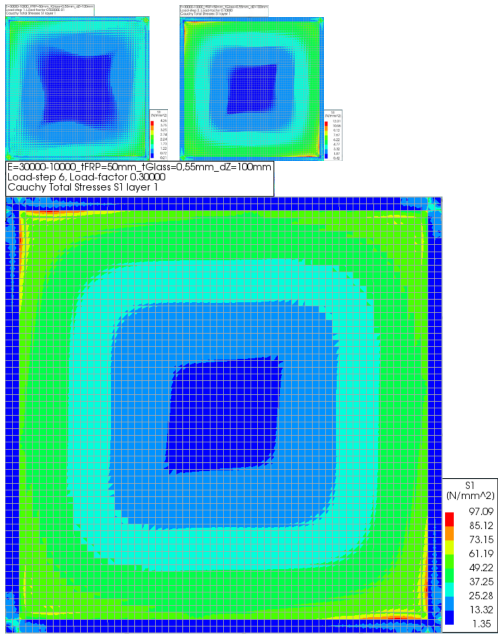


D. Digressive decreased stiffness

Maximum twist

dZ = 30mm

Using a digressive decreased stiffness from the corners to the middle, a too quick decrease can lead to high stress concentrations just near the corners. However, the perfect situation clearly lies between a decreasing stiffness gradient.

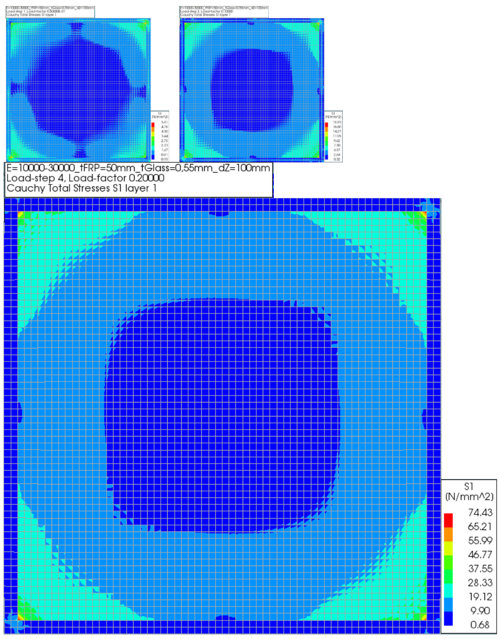


E. Digressive increased stiffness

Maximum twist

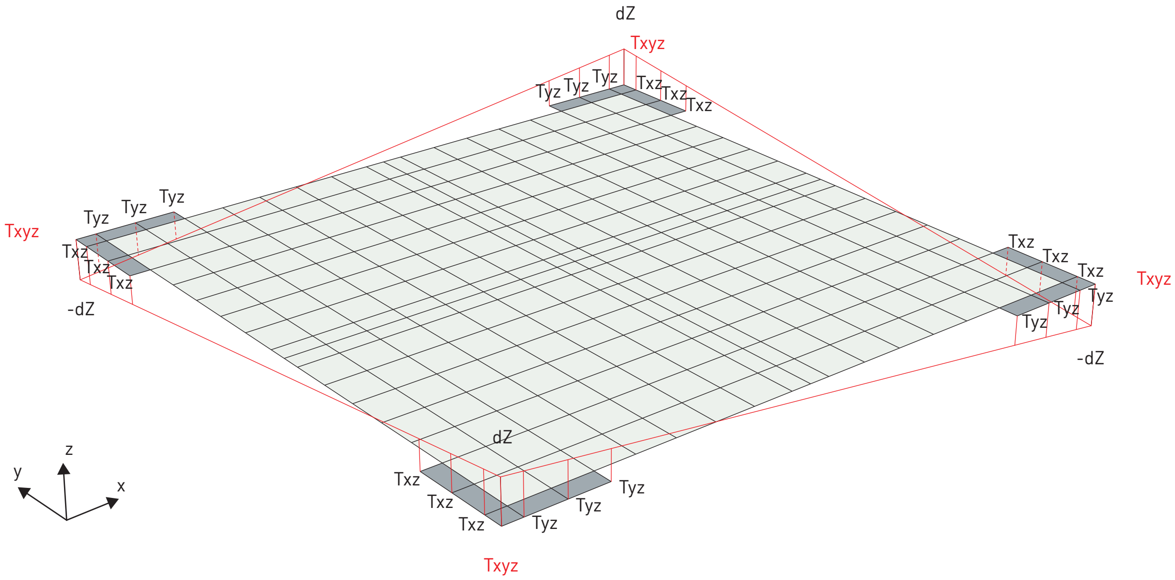
dZ = 20mm

A digressive increased stiffness have high stress concentrations in the corners of the glass, just as the linear increased one, although the peak stresses calculated are lower in this scenario. Probably because overall the stiffness around the corners in this situation is more stiff, thus more favourable.



Conclusion Model I

Double bend a flat thin sheet of glass of 0.55 mm into an anticlastic curvature by a supporting it all around the edges with FRP material of 50 mm can be safely done up to 30 mm when higher stiffness is used in the corners than in the middle.



52. Model II
Twisting from the corners: FRP covers only near the corners

Input: Constraints and prescribed displacements

7.3 NUMERICAL SIMULATION II

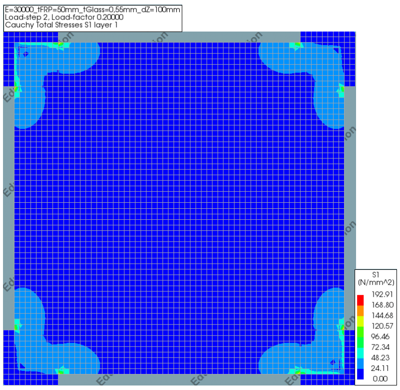
Input

Model II is made out of a single 0.55 mm squared thin sheet of glass covered solely at the corners along the edges with FRP material with a thickness of 50 mm. In this scenario all four corners are totally supported. The corner points are constrained in all three possible translations, yet with a prescribed displacement. All other points are also constrained in each direction by translation, but do however can move free along each edge. In this way points are moving towards the corners instead of towards the middle when twisting compared with the previous model.

In this scenario 50 mm thickness as input for the FRP appeared to be too stiff for several applied stiffness gradients. That is why as input also a thickness of 5 mm is chosen, which is ten times lower.

Results & Discussion

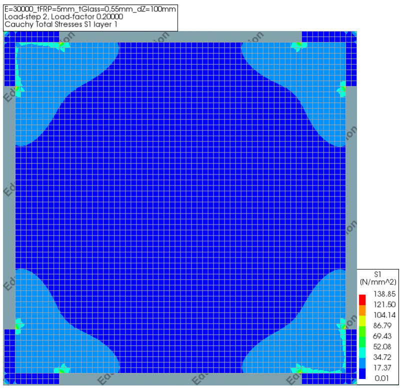
A. Constant stiffness



Maximum twist

dZ = 5mm

tFRP = 50mm



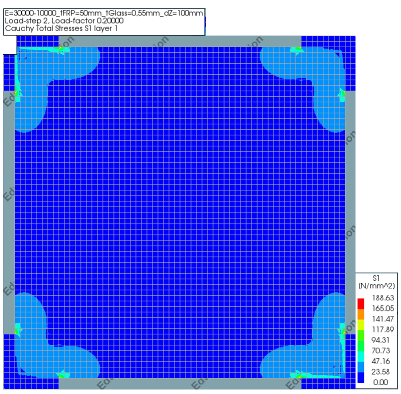
Maximum twist

dZ = 15mm

tFRP = 5mm

Reducing the area where the FRP material covers the edges of the glass directly can be linked to a reduced twist capability in which stress concentration do not becoming too high. Lowering the constant stiffness would become insufficient because the elastic modulus that get a magnitude which cannot contain any (glass) fibres, only epoxy which is not able as matrix itself to transfer a tensile load this high. The only option that structurally would be sufficient is lowering the thickness to maintain the same elastic modulus. A thickness that comes as close as the previous scenario I, is 5 mm. This is a really low thickness which cannot be sufficient if the connection method is chosen determined in chapter 6.

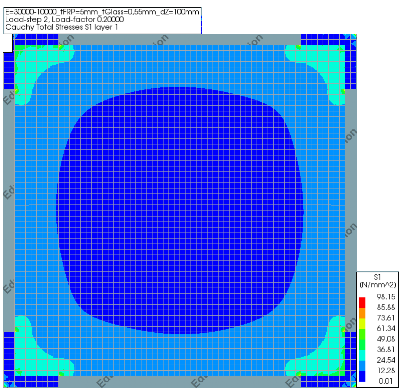
B. Linear decreased stiffness



Maximum twist

dZ = 10mm

tFRP = 50mm



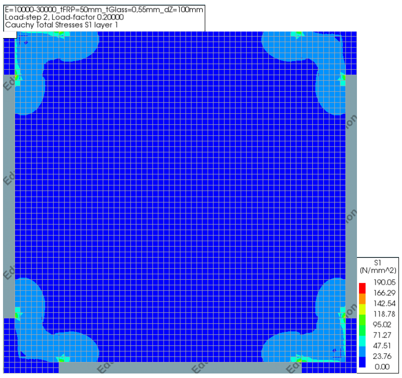
Maximum twist

dZ = 20mm

tFRP = 5mm

By lowering the stiffness in the middle stresses can be transferred further along the edge and eventually into the glass plate. This type of stress development is desired, because it causes a more divided stress distribution within the glass and in the end also a higher possible twist of +/- 25 mm each corner instead of 20 mm.

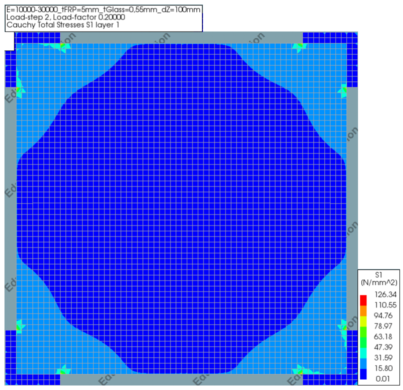
C. Linear increased stiffness



Maximum twist

dZ = 5mm

tFRP = 50mm



Maximum twist

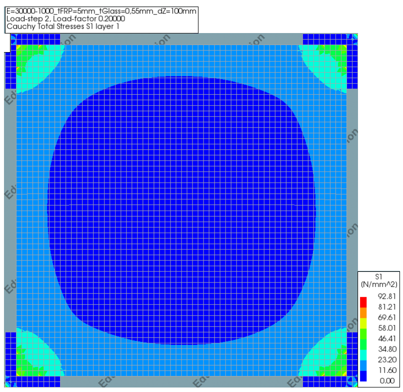
dZ = 15mm

tFRP = 5mm

Now, if this linear stiffness is reversed that instead of the middle, the corner points have lower stiffness, internal stresses in the glass are becoming higher than in the edge and in the end also less twisting is possible.

D. Digressive decreased stiffness

A digressive decreased stiffness give a desired stress development, but only when the thickness of the FRP is low. Because of the fast decrease in stiffness, the edge stiffness becoming quickly too low.



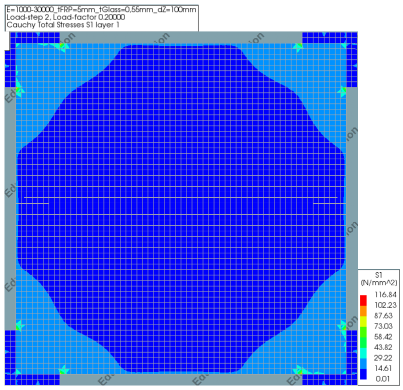
Maximum twist

dZ = 20mm

tFRP = 5mm

E. Digressive increased stiffness

Strangely, a digressive increased stiffness can be twisted also 20 mm, but do have stress concentrations. From this, it can be noticed that if the stiffness is not too high in the corners for Model II, it does not really matter which gradient it has. The most important thing is that is may not be too stiff in the corners, yet it need to have enough fibres to transfer the tension!



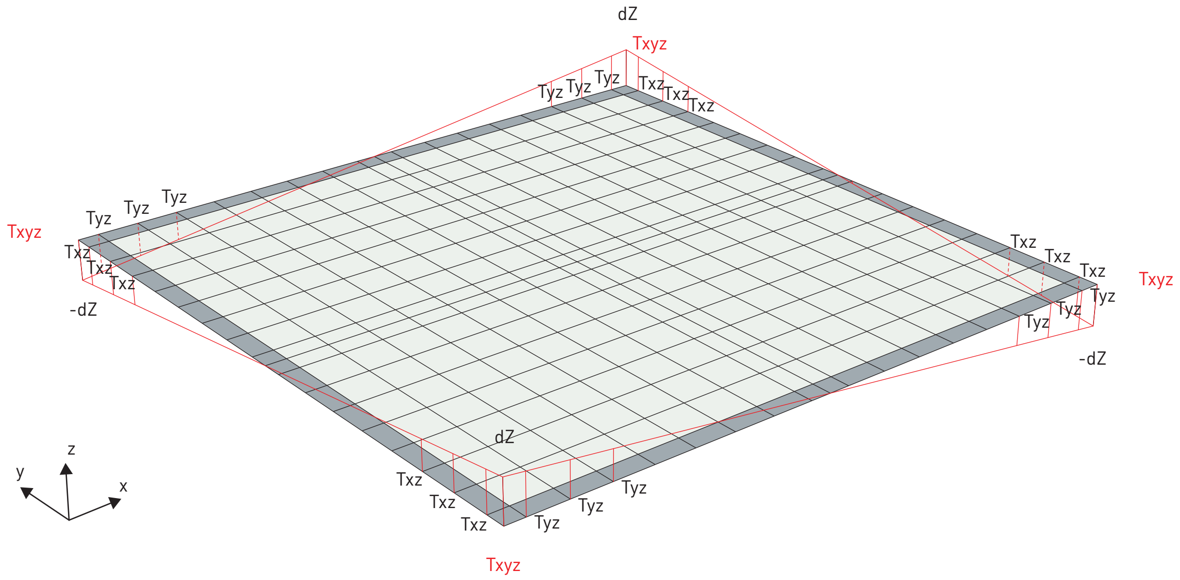
Maximum twist

dZ = 20mm

tFRP = 5mm

Conclusion Model II

Double bend a flat thin sheet of glass of 0.55 mm into an anticlastic curvature by reduced support solely at the corners with FRP material of 50 mm can hardly be done. Because the FRP still needs to transfer a lot of tension, it needs enough fibres which mean that lowering the elastic modulus is limited. Any other option for model II to being capable of twisting the plate to higher displacements is by lowering the thickness of the FRP edge. Which gradient is being applied does not really matter. Every scenario with model II has its stress concentrations because of the reduced and therefore suddenly stopped FRP material.



