Kinetic Thin Glass Façade

A study on the feasibility of a water- and airtight
kinetic façade with a bending-active thin glass element

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Abstract

With the rapid development of research and production techniques, the construction industry shifts increasingly towards more demanding and ambitious projects. As a consequence, new types of use for traditional building materials emerge to create more prestigious buildings. As a relatively new product, ultra-thin glass constitutes a promising prospect in this regard due to its low weight and its ability to be bent up to small radii. A possible application is a kinetic thin glass façade, where the glass is bent to ventilate the interior. However, the realisation of this concept poses a number of challenges. These include the difficulty of achieving water- and airtightness at its bent edges, as well as the lack of stiffness of the glass and its compliance with safety regulations, requiring its lamination.

The aim of this study is to propose a possible design with the intention to tackle the named challenges. To this end, the research question is as follows: *How can a kinetic façade element featuring a bendable thin glass panel be designed to be water- and airtight in closed condition?* This question involves both structural and design aspects that need to be approached.

The research question is answered through a structural analysis part and a part dedicated to the investigation of possible solutions for achieving water- and airtightness. The structural analysis is performed via numerical analysis to test several glass laminate configurations under bending and wind load. The selected configuration consists of two thin glass sheets with a thickness of 0.55 mm laminated by a 0.38 mm – thick soft acoustic interlayer. The exploration of solutions for water- and airtightness is done via proposal and critical assessment of three possible alternatives, one of which is selected for further elaboration to create a final product. The selected proposal involves the use of an electro-permanent magnetic frame combined with a gasket attracting a metal strip attached to the glazing and thus creating a water- and airtight barrier. At the end, a mock-up of smaller scale is built to showcase the mode of operation of the final product.

Consequently, this paper presents a possible solution for the posed question to offer an insight into the field and to form a basis for further research for the development of a similar product. Many choices made during this research are subjective and are open for improvement or suggestions for a different approach. In addition, further research could be undertaken to investigate the possibility to create an insulating kinetic thin glass unit, which would be a step further towards the development of a product fulfilling the main requirements of a single-skin façade.

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List of Abbreviations

AlNiCo	Aluminium-Nickel-Copper
ASTM	American Society for Testing and Materials
BIPV	building integrated photovoltaics
e.g.	for example, lat: exempli gratia
EPDM	ethylene propylene diene monomer
FE	finite element
i.e.	that is, in other words; lat: id est
n.d.	no date
NdFeB	Neodymium magnet
PVB	Polyvinylbutyral
TRLV	Technical Regulations for the use of Glazing with Linear Supports, translated from: Technische Richtlinien für die Verwendung von linenförmig gelagerten Verglasungen
UV	ultraviolet

1. Research Definition

1.1. Introduction

The desire for transparency in buildings in contemporary architecture where opaque building elements are increasingly replaced by transparent elements makes the use of glass as a construction material more and more desirable. On top of that, the realization of glass constructions are becoming increasingly challenging together with the growth of expectations. Numerous recent projects around the world clearly demonstrate this trend (Figures 1, 2 and 3). The rapid development of research and production techniques adds to the increased use of this material, which can be considered special amongst other known materials due to its high light transmission ability, allowing views to the exterior and daylight entrance into enclosed spaces. The decisive impact of research and production techniques is undoubtedly one of the key factors in this trend. This statement is supported by Baum (2007) with the following sentence; *"Initially, it was not the architects who took architecture into the modern age, but rather engineers and planners from so called non-artistic disciplines".*

Figure 1 Hiroshi Senju Museum, Karuizawa, Japan (aasarchitecture.com, 2012)

Figure 2 Apple Fifth Avenue, New York City, USA (mac.softpedia.com, 2014)

Figure 3 Strasbourg Railway Station, Strasbourg, France (raileurope-world.com, 2017)

The argument about the increasing use of glass is supported by a market research. The research indicates an incrementally growing demand for flat glass throughout the entire world. While it should be noted that not all flat glass is meant for the building industry, it is worth mentioning that a large proportion with around 80% of flat glass production is targeting this industry, while the rest is meant for the automotive industry (Freedonia, 2014). This growing trend is projected to continue at least over the next decade and most likely even further (Table 1).

WORLD FLAT GLASS DEMAND BY REGION	2003	2008	2013	2018	2023
Fabricated Flat Glass Demand (mn $)	**38800**	**53290**	**72000**	**68140**	**139900**
North America	11240	11910	13000	17050	20750
Western Europe	12340	14690	13800	16450	18900
China	1865	6815	21750	3790	60600
Japan	5975	7095	6780	7350	7910
Other Asia/Pacific	4070	6450	8970	12650	17390
Other Regions	3310	6330	7700	10850	14350

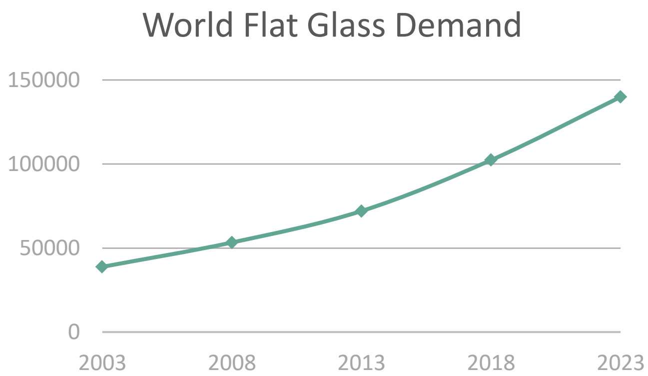


Table 1 Word flat glass demand (Freedonia, 2014)

Despite its popularity, glass, as every other construction material, poses challenges related to its chemical composition such as its high density leading to heavy building elements or its brittleness limiting the possibilities of architectural expression. If complex shapes are to be created with glass, they are either restricted due to potentially high costs of hot bending processes or due to technical limitations, such as too large minimum bending radii of cold formed glasses. Moreover, while the growing trend of flat glass use is encouraging for the glass industry as well as contemporary architecture, it does raise concerns in terms of sustainability, since the production of glass is highly energy- and carbon-intensive.

Researches are conducted in different fields to tackle all the previously mentioned challenges one by one. A promising alternative to tackle all of them at once is the use of thin glass. Generally, glasses of a thickness of 2 mm or less fall into the category of thin glass (Figure 4 Hand in lab gloves bends Willow glass between fingers (Corning, 2016)). The main characteristic of this glass is that it is chemically tempered and has a different chemical composition. In comparison to regular glass, thin glass stands out with its lowered use of raw materials, its low weight due to its lower thickness (same density), its higher flexibility, the higher impact resistance of its surface and its excellent optical quality.

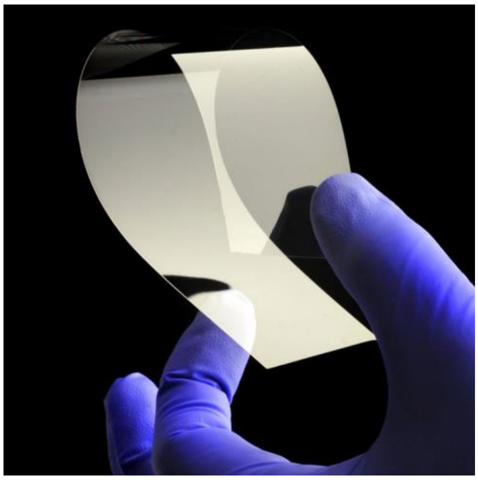


Figure 4 Hand in lab gloves bends Willow glass between fingers (Corning, 2016)

Thanks to these characteristics, this material, which at the present time is commonly applied in electronic devices such as smartphones or laptops, also opens entirely new perspectives in glass design for architecture that would be unthinkable by the use of regular glass. The aforementioned development of research and production methods also results in a higher expectation for the aesthetic use of glass. This challenges architects and engineers to come up with new creative ideas to be implemented into the built environment. Thin glass offers a great potential in this regard due to its flexibility and its excellent optical properties. Amongst other alternatives, a possible application of thin glass in architecture is its implementation into an adaptive façade system whose shape can be altered by bending the glass panel systematically for different purposes such as ventilation or structural stability.

1.2. Problem Statement

As much as thin glass is a promising prospect for the future, there has not been done much research for its application in architecture yet. One reason for this is that the use of this material in architecture poses a number of challenges, which again results in them remaining unresolved due to lack of research.

The arguably most challenging aspect in the use of thin glass is its lack of stiffness. Since wind load is a crucial factor to be taken into account, it can become difficult to cope with the stability issues of such a thin material under its impact. While lack of stiffness can lead to safety issues under wind load for people surrounding it, it can also result in high noise levels due to vibrations that negatively affect the acoustic comfort of the indoor space. Another aspect that restricts the use of thin glass in façade applications can be the relatively high cost of the chemical toughening process. According to some researches focusing on the chemical strengthening of glass, this limiting factor could however be resolved with a better understanding of the process over time (Gy, 2007). Also, the research activity in this field would benefit from a higher product demand that can be obtained by e.g. encouraging architects to use this product in the building industry.

Apart from the issues with the glass itself, there are also challenges related to the application of thin glass in kinetic facades one would face when attempting to translate theoretical concepts into reality. A major challenge at this point is to achieve absolute water- and airtightness, which is one of the main requirements of building skins, at the bent edges of the glass.

Furthermore, safety regulations require glass panels to be laminated depending on their field of use. Researches on bending of thin glass have so far only been done with a single layer of glass, which would be inapplicable in public spaces due to safety concerns.

One last aspect that also plays an important part in the use of thin glass is whether its thermal and acoustic performance can compete with regular glass. This aspect, however, is outside of the scope of this research in order to keep the focus on the structural and practical aspects.

1.3. Research Aim

The aim of this research is to investigate the possibilities for developing a façade panel consisting of one or more laminated thin aluminosilicate glass panel(s) that can be bent systematically for purposes such as ventilation. The panel should at the same time comply with safety regulations for regular glass panels as much as possible so as to provide a solid basis for a product that can be applied in public spaces. Additionally, it should offer sufficient water- and airtightness properties to create an indoor environment that is protected from wind and rain.

1.4. Research Objectives and Final Product

The Objectives of this research are:

1. To investigate possibilities to create a kinetic façade element featuring a bendable thin glass panel that is both air- and watertight upon being closed by examining possible alternative designs.

2. To explore multiple uses for the product with regard to limiting factors and new possibilities

3. To examine the effects of laminating a thin glass panel on its stiffness for structural stability

4. To determine to which extent lamination limits the flexibility of thin glass to provide a sufficient opening for ventilation

5. To analyse the most suitable solution for boundary conditions and forces to bend the glass with attention to its structural behaviour and the water- and airtightness at its bent edges

The final product will be a prototype of the proposed kinetic thin glass façade element.

1.5. Research Question

Main Question:

How can a kinetic façade element featuring a bendable thin glass panel be designed to be water- and airtight in closed condition?

Sub-Questions:

- *Which is the most suitable application for the proposed façade with regard to its limitations and created possibilities?*

- *Which principles can be considered to achieve water- and airtightness in a façade with a bendable glass element?*

- *Which of the proposed principles is the most feasible solution with regard to practical feasibility and structural suitability?*

- *How does lamination of multiple thin glass sheets affect the structural behaviour in a way to find a balance between flexibility and stiffness?*

- *What is the effect of changing glass thicknesses, interlayer thicknesses and interlayer stiffnesses regarding the structural behaviour of the glass laminate?*

1.6. Relevance

Trends constantly change in every industry, whether it be automotive, electronic or clothing. So do they in architecture, requiring innovative designs and production methods. Glass is a material that has proved itself very useful over centuries and over the years it has been improved to a point, where its thickness can be as little as 25 µm (Schott AG, 2017). This development opens entirely new perspectives in glass design, since it facilitates the creation of complex shapes in a much easier or even a more economical way. Additionally, due to the reduction in the use of raw materials compared to regular glass, this product can reduce the impact on the environment that is caused by the melting process. Furthermore, it has the potential to reduce the weight of the façade and the supporting structures that can also reduce the total embodied energy of the building while creating a potential for more economical constructions.

The current research progress in the field of thin glass is not enough for the product to be implemented into buildings. Previous researches for its application in façades mainly lack the aspects of safety, stiffness and structural stability as well as water- and airtightness, which makes its application in buildings unlikely for the foreseeable future. The purpose of this research is to take the research progress of thin glass a step further towards its application in future buildings.

1.7. Research Methodology and Report Outline

The literature review part of the research consists of a thorough literature study to understand the differences between regular glass and thin glass properties and chemical compositions along with possibilities and limitations of cold bending of thin glass. Additionally, the literature study aims to clarify polymer behaviour in laminated glass configurations, the principles of kinetic structures, the impact of geometry in glass bending and which requirements exist for a façade in terms of water- and airtightness according to standards and how these are achieved in conventional façades.

The design part begins with an exploration of possible applications for the proposed façade. Subsequently, a number of options are proposed with different principles attempting to tackle the water- and airtightness issue. These are then evaluated based on their practical feasibility and structural suitability in relation to the attempted use, whereupon the most suitable concept is selected. The selected design will then be elaborated to create a final product including technical detail drawings, visualisations and a physical mock-up to demonstrate its working principle.

The methodology of the research is illustrated in Figure 5 Methodology and Outline.

The outline of the report follows the same chronological order as the methodology;

Chapter 1, being this very chapter, provides the research framework.

Chapter 2 presents the results of the literature review that has been done during the definition of the research framework and during the design phase

Chapter 3 describes the approach and achieved results during the research and design phase in a chronological order and presents the final product and mock-up.

Chapter 4 provides a conclusion of the findings of this work and proposes recommendations for possible future studies in this field.

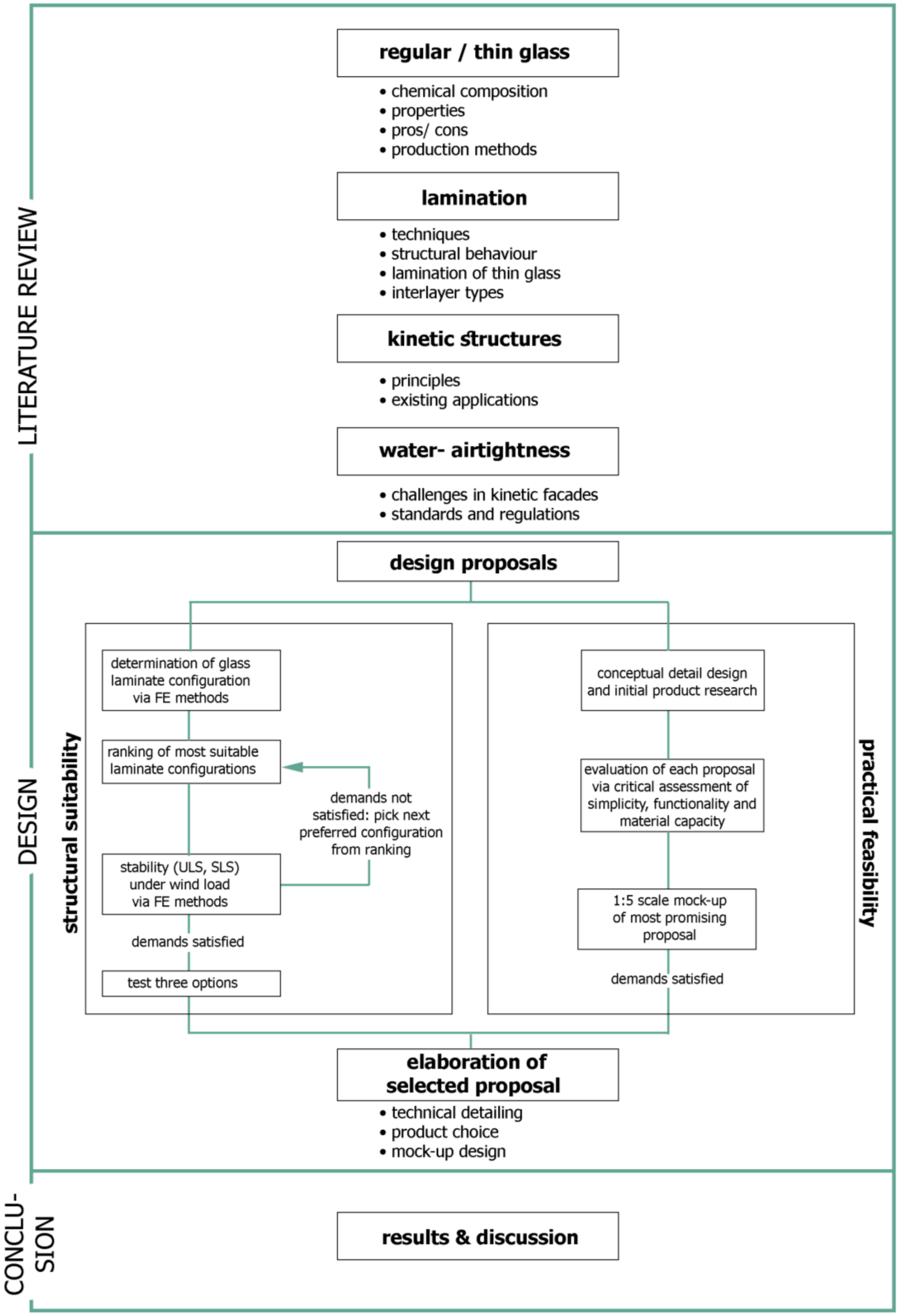


Figure 5 Methodology and Outline

1.8. Planning and Organisation

		P1	2.1	2.2	2.3	2.4	2.5	2.6	2.7	P2	2.8	2.9	2.10	3.1	3.2	3.3	3.4	3.5	3.6	3.7	P3	3.8	3.9	3.10	4.1	4.2	4.3	P4	4.4	4.5	4.6	4.7	4.8	4.9	4.10	P5
Literature Study	Thin- / Regular Glass		X																																	
	Cold Bending			X							X	X	X	X																						
	Geometry ↔ Bending			X	X																															
	Water- Airtightness					X	X								X	X																				
	Lamination/Polymer Behaviour							X	X		X	X	X	X																						
	Kinetic Structures								X		X				X	X																				
	Research Definition				X	X	X	X	X																											
Design Options	Numerical Analysis Execution											X	X	X	X																					
	Numerical Analysis Evaluation														X	X	X																			
	Feasibility: Theory																X	X	X	X																
	Feasibility: Physical Model																		X																	
	Final Design Choice																		X	X																
Elaboration	Product Choice																					X	X													
	Mode of Operation																						X	X												
	Technical Detailing																							X	X	X	X									
Prototype & Concluding	Building Final Mock-up																												X	X	X	X				
	Conclusions & Future Proposals																									X	X									
	Drawings & Renderings																								X	X							X	X	X	

2. Literature Review

2.1. Glass as a Building Material

This chapter will give a brief overview of the material glass, with respect to its basic properties, chemical composition and production and treatment methods. However, it is not meant to give a complete overview of every single property and all available production and treatment methods of glass, but instead it will solely focus on aspects that are directly related to this research.

2.1.1. Definition of Glass

The American Society for Testing Material (ASTM) describes glass as an "inorganic product of fusion, which has been cooled to a rigid condition without crystallisation". This definition comprehends many characteristics that grant this material its uniqueness. One characteristic it indicates is its property of not having a defined melting point. Instead, it undergoes a constant transition from a brittle material via the viscoelastic range to a viscous melt (Unnewehr, 2009). This is due to another indication in the referred definition, being the amorphous structure of glass, where the molecules are not ordered as they are in a crystalline solid (e.g. ice). This lead to other definitions for glass being a "frozen, supercooled liquid" (Tammann, n.d.), since the melting point is not spottable as it is in the case of crystalline solids (Figure 6, Mensinger & Schuler, 2013)

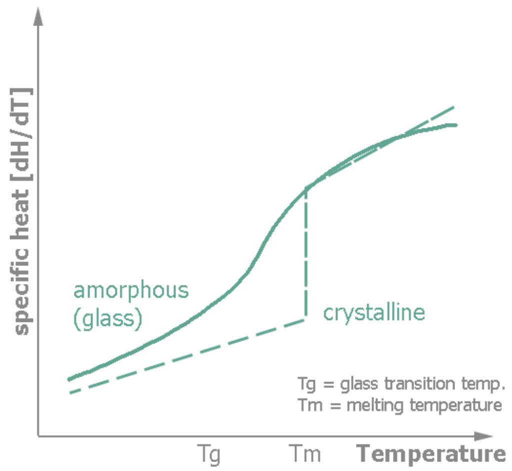


Figure 6 Change of specific heat for amorphous and crystalline solids depending on temperature (Mensinger & Schuler, 2013)

2.1.2. Chemical Composition

There are many different types of glass. These include soda-lime glasses, borosilicate glasses, lead glasses and ceramic glasses amongst others. Each of these glass types contain quartz sand, i.e. silicon dioxide (SiO_2, also referred to as silica) as a network former and determines the basic structure of the glass. Quartz on its own would make excellent glass but since it has a very high melting temperature (~1700°C), other ingredients that act as fluxes are mixed to reduce the melting point. Additionally stabilisers are added to improve the hardness and chemical resistance of the glass (Unnewehr, 2009; Kolb, n.d.).

Amongst the aforementioned glass types, soda-lime glass is the most commonly used in the building industry. For this type, the additional ingredients acting as flux and stabiliser are soda/sodium oxide (Na_2O) and lime/calcium oxide (CaO) respectively, whereas they are added as sodium carbonate (Na_2CO_3) and calcium carbonate (Ca_2CO3) where carbon dioxide (CO_2) is emitted in the process (Mensinger & Schuler, 2013). Apart from these components, small amounts of other components also exist in the mixture. The ratio for each component has been standardized for Europe in EN 572 Part 1 (Table 2). Note that the ultimate percentages can vary and therefore the presented ratios are averaged.

Composition of soda-lime glass		
Silicon dioxide	SiO_2	73%
Calcium oxide	CaO	8%
Sodium oxide	Na_2O	14%
Magnesium oxide	MgO	3%
Aluminium oxide	Al_2O_3	2%

Table 2 Composition of soda-lime glass according to EN 572-1 (averaged)

For thin glass products, aluminosilicate glass is a very commonly used type due to its eligibility for the chemical toughening process. More on the processes will follow in chapter 2.2. The most remarkable difference of this glass type in comparison to soda-lime glass is, as the name already indicates, the increased amount of aluminium oxide, while the sodium oxide amount is radically decreased (Table 3Table 3 Composition of aluminosilicate glass (CES Edupack 2015)).

Composition of aluminosilicate glass		
Silicon dioxide	SiO_2	62%
Calcium oxide	CaO	8%
Sodium oxide	Na_2O	1%
Magnesium oxide	MgO	7%
Aluminium oxide	Al_2O_3	17%
Boric oxide	B_2O_3	5%

Table 3 Composition of aluminosilicate glass (CES Edupack 2015)

2.1.3. Material Properties

The most prominent characteristics of glass, its transparency and its fragility are both related to its chemical structure. The reason for its transparency is the amorphous structure mentioned in chapter 2.1.1. The lack of boundary surfaces in the material prevent the reflection of light in the range of visible and longwave UV-A light; the atomic structure cannot absorb this light, which means that light can pass through unhindered. Its tendency to sudden failure, which characterises glass as a typical brittle material, can be traced back to the high proportion of silicate. The maximum elongation of glass before failure averages to 0.1%, which makes it impossible to predict failure. Furthermore, glass is an ideal-elastic material, meaning that before reaching its marginal strength, it does not undergo a plastic deformation and therefore can form back to its initial shape after unloading. Additionally, its deformation does not depend on load duration. This characteristic can be described as ideal-elastic. A comparison of the stress-strain behaviour of glass to steel and wood is shown in Figure 7.

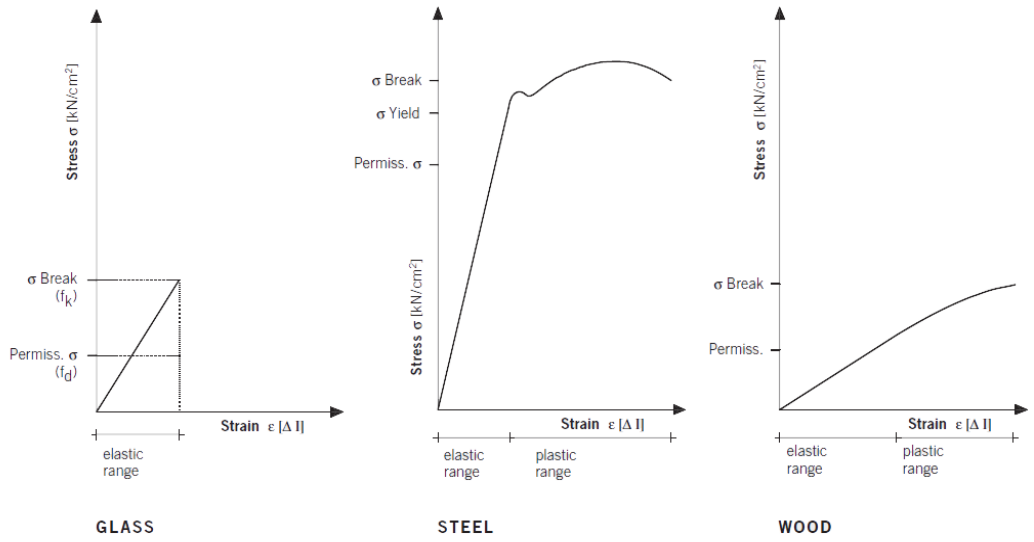


Figure 7 Stress-strain diagram of glass compared to steel and wood (Wurm, 2007)

The strength of glass is not an intrinsic property with a definitely ascribed value. In fact, it largely depends on the surface flaws of the glass sheet (Gy, 2007). This is especially relevant for the tensile strength, where a distinction between the theoretical and the practical tensile strength has to be made. The theoretical strength of common sheet glass equals to 6500 to 8000 N/mm², assuming the surface of the glass has no flaws. In practice, however, it is virtually impossible for a glass product to have a flawless surface, which leads to local stress peaks at the places where defects occur (Figure 8). This results in a very low characteristic value for the tensile strength of glass in the range of 30-80 N/mm². The practical compressive strength, however, reaches theoretical values of 400-900 N/mm² (Unnewehr, 2009). The general properties of soda-lime glass are shown in Table 4.

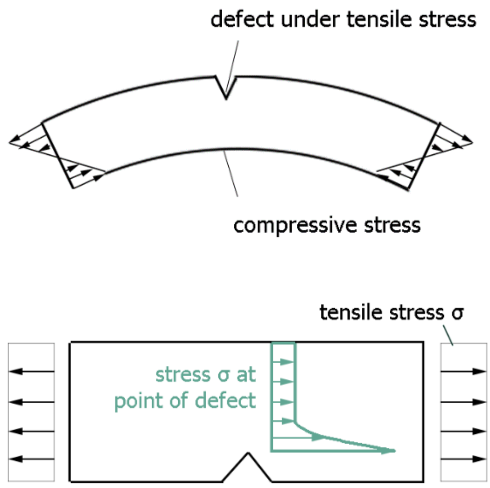


Figure 8 stress accumulation at micro-scale defects

Property	Symbol	Value with units
Density at 18°C	ρ	2500 kg/m³
Vickers Hardness before - after hardening		533 - 580
Young's Modulus	E	70 GPa
Poisson's ratio	μ	0.2
Shear Modulus	G	30 GPa
Average coefficient of thermal expansion	α	9 x 10^-6 1/K
Average refractive index in the visible range	n	1.5

Table 4 General physical properties of soda-lime glass (Balkow, 1999)

Regarding the durability of glass, it stands out with its hardness that describes its scratch resistance with 6 – 7 on the Mohs scale. Apart from its scratch resistance, glass is also generally resistant to acids and alkaline solutions due to the high amount of silica contained in its network. One exception is hydrofluoric acid that is used to etch glass surfaces. Glass is also resistant to water, however in the long term it can exhibit white stains on its surface due to ponding that leads to corrosion (Balkow, 1999; Unnewehr, 2009).

The properties of aluminosilicate glass slightly deviate from those of the regular annealed soda-lime glass. These are presented in Table 5. As can be seen, many properties are similar. The differences that are worth mentioning are the higher Young's and shear moduli and hardness of the aluminosilicate product. Another noticeable aspect is the lower thermal expansion coefficient of aluminosilicate glass in comparison to soda-lime glass.

Property	Symbol	Value with units
Density at 18°C	ρ	2500 kg/m³
Vickers Hardness before - after hardening		595 - 637
Young's Modulus	E	87 GPa
Poisson's ratio	μ	0.2
Shear Modulus	G	36 GPa
Average coefficient of thermal expansion	α	4.6 x 10^-6 1/K
Average refractive index in the visible range	n	1.5

Table 5 General physical properties of aluminosilicate glass (CES Edupack 2015)

At this point, it is important to mention that these are the values for the final product of the online processing presented in the next chapter. However, in most cases, as well as in this research, the glass is further strengthened via offline processing techniques that will be presented in chapter 2.2. Some of the presented properties can change after the toughening process. Therefore, these properties should not be regarded as the final values of the applied product.

2.1.4. Manufacturing the Basic Product

Various methods are available for the production of flat glass. Today, almost all the existing flat glass is made by using the float glass method, which proved itself as an effective method for the production of flat glass in batches, also providing a smooth surface without the need for additional treatments. The production runs in several stages. The first stage is the melting of the raw materials mentioned in chapter 2.1.2. in a large furnace at ~1550 °C where they combine to form molten glass. Afterwards, the molten glass is fed onto the surface of a bath of liquid tin at 1050°C, where the glass floats on top of the tin, which has a higher density than glass. There it flows onwards, whereas the speed at which the solidifying glass ribbon is drawn off defines its thickness. In the float bath the glass cools down to about 600 °C, giving the glass sufficient inherent strength to be lifted onto rollers to the annealing lehr to be cooled further down to 100°C. At this stage, the glass has gained its optimum flatness and solidity. After this process, the glass is ready for cutting to a maximum size of 6x3.21 meters or according to customer orders before being stacked for transportation. Thicknesses that can be achieved using this method are 0.5-25 mm, whereas the most common thicknesses lie between 2-19 mm ("Glass For Europe", 2017; Unnewehr, 2009). A sketch of the float glass process is visualised in Figure 9.

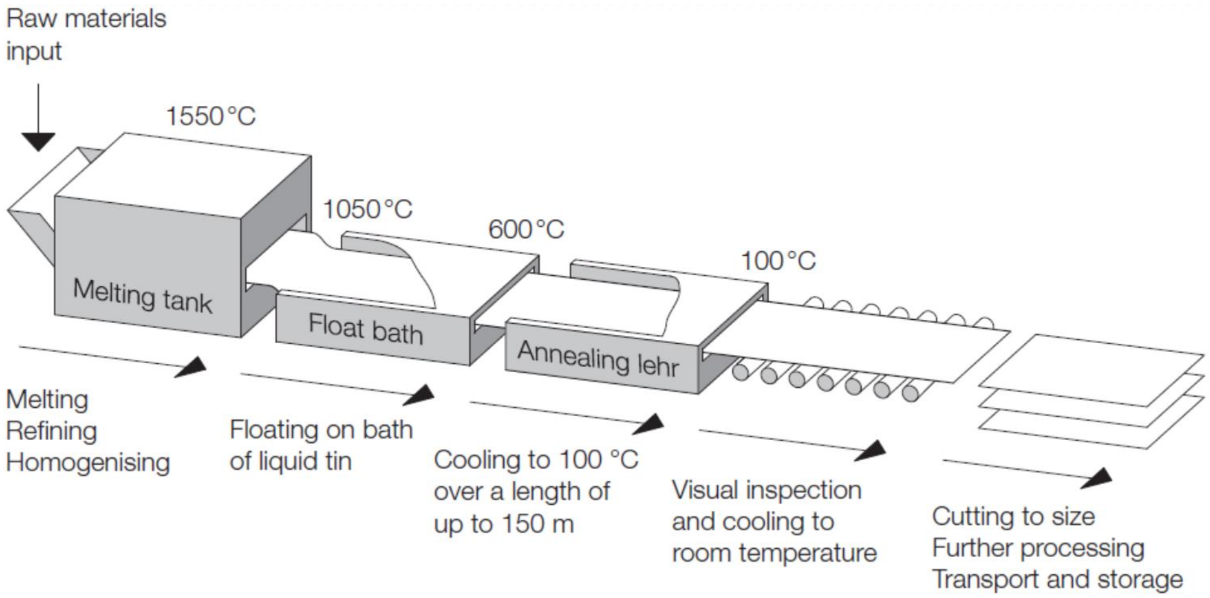


Figure 9 Sketch of the principle of the float glass process (Unnewehr, 2009)

An alternative to the float glass method is the overflow fusion process. This method is especially useful for the production of thinner glass sheets of thicknesses of one or more millimetres down to as thin as 100 microns (Corning Inc., 2017). Similar to the float process, the first step of this method is to melt the glass into a homogeneous mixture and is released into a large collection through a V-shaped bottom, known as isopipe, which is carefully heated to manage the viscosity of the mixture and ensure uniform flow. The molten glass flows evenly over the top edges of the isopipe, forming two thin, sheet-like streams along the outer surfaces before they meet at the bottom and fuse into a single sheet. The sheet then lengthens and cools in mid-air without contact to any other material, resulting in a smooth surface on both sides unlike the float glass, at which a differentiation is made between the tin side and the air side. The cooled and stabilized glass sheet can be cut at the bottom of the

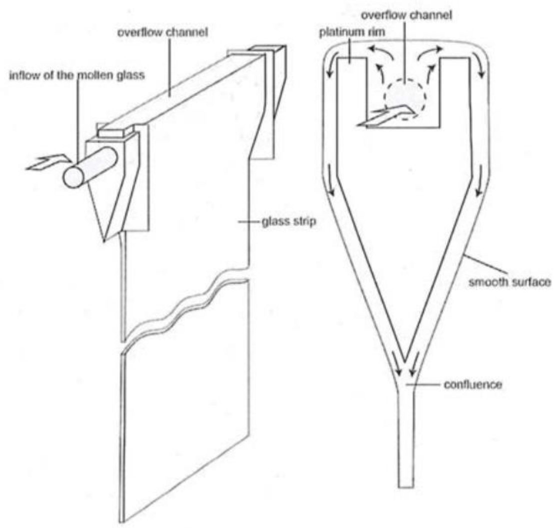


Figure 10 Overflow Fusion Process (Schneider, 2015)

draw and moved to complete the processing (Corning Inc., 2017). A sketch of the process can be seen at Figure 10.

Although the overflow methods appears to be especially suited for the production of thin glass products, it is not the only method it is manufactured with. The production of thin glass is also possible with the float glass process, as it is the case with AGC's Leoflex and Dragontrail products, whereas the overflow process is used for Corning's Gorilla Glass product. Other processes are also applied by other manufacturers, such as the Schott AG's downdraw process which is quite similar to overflow.

2.1.5. Sheet Glass Treatments

There is a number of different sheet glass treatment methods to customise the glass according to the purpose it will serve. These methods include, but are not limited to, mechanical working to cut the sheet into the appropriate size, edge working to eliminate irregularities for safety and structural purposes, surface treatments such as coating for energy saving or enamelling for artistic purposes, toughening to increase its strength, laminating to create more layers for safety and bending into the desired shape. As also mentioned earlier, this chapter focuses exclusively on topics relevant to the research. Therefore, only the last three mentioned topics "toughening", "laminating" and "bending" will be elaborated in the following pages in separate sub-chapters, since they play an important role in the research process.

2.2. Prestressing of Glass

The basic float glass that comes out of the float line is rarely strong enough to conform to regulations and to provide a safe environment for its surroundings. The main reason hereby is its significantly lower tensile strength compared to its compressive strength (see chapter 2.1.3). Tensile stress also occurs on one side of the glass in cases where it is deflected. Being exposed to wind or other unexpected impacts, flat glass is prone to tensile stress in almost all cases. Therefore, secondary processes are required to prestress glass, whose principle is similar to that of prestressed concrete; the glass is given an inherent compressive stress at its surfaces that has to be overcome first for tensile stress to build up at this spot. This way, the point where the tensile stress exceeds the glasses tensile limit, which results in fracture, is reached at a higher deflection rate (Unnewehr, 2009). Apart from the mechanical strength, also the thermal shock resistance is increased. Several methods exist to pre-stress glass. In the following pages, the manufacture and properties of thermally toughened safety glass, heat-strengthened glass and chemically toughened glass are introduced.

2.2.1. Thermally Toughened Safety Glass

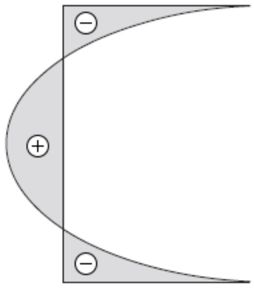


Figure 11 Stress distribution over the thickness of toughened glass. Adapted from: Unnewehr, 2009

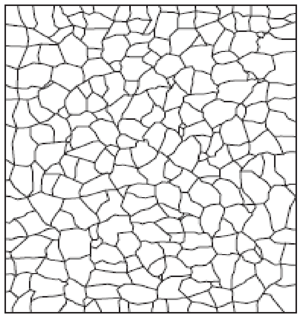


Figure 12 Fracture pattern of thermally toughened glass. Adapted from: Unnewehr, 2009

This type of glass, which is also referred to as tempered glass, can be manufactured by heating the basic glass product to about 650 °C, which is about 100 °C above its transformation point, and rapidly cooling it. This way, the surface of the glass is cooled down below the transformation point, while the hot core still has the urge to expand. Meanwhile, the surface that is already cooled down is prevented from contracting, which results in the desired compressive stresses on the glass surface that is in equilibrium with the tensile stresses at the core of the glass (Figure 11). The area of the compressive stresses amounts to 2 x 20 % of the entire thickness of the glass, while the maximum compressive stress equals to around 2.3 times of the maximum tensile stress in the centre. Through this process, the glass reaches a much higher characteristic minimum bending strength (Mensinger & Schuler, 2013). The values are presented further in chapter 2.2.4.

Upon failure, thermally toughened safety glass will split in a large number of small fragments (Figure 12). In case of lamination, this type of glass will however suddenly fall as one whole piece containing of the fragments adhering to the interlayer. Therefore, its use in heights above head level is restricted by many regulations. The fracture can also happen unexpectedly due to nickel-sulphide nanoparticle inclusions in the glass that can expand upon being exposed to an energy source. This leads to additional stress on top of the ones that are caused due to the pre-stressing process. A method to prevent this kind of failure is the heat-soak test, where the glass is exposed to temperatures of around 270 °C to accelerate the expansion of the nickel-sulphide particles. The chance for sudden failure is hereby reduced. (Balkow, 1999; Mensinger & Schuler, 2013).

2.2.2. Heat-Strengthened Glass

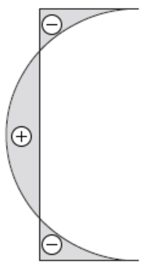


Figure 13 Stress distribution over the thickness of heat-strengthened glass. Adapted from: Unnewehr, 2009

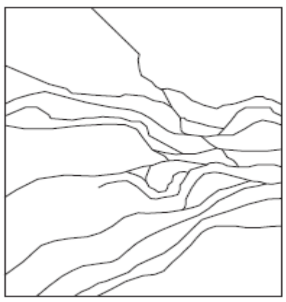


Figure 14 Fracture pattern of heat-strengthened glass. Adapted from: Unnewehr, 2009

In construction engineering, strength is not the only deciding factor for safety, but also the residual capacity of a material that can bare loads for a certain period of time even after fracture. In contrast to fully tempered glass as shown above, heat-strengthened glass fulfils this requirement by exhibiting large fragments rather than small ones. This way, if laminated, the large fragments of heat-strengthened glass will interlock, being able to resist a certain amount of compressive forces, while the interlayer is taking the tensile stress. This effect will be further discussed in chapter 2.4. The drawback of this glass type compared to thermally toughened safety glass is its lower characteristic minimum bending strength compared to thermally toughened glass. However, it is suited for overhead applications, since it allows enough time for the evacuation of its proximity after its failure.

This strengthening method takes place at a similar temperature as the thermal toughening process. The difference is, however, that the cooling process is done much slower, allowing the core to expand more before the surface hardens. The glass industry has limited the production of heat-strengthened glass to a thickness of 12 mm, as higher thicknesses result in tinier fragments and do not result in a substantial increase of its strength. (Mensinger & Schuler, 2013).

2.2.3. Chemically Toughened Glass

This toughening process plays a special role when it comes to the application of thin glass, since it is especially suited for this glass type. Almost all of the flat glass products that are categorized as thin glass, are chemically treated.

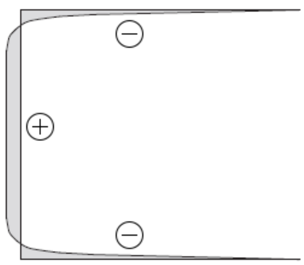


Figure 15 Stress distribution over the thickness of chemically toughened glass. Adapted from: Unnewehr, 2009

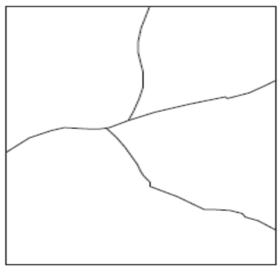


Figure 16 Fracture pattern of annealed and chemically toughened glass. Adapted from: Unnewehr, 2009

In contrast to the previously introduced strengthening methods, chemical toughening takes place below the transformation point of glass. Thereby it is immerged into a molten alkali salt, which consists of alkali ions that possess a larger ionic radius than those of those included in the glass composition. Once being thermally activated, the ions included in the glass are exchanged with those with a larger radius from the solution. This creates a compressive stress layer on the surface of the glass due to the "stuffing" effect created by the larger ions (Gy, 2007). The residual compressive stress that is incorporated at the surface with this method is larger than that of the thermally toughened or heat-strengthened versions. This way, a higher ultimate bending strength can be reached (Balkow, 1999). It also leads to a higher damage resistance of the surface, making it suitable for products that are exposed to impact in their everyday use. However, the thickness this compressive layer can reach, also called the depth of compression, is much lower than those of the other versions (Figure 15). This value can vary according to the type of glass that is used and the processing time and temperature. Just as in thermally treated glass, the compressive stress is opposed by a tensile stress at the core to reach an equilibrium. In this case, however, the maximum tensile stress is lower, since it is distributed over a larger thickness.

All silicate glasses are suited for chemical tempering, provided there are enough mobile cations available in the composition. However, alkali aluminosilicate glasses can be ion-exchanged to larger depths of compression and higher surface resistances in shorter amounts of time and are therefore more suitable towards chemical strengthening (ACerS, D. C. H. D. C., 2011). Usually, glass manufacturers offer both variants in their product range. The fracture pattern of chemically strengthened glass is similar to that of annealed glass (Figure 16).

2.2.4. Comparison of the Toughening Methods

The different strengthening methods also lead to slightly differing mechanical, optical and thermal properties of the final products. Table 6 shows the main property differences between chemically and thermally tempered (toughened) glass. The values for the chemically tempered glass are taken from the Leoflex product by AGC (Appendix 1). Heat-strengthened glass is not included in this comparison, as it is mostly chosen for its residual capacity after failure rather than its strength, therefore serving another purpose.

		chem. tempered (Leoflex)	thermally tempered
Mechanical Characteristics			
Strength / Marginal Stress	MPa	**260**	80
Young's modulus	MPa	**74 000**	70 000
Poission's ratio	-	**0.23**	0.2
Density	g/cm³	**2.48**	2.5
Vickers Hardness	-	**673**	527
Optical Characteristics			
Energy transmission rate	%	**91.6**	91.1
Thermal Characteristics			
Expansion coefficient	1/K	**9.8 x 10^-6**	9 x 10^-6
Strain point	°C	**556**	500

Table 6 Comparison of chemically and thermally tempered glass (source: AGC, 2015)

The main differences are visible in their strength, Young's modulus and Poisson's ratio, which greatly influence the structural behaviour of the material.