53. Model III
Twisting from the corners: FRP covers all edges of the glass

Input: Constraints and prescribed displacements

7.4 NUMERICAL SIMULATION III

Input

Model III is made out of a single 0.55 mm squared thin sheet of glass covered with FRP material all along the edges with a thickness of 50 mm. In this scenario only at and nearby the four corners the composed panel is supported. The corner points are constrained in all three possible translations, yet with a prescribed displacement. All other points are also constrained in each direction by translation, but do however can move free along each edge. The points around the middle of the FRP edge is not constrained at all. In this way points are moving towards the corners instead of towards the middle when twisting compared with model I and each twisted corner is connected with each other by the FRP edge compared to model II.

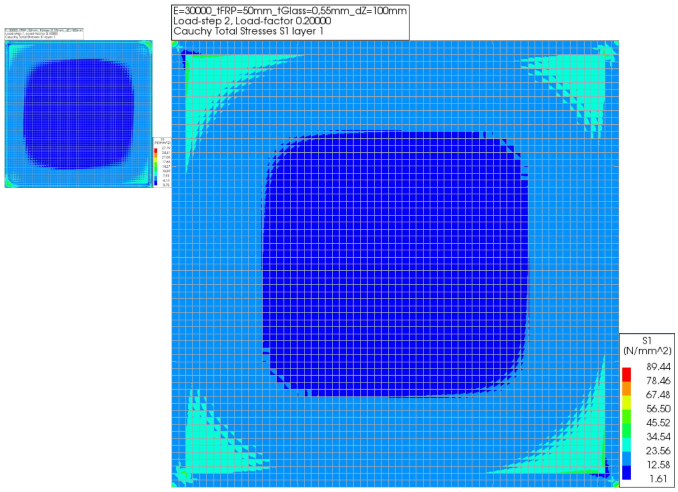
Results & Discussion

A. Constant stiffness

Maximum twist

dZ = 20mm

Because the FRP edge now is connected it is able to transfer its tensile stresses further into the edge and glass plate which gave lower internal stresses in the glass and in the end a higher capability of twisting the glass.

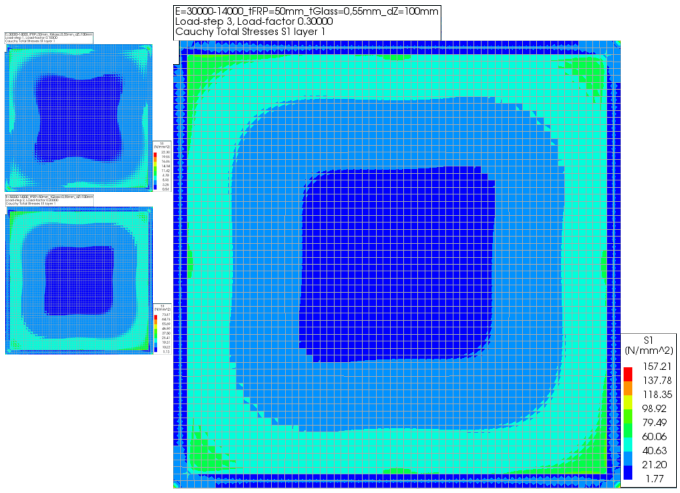


B. Linear decreased stiffness

Maximum twist

dZ = 30mm

By making the corners stiffer than the middle, the tensile stresses get further transferred than an edge with a constant stiffness which give even a higher capability to maximise the twist.

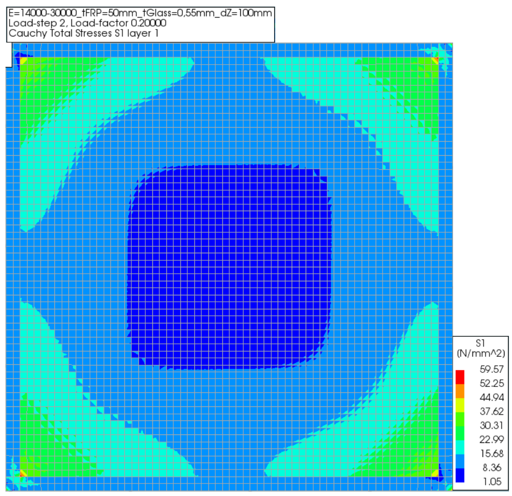


C. Linear increased stiffness

Maximum twist

dZ = 20mm

Just like the previous models, beginning the edge stiffness low from the corners and higher in the middle, causes directly stress development in the corners of the glass. It is desirable that the biggest stresses are in the FRP and transfer these flow of stresses along the edge to eventually give a more distributed stress pattern in the glass.

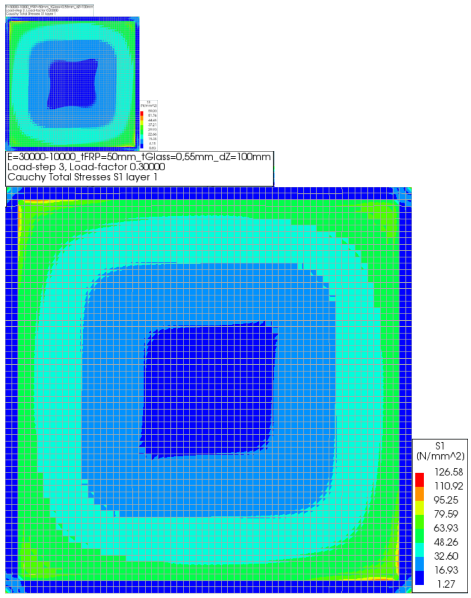


D. Digressive decreased stiffness

Maximum twist

dZ = 30mm

Digressive decreased stiffness is kind of the same of the linear decreased one.

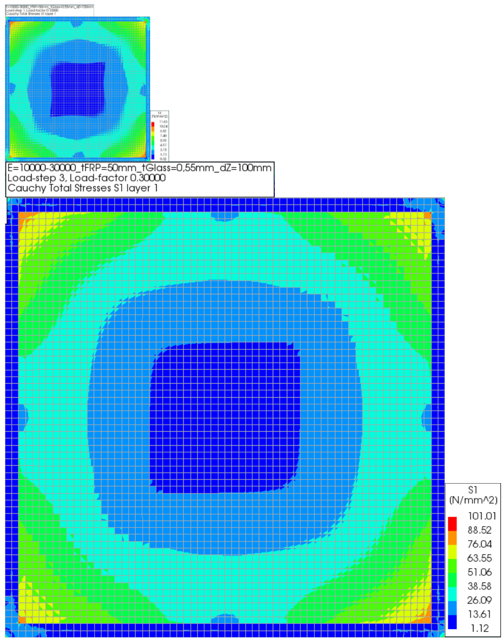


E. Digressive increased stiffness

Maximum twist

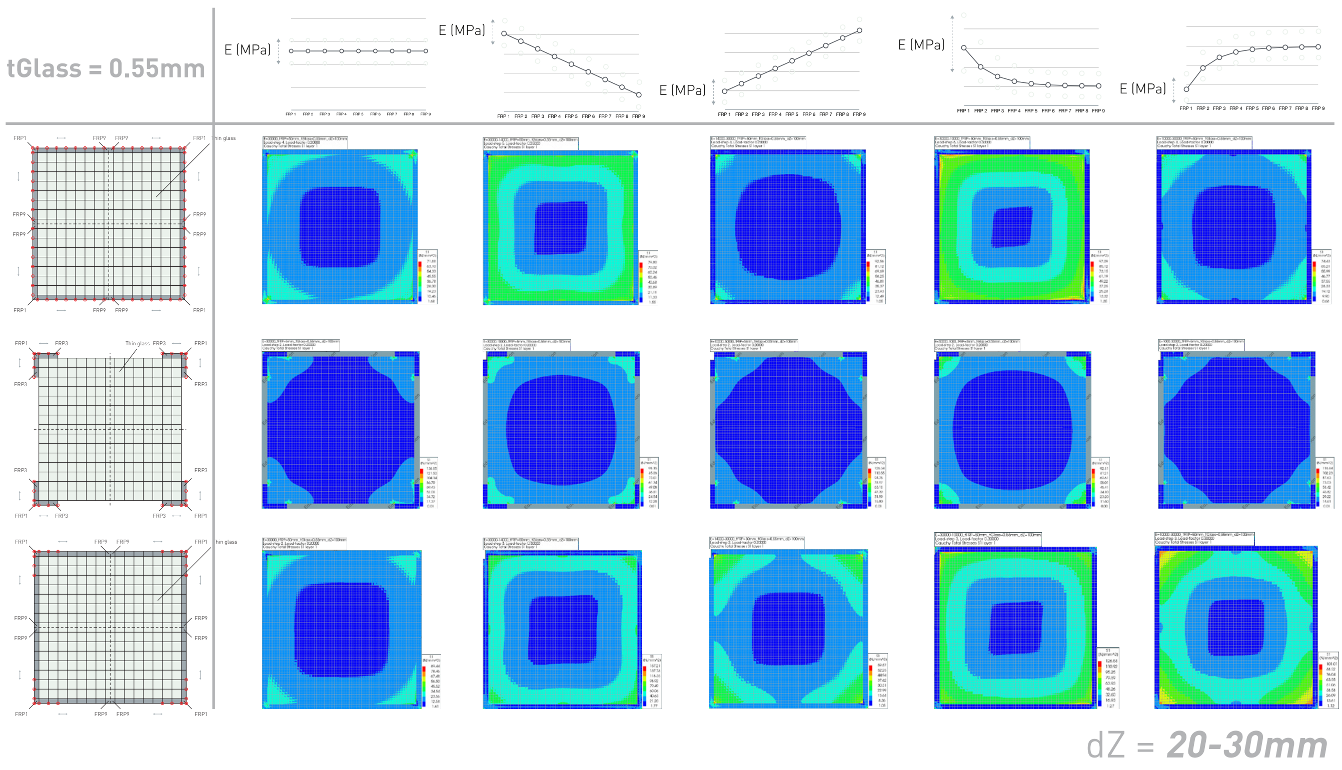
dZ = 30mm

Digressive increased stiffness is just as worse as the linear increased stiffness edge. Same reason: stresses caused by the displacement can transfer directly to the glass without equalisation.



Conclusion Model III

Model III show same results as model I, but than better because of lower stresses within the glass. Although, the stresses within the FRP edge are higher. Yet this is exactly what is favourable, because when glass gets cracked, it breaks totally because its brittle. FRP is a composed material with higher stretchability. This needed stretchability and strengthens now needs to converted into a structural design.



54. Summary all applied stiffness gradients to all three models

Searching for the proper stiffness gradient that give the most equally divided stress pattern

7.5 Case study analysis & connection chosen method

To determine which stiffness is needed to get the best equally divided stress distribution within the glass plate while double bending it to an anticlastic surface three models are analysed with each five different gradients of stiffness.

For all three models it appeared that twisting of the panel is possible, when the edge is adjusted to the right material and geometry properties.

To create a maximum twist in all three models, stresses created from the prescribed displacement of +/- 30 mm each corner need to be divided as much as possible within the glass plate. It appeared that the best results can be obtained using model I and III, because of the continuously composite edge all around the thin sheet of glass. The edge transfers stresses best if the corners are more stiff than the middle parts of the edge with a gradient that is linear decreased from the corners.

Model II, however, have not a continuously composite edge and high stress development is unavoidable within the glass plate at the place near the edge stops. This stresses becoming too high to twist the glass if an edge thickness is used of 50 mm. Reducing the stresses only can be fulfilled if the connection is less stiffer. Because the material itself also need to be able of transferring the tension, it cannot be made with no fibres within the composite. Therefore the thickness of the edge only can be lowered to get a less stiffer element. By lowering the thickness ten times, model II can be twisted as much as model I and III. The stiffness overall can be constant. Although a dynamic edge stiffness is not necessary, a linear decreased stiffness would also be the most sufficient scenario for this model.

Because the "ZIP" connection method already is determined, model II become insufficient because of the low thickness. A certain thickness with this connection method is desired, because it otherwise will fail.

A continuously dynamic composite edge with higher stiffness in the corners and lower stiffness in the middle can be translated as thick at the corners and thin at the middle. Considering the support of model I, all sides need to be supported, especially at the middle. Because exactly the middle parts need to have lower stiffness and therefor has low thickness, creating a support will give the same problems as with model II. Model III is therefor the most appropriate one for the chosen connection method, because it has only support at the corners and is able creating exactly at that places the ZIP connection.

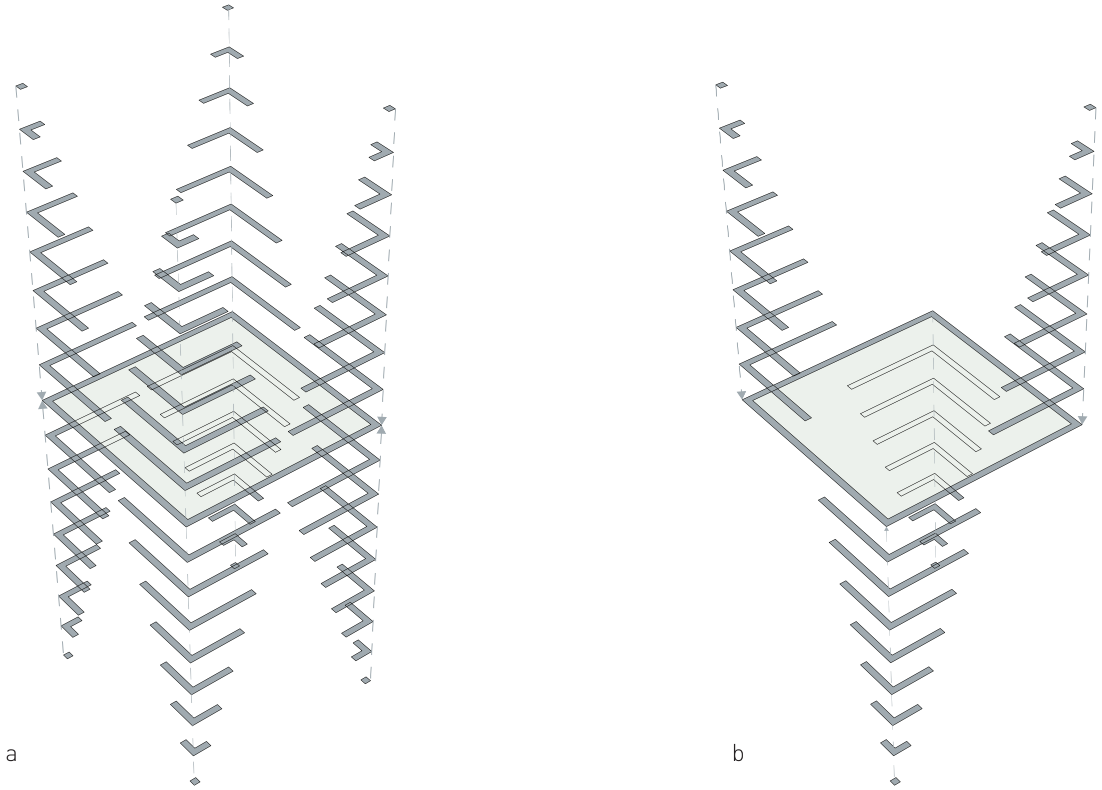
7.6 CONCLUSION & FURTHER RESEARCH

The best results that fulfil a maximum twist of a thin sheet of glass are obtained if it is being continuously covered around the edges with a composite material that has a dynamic edge stiffness with higher stiffness at the corners than the middle parts. To create a twist of 4% of the total panel length or width, with a ZIP connection method, model III is most sufficient because of the higher thickness exactly at the corners where the support of the panel is made. Further research how the definitive panel design will look like is showed in the next chapter.

08

DEFINITIVE DESIGN
OF A DOUBLE ANTICLASTIC CURVED THIN GLASS PANEL WITH A GLASS FIBRE-REINFORCED POLYMER DOVETAIL EDGE CONNECTION.

How can a panel being connected and in which panel configurations?



55. 3D exploded perspective view built up FRP layers
a. Linear decreased stiffness from corners to middle
b. Optimised linear decreased stiffness from corners to middle

8.1 OPTIMISATION DYNAMIC COMPOSITE EDGE

In the previous chapter it is determined that a dynamically made composite edge would contribute to a better divided stress distribution. To get stiffer corners the fibre volume can be increased or FRP material can be added. The easiest way is to compose the edge from a material that has the same material properties. In this way a basic (pre-fab) FRP layer could make the fabrication process easier. The direction of the fibres could be changed in each layere, but a same semi-finished product is repetitively used.

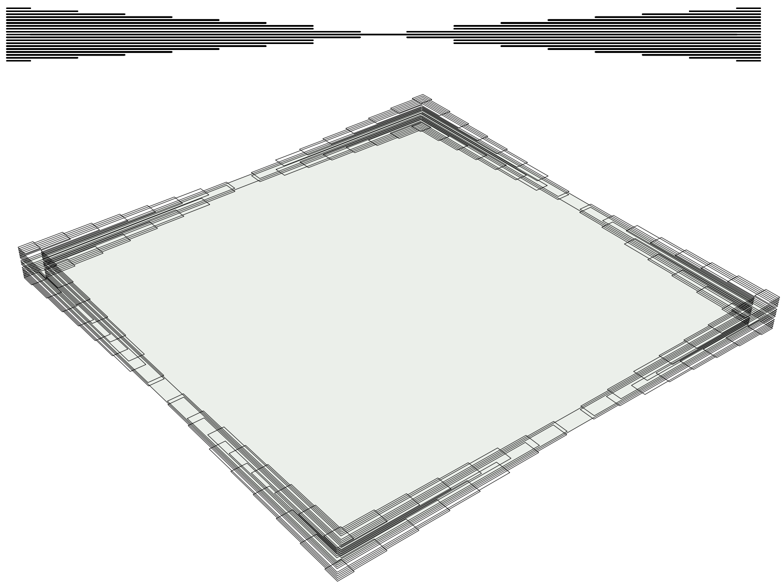
Translated to a structural design, the corners would get thicker than the middle parts of the edge in a four-symmetrical way (fig. 55a) or in a two-symmetrical way (fig. 55b). Aesthetically, the second one could result into a design that might look smoother, but it depends on how a single panel is configured into a configuration of multiple panels.

Creating a configuration of multiple panels raises questions on how the prescribed displacement is going to be put in motion and in what way. In the next paragraph this will be discussed.

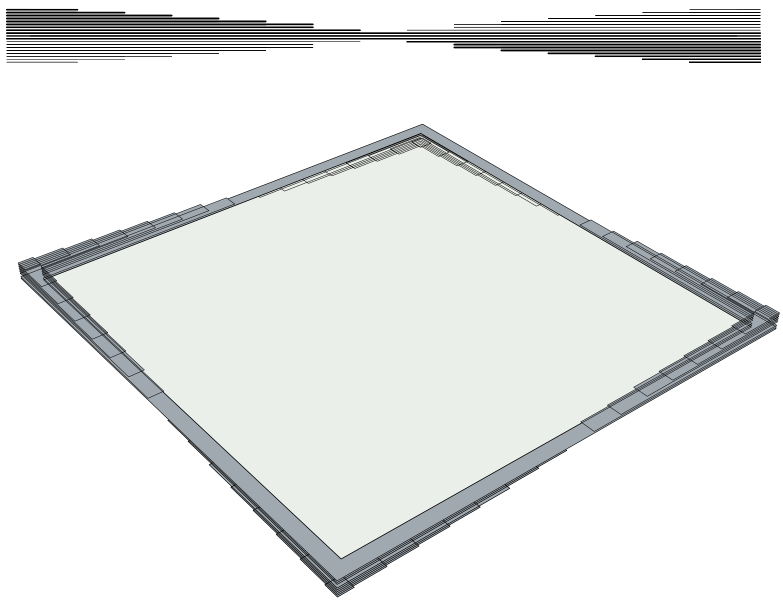
56. Technical lay-up GFRP

a. composed panel design (t) side view, (b) 3D perspective view

b. optimised composed panel design (t) side view, (b) 3D perspective view



a



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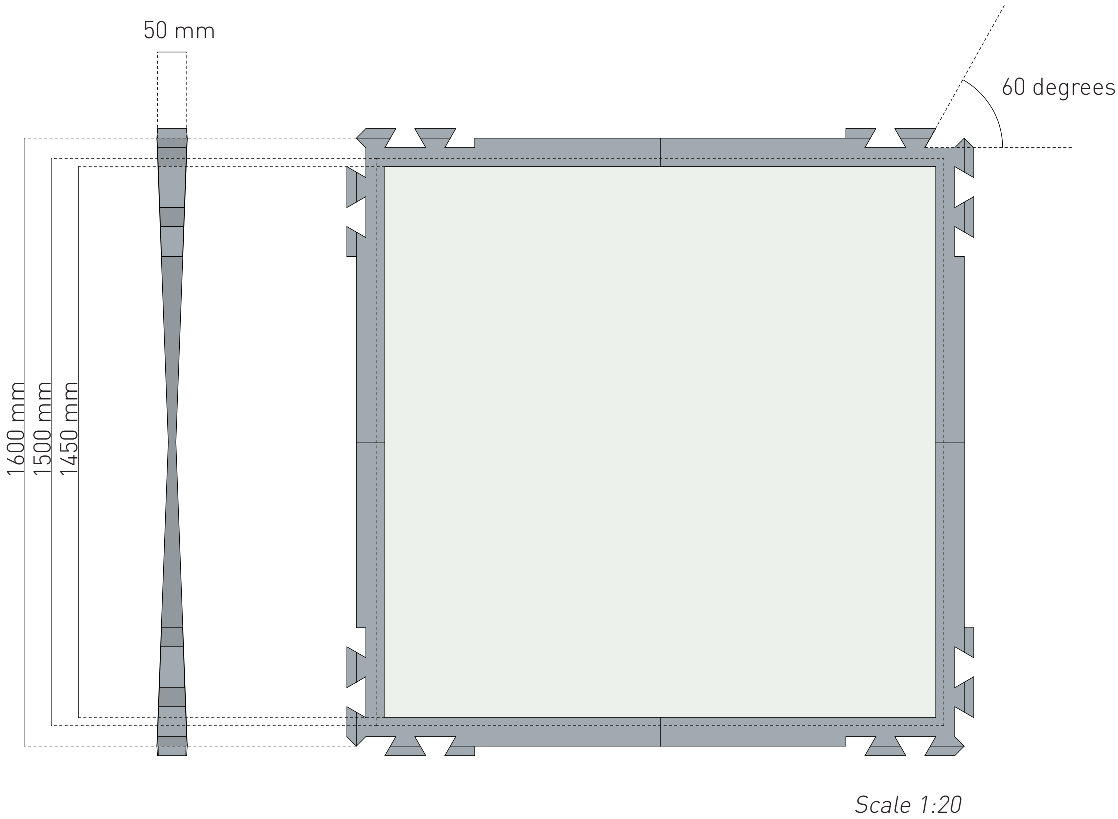


57. Single panel design with cut ZIP connection

After prescribed displacement of +/- 30 mm (l) side view (r) top view

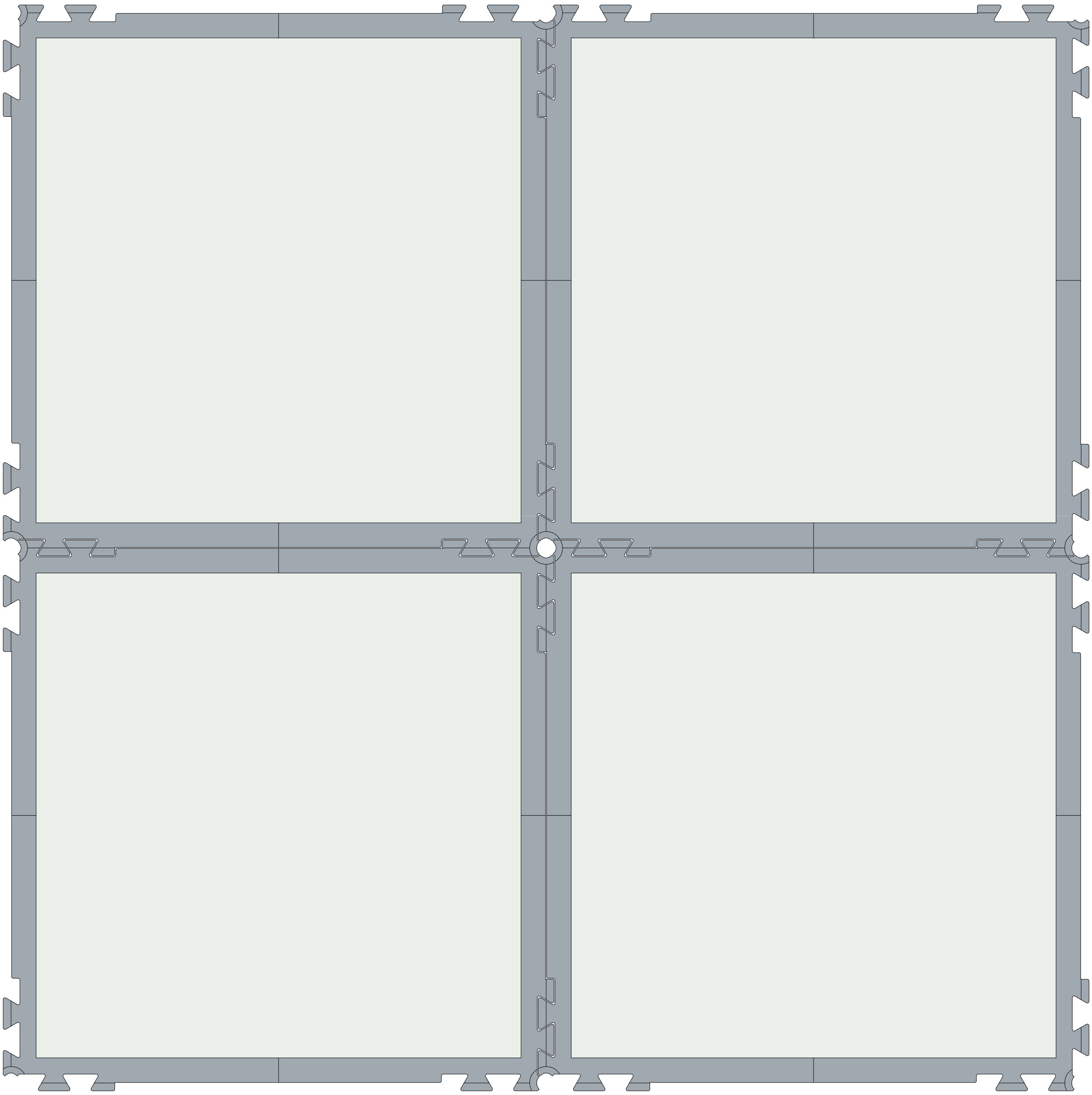
8.2 INTEGRATED THE DOVETAIL JOINT

A single panel can be bent from a flat shape into a double anticlastic curvature by using a material with the opposite form of the edges of the panel. The shape is determined by design and numerical analysis and is made with a connection method of a cut dovetail joint integrated within the edges, solely at the corners (fig. 57).