Gy (2007) listed a number of advantages and drawbacks of chemically strengthened glass compared to conventional thermally tempered glass. Additionally, the glass manufacturer AGC (2015) mentioned advantages of chemically strengthened glass. A compilation of the advantages and drawbacks relevant to the design of this research are listed below;

Advantages of chemically strengthened glass:

- higher surface compression stress, allowing larger deflections
- lightweight elements possible through lower thickness
- the optical quality is kept the same as that of the original glass, whereas after thermal tempering, the manipulation of a somewhat softened glass is required. Additionally,

there is no "strain pattern", which is an optical defect that is visible on thermally tempered glass when lightening is slightly polarized

- very thin glass can be strengthened by ion exchange, whereas it is very hard to provide reinforcement to glass thinner than 2 mm on an industrial thermal tempering installation (air cooling)
- through possibility to strengthen thin glass, lower stiffness possible, enabling cold bending with lower forces
- thin glass facilitates design of lightweight elements through lower thicknesses
- complex-shaped glass items can be reinforced (not feasible with thermal tempering)
- chemically more stable than thermally toughened glass
- higher resistance against weathering after accelerated weathering test

Disadvantages:

- smaller compression depth compared to thermally toughened glass
- the lower stiffness as a result of lower thicknesses can also lead to a drawback for the glass to be unstable under wind loading if measures are not taken
- The main drawback of chemical tempering is the cost. Because of the high cost, compared to conventional thermal tempering, this reinforcement process can only be applied for high value applications

One characteristic that can neither be categorized as an advantage nor as a drawback is the larger fragmentation of chemically strengthened glass compared to that of thermally toughened glass, since the preference largely depends on the application. In the case of laminated thin glass on a façade, it is assumed to be more of an advantage, since the small fragmentation of tempered glass would lead to the fractured composite to fall as one piece, folded similar to a piece of cloth. With larger fragments, the glass is more likely to be held in place after fracture appears. However, an interlocking of the fragments similar to that of heat strengthened glass is not expected, since the thickness would be too low for this effect.

2.3. Testing and Determination of Bending Strength

Thin glass under bending results in large deflections, so that simple theory to describe the load-deflection and load-stress relationship cannot be applied accurately (Siebert, 2013). This is due to geometric nonlinearity that comes into effect when the element is deformed at high rates. As a simple example, a beam with a low stiffness under constant normal force N and its dead load under gravity is given. This loading situation would cause the beam to bend. The deflection in the central node would cause a higher bending moment M at this spot due to the increasing distance r perpendicular to the normal force, since $M = N x r$. The increased bending moment would then again result in higher deflections (Figure 17 and Figure 18).

Not only does thin glass require a totally new kind of thinking, also possible test scenarios for determination of the ultimate bending strength are currently not distinctly regulated in standards. Different test set-ups published in several papers show possibilities for alternative determination of the ultimate bending strength of thin glass (Neugebauer, 2016). Even so, due to the lack of regulations, the provided ultimate bending strength property of each manufacturer and the results retrieved from various researches can strongly fluctuate. The manufacturer's specifications regarding this value are usually lower than those achieved in researches, since results from the lower quantile are considered to remain on the safe side.

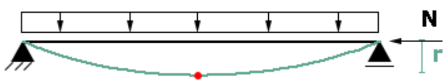


Figure 17 Geometric nonlinearity of a largely deflected simple beam

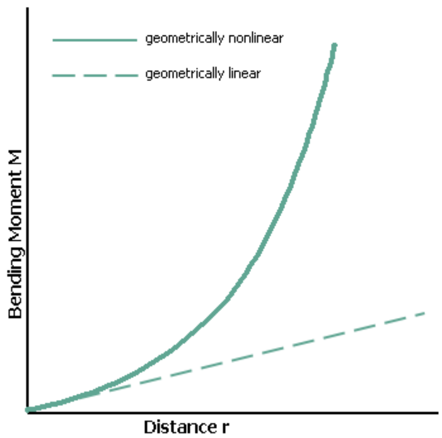


Figure 18 Distance-bending moment relationship of geometric linear and nonlinear calculations

2.4. Lamination of Glass

Laminated glass consists of at least two glass sheets that are bonded to each other. The bonding mostly happens with a Polyvinylbutyral (PVB) interlayer placed in between the glass sheets that has an adhering effect. In special cases, also different interlayers such as SentryGlas (Dupont) come into use for purposes such as extra structural strength. The glass laminate configuration can consist of different types and thicknesses of glazing, whether it be tempered, heat strengthened or chemically strengthened glass.

Laminated glass is frequently used in architecture. The reason for its popularity is that it adds safety to the strength of glass, while keeping it transparent. The additional safety comes from the ability of the interlayer to keep the glass fragments attached after its failure and in some cases such as in that of heat-strengthened glass, provides a residual strength. This way, the risk of injuries can be limited and protection can be provided against vandalism and burglary (Molnár, Vigh, Stocker, & Dunai, 2012). The application of laminated glass is mandated in regulations in different forms according to requirements. For instance, the German Technical Regulations for the use of Glazing with Linear Supports (TRLV), requires the bottom glass layer to comprise of a laminated sheet with annealed or heat-strengthened glass in case of overhead glazing, while a walkable glazing should consist of at least three layers with the top layer being toughened or heat-strengthened glass.

2.4.1. Manufacturing of Laminated Glass

The lamination process takes place in several steps. One of these steps is the removal of the air trapped between the interlayer and the glass. For this step, two major air removal processes exist: the nip-roll or calendar method and the vacuum process. In architecture, the nip-roll method is more common because of the large sizes. This method will be described briefly.

First, the ready-cut single glass sheets are cleaned in a washing plant to remove any remaining grease, oil and dust that is attached to the surface. Afterwards, the cleaned glass is placed on a positioning table with the interlayer and the other glass sheet(s) placed on top of it to form a sandwich. The layering takes place in an air-conditioned room with temperatures of 18 – 20 °C and a relative humidity of ~25%. This is needed to achieve the required interlayer humidity during the layering process. The next step, which is the nip-roll de-airing process, takes place in two heating zone. The first zone is heated to a temperature of 35-45 °C with heat rays. Subsequently, the sandwich passes through a pair of rubber-surfaced cylinder rollers. In the second part, the sandwich enters a heating zone with temperatures of 60 – 70 °C, where it gets rolled once more. After all the air is removed between the glass and interlayer and the edges are continuously sealed to prevent air penetration, it is ready for the last step – the autoclave process. The autoclave process is the one that causes the adhesion effect between the glass and the interlayer. To achieve the best possible bonding, the decisive parameters in this step are the right choice of temperature, pressure, duration of the process and the heating- and cooling time in the autoclave. This needs to happen slowly to prevent stress building in the glass sheets. The process can last one to six hours. Figure 19 illustrates the steps of the lamination process (Mensinger & Schuler, 2013; Molnár, Vigh, Stocker, & Dunai, 2012).

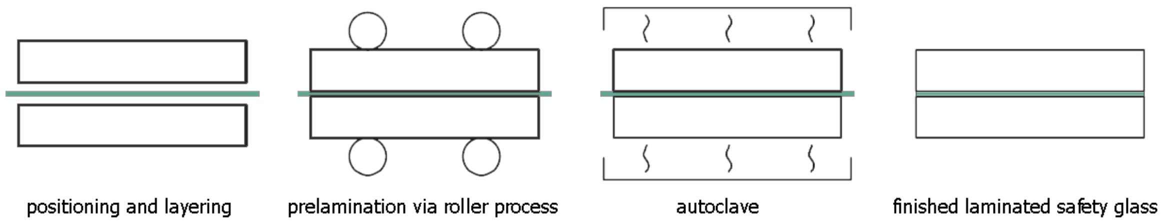


Figure 19 Manufacturing of laminated glass. Adapted from: Wurm, 2007

The vacuum process is suited for the production of glass laminates with a high curvature. However, laminates with large sizes can also be produced with this method. Companies such as Glasbau Seele can produce laminated glass up to 12 metres long using the vacuum process (Wurm, 2007). In this process, the layered sandwich is placed into a rubber bag under a temperature of 120 °C, where it is vacuumed to remove the air between the glass and interlayer.

2.4.2. Interlayer Properties

The interlayer of a glass laminate generally consists of a thermoplast whose deformation behaviour exhibits a viscoelastic behaviour that strongly depends on the thermodynamic condition of the material. The state of aggregation of PVB can differ from solid to fluid within a temperature range of -20 °C to +80 °C (Mensinger & Schuler, 2013; Figure 20). Especially its state at room temperature should be regarded carefully, as the gradient is quite steep at this point. The reason for this is that the glass transition range of PVB lies within ~10 to 30 °C, where it changes its behaviour from solid to rubber elastic. Temperature however is not the only factor the PVB properties depend on. Along with thermoplasticity, it also shows a viscoelastic behaviour in all states of aggregation. This means that the stiffness of this material also depends on the load duration (Figure 21). As a rule of thumb, also as seen on the graphs, the shear modulus decreases with rising temperatures and increasing load duration. Further factors that affect the interlayer's stiffness are humidity and UV-radiation. The non-linear material property of PVB therefore makes it difficult for manufacturers to give exact specifications for their products. The shear and Young's moduli are therefore usually given in matrices. An example of a matrix summing up the structural properties of different interlayers is shown in Appendix 2.

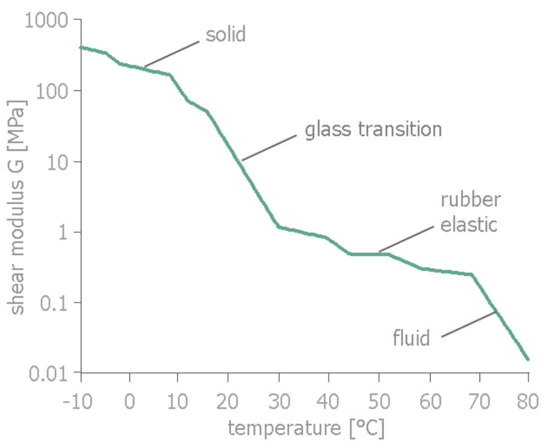


Figure 20 qualitative temperature dependent shear modulus trend of PVB (Adapted from: Mensinger & Schuler 2013)

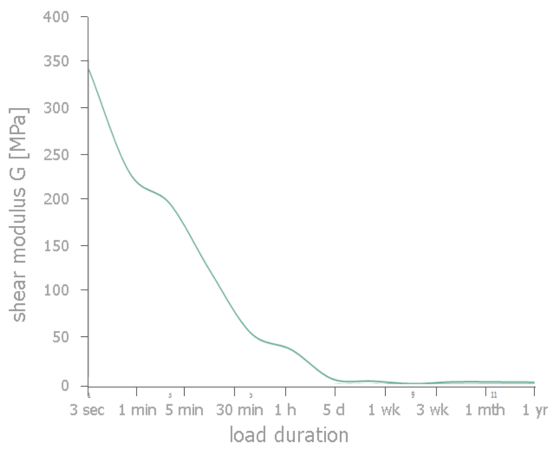


Figure 21 qualitative shear modulus trend depending on load duration on basis of data made available by Kuraray Trosifol

The presented graphics are only representative, since interlayers are offered in a large variety with different stiffnesses and other characteristics. The Portfolio of the Trosifol product range for applications in Architecture by Kuraray is shown in Appendix 3. For instance, acoustic interlayers are softer and not suitable for structural applications, while products such as SentryGlas stand out with their exceptional stiffness. The required values for a typical PVB is at least 20 N/mm² for its tensile strength and a maximum elongation of 250% at 23°C (Belis, 2007).

As stated by Timmel (2007), the non-linearity underlines the importance of being careful with experimental data in numerical simulations. The same goes for using a simplified linear material behaviour in numerical analyses. When using a linear material property, slight inaccuracies in the results are to be expected. In this case, it should be made sure that these inaccuracies lie on the "safe side", in other words, the resulting values should reflect the less favourable situation in a structural calculation.

PVB interlayers are available in standard thicknesses that are a multiple of 0.38 mm. Different thicknesses can have different effects on the overall structural behaviour of the laminate. This will be further elaborated in the following chapter.

2.4.3. Mechanical Behaviour of Laminates

As described in chapters 2.1.3 and 2.4.2, glass has a linear-elastic and the PVB interlayer a viscoelastic material behaviour. Once these two materials are combined in form of a sandwich, it results in a composite material, where the different layers cooperate mechanically under bending load. The behaviour of the laminate differs from that of a monolithic glass due to the extra load bearing capacity caused by the interaction of the interlayer. Hereby, it is challenging to define the bonding behaviour of the composite. Assuming two plates on top of each other with absolutely no bonding effect are exposed to a lateral load, the cross-sectional stress diagram would consist of two identical compressive-tensile stress diagrams for each layer. If these plates would be completely bonded, the diagram would change to a single transition from compression on top and tension at the bottom over the total thickness of the laminate, with lower peaks. In practice, however, the state of the laminate is between these two states (Figure 22).

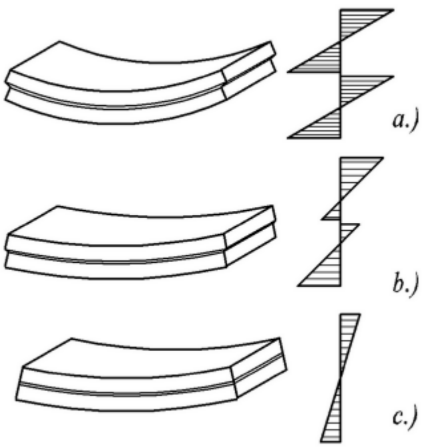


Figure 22 Interaction between glass and interlayer a.) no bonding, b.) partial bonding, c.) complete bonding. (Molnár, Vigh, Stocker, & Dunai, 2012)

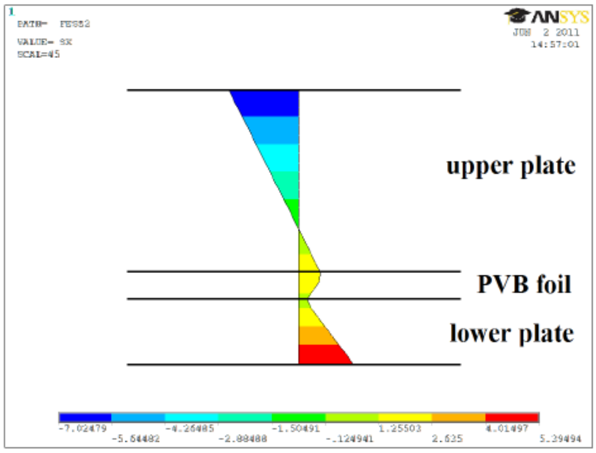


Figure 23 Cross-sectional stress diagram of an assymetric laminate composition following a numerical analysis (Molnár, Vigh, Stocker, & Dunai, 2012)

The stress magnitudes can be manipulated by varying the layer thicknesses. Since the tensile strength of glass is only about 10% of its compressive strength, it is very likely to fail at the surface, where tensile stresses occur. Therefore it could be advantageous to decrease the thickness of the layer that is bending outwards, i.e. the layer with larger tensile stresses, in order to reduce it while increasing the maximum compressive stress at the top. This has been numerically tested by Molnar et. al. (2012; Figure 23). This method is worth investigating so as to reduce the peak tensile stresses.

However, for the application of thin glass, its advantageous effect could be negligible, since the total thickness of the laminate is relatively low.

Furthermore, the thickness of the interlayer also directly affects the overall stiffness of the composite. For a given shear stiffness, a thicker interlayer results in a stiffer laminate. This is due to the fact that with the glass plates situated farther apart from each other, the cross section has a larger moment of inertia and is therefore more difficult to bend. Thus, in the case of this research, where bending is desired, the use of a thinner interlayer is preferred to reduce the required force to bend the panel. This choice is, however, restricted by the stress building in the panel. A thin interlayer is less capable of redistributing the shear stresses between the glass panels and are therefore more likely to fail at the same bending radius. This is explained by the varying angle of thin and thick interlayers under shear loading (Figure 24). If a thin interlayer is to be chosen, it needs to be soft enough to sufficiently redistribute the stress.

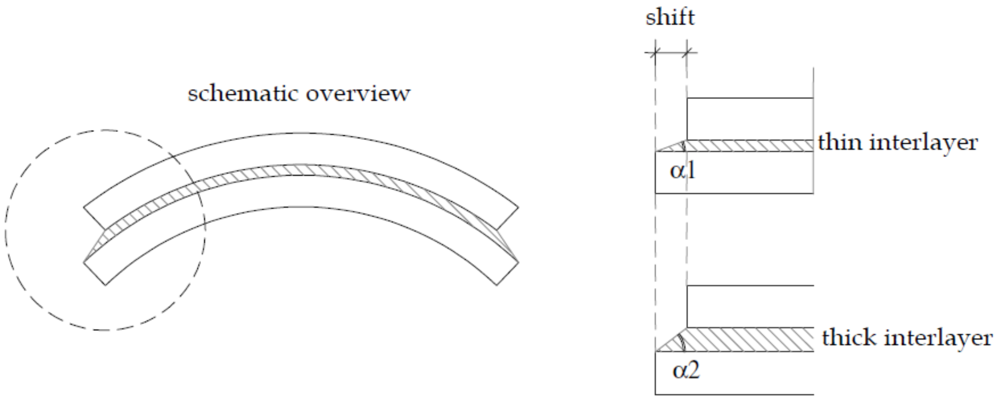


Figure 24 Shear of the interlayer (Belis et. al., 2007)

Apart from increasing the effective thickness, one main reason for the use of laminated glass is the safety aspect. Since glass itself is a brittle material, suddenly failing without plastic deformation, through the lamination with a PVB interlayer, it gains some residual load-bearing capacity. In a glass laminate with usual glass thicknesses of 2 mm and above, the failure process can be divided into three stages (Figure 25).

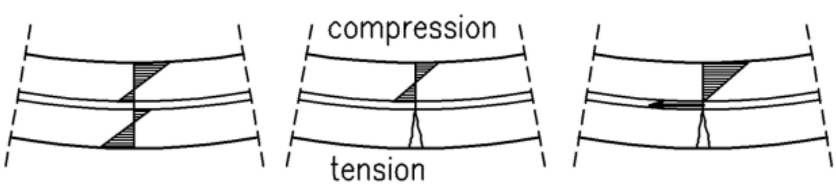


Figure 25 Theoretical failure stages of laminated glass (Kott, Vogel, 2004)

The first stage is before any sign of failure, where both glass plates are intact. In this case the stress is distributed as described in Figure 22. The only load on the laminating film at this stage is the shear stress. At the second stage, the bottom glass layer fails. Thus, the whole load is carried by the upper layer and the stress distribution in that one becomes symmetrical. The laminate can carry less load, however it is able to resist more deflection. The last stage describes the situation after the failure of the upper glass layer. At this stage, the interlayer is exposed to tensile stress. Due to the locking of the particles of the upper layer, it can still carry the compressive load.

This effect is however not expected in the case of failure of a thin glass laminate. There are two reasons behind this; Firstly, the glass is expected to fail once it reaches a small radius. At this point the energy stored in the glass is so high that the glass would burst into very small, dust-like particles. Secondly, assuming the fragments have a similar size as the regular laminate, the thickness of the upper layer would most likely not be enough to be locked to each other. Therefore, the advantageous effect of glass laminates in terms of safety should not be taken as granted. The effect of the interlayer in this case would be to hold larger fragments of glass together to prevent them from injuring people in direct proximity.

2.5. Bending of Glass

Curved glazing elements are increasingly used for façade, balustrade or overhead glazing applications, as they allow unique architectural expressions. They are however predominantly applied in more ambitious projects due to being cost- and labour-intensive.

Along with annealed glass, also thermally and chemically tempered glazing elements offer themselves for bending. Generally, it can be distinguished between cold- and hot-bent glasses that are, as the names already indicate, produced with different post-processing techniques. In the following chapters, the bending techniques and the field of application for each product are briefly explained. Ultimately, their advantages and disadvantages are listed.

2.5.1. Hot-Bending

The hot-bending process involves reheating the finished flat glass product into the viscous state. This requires temperatures of around 600 – 650 °C. Subsequently, the glass is either formed by being placed into a mould or by using its own weight to deform into the desired shape before being cooled down. Glasses that are bent this way will be free of permanent bending stresses, for being shaped in the viscous state. The quality of hot-bent glass is significantly dependent on the manufacturer's experience. Problems can occur especially at meeting tolerances and the equal pre-stressing distribution over the whole surface or the cross section (Mensinger & Schuler, 2013).

Hot-bending enables extreme glass curvatures that allow a bending angle of as much as 90° (Sedak GmbH, 2017). The freedom of shape also makes it possible to use the glass as structural element by bending it into a geometrically stable shape. The glass façade of the Museum aan de Stroom in Antwerp, Belgium (Figure 26) is a good example of a glass application that could not be realized with flat glass panels due to their lack of stability. Apart from curvatures with small radii, also double curvatures are possible with hot-bending. This kind of shape is generally preferred for architectural purposes rather than structural. An example of a hot-bent double curved glass façade is that of the Elbphilarmonie in Hamburg, Germany (Figure 27).

Figure 26 Museum aan de Stroom (widewalls.ch, 2017)

Figure 27 Elbphilarmonie (Schielke, 2017)

2.5.2. Cold-Bending

Cold-bending, also referred to as cold-forming, is an inexpensive alternative to the hot-bending process. The reasons for it to be more economical is for one thing, that heating up to the glass transition temperature is not necessary and for another the elimination of the need for a mould. The cold-bending method can be subdivided into two different processes: cold bending over rigid framework and cold bending during lamination (Sedak GmbH, 2017).

In the method of cold bending over a rigid framework, clamps or point fixings force the glass plate into a curved shape in the cold state, although this method can only be used for single curved surfaces. Thereby, the general rule is, the thicker and stiffer the glass sheet, the less it can be curved. Further, cold-bent glass can only reach curvatures with relatively large radii compared to the hot-bent version. Compared to a flat laminated glass panel, cold-bent panels increase the load-carrying capacity. Distributed loads such as wind and snow are primarily carried via membrane forces and less via bending. (Wurm, 2007; Seele GmbH, 2017). An example for a cold-bent freeform shell structure is shown in Figure 28, where each triangle and node in the structure is unique.

The cold bending during lamination process involves bending the individual panes of a glass laminate prior to laminating and subsequently laminating them with the new curved geometry. The finished laminated pane retains its bent shape after autoclaving without the need for a supporting framework. The minimum cold-bending radius is about 1500 times the thickness of the glass, although tighter radii might be possible (Sedak GmbH, 2017). Since the temperature in the autoclave of 140 °C is much lower than that needed for hot-bending (600 °C), this process is also called cold-bending (BauNetz GmbH, 2017). Figure 29 illustrates an example of a glass façade formed by using this method.

Cold forming results in permanent tensile bending stresses throughout the component's lifetime. Therefore, special attention needs to be paid into load combinations of bending stresses along with those resulting from service- and live loads. Depending on the orientation of the curvature, the bending stress can be either advantageous or disadvantageous. Furthermore, in case of cold-bending of laminated glass, initially, high stresses can occur in the interlayer that later on decrease due to the relaxation of the foil (Mensinger & Schuler, 2013).

Figure 28 Westfield, London (Seele GmbH, 2017)

Figure 29 Gare de Strasbourg (architonic.com)

2.5.3. Comparison of Bending Techniques

Table 7 summarizes all the previously mentioned plus some additional advantages of both bending techniques. The two cold-bending processes are included in one column, as the same advantages apply for both of them, unless stated otherwise.