A bigger hypar surface

To create a bigger hypar surface of thin glass, square sheets of thin glass are attached together like a patchwork blanket, yet with the same connection method as proposed in this research on the outer edges. The surface becomes bigger and therefore also the wind load that needs to be transferred through the glass.

The support developed in this research, can be performed for each panel, but can also be performed for a combination of panels and only at the outer edges of the extended hypar surface.



Scale 1:20

58. Bend panels

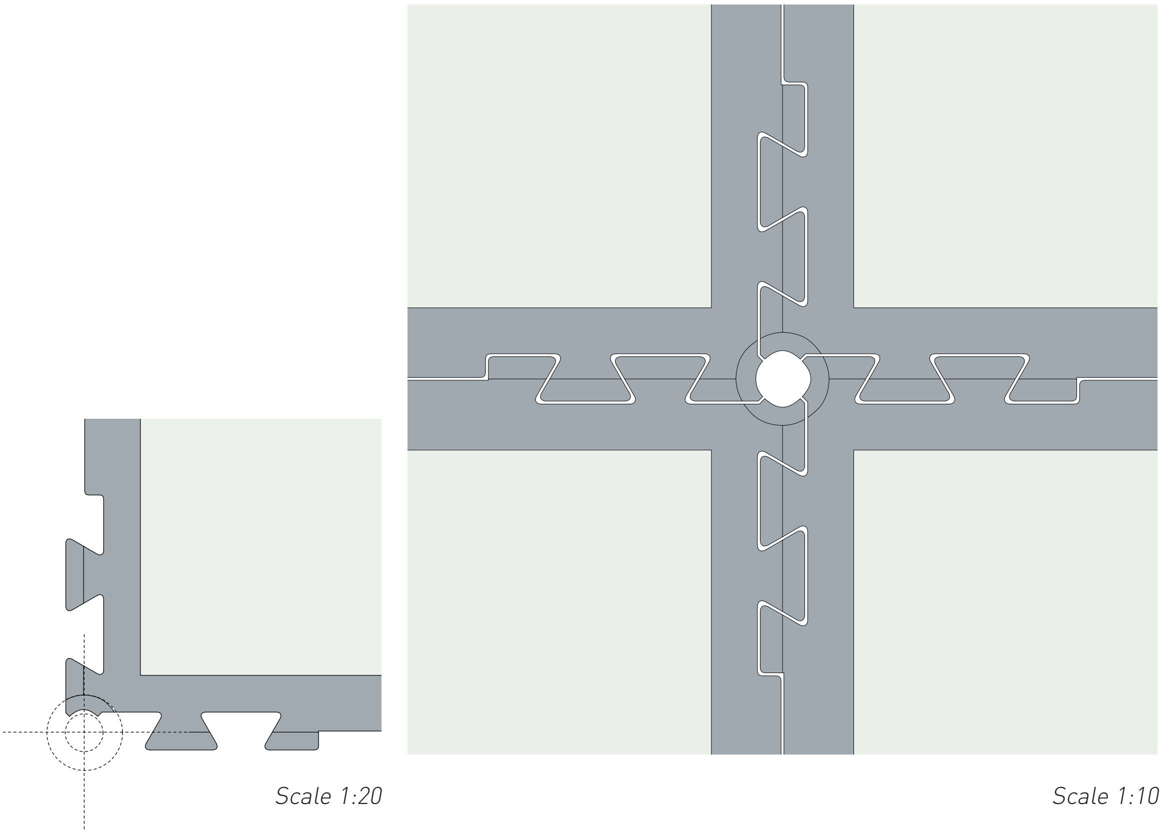
By pushing the corners into the desired prescribed displacement

Detail 1: top view detail of one corner

Detail 2: top view detail of four corners

A repetitive hypar surface for easy assembling

To minimise the effort of fabrication, assembling and extra sub(-) structures the repetitive panel configuration is chosen as final product for this research project. To see how the connection method work, a study model is made where a bolt is used to push the panels together. By placing the bolts at the corners, the structure can be connected together (fig. 58 and 59).



59. Single panel design with cut ZIP connection

After prescribed displacement of +/- 30 mm (l) side view (r) top view

The final part of creating a proof-of-concept is the fabrication of the panel. This is the most complicated part, because each panel needs to fit before, during and after the cold bending. Each panel starts with a flat sheet of thin glass. The edges can then be placed onto each other and fit into each other (fig. 60). By pushing each corner together with a compression load (at the same time), the panels fit further into each other and are twisted automatically in the desired prescribed displacement.

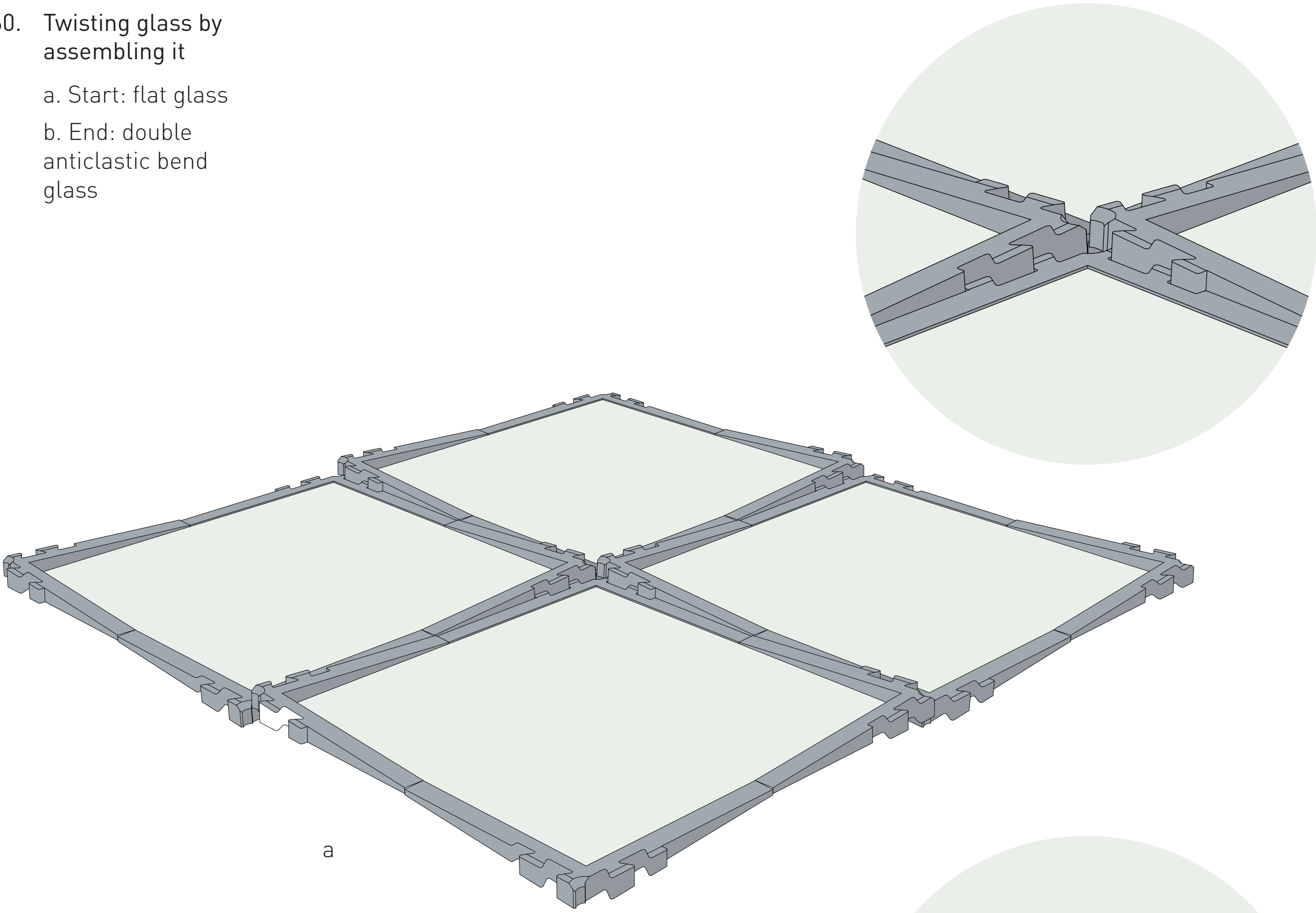
Fabrication

The direction of the double bent anticlastic glass now depends on the geometry of the edge. It is the geometry that determines how the panels are connected together. The direction can be chosen in such a way, that the overall view is repetitive with each panel in the same direction or some panels turned a quarter of a turn which results in highs and lows. In figure 61 this is visualised by the reflections in a render. A double curvature of 4% of the panel length, however, is hardly noticeable. More extreme twisting can be up to 12% of the panel length (fig. 62), without using safety factors.

60. Twisting glass by assembling it

a. Start: flat glass

b. End: double anticlastic bend glass



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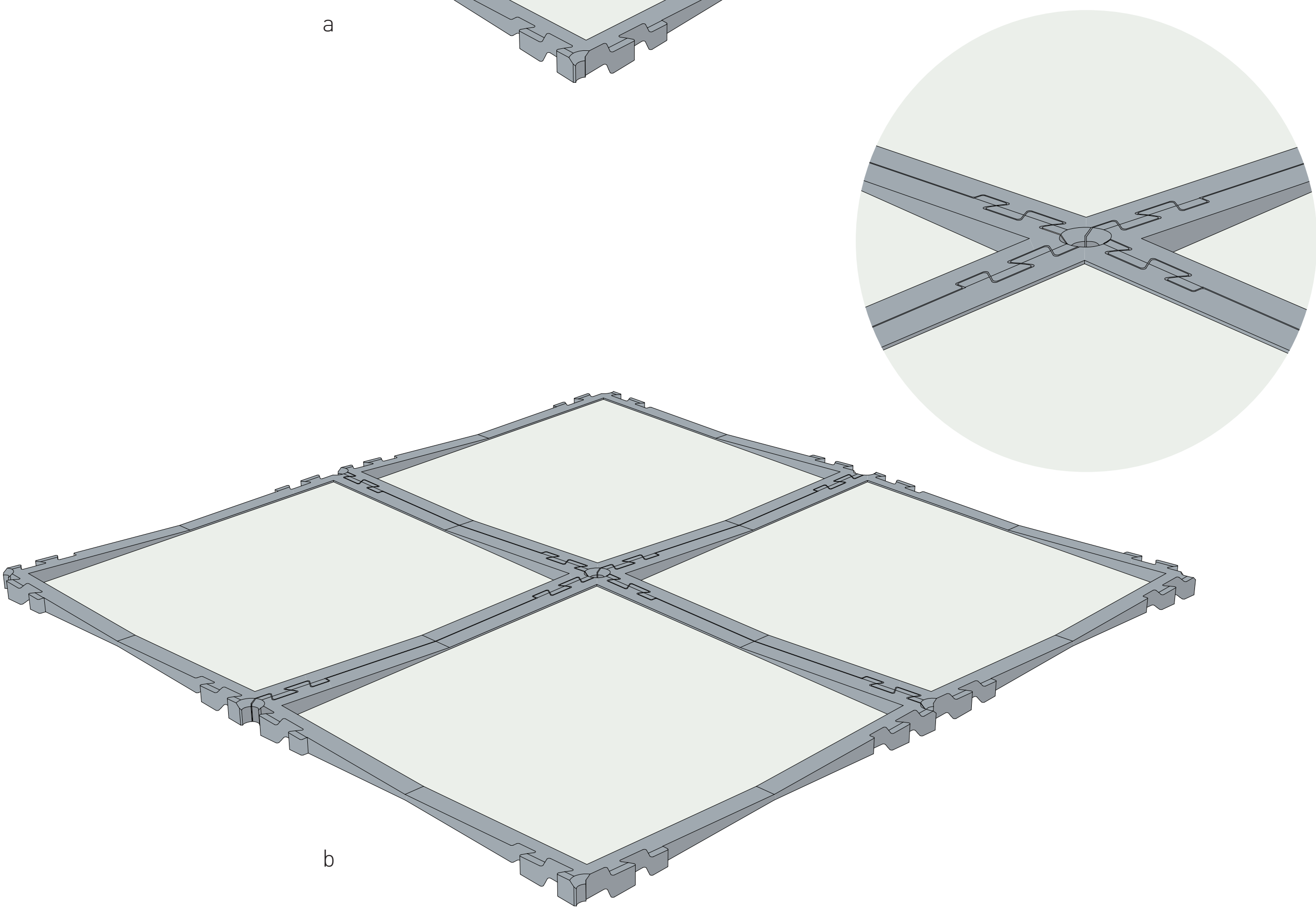

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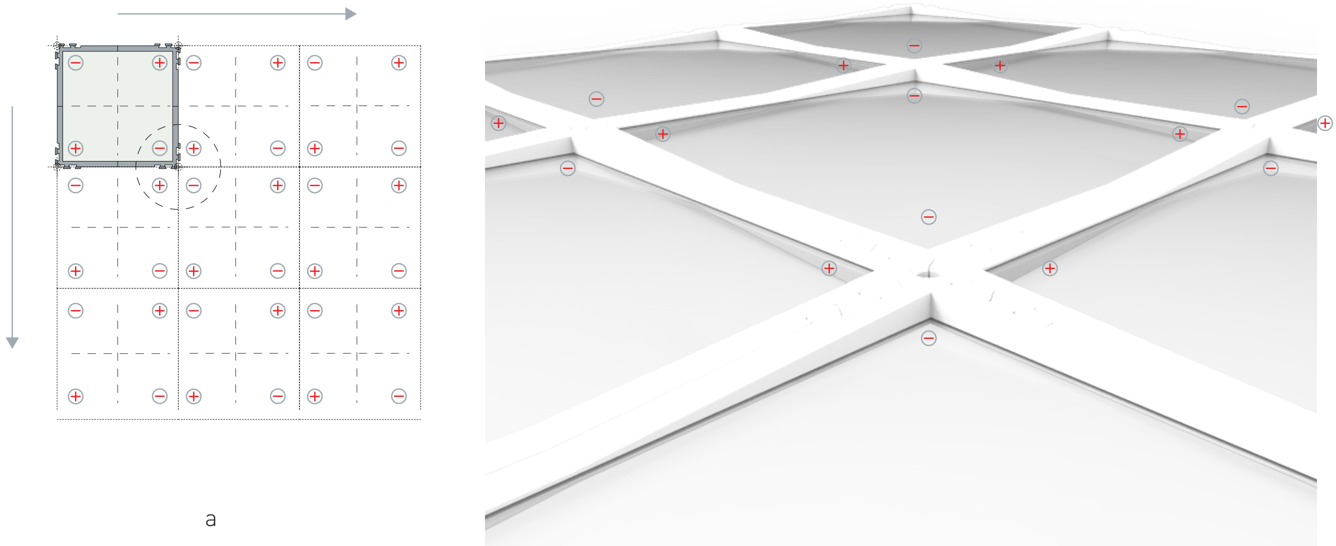

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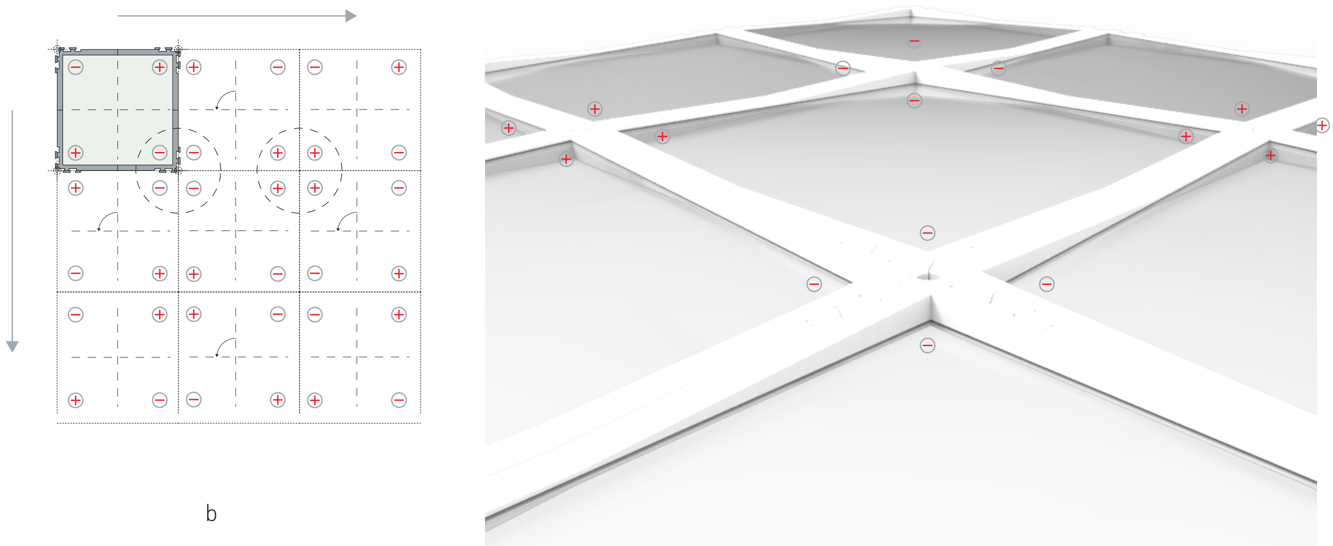


b

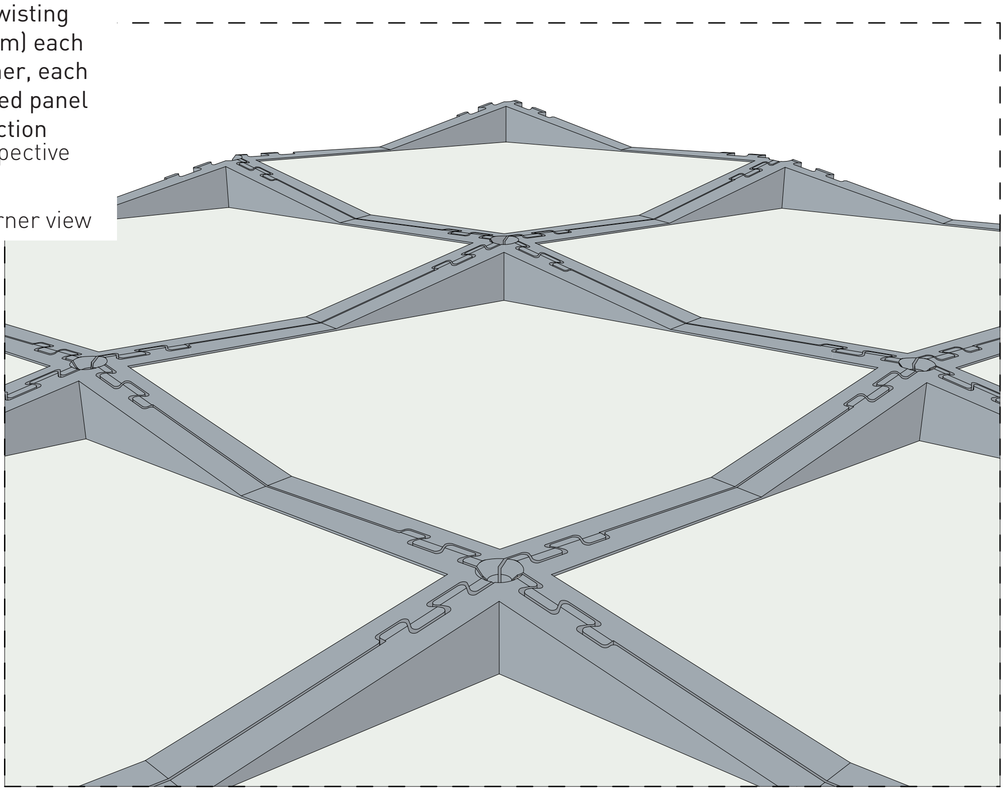
Because of the twisting, the edge is deformed and the prescribed displacement creates a tension load on the composed panel. From the dovetail joint the tension load transfers through the whole panel in a three-dimensional way, so that a double anticlastic curvature is created from a flat thin sheet of glass. If the edge is not fabricated in a proper manner and the composite material cannot transfer its stresses sufficiently, the glass plate will not loaded equally and fail may earlier due to high tensile stress concentrations.

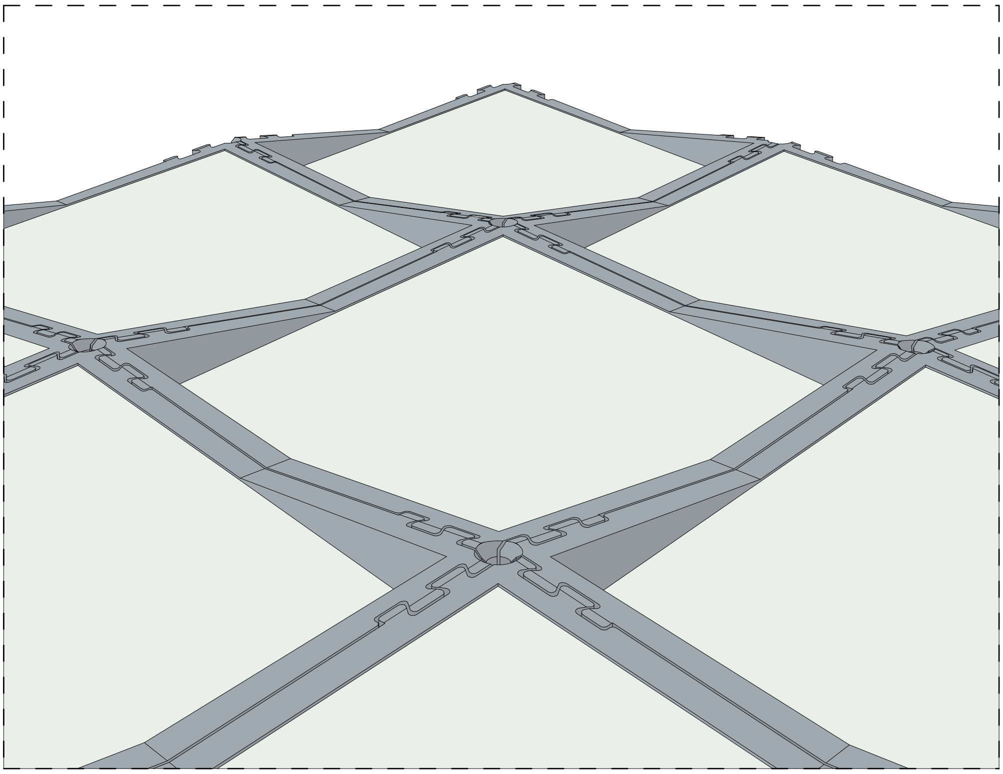
61. Configuration multiple panels rendered 3D perspective view

a. Repetitive

b. Turning the panel 90 degrees, creating highs and lows

62. Extreme twisting (+/- 100 mm) each panel corner, each neighboured panel same direction
a. 3D perspective view
b. Next corner view



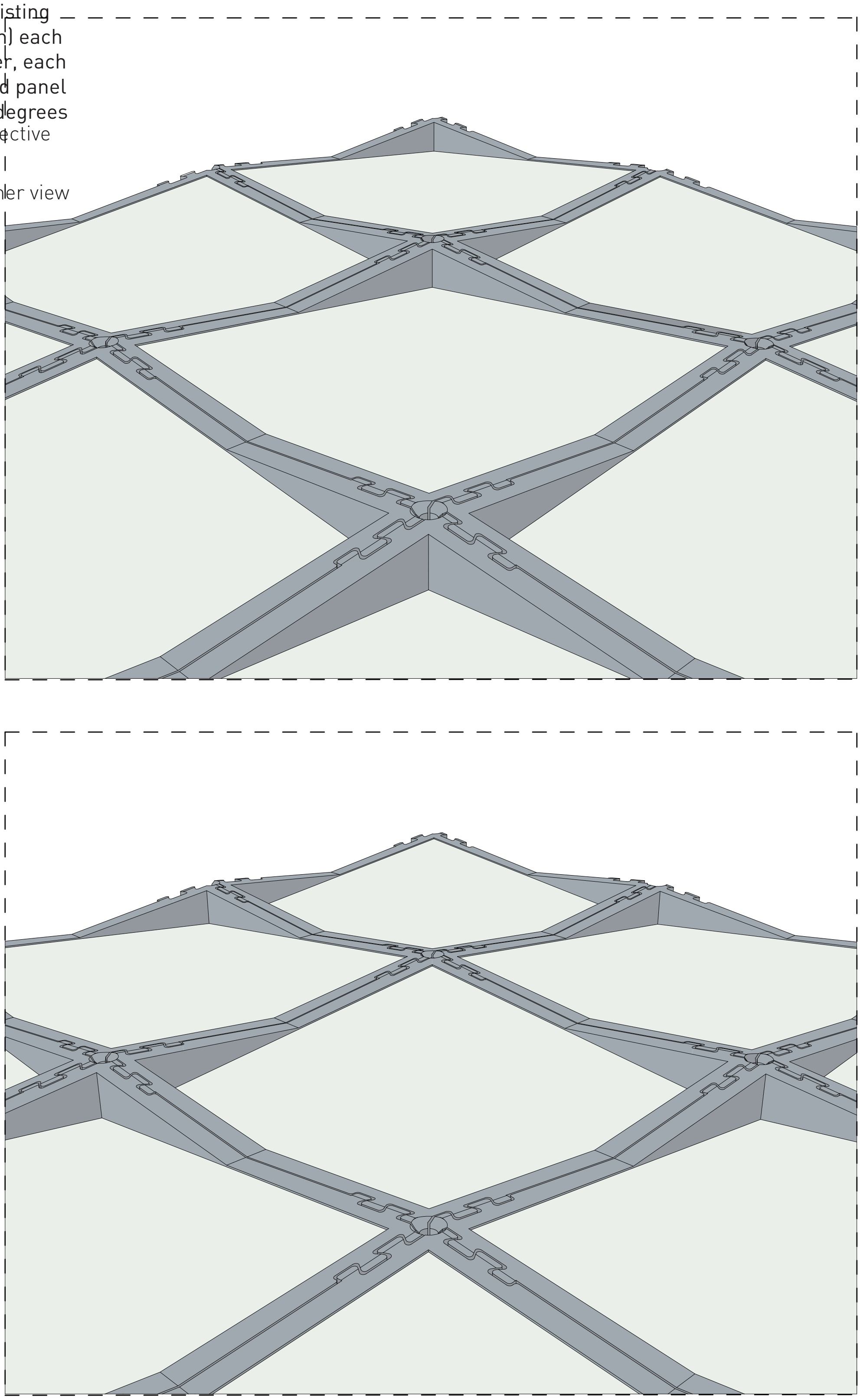


Because of the highly needed precision of the dovetail joint, the panels are cut out with a 3D water jet cutter. Delivering a pre-fabricated product composed out of multiple square layered semi-finished products to a 3D water jet cutter, the whole fabrication process can be quick and clean. For now, study models are made using a 3D-printer, where several panel configurations are shown on scale 1:10 before twisting and after twisting with a prescribed displacement in Z-direction of 30 mm and 100 mm each corner.