Cold-Bent	Hot-Bent
+ economical construction of unique shapes	+ double curved shapes possible
+ lower energy consumption	+ enables extreme curvatures up to 90°
+ no optical distortions	+ no framework required to support shape in contrast to cold-bent panels*
+ short delivery times, especially if replacement necessary	+ no permanent bending stresses
+ more practicable transportation to the site (flat panes)*	
+ no size limitation due to size of furnace	

**only applies for cold-bent over rigid framework*

Table 7 Advantages of different bending techniques

2.6. Realized and Potential Applications of Thin Glass in Architecture

As mentioned earlier, thin glass is so far predominantly used in the electronic industry or the laboratory-/ biotechnology and it has been scarcely researched for the use in architecture. However, a few ideas have been suggested for its potential use, with some concepts being created and in one case even realized. This chapter is meant to give an insight on some potential uses of thin glass in architecture.

Lightweight Safety Glass Laminates

Lightweightness is undoubtedly one of the key advantages of thin glass. The example of the FIFA World Cup 2014 player bench illustrated in Figure 30, is, to the author's knowledge, the only realized application of thin glass in practice. It features a safety glass laminate composed of three layers of AGC's Dragontrail glass. Apart of being lightweight, it also provides improved impact resistance and optical clarity compared to thermally treated glass.

Figure 30 Official Licensed Glass Roof of the 2014 FIFA World Cup(TM) Player Benches (Business Wire, 2013)

(Bendable) Lightweight Roof Structures

The example illustrated in Figure 31 is a lightweight retractable roof structure presented at the Glasstec Conference. Again, the lightweight property of thin glass stands in the foreground, however also its flexibility plays an important role in the realization of this concept. In terms of safety, the concept is, however, still to be improved, as it consists of a single layer of glass that have the potential to injure in case of damage.

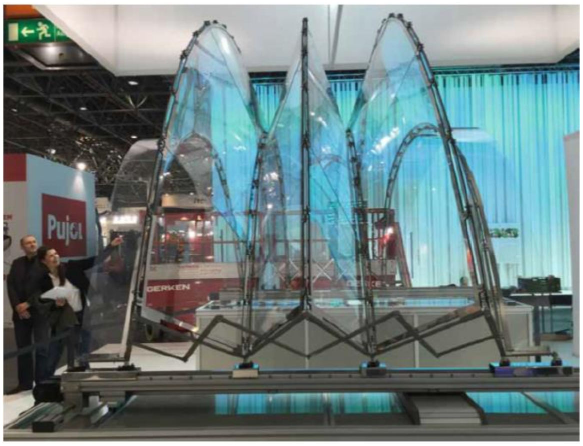


Figure 31 Movable canopy at Glasstec in Düsseldorf (Neugebauer, 2016)

Lightweight Triple IG Units

Thin glass can be potentially used as the middle layer of a triple insulating glass unit. The advantage of this application is that it would have a similar insulating value as an ordinary triple glazed unit with the weight of a double insulating glass unit. This product is ready for the market, as insulating glass units with triple thin glass sheets could already be produced using existing processes and machines (Holzinger, 2011).

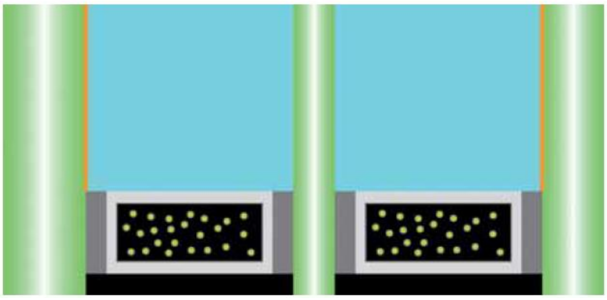


Figure 32 Build-up of triple IG units incorporating a thin glass layer (Holzinger, 2011)

Laminated Flat Plates

The exceptional impact resistance can be utilized in special cases, where the glass element is exposed to potential impacts of people and objects. Further, the use of thin glass plates in the lamination can increase the panel's stiffness when subjected to lateral loads. Figure 33 shows the cross section of a potential laminated flat plate incorporating thin glass layers on the outside.

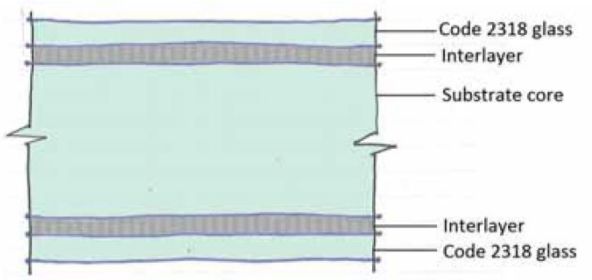


Figure 33 Laminated flat plate incorporating thin glass (Lambert, O'Callaghan, 2013)

Cold-formeed Curved Surfaces

The possibility of cold-bending thin, chemically tempered glass offers opportunities for the realization of curved surfaces to satisfy the contemporary architectural interest towards free-flowing shapes. Thereby, the easy bendability of thin glass, combined with its high flexural strength allow for extreme curvatures, while creating less optical distortions than hot-bent glass. The example in Figure 34 shows a frameless thin glass sculpture with a flowing shape.

Figure 34 Flowing Glass Sculpture (Lambert, O'Callaghan, 2013)

Tensile Membrane Structures

Thin glass can be considered as a stiff fabric or a flexible plate element. By laminating glass to other materials, its out-of-plane stiffness can be increased with the additional material thickness. The creation of a curved surface adds global out-of-plane stiffness through geometrical form. Possible tensile membrane forms are sketched in Figure 35. (Lambert, O'Callaghan, 2013).

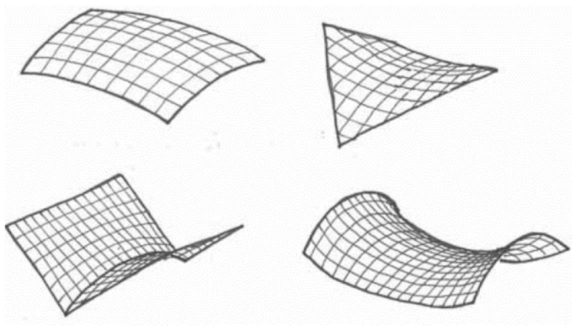


Figure 35 Potential tensile membrane forms (Lambert, O'Callaghan, 2013)

2.7. Active Bending and Elastic Kinetics

When combined with the principle of bending laminated thin glass, the application of kinetic structures offers an entire range of new possibilities in the field of ventilation, sun shading, energy generation, load reduction and architectural expression that have never been attempted before. Apart from kinetics, the proposed idea of the kinetic thin glass façade also includes another principle that plays a crucial role in the realization of the idea, namely the principle of active bending.

Active bending describes the systemized utilisation of large elastic deformations to create curved structures from initially flat or linear elements. Apart from the simplicity it offers for creating curved shapes, this has been a popular method in construction for generations for several other reasons. While in the past, the main reason for the use of this method was the lack of alternative manufacturing techniques for curved building components, today, economic reasons, advantages in transportation and the assembly process as well as the performance and adaptability of the structure play an important role (Lienhardt et al. 2013). This also applies for glass structures. Hot-bent glass elements are often associated with high tooling and transportation costs, while they are also less practicable for transportation compared to flat plates that can be bent on-site. Additionally, they require high precision levels during the manufacturing process due to low on-site tolerances. Active bending involves many approaches and types that

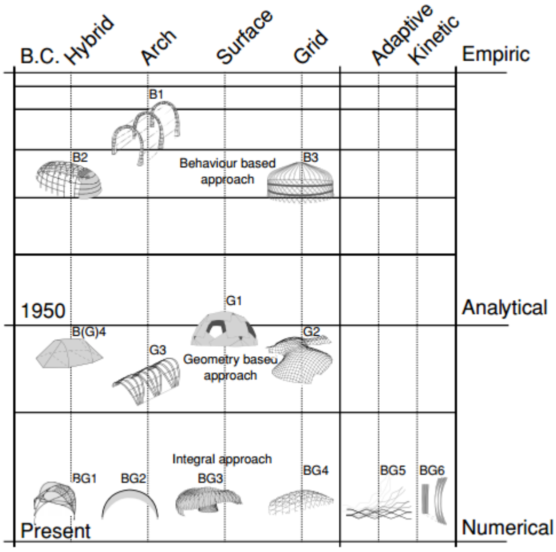


Figure 36 Development of bending active structures (Lienhardt et al., 2013)

have been applied throughout centuries (Figure 36). One popular example is the form finding method that made it possible to drastically reduce the thickness of structures. Recent evolutions in simulation techniques further increased the interest in the principle of active bending, leading to a number of realisations, experimental and temporary structures as well as kinetic applications (Brancart et al., 2016).

In case of shorter time intervals between the adaptive deformations, we may also speak of elastic kinetics. While only a few projects have been realised in a large scale architectural context, there is a potential for growth in kinetic structures in architecture due to the rapidly evolving user needs that require individual and dynamic adaptation of their environment. In this context, transformable structures are an effective means to anticipate and respond to changing demands in minimal time intervals (Bracart et al. 2016). Two examples for the application of kinetics in a large scale architectural context are the Flectofin project that is a nature-inspired sun shading system and the One Ocean Thematic Pavilion in Yeosu, South Korea featuring 108 individual GFRP lamellas that are deformed by controlled buckling for the artistic staging of special lighting effects (Figure 37, Figure 38).

Figure 37 Flectofin sun-shading devices (baulinks.de, 2014)

Figure 38 One Ocean Pavilion, Yeosu, South Korea (ArchDaily, 2012)

The kinetic application of bending active structures does particularly lend itself for the proposed idea of the kinetic thin glass façade. The utilisation of bending deformation can extend the transformational capacity of the structure to a maximum while reducing the complexity of the kinetic system (Brancart et al., 2016). In other words, by bending the glass, a simple linear movement can be transformed into a two-dimensional movement, while keeping the required mechanical parts and joints to handle the translation and bending at a low quantity.

Although it is the availability of state-of-the-art design modelling techniques and structural modelling tools that facilitate design exploration and form-finding of bending-active structures, accurate modelling of the complex relation between their geometry and bending behaviour remains challenging (Brancart et al., 2016). This is especially the case with composite materials such as laminated glass, as it is the combination of linear elastic and a hyperelastic materials.

Furthermore, it is necessary to take resulting bending stress during construction and the structure's entire functional lifetime into account (Brancart, 2016). This includes considering stresses resulting from external loads such as wind loads during the flat plate and the bent state. Therefore, numerical analyses need to be done for multiple load cases for multiple geometrical conditions. This will be elaborated in chapter 3.5. Structural Suitability.

2.8. Water- and Airtightness in Facades

Referring to the statement made in chapter 2.7. Active Bending and Elastic Kinetics about active bending and kinetic structures offering new possibilities, this combination also induces a number of challenges if attempted to be used on building skins. Obviously, one of the biggest challenges is to achieve the building skin's requirement of water- and airtightness, due to the fact that a bent thin glazing requires a sealing system that has not been attempted in construction before. Therefore the creation of a novel solution is necessary for the requirements to be met.

This chapter will introduce the basic principles of water- and airtightness in building skins without going much into detail due to the immense depth of the field. Similar to the previous chapters, it will focus on the parts that are most relevant for the proposed design. Apart from the principles, the standards for requirements and testing will be shortly introduced.

2.8.1. Watertightness in Façades

Watertightness is described as the ability of a closed façade filling to withstand the entry of water to the interior space. In the case of continual or repeated entry of water that then comes into contact with elements that should be kept dry, a problem of water leakage is presented, which flouts the first requirement of façades – watertightness. The most problematic parts of a façade are usually those that form irregularities. These include mouldings, joints, edges and junctions, so that water can enter through openings and seams. Therefore, accumulation of water at these points must be limited and stagnation must be prevented at all costs. Generally, there are six possible ways water can enter through an opening. These include water entrance through kinetic energy, surface tension, gravity, capillarity, dynamic pressure or pressure difference (Figure 39). Even with perfect planning and manufacturing, sooner or later,

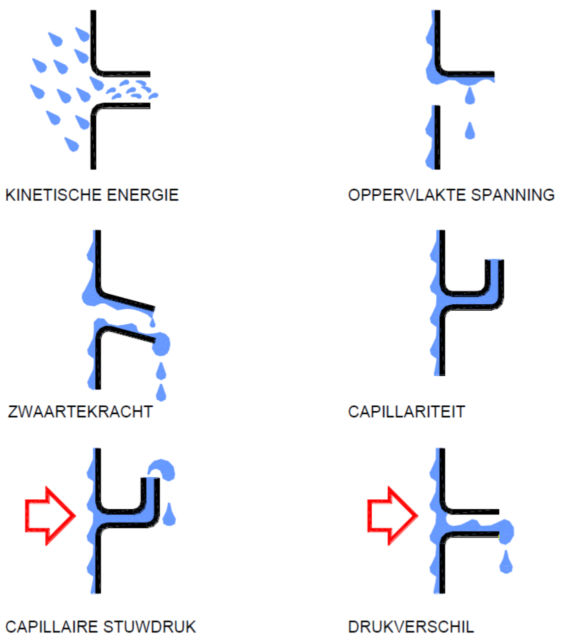


Figure 39 Possible ways for water entrance through openings (Tapper, 2016)

every façade construction will allow water entrance, e.g. through aged and loosened joints (“Façade Design”, n.d.).

Generally, the sealing of openings is effected through pressing the aluminium edge of the window leaf against the rubber lip of the central sealing mould. This works in theory, however in practice, malformations occur due to the choice of the mould and manufacturing tolerances. When supervened with high air velocities, water can be carried to the interior due to the venture effect, which will result in leakage. Usually, a rubber inner seal is applied that is mainly intended to improve the sound insulation value of the window, however another advantage is the increased air flow resistance of the construction that prevents overpressure in the exterior pushing the water inside. This way, pressure equalisation in the cavity is ensured, even if the central sealing fails in certain places (“Façade Design”, n.d.).

The testing method for watertightness in the Netherlands is described in the Dutch standard “NEN 2778 – Moisture Control in Buildings”. The method is based on the international Standard ISO DIN 8247, which lists three types of spraying methods. The quantity of water used in these three methods is 2 litres per minute per square metre. The water must be applied to the surface as evenly as possible. The required test pressures are given in NEN 2778. The façade is considered to be watertight if it does not get wet on the inside after the test (“Façade Design”, n.d.). An example of an on-site test stand is shown in Figure 40.

The standard “NEN 12155 – Curtain walling – Watertightness – Laboratory test under static pressure” describes the laboratory testing method for curtain walls. The procedure is similar to that of NEN 2778. The pages describing the test procedure can be seen in Appendix 5. Figure 41 illustrates an example of a water spray system.

Figure 40 On-site water-tightness testing (gpf-innovation.ch)

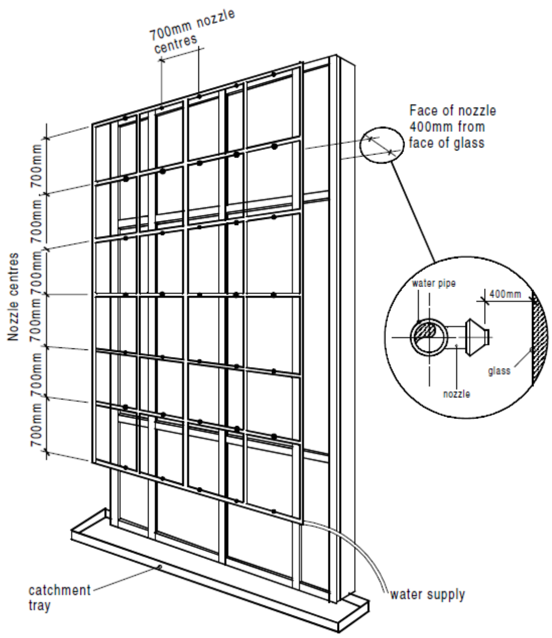


Figure 41 Example of water spray system (NEN-EN 12155)

2.8.2. Airtightness in Façades

Air permeability is the ability of a façade element to let air through if there is a difference in air pressure between its two sides. It is characterised by a volume flow and is expressed in cubic metres per hour as a function of the pressure difference across the façade element considered. Unlike the watertightness requirement, airtightness does not require complete sealing of the façade. A façade is sufficiently airtight if no more air can enter the structure than is allowed in accordance with the standard. Not only is a slight degree of air permeability allowed, it is even desirable, as a healthy indoor environment requires the entrance of some fresh air, even if the window is closed. This counts particularly for dwellings. Thus, apart from a maximum, also a minimum air permeability is specified in standards. Airtightness is achieved by means of an uninterrupted barrier both horizontally from an edge of the building to the other, as well as vertically from foundation to rooftop. Changing barriers within these lines is possible, such as in the rebates of windows or doors, provided that the transitions are perfect ("Façade Design", n.d.).

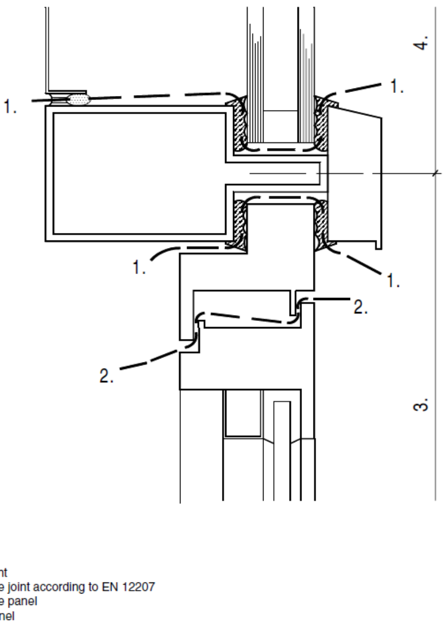


Figure 42 Example of fixed and openable joint (NEN 12152)

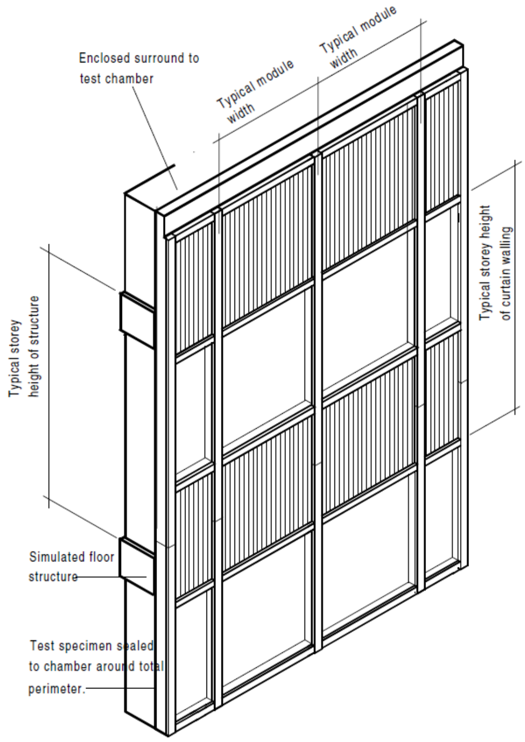


Figure 43 Example of test specimen built onto test chamber (NEN 12153)

Air permeability requirements are regulated in the standards "NEN 2687 - Air leakage of dwellings – Requirements", "NEN 3661 - Window frames - Air permeability, water tightness, rigidity and strength – Requirements" and NEN 2689, which is currently in preparation. Additionally "NEN 12152 - Air permeability - Performance requirements and classification" regulates the requirements and classifications of curtain walls according to their air permeability. According to the standards, some prerequisites apply; comfort, which is achieved by preventing draughts, limitation of unnecessary loss of heat through seams and openings, effective filling of seams and openings and a minimum degree of ventilation for a healthy interior climate ("Façade Design", n.d.).

Testing methods are described in standards "NEN 3660 – Window frames - Air permeability, rigidity and strength - Methods of test" and "NEN 12153 – Curtain walling - Air permeability -

Test method". The relevant pages for the test procedure can be seen in Appendix 6 and Appendix 7. The same test method is applied for both openable and fixed windows (Figure 42). The test specimen must be in a fully operable condition, ready to use. It will then be fixed onto a test chamber (Figure 43). The main principle is based on the application of increasing and decreasing pressure steps (positive or negative) with measurements of air flow at each test pressure. Facades are then classified according to their air permeability rate. The key criterion hereby is the prevention of air draughts.

3. Design

The design chapter presents all the steps included in the research and design phase including the achieved results and observations in a chronological order.

First, the selected case study is presented after a thorough study to define the most suitable application for the proposed design. Subsequently, three alternatives in form of conceptual designs are proposed as possible solutions to tackle the water- and airtightness issue. In the following sub-chapters, these three proposals are critically assessed regarding structural suitability and practical feasibility after the selection of the most suitable glass laminate configuration for the product. The selection of the most suitable design is then made comparing the results of the assessment. Eventually, the selected design is elaborated in terms of technical detailing, mode of operation, product choice and the final design and the mock-up are presented. The design methodology is presented in Figure 44.