8.3 CONCLUSION

The easiest way to twist the panel is when there is just one way possible. Therefore, the glass is non-symmetrically placed as insert into the GFRP edge and multiple panels are fit together in just one direction like puzzle pieces. Aesthetically, a smoother surface can be created and a one-way-restricted dovetail connection is created, where all panels are configured either in the same direction or turned 90 degrees.

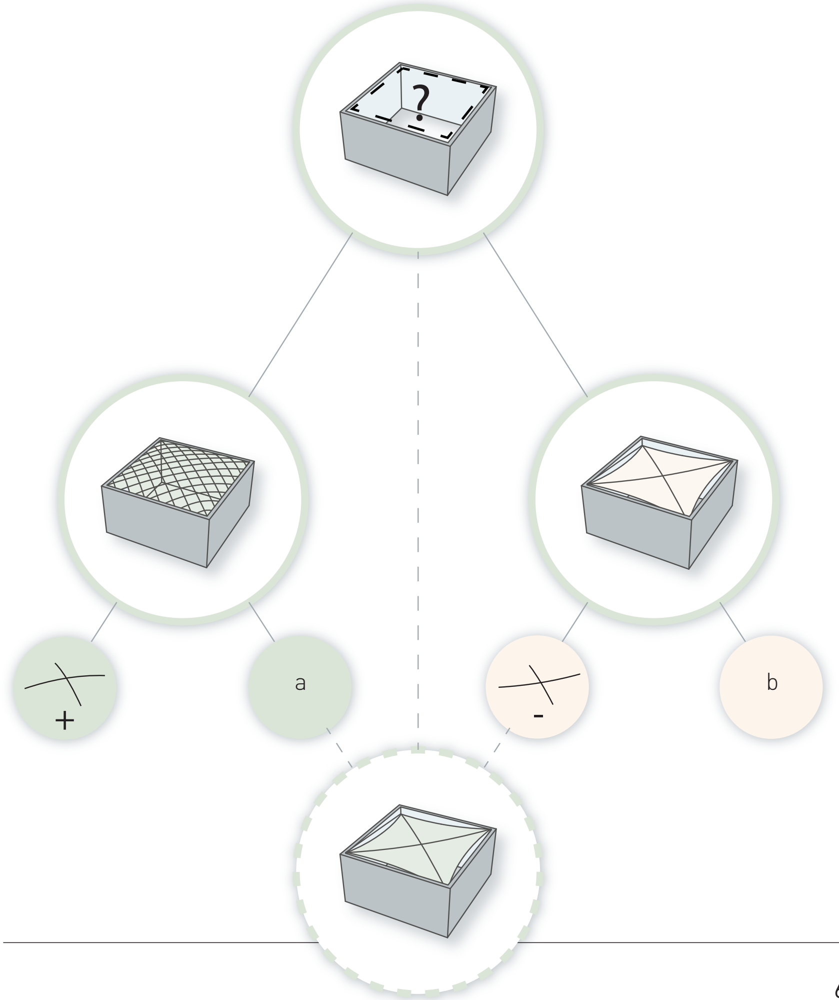
63. Extreme twisting (+/- 100 mm) each panel corner, each neighboured panel turning 90 degrees
a. 3D perspective view
b. Next corner view



09

REFLECTION & OUTLOOK
FUTURE DESIGN APPLICATIONS

Is the challenge, excepted at the beginning of this research, fulfilled? What are the potentials of the final panel design? What needs to be researched before using glass as stiff structural fabric in real-life?



9.1 CHALLENGE ACCEPTED

Initially, the design idea was that high strength thin glass could be an alternative construction material for tent-like structures. Usually, materials such as textile or plastic are used as structural fabric creating tensile membrane structures. Because of the high tensile strength and high membrane behaviour of chemically strengthened thin glass, the only difference would be the material stiffness itself. Instead of a more stretchable structural fabric, glass as stiff structural fabric is now used.

Eventually, it appeared that material all around the edge is needed to divide the tension load created with the prescribed displacement in Z-direction to reduce high stress developments that cause failure of the glass. The result is a less transparent tensile membrane structure than previously thought of. The imagined tent structure made from structural glass gets more transparent if the edge connection are reduced to smaller and thinner parts. If it is made smaller, it goes at the cost of the displacement of the twisting. If it is made thinner, it goes at the cost of the integrated connection method of cutting a dovetail joint in the thicker parts of the edges. For now, the result of the panel design rather fits in a façade than in a roof structure, because of the strong framework that is needed.

64. Transparent tensile structures

The design idea at the beginning of this research (Frei Otto)

a. glass as *stiff* structural fabric

b. textile of plastic as structural fabric

9.2 POTENTIALS OF HIGH STRENGTH THIN GLASS AS STIFF STRUCTURAL FABRIC

Because the objective of this research is to create a double anticlastic bent square surface from a flat squared sheet of thin glass at the start, it already is determined how the tension is added to the twisting. Except for the points on the middle lines of the glass plate, all points will displace to the middle viewed from the top, where the corner points will displace the most.

Considering glass is a stiff material, it will barely stretch. Given that the glass is capable to deform into a hyperbolic parabolic surface, the created gap needs to be filled to fulfil the objective of starting and ending with a squared hypar surface. Therefore the added material needs to be stretchable, but capable of transferring the tension.

The result is a connection method composed of glass and plastic. Plastic is needed to fulfill the objective, but plays a dominant role to create a cold bent double anticlastic curvature of a flat sheet of thin glass. Therefore the final technical design might be called a fabric structure with stiff structural fabric inserts, instead of only a stiff fabric structure.

Although high strength thin glass is a strong and flexible material, it will not contribute to a better transparent built building envelope. The view, however, on using glass as a stiff structural fabric in a tensile structure or compressive structure is totally new and can bring many new designs with it in the future. The potential of high strength thin glass as stiff structural fabric in a larger tensile structure seems very unlikely, but further research how the wind load behaves on such a patchwork blanket structure should be researched with numerical simulations.

The technique of adding tension to the twisting should rather be seen to improve its stiffness than to create a complex shape, because the shape is barely noticeable. In addition to this, the work put in, to see a double curvature, will go at the cost of the transparency. Although the created façade will be light, it will not be transparent enough. With thicker glass and conventionally used techniques to create complex shapes, the facade might become heavy, but certainly more transparent.

9.3 RESEARCH RECOMMENDATIONS

If high strength thin glass will be used as stiff structural fabric, more research should be done in structural behaviour of the glass plate when it is subjected to wind load. Especially numerical simulations of the relation between the prescribed displacement and the deformation of the sheet could provide new insights. Also more pull-out tests with specimens of different manufacturers should be performed in the lab to determine the safe maximum tensile strength of chemically strengthened glass. More research of possible connection methods are needed, if results of the structural calculations are positive.

When a connection method is chosen that is made from a composite dynamic edge and a dovetail joint, more precise calculations of the needed fibre direction and fibre and matrix volume are needed. Also the dovetail connection of GFRP should be tested in the lab. Especially the thickness that is needed to make such a dovetail connection without wrinkling effect and therefore failure of the connection. Creating such a connection method also asks for more research on the fabrication technique.

10

CONCLUSION

The research question formulated of this project is to what extent is it possible to curve a flat sheet of high strength thin (HST) glass into a double anticlastic bent surface by adding tension to the currently used cold twisting technique?

By researching the technology of using HST glass as a stiff structural fabric, it can be stated that adding tension to the twisting of a flat sheet (1.5 m by 1.5 m) of HST glass (0.55 mm) results in a double anticlastic curved surface.

The exceptional flexible mechanical properties of this transparent and lightweight HST glass sheet material makes it interesting to discover the potentials of creating geometrical complex façades in the building industry.

In order to use HST glass as a construction material, it needs to be strengthened by ion-exchange in a chemical salt bath and made with the conventional horizontal production float-line process, resulting in a sheet that can be mass produced and is as thin as 0.55 mm and has maximum dimensions of 1.5 m by 1.5 m square size.

The true tensile strength of this HST glass sheet material with strong membrane behaviour, is tested with pull-out tests in the lab. Safe maximum design tensile stresses of 100 MPa are reached by applying a tensile load in-plane.

The tension load needs to be distributed onto the glass plate and this is achieved by use of a dovetail joint that is integrated within the composed connection material which needs to have dynamic stiffness, because of the twisting movement.

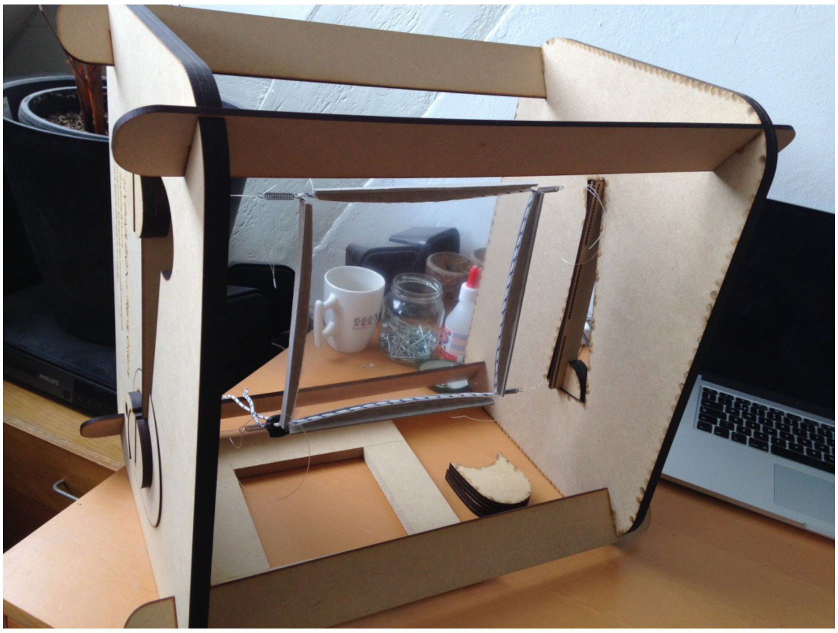
Glass fibre-reinforced polymer (GFRP) material needs to be attached all along the glass plate to optimally distribute the tensile stresses and maximise the twisting and tensioning when support of the edge is solely at the corners. A maximum safe prescribed displacement of +/- 30 mm can be reached. This causes tensile stresses because of the angle of 4% which is achieved due to the twisting of the plate. The stresses are transferred optimally along the edges if the stifness in these edges decreases linearly from its supports at the corners to the middle of each edge, giving an equal stress distribution within the glass plate.

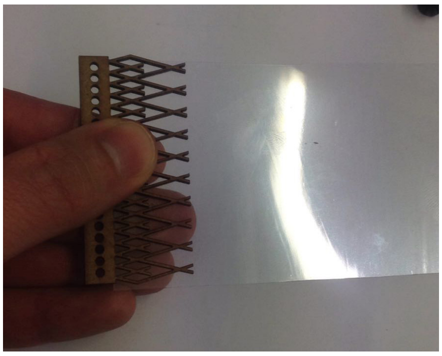
Fabricating each HST glass panel with a dynamic GFRP edge is easiest when semi-finished GFRP sheet materials are used and stacked to reach the thickness that is desired to create the dovetail joint. Linear edge stiffness is achieved by removing material with a 3D water jet laser cutter.

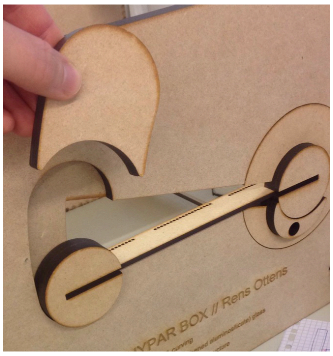
In this research, the size of the created hypar is limited to 1.5 m by 1.5 m plus GFRP edge connection. A one-way-restricted panel connection is created, where all panels are configured either in the same direction or 90 degrees turned. Creating a bigger hypar surface of HST glass could consist of using multiple assembled sheets like a patchwork blanket construction which is supported only at the outer edges of the configured surface. The support can be used as tool to create the double anticlastic curvature in the (assembled) glass panel(s).

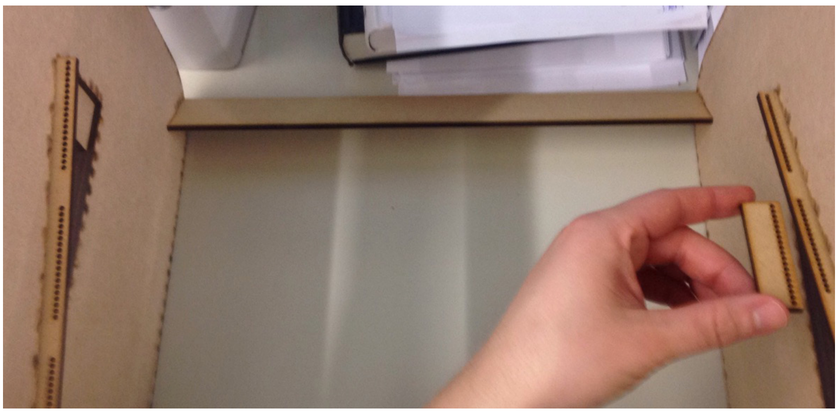
APPENDIX

A. Hyparbox model with alternative tensioning method

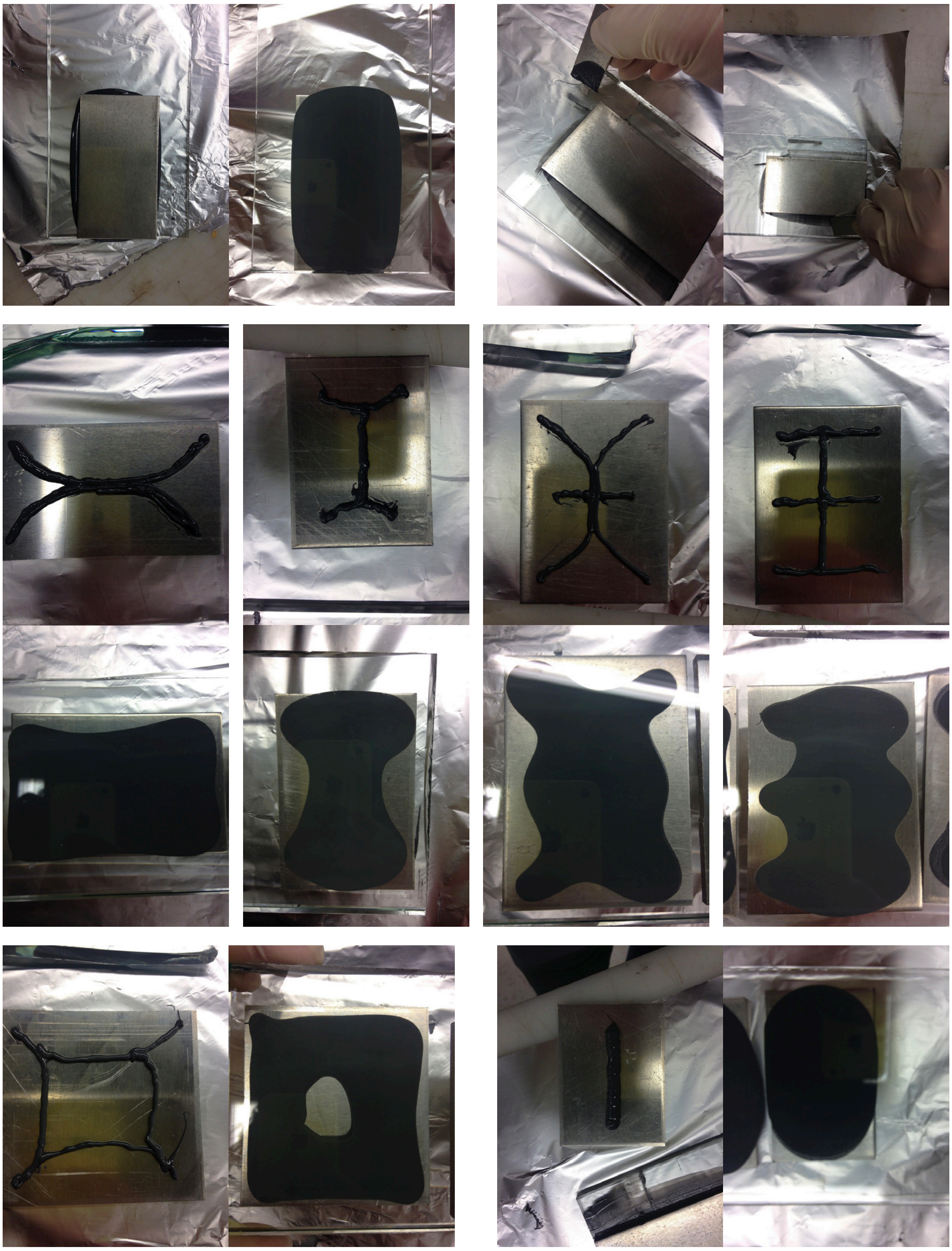








B. Exercise applying Araldite adhesive

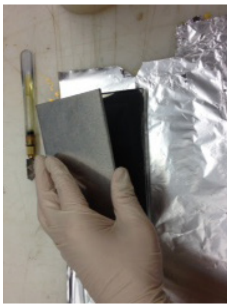
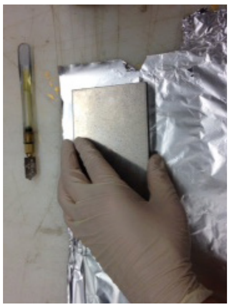


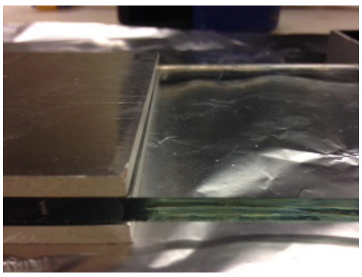
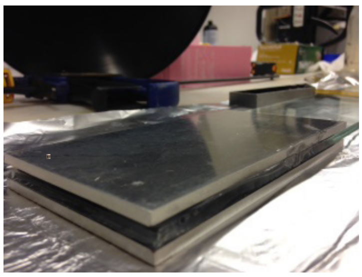




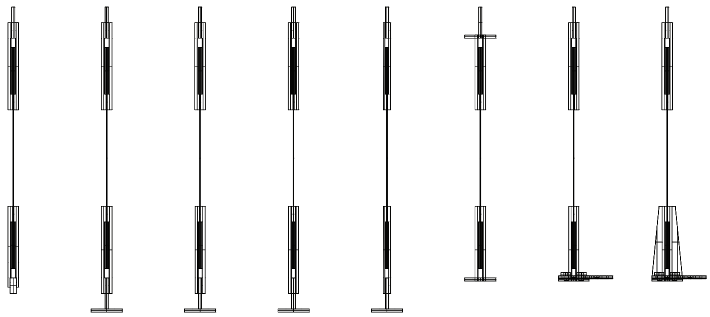


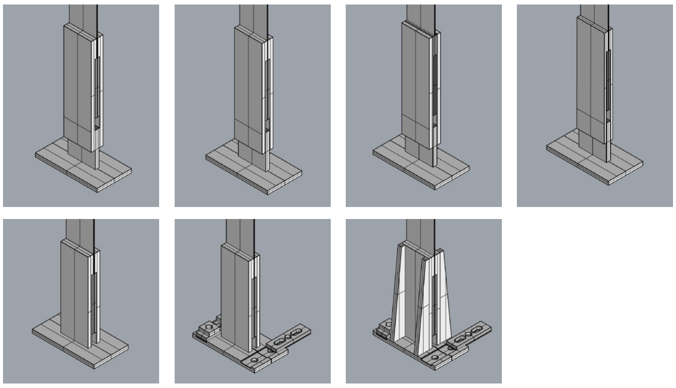


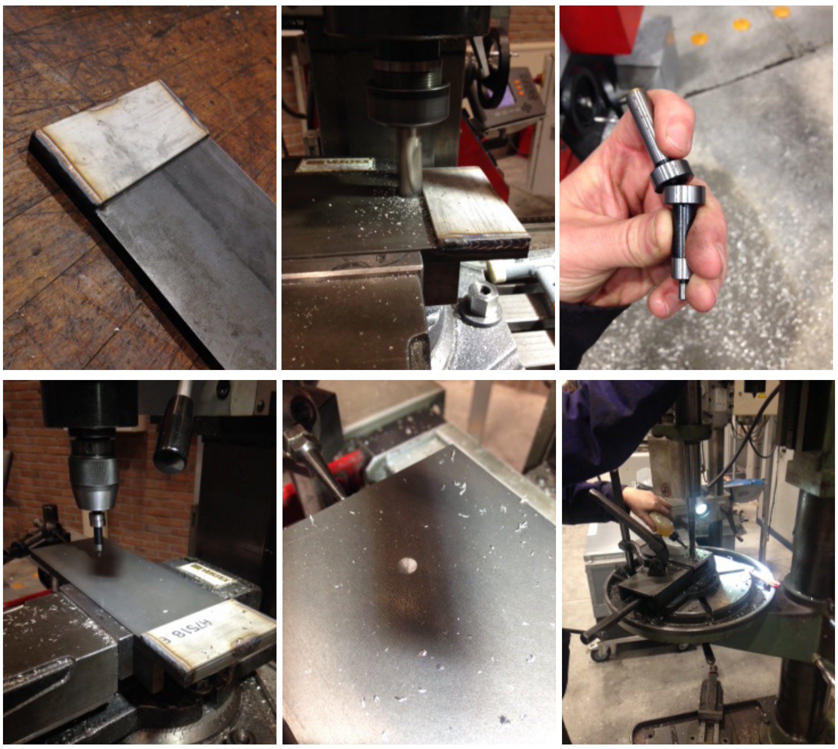



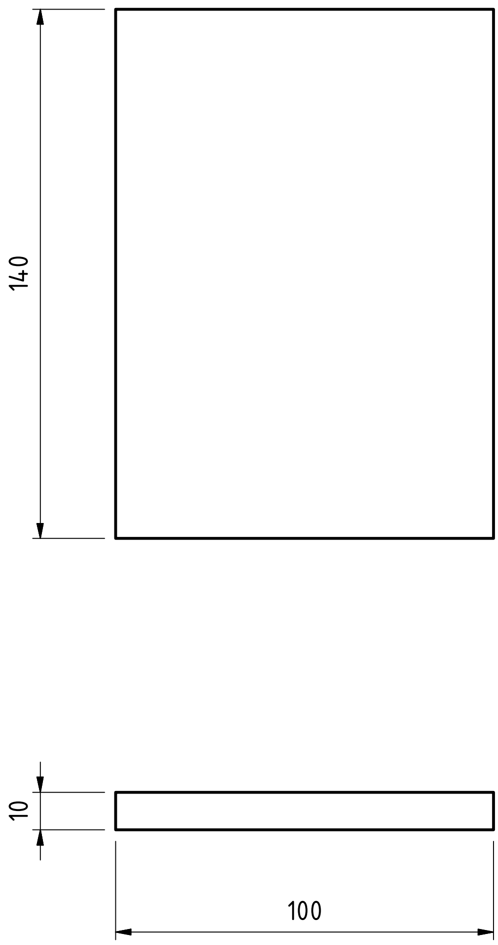




C. Alternative test set-ups & fabrication performed test set-up









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STATUS

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PROJECT NO.

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RO A4
LAST MOD. SCALE
CL 1:2

TITLE

PROJECT

GRADUATION
R. OTTENS

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3039 LN Rotterdam
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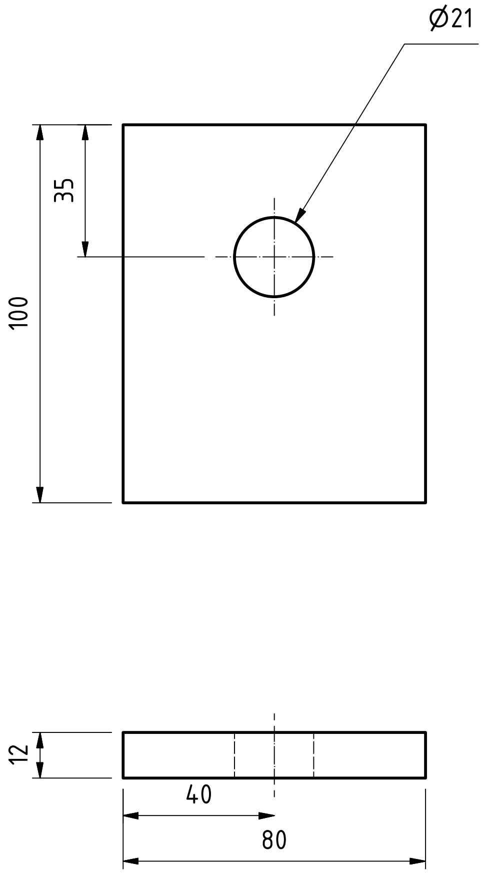
E rens.ottens@gmail.com