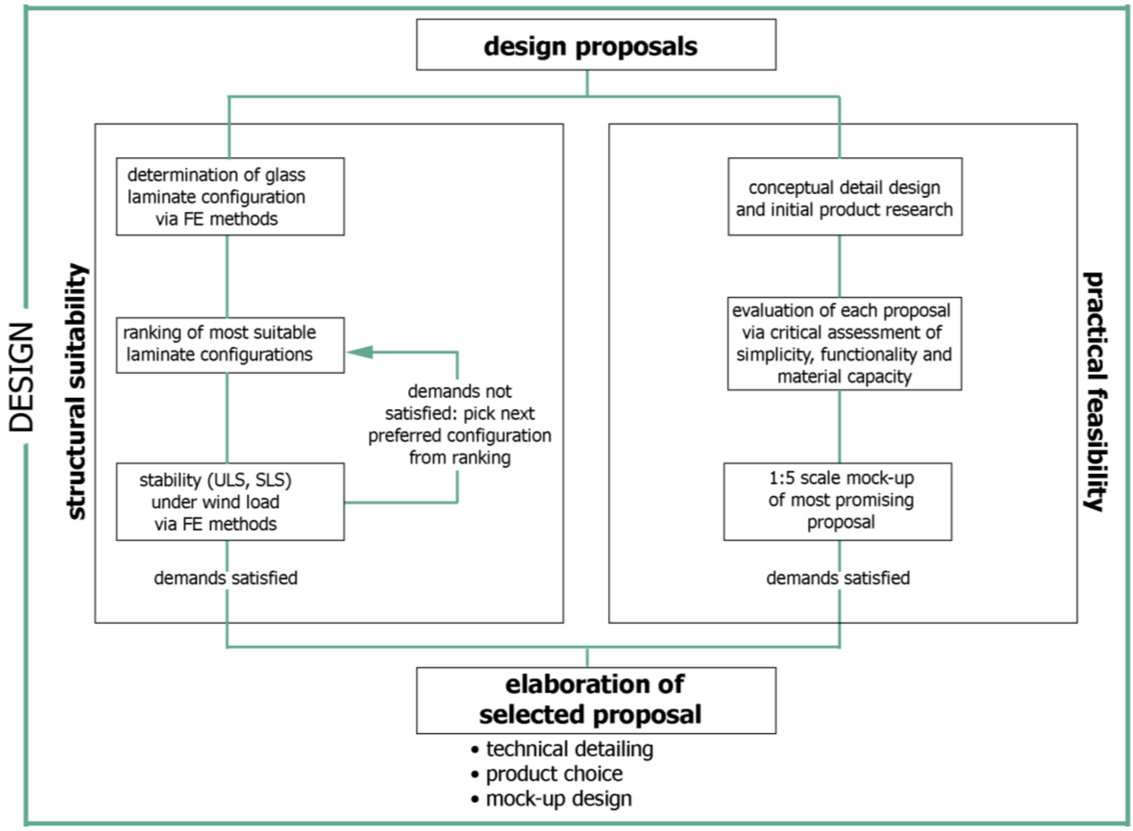


Figure 44 Design Methodology

3.1. Case Study

Before beginning with the design process, a case study will be selected to define the exact requirements and to demonstrate an example of a possible application of the design. The process for the selection will be carried out in three steps; first, the performance of the proposed design idea in different aspects will be analysed and listed. In the second step, possible applications where the design might be applied will be presented, including the corresponding requirement of each application. Finally, a case study will be chosen and presented depending on which requirements can best be fulfilled by the proposed design.

3.1.1. Performance of the Proposed Design

As mentioned in chapter 1.3, the proposed design should consist of one or more laminated aluminosilicate glass panels that can be bent systematically for the purpose of natural ventilation. This offers the possibility to control the opening centrally or individually according to the user's needs and therefore allows flexibility in this context. Additionally, the lamination of the glazing is meant to provide safety to the people in its proximity in case of failure. While the compliance of this aspect with regulations will not be tested within the scope of this research, it is assumed that this requirement is fulfilled for the purpose of defining the most suitable application as accurately as possible. Furthermore, the façade is planned in such a way to provide sufficient water- and airtightness to create an indoor environment that is protected from wind and rain. An additional advantage of the use of thin glass is the high rate of transparency it offers for being a lightweight product not requiring thick frames and its high optical quality compared to regular glass.

Requirements / Qualities	
watertightness	✓
airtightness	✓
thermal insulation	✗
acoustic insulation	✗
safety	✓
stiffness under high wind load	✗
natural ventilation	✓
transparency / optical quality	✓
cost-effectiveness	✗

Table 8 Fulfilled requirements / existing qualities of the proposed design

Apart from the demands the proposed design is meant to fulfil, there is also a number of requirements that are not aimed to be tackled due to the lack of research in those fields. These involve the following; the façade will feature a single layer of laminated glass and will therefore not provide thermal insulation. It is assumed that by creating a double glazed skin with two or more thin glass laminates, an equal thermal performance can be achieved as that of glazing with regular thicknesses. However, how to actively bend a double glazed unit while avoiding problems related to the geometry, due to the creation of different radii, needs to be investigated in a further research. A single layer of laminated glass also negatively affects the acoustic insulation performance of the façade. Air-born sound insulation can either be achieved via the use of the mass law, which requires a heavy single-leaf construction, or a cavity construction, which requires at least two layers of a material. Since both of these are not given with the proposed design, it is assumed that it will perform rather poorly in acoustics. Another limitation of using a thin layer is its lack of stiffness, especially when it comes in contact with wind loading. While its behaviour under wind load will

be analysed via numerical calculations and geometrical measures will be taken accordingly, the initial assumption is, that its stiffness will not be enough to handle high wind loads. Therefore, its use on the outer skin of high rise buildings should be avoided. The last limiting factor is the cost-intensity of the product, due to the cost-intensive chemical tempering process. Therefore, this design would be more suited for rather ambitious projects that are worth investing money. Ideally, the panels should be showcased in a highly visible area of the building due to its innovativeness.

Table 8 sums up all the mentioned fulfilled or unfulfilled requirements and existing qualities of the proposed design in form of a list.

3.1.2. Possible Applications

Single-Skin Façade

A non-bearing single skin façade is also referred to as a curtain wall. A curtain wall is a non-bearing structure made of prefabricated lightweight materials that extends along the height of a building like an outer shell and performs all functions that are part of a façade's performance within a single layer (Tapper, 2016). These involve water- and airtightness, thermal insulation and acoustic insulation amongst other aspects. Therefore, a highly accurate detailing is required and water- and air leakages are unacceptable. Special attention should also be paid to thermal bridges, as they have a large effect in the overall thermal behaviour of the façade. Structurally, it does not bear any loads other than its own dead load and is suspended on the main structure of the building. They can be realized in different types, such as a transom-mullion or a panel system (BauNetz GmbH, 2017).

Requirements / Qualities	
watertightness	✓
airtightness	✓
thermal insulation	✗
acoustic insulation	✗
safety	✓
stiffness for high wind load (only in case of high rise)	✗
natural ventilation	✓
transparency / optical quality	✓

Table 9 Requirements of a single-skin facade

Table 9 provides a summary of the function-specific requirements of single-skin façades along with the indication, which of these are fulfilled by the proposed design.

Double-Skin Façade

Building envelopes consisting of two façade layers are called double-skin façades. Generally, the outer skin acts solely as a weather shield (secondary skin), while the inner skin provides the thermal insulation function (primary skin). Special forms of double-skin façades exist that will not be elaborated in this paper.

The primary skin generally consists of an insulating glass unit, while the secondary skin is made of a single monolithic or laminated glass layer. The façade cavity varies between 0.6 and 1 m in depth and acts as a thermal buffer zone.

Requirements / Qualities	
watertightness	✓
airtightness	✓
safety	✓
stiffness for high wind load (only in case of high rise)	✗
natural ventilation	✓
transparency / optical quality	✓

Table 10 Requirements for the outer skin of a double--skin facade

Compared to conventional glass façades, double-skin façades offer an improved thermal performance, reducing transmission heat losses in winter and protecting the sun shading devices from weathering. Additionally, they enable natural ventilation even in high rise buildings.

The drawbacks of this façade type are mainly the high required investment and maintenance costs and an increased building volume (BauNetz GmbH, 2017).

The function-specific requirements for the secondary skin of a double skin façade are listed in Table 10 along with the indication, which of these are fulfilled by the proposed design.

Lightweight Glazed Roof Constructions / Glass Domes

Glass roofs are often found in public buildings to cover atria or similar spaces. They provide a maximum amount of daylight, while protecting the interior from rain and wind and in some cases also provide thermal insulation. Additionally, they make up a lightweight structure, not requiring heavy building elements to bear the load.

Requirements / Qualities	
watertightness	✓
airtightness	✓
thermal insulation (if necessary)	✗
safety	✗
stiffness for maintenance	✗
natural ventilation	✓
transparency / optical quality	✓

Table 11 Requirements of glazed roof constructions

However, structurally, the glazing needs to possess a residual load-bearing capacity in case of failure. The reason for the necessity of that requirement is that for maintenance reasons (mostly cleaning), they need to be accessible, even if not walkable. According to regulations, accessible glazing needs to provide proper residual capacity in case of failure to prevent injuries. This requirement is not fulfilled with thin glazing since its residual load bearing capacity is not researched. Additionally, its stiffness would most likely be not enough to bear the load of a person without drastically deforming, even though precautions may be taken by adjusting the geometry. Therefore, the safety aspect would not be satisfied in this application.

The requirements for glazed roof constructions and their fulfilment by the proposed design are listed in Table 11.

Interior Glazing Application

Similar to lightweight glazed roof applications, interior glazing applications are also often found in atria to divide the public space from private spaces. Also for reasons such as flexibility in case of changing demands for the interior space, the use of glass as a partition wall is especially suited. The high visibility within partitioned spaces adds another reason for its use.

Requirements / Qualities	
thermal insulation (only if heated and unheated spaces are divided)	✗
acoustic insulation	✗
safety	✓
transparency / optical quality	✓

Table 12 Requirements of interior glazing applications

In contrast to other applications, obviously, the use of glazing in interior spaces does not require water- or airtightness, except for applications that divide a heated space from a non-insulated semi-outdoor space, in which case thermal insulation would be required. The main requirement for interior glass partitions, however, is the acoustic insulation. Whether it be a partition between an atrium and private spaces, or a partition wall between two office rooms, the main purpose of a glazing is to reduce the noise from surrounding spaces. As mentioned earlier, the proposed design is not suited for acoustic insulation and is therefore not meant to be an acoustic partition. Furthermore, its main purpose, the operability and the water- and airtightness properties do not exactly suit the needs of an interior application. The requirements of interior glazings are listed in

Greenhouse / Botanical Garden

Greenhouses are undoubtedly the most suited field of application for glass in buildings. Their need for maximum transparency and sunlight penetration underlines this statement.

Requirements / Qualities	
watertightness	✓
airtightness	✓
thermal insulation	✗
safety	✓
natural ventilation	✓
transparency / optical quality	✓
showcasing the innovation	✗

Table 13 Requirements of greenhouses and botanical gardens

Many of the requirements of a greenhouse are met by the properties of the proposed design; the water- and airtightness, high transparency and optical quality, the possibility for natural ventilation are some of them. Furthermore, the lacking acoustical insulation property is not required in greenhouses. Due to the cost-intensity, the application of this design would not be suited for regular greenhouses used in agriculture. Same goes for the innovativeness of the product that would not make sense to be used in places that are not visited by many people. An alternative for that would be to use it for the skin of botanical gardens that are open to public and in most cases have a certain architectural value.

Despite all the positive facts, with the new regulations, greenhouses should be thermally insulated. Except for old structures that do not meet current regulations, almost all greenhouses and botanical gardens are made of double-glazed units to limit heat loss in winter. Replacing some of them with a single layer of glass would not only cause a high heat loss, but also condensation and dripping of the condensed water. Furthermore, the air outlet of these structures are often placed at the top of the building, making use of the stack effect. This would require the thin glass elements to be placed on top of the roof where it is not visible, hiding one of its main purposes, the showcasing of the innovation behind the product.

The requirements for greenhouses and botanical gardens are listed in Table 13.

Considering all the mentioned facts and comparing the offered properties with the requirements of each application, the conclusion is that secondary skin of the double skin façade is the most suitable field of application for the proposed design. Its only requirement, the stiffness, which is not matched by the design can be bypassed by using it at a low building with a small number of floors. The finally selected case study will be presented in the coming chapter along with its description and the reasons why it is chosen as a case study.

3.1.3. Selected Case Study

The selected case study for this project is the European headquarter building of the glass manufacturer AGC, located in Gosselies, Belgium. This chapter provides general information about the building, the proposed alternative design for the selected façade, as well as reasons for the choice of this case study.

"The AGC Technovation Center is a fully dedicated facility to research, development and analysis of AGC glass products. It contains within a single and unique building laboratory, research equipment's, halls, industrial areas, offices, and meeting-room dedicated to the different AGC services and research team.
As the North part of the project is dedicated to halls, laboratories, research and volume consuming pilot activities, the curved zone in the South part includes the main entrance, the public areas and part of the management and administrative activities.
That curved facade is the main visible and totally emblematic part of the building. Facing South, the cladding of this façade is made of white lacquered glass defining a large horizontal frame. Within the white

Programme	Construction of a research centre for the analysis and the development of AGC glass products.
Location	Rue Louis Blériot - 6041 Gosselies
Client	AGC
Building type	Industries
Status	Achieved
Conception	2010
Completion	2013
Total surface	22 000 m^2
Actors	Structural engineer: PIRNAY ARTELIA Building services: ARTELIA Landscape architect: ASSAR ARCHITECTS General contractor: GALERE CIT BLATON
Awards	- 2015 FINALIST MIPIM AWARD in the "Best industrial & logistics development" category

Table 14 AGC Technovation Center Building Information (Assar Architects, 2017)

frame a double layered open skin façade is developed. Sun shaded and protected by alternated photovoltaics glass panels, a thermal high performance glazed façade is developed in retreat. A gallery is created between those two layers adding sun shading benefits and easy walkable maintenance access.” (Assar Architects, 2017; Figure 45)

Figure 45 Front view of the case study building (Assar Architects, 2017)

The curved façade in question offers a good opportunity for an alternative design proposal. The main criterion for the selection of the case study is a low requirement concerning thermal and acoustical performance, since the proposed design is not intended to provide these functions. The selected façade is currently an open skin façade with no such functions and is therefore suitable (Figure 46). Furthermore, the approximated cavity width of about one meter is also a reasonable dimension for the projected new purpose of the alternative design to be proposed (Figure 47). Another aspect is that the new headquarter building is meant to be the representative mirror of the company’s glass innovation and acts as a large “show room”. Six different types of glass cover about 50 % of the façade area, which include the earlier mentioned BIPV-glass, solar-control-glass, enamelled glass, “smart windows” with electrically switchable glazing, coloured glazing and fire-

Figure 46 AGC Technovation Center front facade view (Assar Architects, 2017)

safety-glazing (Heinze.de, 2017). The inclusion of ultra-thin glass, as a product that has never been used in architecture before, would be an additional feature, increasing the number of innovative glass products to seven.

The proposed alternative design intends to change the open skin façade into a closed cavity façade by closing the gaps in between the BIPV-glass panels with the kinetic thin glass panels. With the water- and airtight outer skin, the cavity will be completely protected from exterior weather conditions. The cavity will act as a buffer zone between the outdoor and indoor climate and can therefore have an energy consumption reducing effect. Additionally, the currently high thermal and acoustic insulation requirement of the inner skin may be reduced. The kinetic façade featuring openable windows through active bending, enable natural ventilation and therefore prevent overheating in summer, as well as condensation on the glazing. Due to the high optical quality of the thin glazing, the view to the exterior will not be obstructed and daylight entrance will almost not be affected at all. Also, forming the front façade of the building, a bendable thin glass façade would make a strong statement about the possibility of the use in thin glass in architecture.

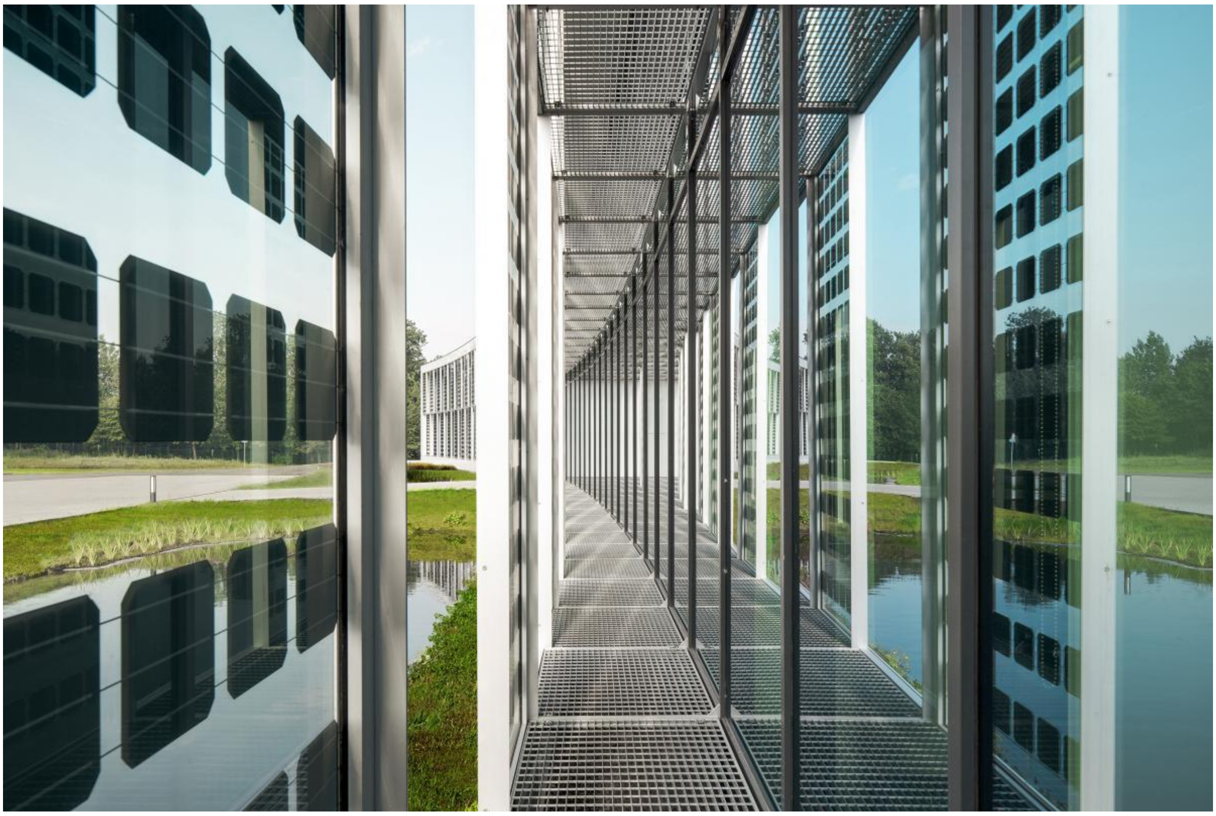


Figure 47 Cavity of the open skin facade (Assar Architects, 2017)

3.2. Design Proposals

The attempted design aims for a water- and airtight façade in closed condition (Figure 48 a). The glazing will be connected to two shafts that are movable in the plane of the glazing. This way, the glazing will be forced to bend, providing an opening for natural ventilation (Figure 48 b). The shafts can either be moved with the help of electrically controlled actuators, or mechanically. Once the movement has reached its final stage, the two shafts will be fixed at their positions, giving stability to the glass pane (Figure 48 c). A simple physical model in a scale of 1:20 was built to illustrate the working principle of the attempted design (Figure 49).

To achieve sufficient water- and airtightness, three initial design ideas were created that combine ventilation of the interior space by bending the glass while providing a water- and airtight layer in the closed position as well as attempts to meet safety requirements by laminating the thin glass plates. These proposals were made based on the literature reviews of chapter 2. The three ideas will be presented conceptually in this chapter along with initial sketches, inspirations and similar products at use. In the subsequent chapters, each of these options will be further investigated in terms of structural suitability and practical feasibility to decide which of the proposals is the most feasible and worth being elaborated further.

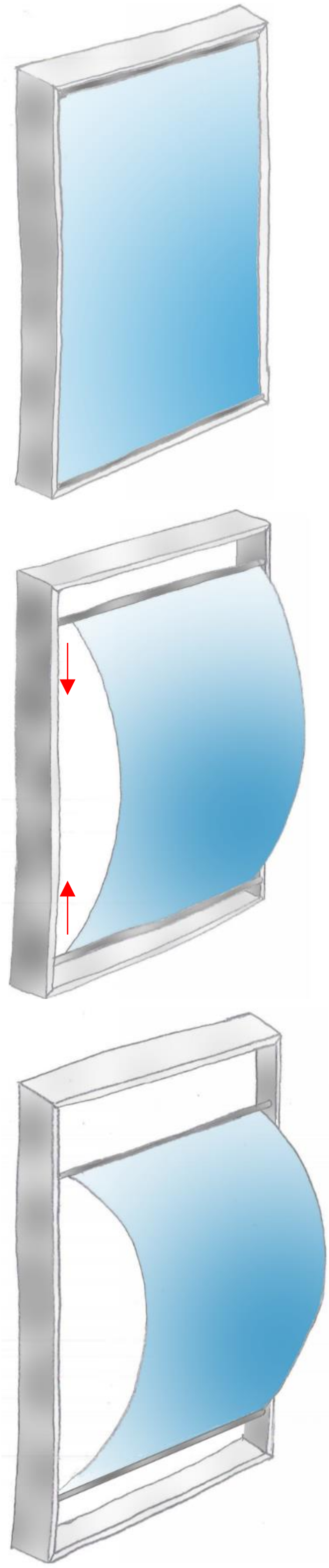


Figure 48 Conceptual sketch of the aimed design a) closed position, b) opening movement c) open position

Figure 49 Initial physical model, scale 1:20

3.2.1. Option 1: Magnetic Force

In the first of the three design options, the use of magnetic force is proposed to offer a water- and airtight building skin. Thereby, the bent edges create the main challenge. In this option, this challenge is aimed to be solved by the application of a thin metal strip or coating to the edges of the glazing, which is attracted to a magnet strip attached to the fixed frame once closed. The magnet needs to act in combination with a rubber gasket, so as to provide a water- and airtight line of defence (Figure 50).

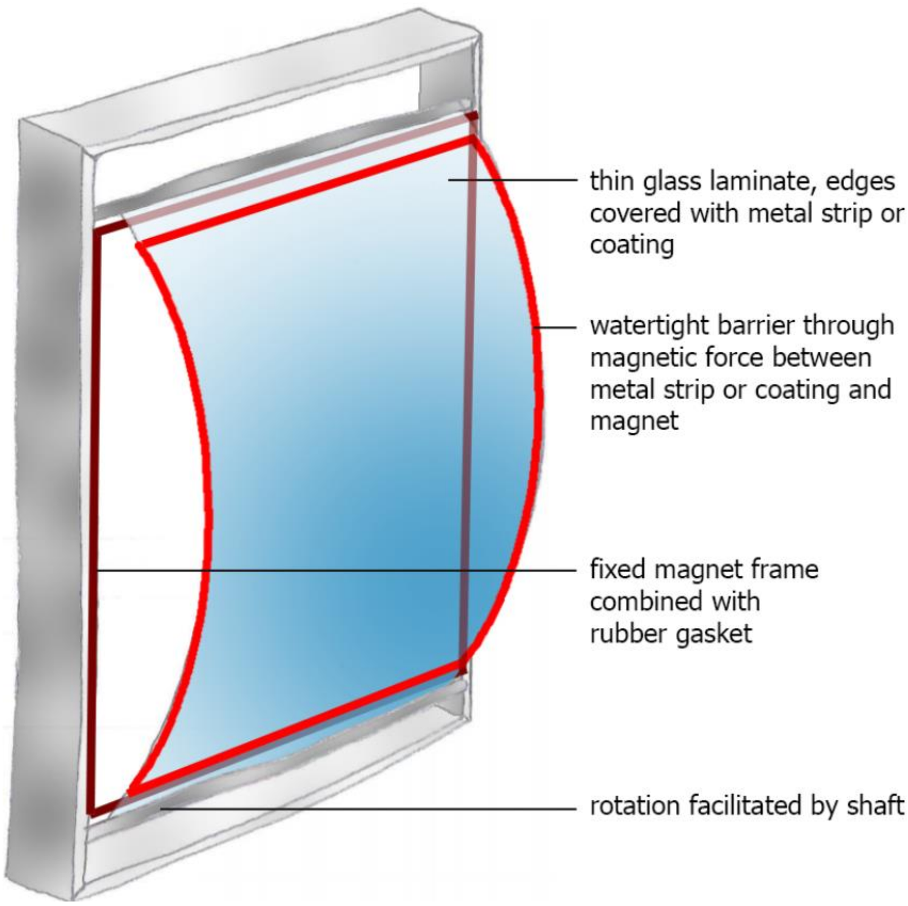


Figure 50 Conceptual sketch of concept 1: Magnetic Force

The inspiration for this proposal comes from the application of magnets in everyday objects. For instance, magnetic force is used for sealing refrigerator doors against airflow between the in- and outside. For watertightness however, it does not perform very well. Another example is the magnetic shower door gasket, which does work for watertightness. Similar to what is proposed in this design, both objects are a combination of magnet and rubber gasket (Figure 51).

Figure 51 Example of a refrigerator door gasket (left) and different types of shower door gaskets (right)
image sources: frag-den-heimwerker.com, rubber-magnet.com

These magnets are rather rigid and do not show much potential for an application including a bending movement. Applications of flexible magnets can however be found for magnetic insect screens, which are attached to a window frame with a magnetic force, provided by a flexible magnet strip (Figure 52, left). Another similar application, even though with a rigid magnet, is the magnetic insulation window, which is an economical method to reduce the U-value of outdated windows (Figure 52, right). This application also gives hope regarding the magnetic force being enough to withstand wind forces and is therefore significant.

Figure 52 Magnetic insect screen (left), magnetic insulation window (right)
image sources: lelong.com.my, magnetite.com.au

3.2.2. Option 2: Tensile Force

The second design proposal is similar to the first one, however instead of magnetic force, the pressure between the glazing and the rubber gasket is aimed to be achieved with a tensile force applied to the glazing (Figure 53). The glazing will be pulled up and down by the two shafts, so that the bent edges of the glazing press against the frame. A possible advantage of this concept may be the avoidance of the two extra horizontal frames that is required for the magnet concept. Instead, in this case, the shafts could be equipped with additional gaskets that could shut against the frame once the window is closed.

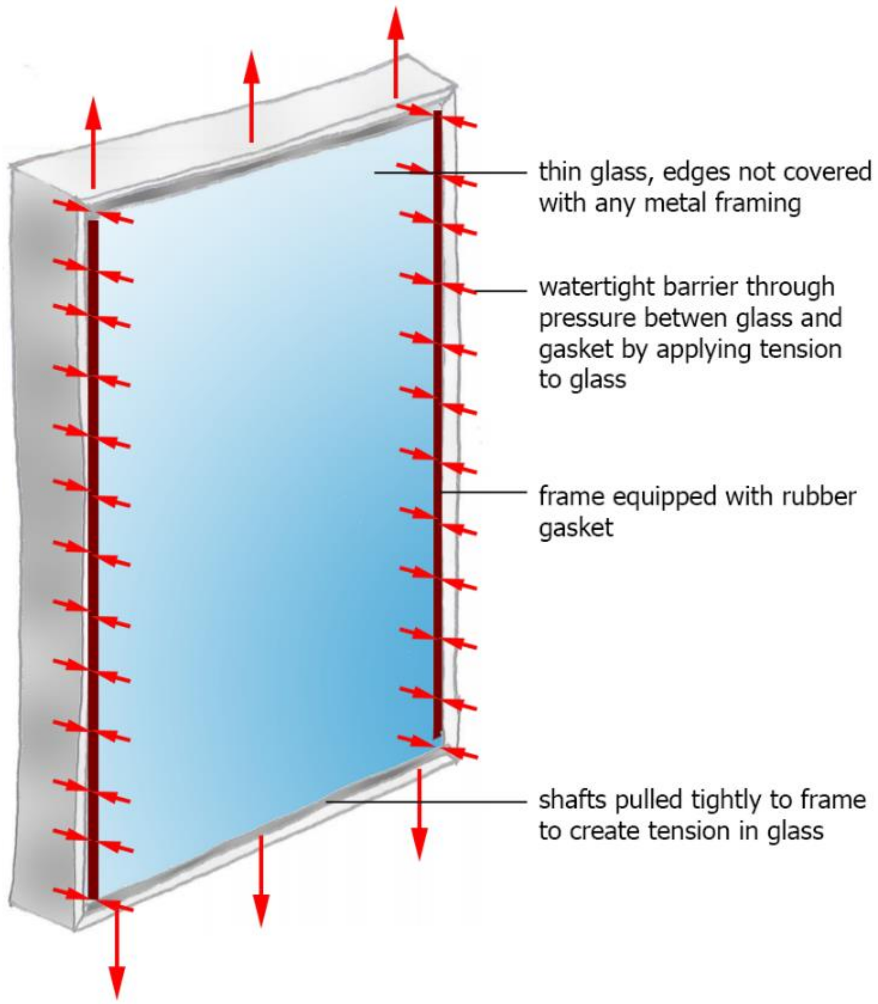


Figure 53 Conceptual sketch of concept 2: Tensile Force

3.2.3. Option 3: Elastic Fabric

The third design proposal follows a different method than the first two. In this option, the bent edges which are the most challenging part are permanently sealed with a water-repellent, elastic fabric to be water- and airtight even in open condition. Once the window is opened, the only airflow will be the upper and lower part between the shafts and the frame, therefore it may require the glass to be bent more than in the other two proposals.

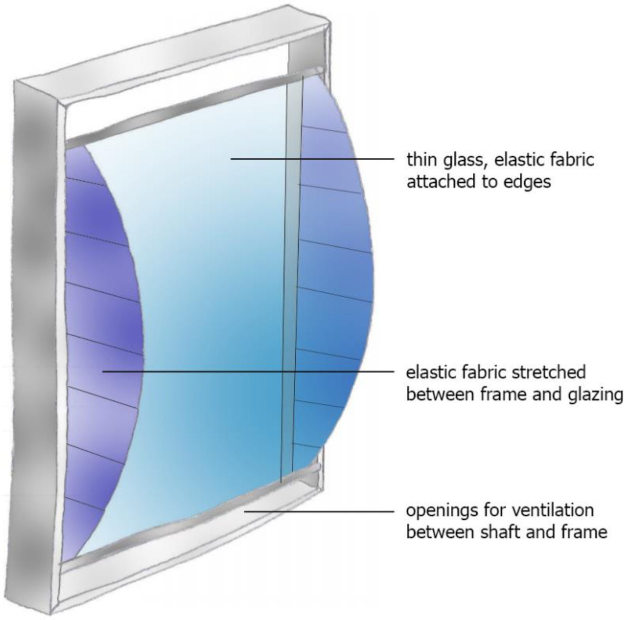


Figure 54 Conceptual sketch of option 3a: Elastic Fabric with fabric stretched in a single frame

There are two possible ways to accomplish this method; one is to place the fabric between the glazing and the same frame supporting it. The other option would be to add another narrow frame between two glazed panels, and to stretch the fabric from one glazing to the other. The conceptual sketches of the two options are shown in Figure 54 and Figure 55. These will be called Option 3a and Option 3b respectively.

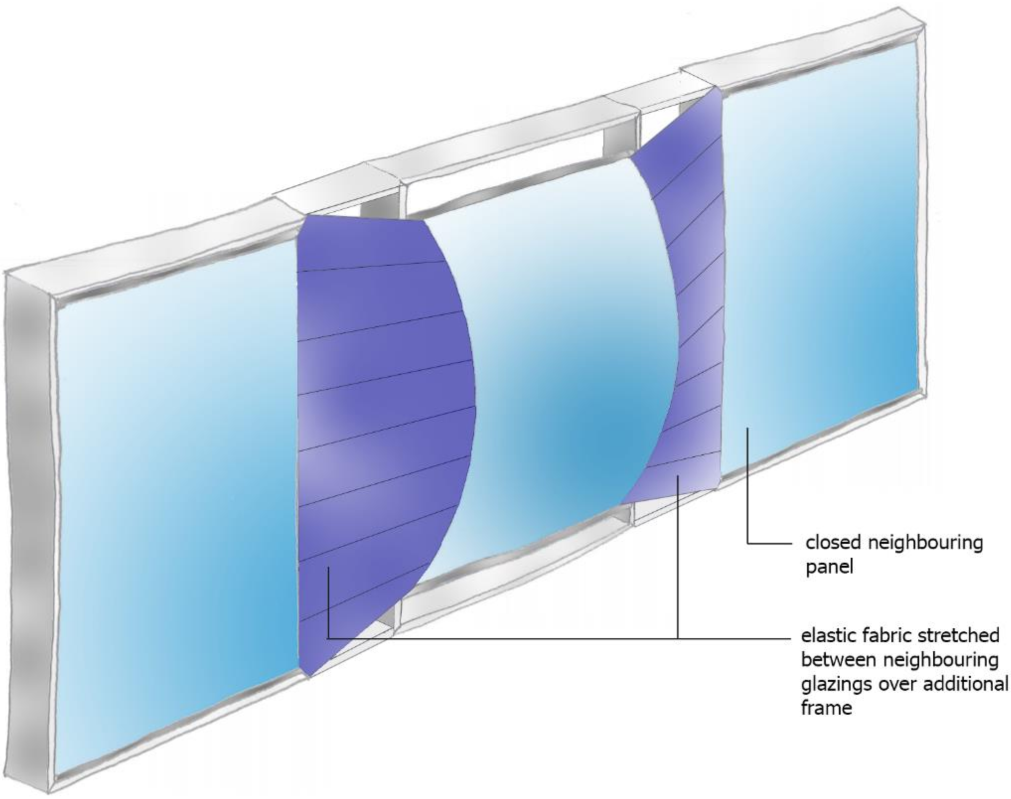


Figure 55 Conceptual sketch of option 3b: Elastic Fabric with fabric stretched between edges of neighbouring glazings

Both options have different advantages and disadvantages. The most significant ones are for instance, Option 3a allowing more transparency, while the fabric in Option 3b needs to be less elastic due to the already available initial length before stretching.

As the material of the fabric, PU-coated spandex is proposed. It is commonly used in everyday objects, which are elastic and watertight at the same time. Some examples are working gloves or swim caps (Figure 56). An example for its use in a more technically demanding product is the BMW Gina concept car, which is fully covered in PU-coated spandex (Figure 57).

Figure 56 Working gloves and swim cap

Figure 57 BMW Gina concept car

3.3. Practical Feasibility

The principles presented in the literature review to achieve water- and airtightness proved effective in construction over decades, despite repeated minor problems. Therefore, it is reasonable to follow similar principles for the design of a façade involving thin glass. However, there are a number of concerns involved in the translation of these principles into the attempted design proposal in this study.

One of these challenges is undoubtedly related to the availability of only a thin layer of glazing to create a water- and airtight barrier at the point where the glazing and the frame come in contact, in contrast to the thicker conventional window frame (Figure 58). Pressure equalisation through double sealing proves difficult given the fact that, instead of a window frame, there is only a very thin glass layer available for sealing. The thin glass laminate presents a challenge for creating a second line of defence, in case the first one, which separates two spaces with differing air pressures, fails locally. This drastically increases the risk of leakages, which is why a solution for creating a second layer with an additional rubber gasket is vital. The same goes for airtightness, as a possible flaw could result in draughts and affect the indoor comfort negatively. A second gasket layer would therefore also benefit the purpose of airtightness.

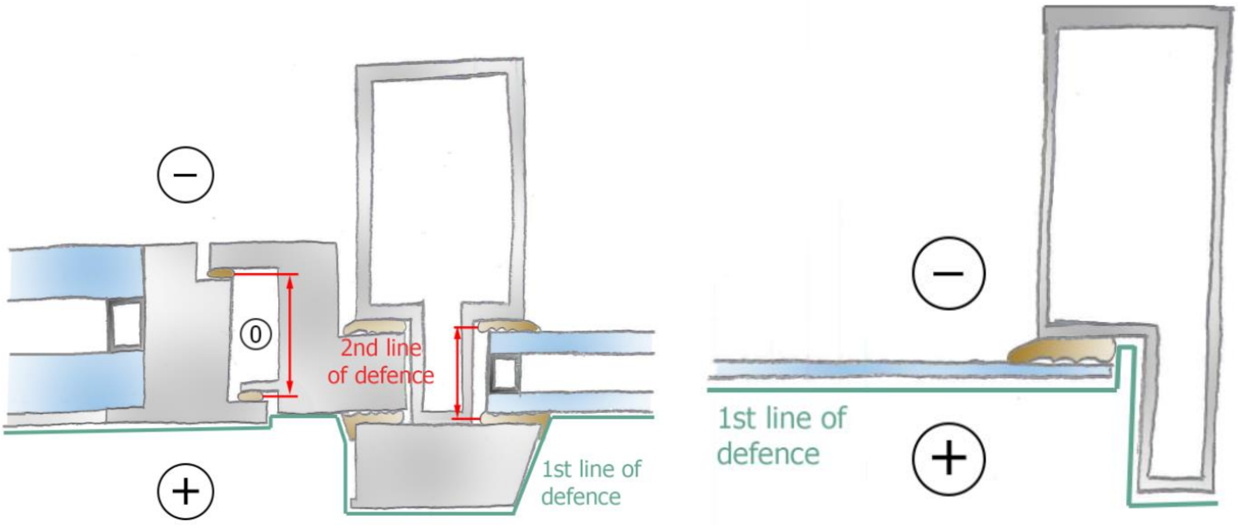


Figure 58 Lines of defence in conventional window frame (left) and thin glass (right)

Another challenge is related to the bending of the glass pane. While it is already difficult to create a flawless seal in a conventional window frame involving two straight edges, achieving the accuracy with a bent edge will surely prove more difficult. This is not related to design and detailing, but more to manufacturing tolerances and the installation accuracy. On top of that, as mentioned in chapter 2.8. Water- and Airtightness in Facades, over time, water- and air-leakage problems occur due to ageing and shrinkage of the rubber gaskets. Shrinkage is usually taken into account by placing slightly longer rubber gaskets than needed at first (+2 to 3% of section length). This partially causes the gaskets to slightly overlap at some points. This raises the question, how overlapping gaskets would affect the performance in a bent frame and how it would behave after shrinkage. Therefore, it is necessary to pay extra attention to these details in this case.

One other aspect to pay attention to is how to create the necessary pressure between the rubber gasket and the stiff frame. In conventional windows, the window leaf is “locked” onto the fixed frame by means of a window handle. Just as it is the case with rubber sealants, the thin glass also does not offer enough depth to place a similar lock inside the section. Therefore alternative means must be considered.

The following sub-chapters present the idea of each proposed option regarding the practical feasibility of the details.

3.3.1. Practical Feasibility: Option 1

Option 1, as presented in chapter 3.2. Design Proposals, employs the principle of magnetic force for water- and airtightness. This option offers a promising prospect to achieve the goal, however as expected, it poses a number of challenges in this regard. One of them is that in case of a permanent magnet, the magnetic force may obstruct the outwards bending movement of the glass by pulling it backwards. This may result in a number of complications, such as an additional required force for bending, an abrupt bending movement, or even bending in the undesirable direction. This can, however, be easily solved by applying an outwards initial bending radius to the glass in the closed condition, which will guide the bending movement into the desired direction. The introduction of an initial curvature also has additional benefits, such as the extra stability the glass gains through geometry as presented earlier, but also a lower required bending force in general due to the offset central node, through which it gains a moment from the beginning of the force introduction (Figure 59).

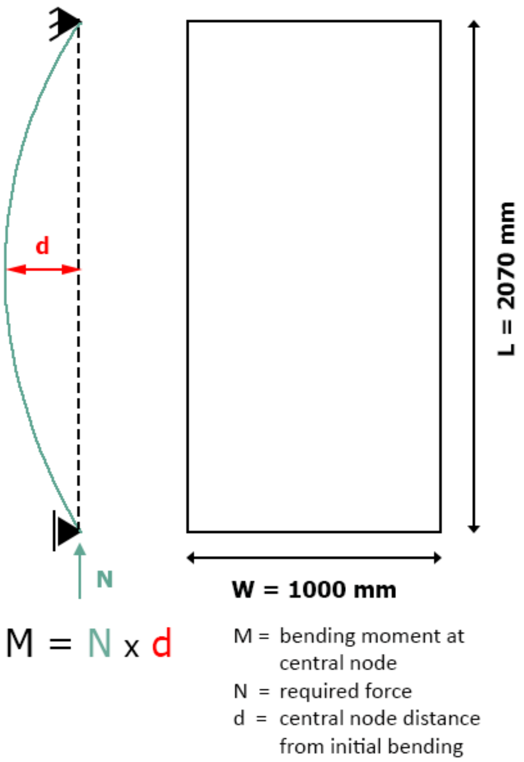


Figure 59 Initial bending radius resulting in a higher moment

Even with an initial curve, the aforementioned abrupt opening of the window may not be solved. This is due to the friction that occurs between the magnet and the metal strip attached to the glazing. It is expected that the force that is applied to the shafts to bend the glass will not have any effect on the geometry at first until the point is reached, where the magnet’s holding force is exceeded by that of the applied force. After the exceedance, the glass is likely to open with a sudden uncontrolled movement that could cause high noise levels, endanger people in its close proximity, or even result in a failure of the glass.

To test this behaviour, a mock-up in the scale 1:5 was built that imitates the opening movement of the proposed design. The shape of the frames are given a curve as explained above. The radius of the curve, when applied in full scale, would equal 2626 mm. In the scale 1:5, it accounts to 525 mm. For the magnet frame, a permanent magnet strip was attached to the wooden frame and a metal strip of equal width to the acrylic that is replacing the glass in this mock-up. The required rails at each corner are replaced by a gap created between the wooden frame and the wooden strip. The model can be seen in Figure 63 and Figure 64.

As anticipated, applying a force on the two shafts at the top and bottom resulted in an abrupt opening movement. It also required a high force for bending despite the initial curvature. However, by applying a very small lateral force near the edges in the centre of the glass pane at the same time while pushing the shafts at the edges up and down, both problems were solved. This means, a pushing device located in the centre of the vertical frames could prove useful in that matter. Alternatively, the use of a switchable magnet can be considered, whose magnetic flux could be interrupted temporarily each time the window is to be opened or closed.

The water- and airtight barrier is designed to be located along the vertical edges of the glass. The horizontal sealants in contrast, are located more inside rather than directly at the edge. This is due to the fact that the shafts need space to move vertically. The sealant will form a rectangle of the same width as the glass, however a smaller height (Figure 60). The horizontal gaskets will therefore need two additional frames spanning from the two posts of the main structural frame. This is unavoidable to achieve an uninterrupted barrier due to the kinetic movement tolerances.

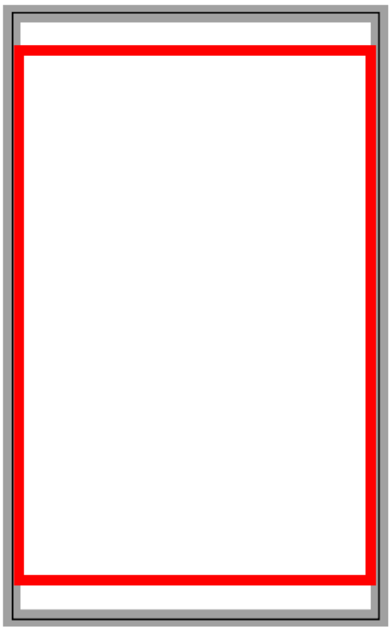


Figure 60 Rectangular gasket line with two supporting horizontal frames. Grey: structural frame of the panel with glass resting in front, red: water- and airtight barrier

One more concern is whether the magnet's holding force will be enough to withstand wind loads, especially the suction. Results of initial hand calculations indicate that the magnetic force would easily be enough even with regular ferrite magnets. For the calculation, a suction of 1 kN/m^2 is assumed. On the full size of 2 m^2, this would result in a total of 2 kN. Based on the conceptual design, the length of the entire magnet frame is approximately 5.6 m, which would require the magnet to have a strength of around 0.36 N/mm, which is lower than the strength of most conventional magnets. Based on these presumptions, the magnet force is not likely to pose any challenge related to wind stability.

Another prerequisite is to reach enough pressure between the gasket and the glass to comply with water- and airtightness regulations. For this purpose, a more or less equal pressure must be achieved throughout the entire length of the gasket. This is feasible by the use of magnets, since it allows a linearly equal force throughout its length. One main challenge related to this matter is to design a sealant with two lines of defence due to the availability of only a thin glass layer as explained earlier. A possible solution is shown in two conceptual sketches of the vertical and horizontal details of the magnet-gasket combination (Figure 61, Figure 62).