REV DATE APR



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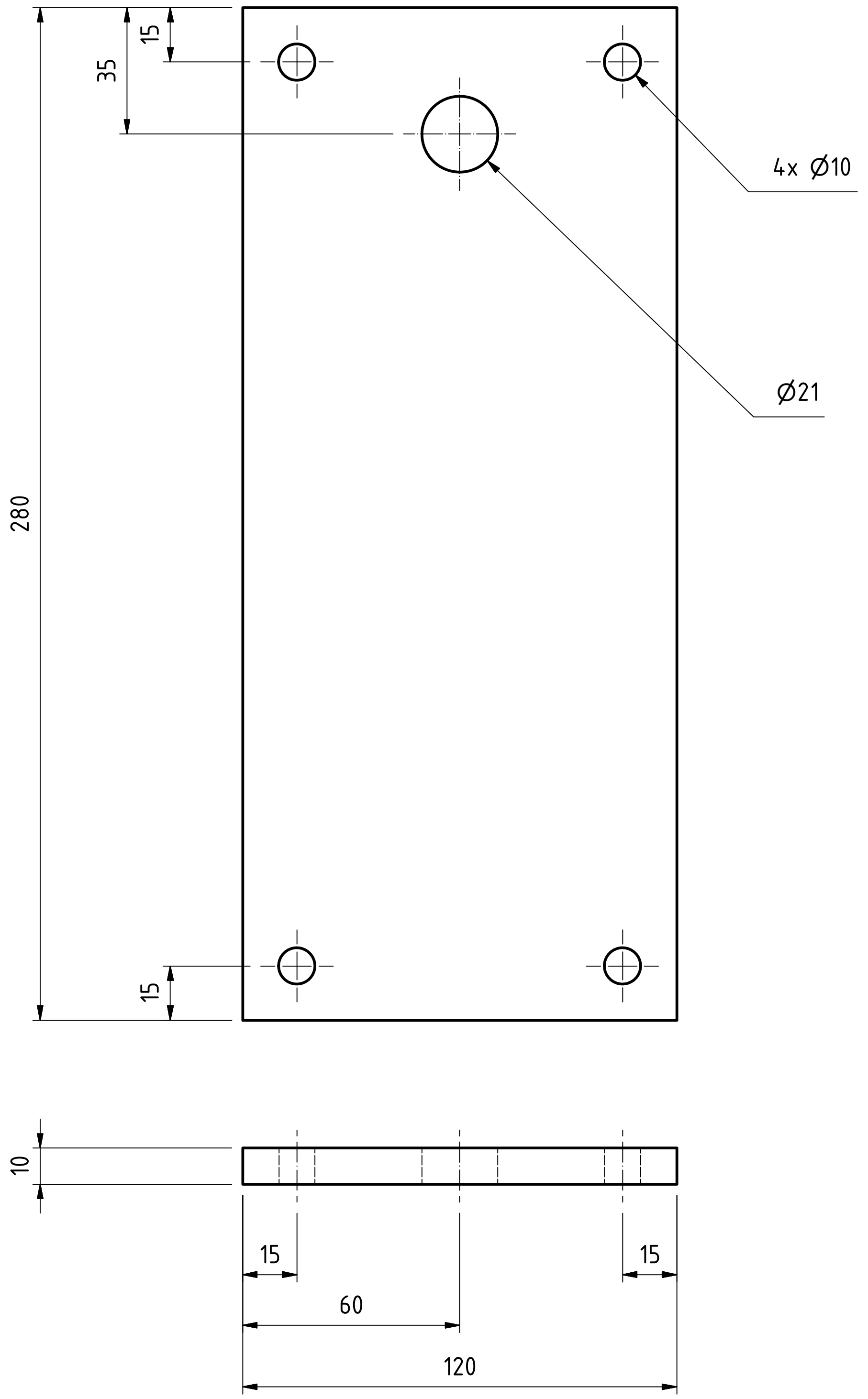

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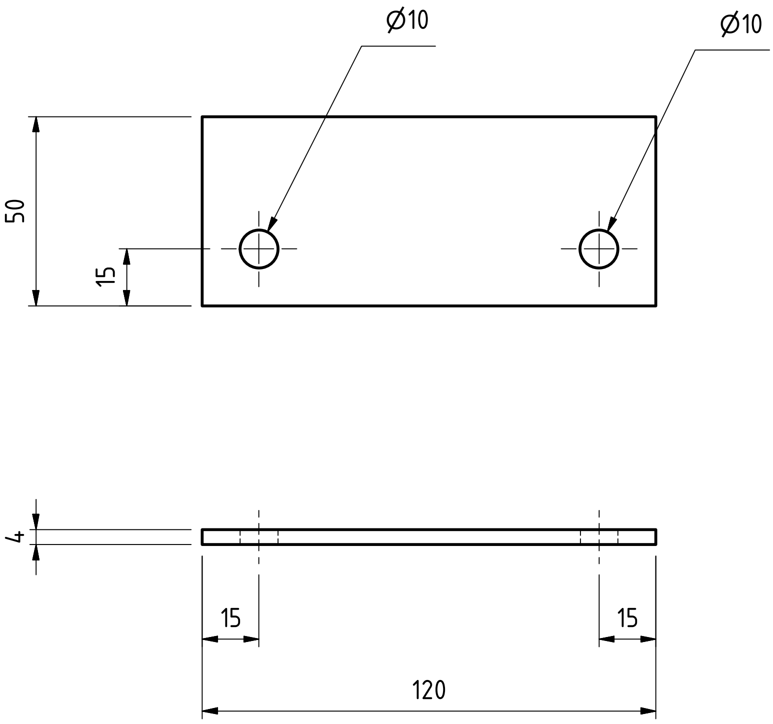

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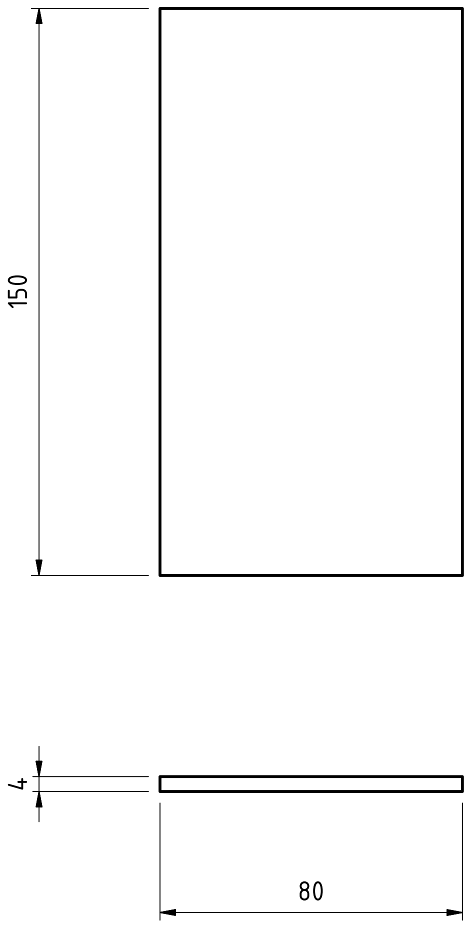

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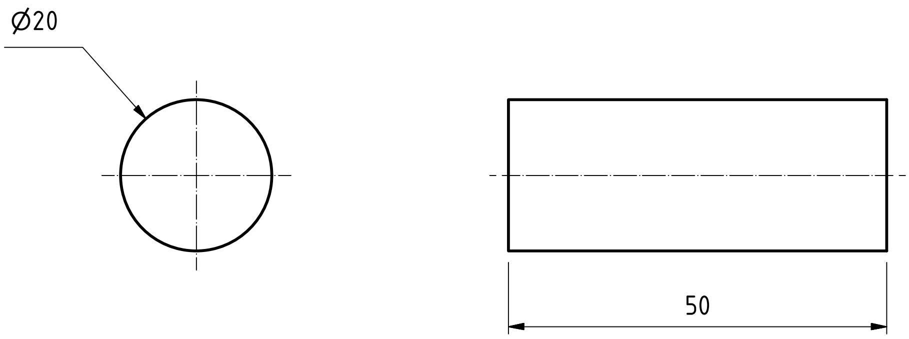

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TITLE

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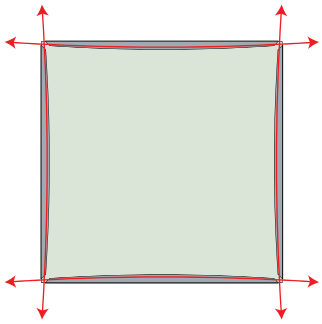
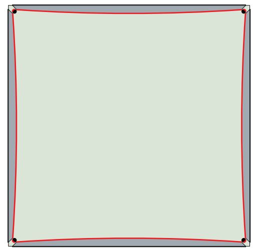
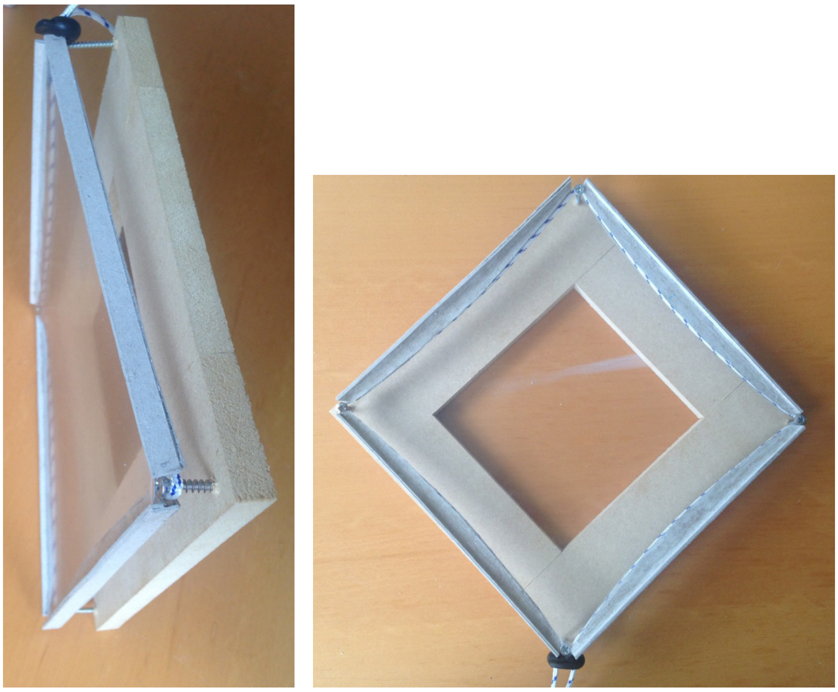
D. Alternative tensioning method concept

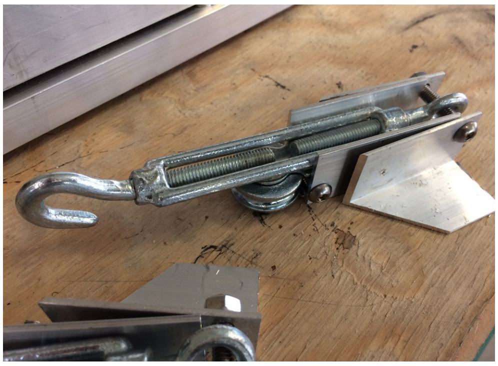
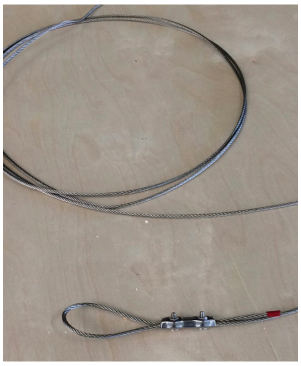
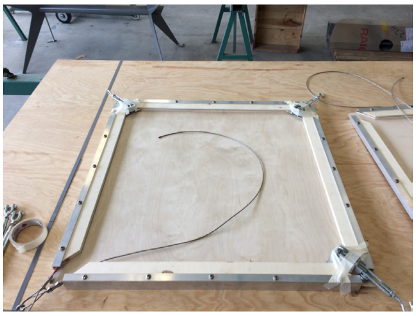
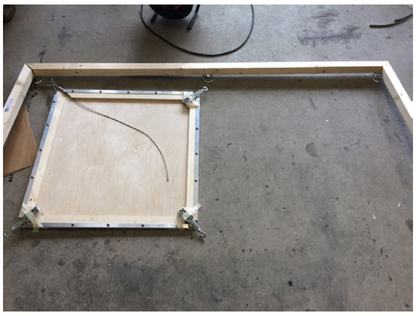




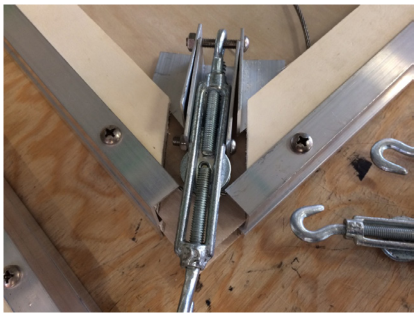


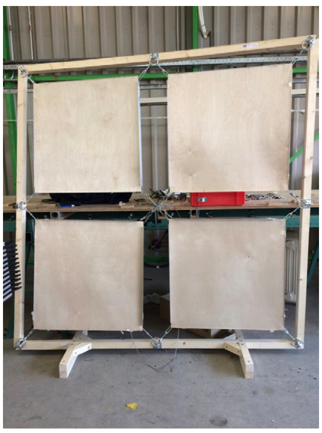
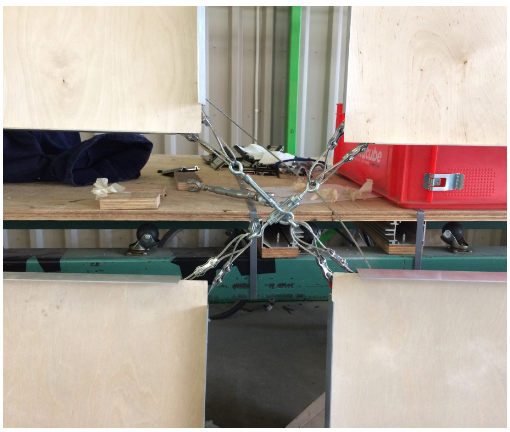
E. Alternative tensioning method mock-up





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Picture credits

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b. Dome structure.
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Source: Corning Incorporated Youtube Channel, 2012.
c. Principle ROR test.
Source: Santarsiero, 2014.
d. Principle 4PB test.
Source: Santarsiero, 2014.

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Source: C. Louter.

Fig. 40 & 41. Results pull-out test; photos
Source: C. Louter.