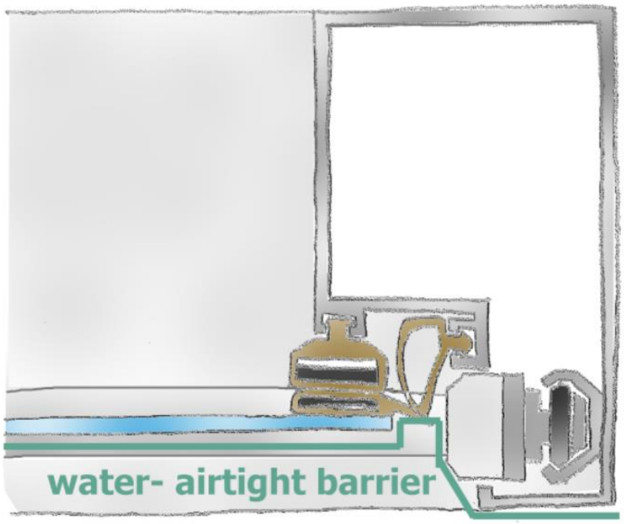


Figure 61 Conceptual sketch of the horizontal section detail of option 1

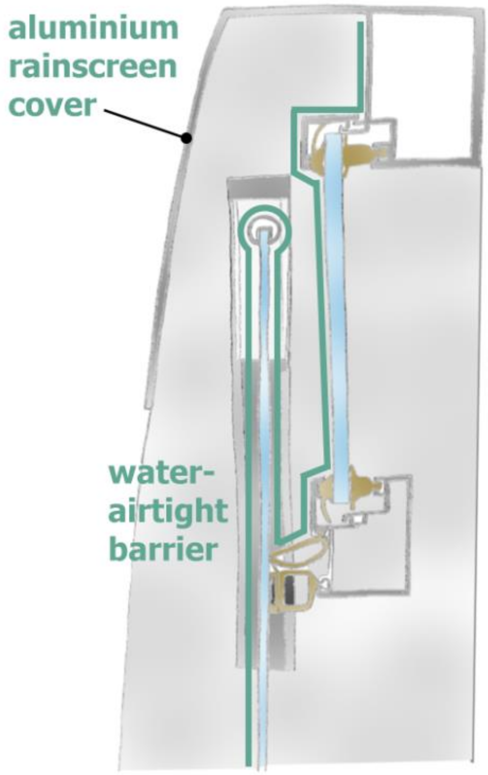


Figure 62 Conceptual sketch of the vertical section detail of option 1

Figure 63 1:5 scale mock-up. Top left: front view; top right: rear view; bottom left: side view, closed; bottom right: side view, open

Figure 64 1:5 scale model: top left: isometric view, closed; top right: rear isometric; bottom left: isometric view, open; bottom right: details

3.3.2. Practical Feasibility: Option 2

Option 2 presents an alternative to magnetic force to achieve water- and airtightness, while eliminating the two extra horizontal frames the first option required that served as supporting structure for the sealants.

The challenges associated with this alternative are numerous. The first concern that will most likely pose a challenge is the creation of sufficient pressure on the sealants through the tension created in the glazing as shown earlier in Figure 53. The slight initial curvature given to the frame as explained in chapter 3.3.1. Practical Feasibility: Option 1 would be helpful to reach the desired pressure between the sealant and the glazing, as pulling a curved sheet will perform more pressure onto the frame compared to pulling a straight sheet. However, this method may result in other problems such as an unequal distribution of pressure throughout the length of the vertical sealants, unlike the magnet option. Thereby, the highest pressure is to be expected at the centre of the vertical sealants, while the pressure at the top and bottom remain low. This is also supported by a computational analysis (Figure 65).

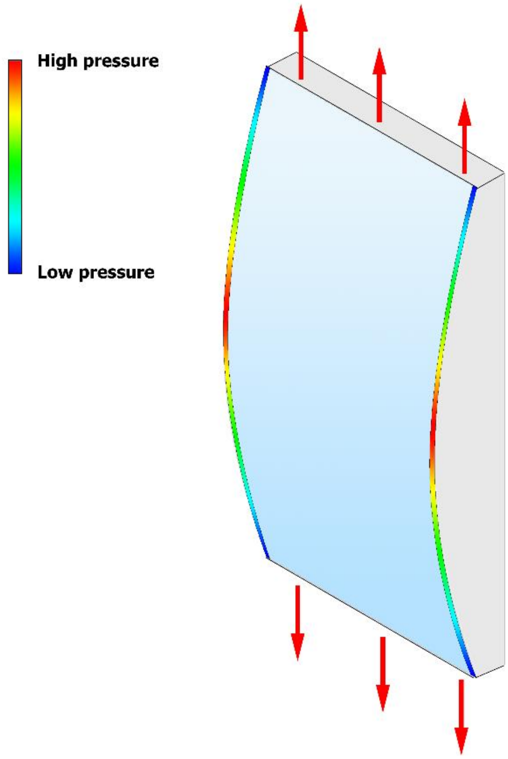


Figure 65 Pressure distribution along the sealant

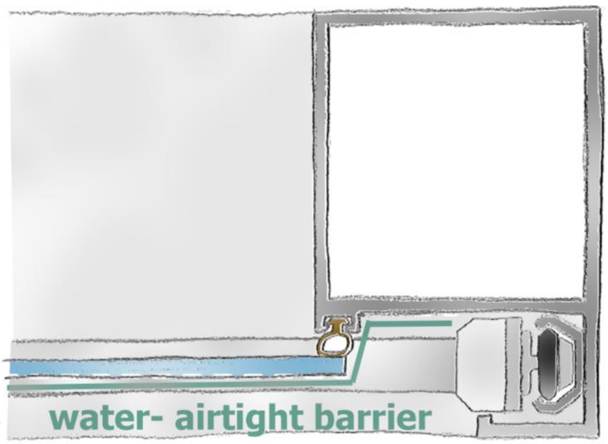


Figure 66 Conceptual sketch of the horizontal section detail of option 2

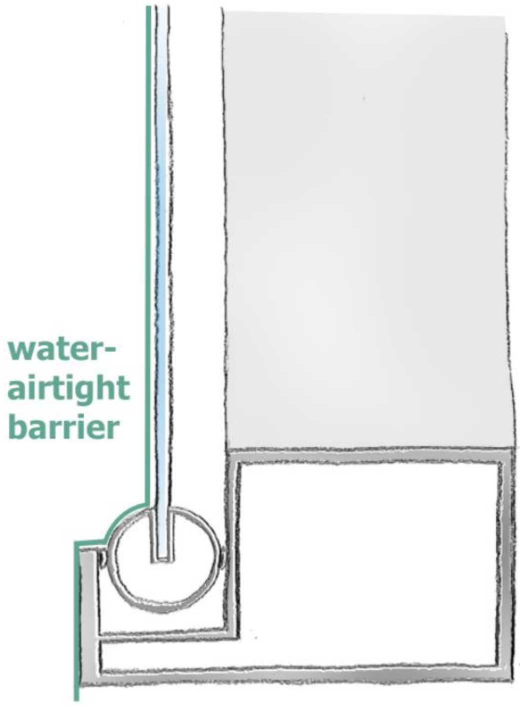
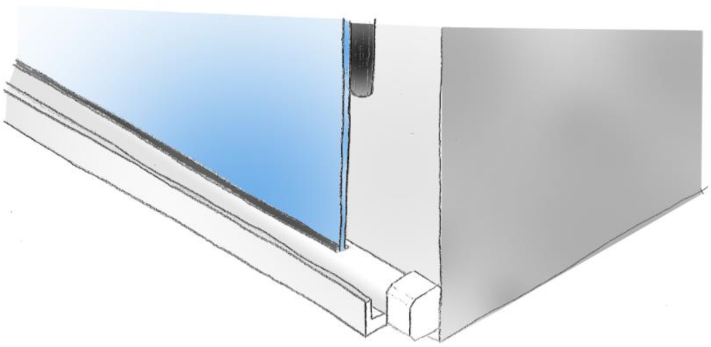
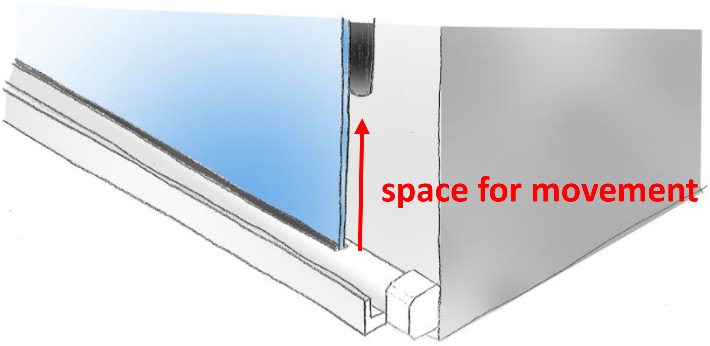


Figure 67 Conceptual sketch of the vertical section detail of option 2





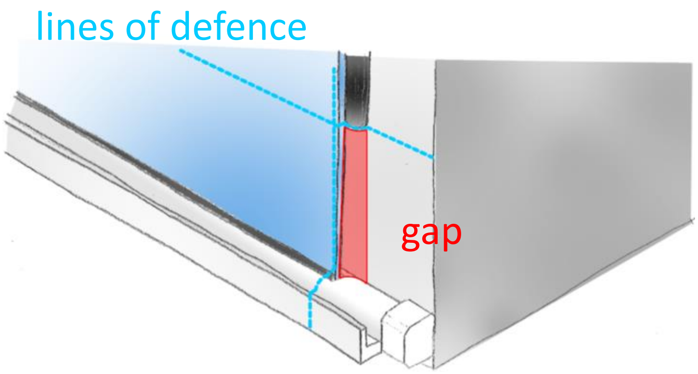


Figure 68 Interruption of the gasket

Assuming the pressure is equally distributed, there are still difficulties concerning detailing without the two extra horizontal frames as in option 1. Eliminating those frames was aimed to be achieved by sealing the top and bottom horizontal edges by placing the shaft into a housing equipped with rubber gaskets. Once the shafts would slide into the housing, the edges would be sealed (Figure 66 and Figure 67). Thinking in two dimensions, as shown in the figures, the principle seems to work. However, when the design is considered three dimensionally, a problem occurs at the corners. Due to the kinetic movement, a small part of the vertical edges are equipped with a rail that enables a vertical movement of the shafts. This requires an interruption of the gasket for around 10 cm at each corner, which makes it difficult to create a continuous barrier (Figure 68). Solving this issue would require a rather complicated detail design, which does not comply with one of the main selection criteria to choose the most suitable option – to keep the design as simple as possible. Therefore, a rectangular uninterrupted barrier as in Option 1 appears to be the most suitable solution, which eliminates the main potential advantage of Option 2 over Option 1, which was to eradicate the horizontal frames.

A further question is how to reach a sufficient pressure between the gasket and the glass through a tensile force. Therefore, a high force needs to be applied to the shafts on each side. The required force is even increased in case of wind suction, which is very unpredictable. The pressure could either be achieved by the use of springs or electrically controlled actuators. The large force that is required may result in wear, which raises the concern of high maintenance intensity and short product lifetime. Furthermore, acting like a simple beam, the shaft may deform too much if its diameter is kept small, which may cause an unpleasant view.

3.3.3. Practical Feasibility: Option 3

Option 3 aims to seek an alternative approach to solve the water- and airtightness issue by permanently sealing the bent edges, even in open condition. Although this approach seems to solve the one issue, it has the potential to lead to other kinds of complications.

In chapter 3.2.3. Option 3: Elastic Fabric, two alternatives are presented for this option. Option 3a stretches the fabric from the glass edge to the aluminium frame of the same panel, while Option 3b stretches it from the edge of one glass pane to that of the neighbouring panel's glass pane. For the reader's ease, in this chapter, the problems that are likely to occur are explained with only the Option 3a. This explains the difficulties for both alternatives at one time, since both are faced with similar challenges.

A crucial difference of this option is that the side openings, which provide the largest openings for ventilation, are always sealed by the fabric. The only opening left in this case are the top and bottom openings (Figure 69). This may require the glass to be bent with a stronger curvature to provide the interior with enough natural ventilation. However, according to the numerical calculation results which are presented in chapters 3.4. Glass Laminate Configuration and 3.5. Structural Suitability, even the stronger curvature is not likely to pose a problem regarding the exceedance of the maximum stress capacity of the glass. Therefore, this aspect can be more regarded as a limitation rather than a problem.

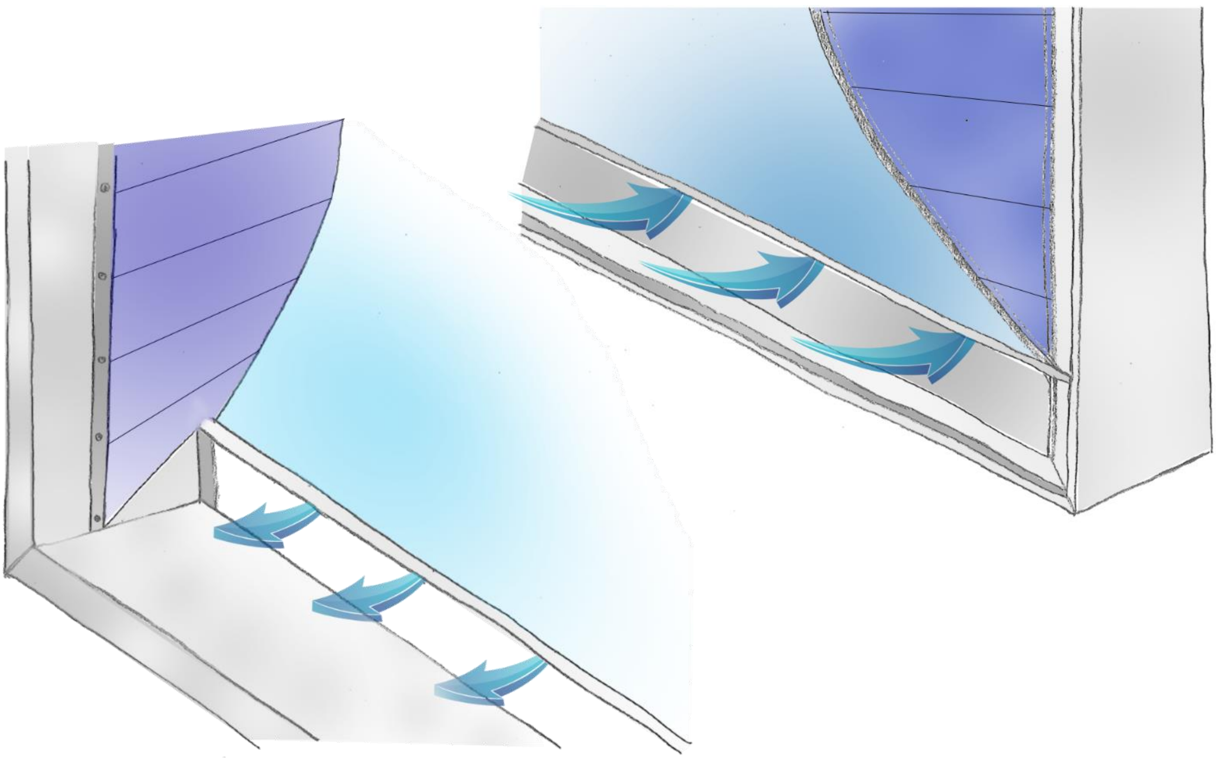


Figure 69 Bottom ventilation opening of Option 3a

The extra required curvature may not challenge the chemically treated glass in terms of stress, however it may challenge the stretching capacity of the elastic fabric that covers the edges. Figure 70 illustrates the fabric in both the closed and open conditions. The length at the top and bottom in closed condition are taken as reference. The length at the centre in closed condition amounts to 3.8 times that of the top and bottom length. When opened, this number goes up to 6.9 times the length. This would require the fabric to be stretched to 690 % of its original length, which does not seem to be feasible, especially, when the fabric is PU-coated for water- and airproofness. This difference can of course be reduced by using a fabric that is cut in the shape of the fabric in the closed condition. In this case, the stretching can be reduced to 200 %, which may be within the limits if the coating is not too thick. Nevertheless, the frequent stretching may result in abrasion over time and lead to an unpleasant view or even to the fabric getting stuck in between the glazing and the frame upon closing.

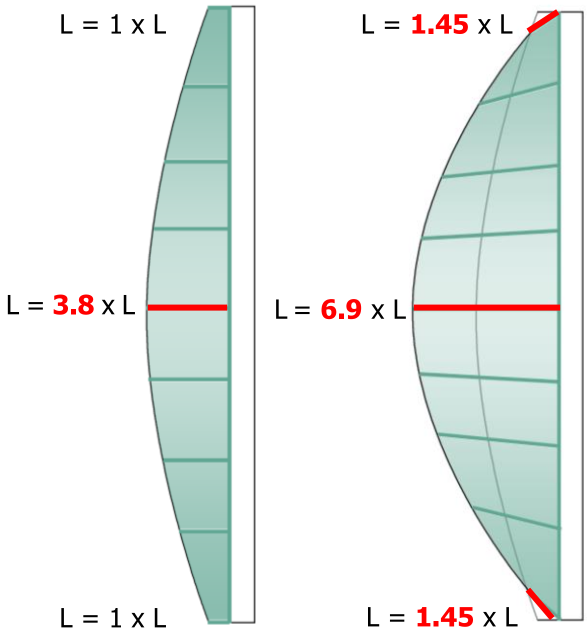


Figure 70 Uneven stretching of the fabric

Another effect of the fabric may be pulling back the edges of the glass, due to its tendency to get back to its original length once stretched. If the force becomes too large, it will tend to pull the glass back, thus counteracting the pushing force of the actuators in the corners. Additionally, it could also have a crucial visual impact on a glass laminate of only a few millimetres leading to optical distortions.

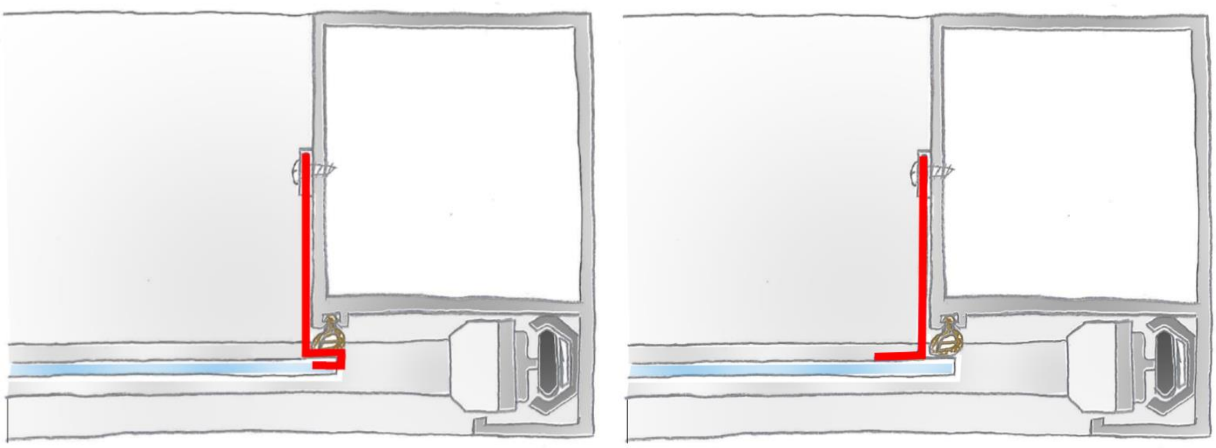


Figure 71 Fabric laminated between glass sheets (left) and glued on surface (right)

Regarding the assembly, the connection between the glass and fabric may pose a challenge. One option could be to insert the fabric between the two glass panes during lamination, which would make a strong bonding. However, since the glass needs to rest on the aluminium frame, the location of the fabric would be inconvenient (Figure 71, left). Therefore, the only option left is to glue the fabric onto the glass surface (Figure 71, right). To guarantee a stable connection, this would require a certain area to be glued, which raises the question, how aesthetically appealing it will be, since it will be visible from the outside. Furthermore, the glue needs to be very strong due to the smooth surface of the glass, which is inconvenient for gluing.

When the fabric is glued on the surface as shown in Figure 71 (right), similar to the case of Option 2, there seems to be a seamless barrier for water- and airtightness in 2D (Figure 73 and Figure 74). However, once again, when regarded in 3D, there is an obvious flaw in the corner joint, highly susceptible to both water- and air leakage (Figure 72). If this weak spot is to be avoided, it is necessary to either change the detail completely or to take additional measures, which would overcomplicate the design, also making the production and assembly less feasible.

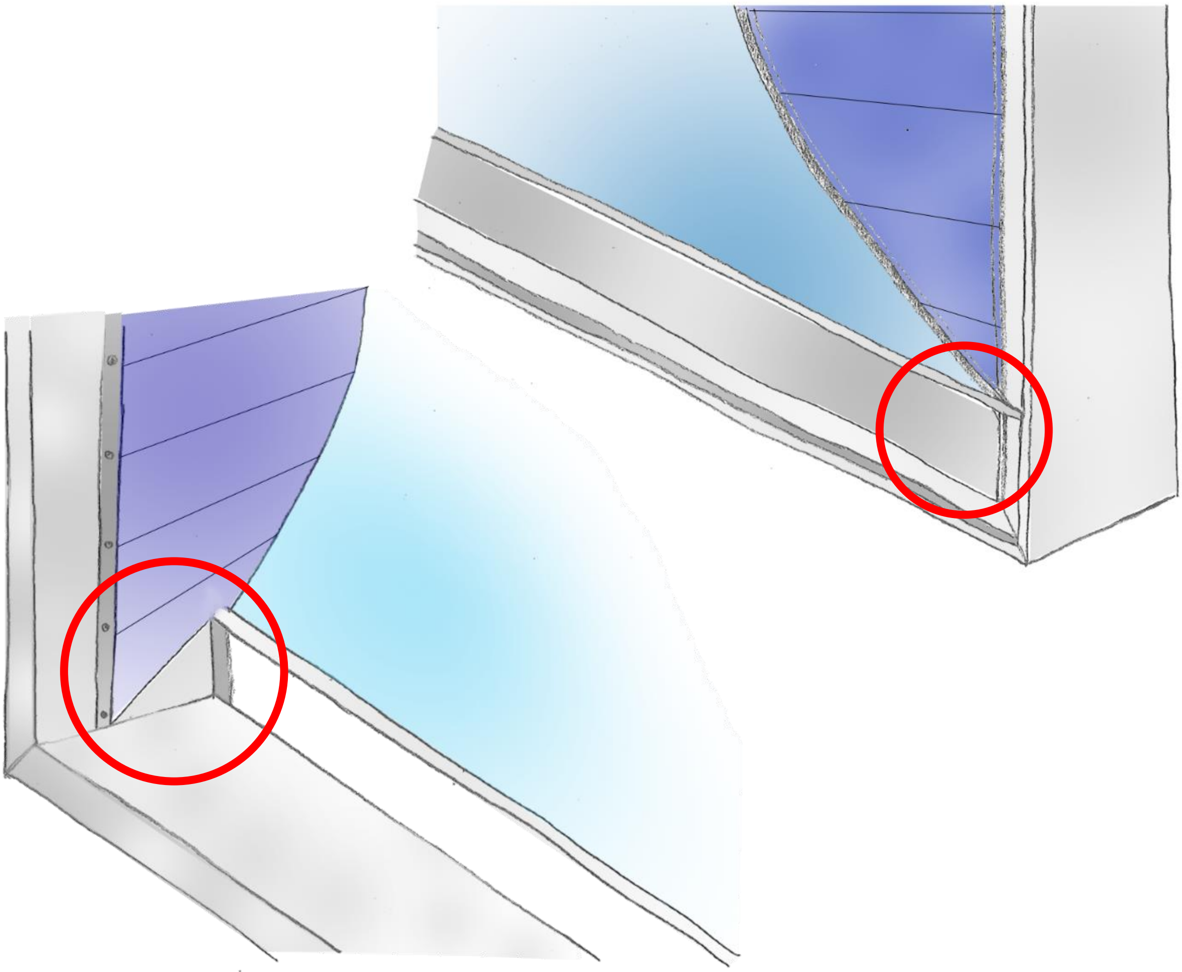


Figure 72 Weak spot for water- and airtightness

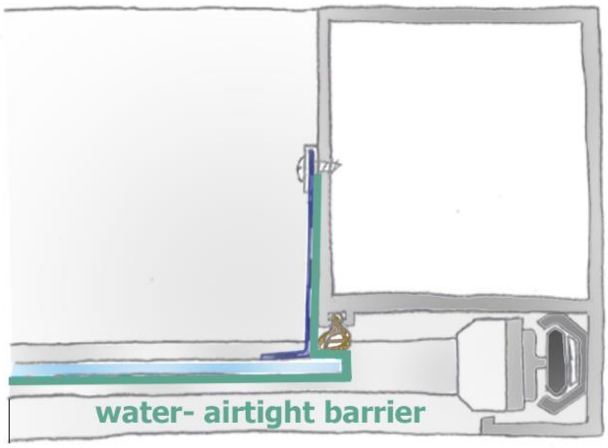


Figure 73 Conceptual sketch of the horizontal section detail of option 3

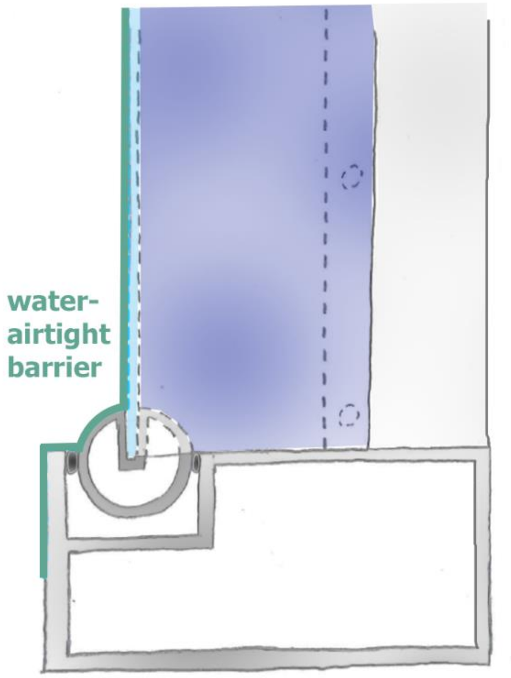


Figure 74 Conceptual sketch of the vertical section detail of option 3

One last drawback of this option is that it restricts the view to the sides once opened. The water- and airproof PU-coated fabric will be most likely opaque, or translucent at best. This could, however, also be turned into an opportunity to make use of them as sun blinds if used wisely.

3.4. Glass Laminate Configuration

Each of the presented design proposals result in different types of supports and forces. In order to determine the structural suitability of each proposed design, finite element analyses will be carried out. The desired structural properties that will work in favour of the design proposals are as follows;

a) the smallest radius that can be achieved by controlled bending
b) the lowest maximal principal stresses in the glass in both, closed and opened conditions
c) the highest stability of the glass laminate against external loads (e.g. wind)
d) the minimum required force to achieve the radius

As much as these properties depend on the support types and load cases, the composition of the glass laminate also has a large effect on them. Therefore, before commencing the analysis for the structural suitability of the each design option, the configuration of the laminated glass panel must be determined. Once the most appropriate configuration is found, it can be applied to all the design proposals.

This part will solely focus on the effect of the glass laminate composition on its minimum bending radius, the stresses that result from it and the required force to achieve the result. Determining the configuration beforehand will be helpful later for the comparison of the structural effects of the different design proposals, as it will be easier to measure the effects of the changing supporting conditions.

3.4.1. Methodology of Numerical Analysis

To find out the most suitable configuration, the only variables need to be the glass- and PVB thicknesses, as well as the PVB stiffness dependent on the PVB-type. Therefore, the size of the laminate sheets will be fixed to 2070x1000 mm for each of the test objects, which is the size of the glass sheets used in the case study. Using this size for the determination of the laminate configuration will make it more convenient later to test the effect of lateral wind loads, as the resulting stresses from external loads depend on the sheet size.

To determine the most suitable configuration for the glass laminate, several configurations will be tested. The variables are limited to three different glass thicknesses, namely 0.55 mm, 0.85 mm and 1.1 mm, which are a range of the standard thin glass thicknesses offered by AGC. Possible standard PVB thicknesses that are available are 0.38 mm, 0.76 mm and 1.52 mm, which form the second variable. Additionally, a range of different PVB stiffnesses will be tested that represent the stiffnesses of several PVB types (acoustic interlayer, standard PVB, SentryGlas, extra stiff interlayer) in different temperatures (10-30 °C) and under different load durations (3 seconds – 1 month). All of these mentioned factors highly affect the interlayer properties. The stiffness range is taken from the Kuraray Structural Glazing Bulletin (Appendix 1), which sums up the properties of the mentioned PVB-types in variable conditions. For the comparison, five different stiffnesses are selected from the table in the Appendix, which include the highest and the lowest stiffnesses shown in the table, plus three more which are situated in-between them. The values between the two maxima are chosen in such a way, that they create an equally distributed range of five values in total. The Young's and shear moduli of the selected stiffness levels are listed in Table 15, along with the the PVB-type, temperature and load duration they represent.

PVB Type No.	Young's Modulus E [MPa]	Shear Modulus G [MPa]	PVB Type	Temperature [°C]	Load Duration
E1	2030	700	Trosifol Extra Stiff	10	3 sec
E2	1450	500	Trosifol Extra Stiff	10	5 min
E3	943	325	Other Stiff PVB	20	3 sec
E4	435	150	SentryGlas	20	1 d
E5	0.3	0.1	Trosifol PVB	30	1 mo

Table 15 List of PVB-types

For this study, the use of an acoustic interlayer is of special interest due to its very low stiffness. However, experimental data does not exist on acoustic interlayers, since it is not suitable for use in structural applications. Nevertheless, the assumption for its stiffness value is 1/10 of that of standard PVB. Therefore, it is assumed that its Young's and shear moduli will be close to zero even in shorter load durations or temperatures.

Apart from varying glass thicknesses, PVB thicknesses and PVB types, also asymmetric laminate configurations are considered to investigate the stress reducing effect of asymmetric glass laminate configurations described in chapter 2.4.3. Therefore, glass thickness combinations of 0.55 - 1.1 mm, 0.55 - 0.86 mm and 0.86 – 1.1 mm are also to be investigated, with the thinner sheet always being on the outer side of the curved radius. The configurations with its varying and fixed values is illustrated in Figure 75.

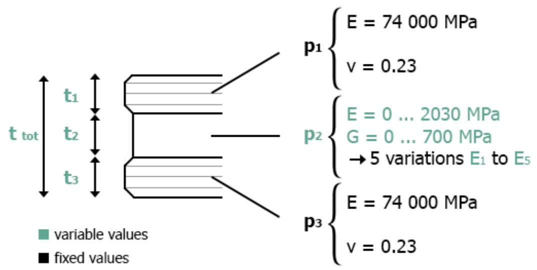


Figure 75 Glass laminate configuration with variable and fixed values

If all the possible combinations with the mentioned variables were to be tested, the number of those would equal to 86 unique configurations in total. Since it is not feasible to numerically analyse that many possibilities, a reference configuration will be selected consisting of the middle values of each variable. Thus, for the reference, a symmetric configuration of the glass thickness of 0.85 mm on both sides,

t1 / t3 =	0.55		0.85		1.1	[mm]
t2 =	0.38		0.76		1.52	[mm]
P2 =	E1	E2	E3	E4	E5	
			ref			

Table 16 Variable values and reference configuration (for E1 to E5 see Table 15)

a PVB thickness of 0.76 mm and the PVB type E3 will be selected (Table 16). Later, the effect of changing the glass thickness, the PVB thickness, PVB type and that of asymmetric configurations will be analysed by only changing the corresponding variables one by one (e.g. only changing glass thickness while keeping other properties to view the effect of glass thickness). Later their results will be compared to that of the reference configuration. This way, the more favourable conditions can be determined by only analysing 11 different configurations instead of 86. The configurations in-between can then be assumed by viewing the results of those tested. The configurations to be analysed are listed in Table 17.

Config No.	1st glass thickness t_1 [mm]	PVB thickness t_2 [mm]	2nd glass thickness t_3 [mm]	PVB Type p2	
0	0.85	0.76	0.85	E3	reference
1	**0.55**	0.76	**0.55**	E3	effect of glass thickness
2	**1.1**	0.76	**1.1**	E3	
3	0.85	0.38	0.85	E3	effect of PVB thickness
4	0.85	1.52	0.85	E3	
5	0.85	0.76	0.85	**E1**	effect of PVB properties
6	0.85	0.76	0.85	**E2**	
7	0.85	0.76	0.85	**E4**	
8	0.85	0.76	0.85	**E5**	
9	**1.1**	0.76	0.85	E3	effect of asymmetry
10	**1.1**	0.76	**0.55**	E3	
11	0.85	0.76	**0.55**	E3	

Table 17 List of glass laminate configurations to be analysed

The results to be focused on will be the minimum radius that is achieved at the maximum principal stress of 260 MPa, which is specified as the marginal strength by AGC for the Leoflex product. Additionally, while it will not have any deciding effect for the selection of the most suitable glass laminate configuration, also the reaction forces will be examined to get an idea of how different configurations affect the force that is to be applied to bring the glass into the desired shape.

3.4.2. Model Development

The numerical models were analysed using Ansys Workbench 16.0. Regarding the material properties, the model is simplified using linear material behaviour. For the glass, this reflects just about the real case, since glass preserves its linear-elastic behaviour within the temperature range that is common in architecture and its behaviour does not depend on load duration. Although this is not the case for the PVB interlayer due to its viscoelastic and thermoplastic characteristics, these effects are already taken into account by creating the stiffness range shown in Table 15 which includes time and temperature effects. It is important to mention that the values of E = 0.3 MPa and G = 0.1 MPa for PVB type E5 as shown in the table could not be used in the numerical analysis, as it led to convergence errors. These values were replaced by E = 100 MPa and G = 34.5 MPa instead, which are the lowest possible values that did not result in any error.

The stiffness values of the thin glass sheets are set according to the specifications of AGC Leoflex with the Young's Modulus E = 74 000 MPa and Poisson's ratio v = 0.23 and are fixed for every single analysis. For the PVB stiffness, the stiffness of the reference PVB of E = 943 MPa and G = 325 with a Poisson's ratio of 0.45 is used except for the test numbers 5 to 8, where the effect of the PVB stiffness is tested (Table 17).

For the geometry of the model, a 2D-shell-model is used. The shell of the size 2070x1000 mm has a very slight curvature, which is needed to create a bending behaviour in the FE-model. For this reason, the middle node of the shell is offset by 1 mm out of plane, which is large enough to make the shell bend under in-plane loading and small enough to not have any effect on the resulting stresses. The layers of the composite structure are attached to the two dimensional geometry separately by inputting the desired thicknesses and attaching the corresponding materials. For the mesh, a mesh with an element size of 25 mm was created, since smaller sizes result in errors due to excessive distortion of the elements. The difference in results between this mesh size and finer mesh sizes was found out to be minimal after several trials and therefore negligible.

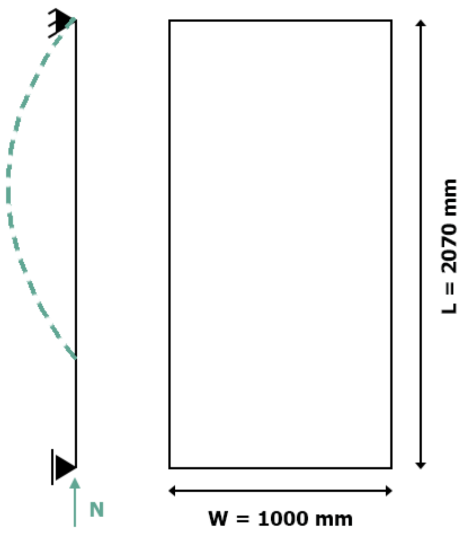
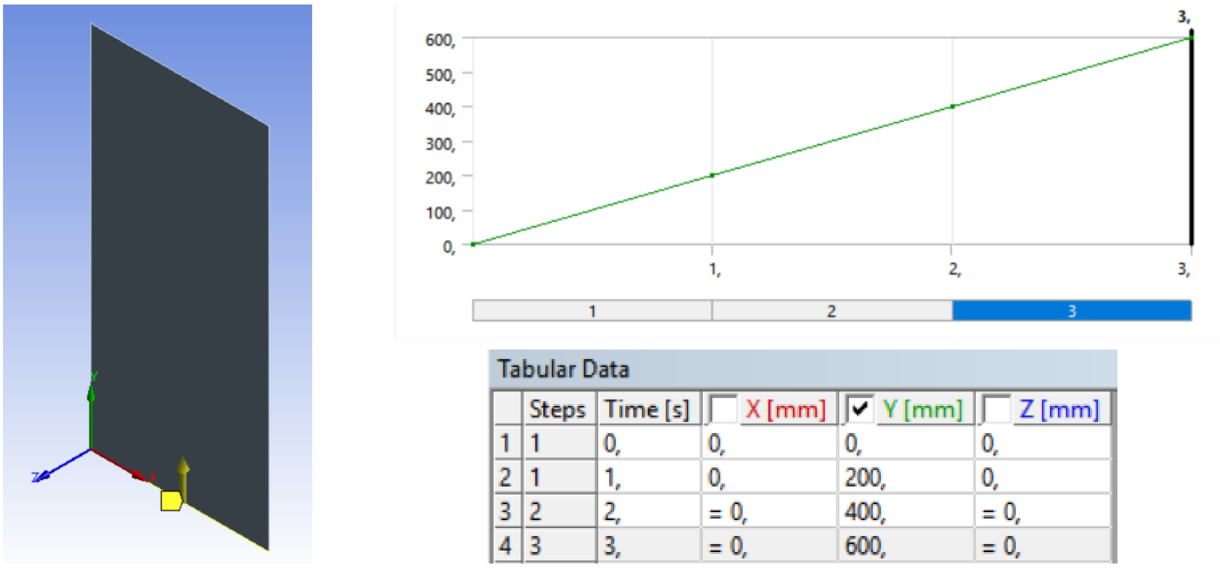


Figure 76 Shell geometry, supports and conceptual bending curve

As for the supports, a simple support type was chosen for the top edge of the sheet, which restricts movements in any direction but allows rotation. For the bottom edge, a remote displacement is used that allows movement in-plane in the length direction of the sheet and restricts it in the other two directions. Rotation around the edge is again allowed same as the upper edge. To create the bending effect, a prescribed displacement is placed at the bottom edge, which can move in-plane (Figure 76). The displacement is carried out in three steps; starting from 0 mm towards 200 mm in the first step with 15 sub steps. The number of sub steps in this step is deliberately kept high, since it is the most crucial time period due to the drastic change of the shape of the shell from a straight into a curved shape. At this point it is important to register the stress-displacement relation as accurately as possible. The second and third steps also add 200 mm of displacement each, reaching 600 mm in total at the end, however this time with only five sub steps per step, which is expected to provide enough accuracy, as at this time period, the stress-displacement relation is anticipated to be close to linear. A deformation as large as 600 mm is most likely not necessary for the ventilation of the interior space, however it will give a better idea of how the stress-deformation-relation changes with larger deflections. Large deflection effects are turned on for the analysis to facilitate a geometrically non-linear analysis, which is necessary due to the large deflection, which by far exceeds the shell thickness. The graph showing the linearly increasing displacement and a visualisation of the sheet model is shown in Figure 77.



Tabular Data

	Steps	Time [s]	X [mm]	Y [mm]	Z [mm]
1	1	0,	0,	0,	0,
2	1	1,	0,	200,	0,
3	2	2,	= 0,	400,	= 0,
4	3	3,	= 0,	600,	= 0,

Figure 77 Left: sheet model with global coordinate system and direction of the displacement; top right: linearly increasing displacement subdivided into three steps; bottom right: tabular data showing displacement according to direction

3.4.3. Results – General Observations

Prior to comparing the effects of changing the variables of glass thickness, PVB thickness and PVB type, some general observations of the FE-analysis results will be discussed to better understand the relationship between geometry and stress. For this purpose, at the moment, only the reference glass laminate configuration will be analysed.

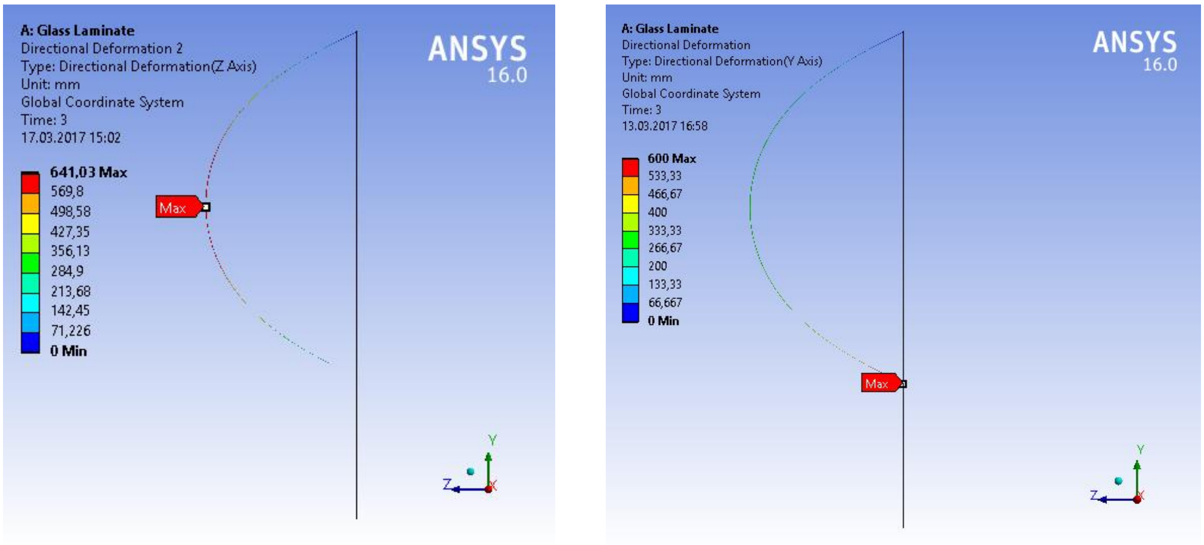


Figure 78 In- and out-of-plane deformation values at the final stage

First, a closer look will be taken to the geometry of the bent shape considering the in-plane and out-of-plane deformations. In Figure 78, it is visible that the values for the deformation in the y- and z-axis are not the same. While the in-plane deformation (y-axis) shows the value of the prescribed deformation of 600 mm (Figure 78, right), the output for the out-of-plane deformation (z-axis) is higher with 641.03 mm (Figure 78, left).

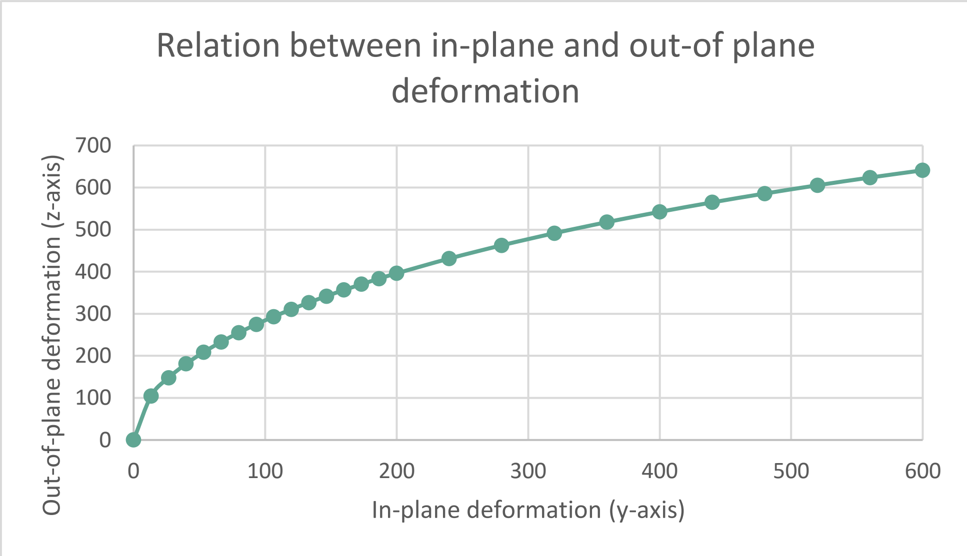
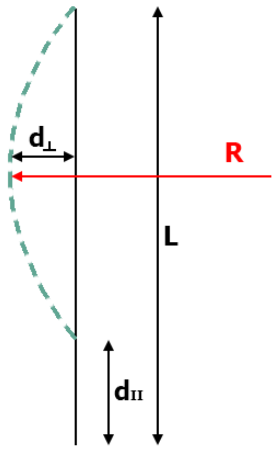


Figure 79 Relation between in-plane and out-of-plane deformations

At this stage, it can be interesting to see how the two deformations relate to each other during the deformation process. This relation is plotted on the graph shown in Figure 79 with the linear in-plane displacement on the x-axis of the graph and the out-of-plane displacement on the y-axis. There, it is clearly visible that these two deformations do not have a linear dependency on each other. The first millimetres of in-plane displacement results in a quick increase in lateral displacement, which changes during the course of time with less lateral displacement per in-plane displacement towards the end. In general, from the graph, it can be derived that at the early stages of the deformation, the in-plane deformation is much larger. This can be regarded as an advantage, since a large ventilation opening is created at the edges with even a small curvature of the glass. Therefore a small deformation might be enough to ventilate the interior space sufficiently.

A further observation concerns the final shape of the sheet after deformation. When viewed from the side, the deformed shape does not form an exact segment of a circle but features a more strongly curved shape. The areas close to the edges are therefore more flat shaped. Figure 80 illustrates the actual shape of the deformed glass sheet (blue) in comparison to a perfect circle with the same radius (red). Since the numerical calculation does not provide an output for the radius, it first needed to be derived with a mathematical formula. The values that are helpful for the derivation are the in-plane and lateral deformations. The formula for the calculation of the radius is shown below.

$$R = \frac{(\frac{L - d_{II}}{2})^2 + d_{\perp}^2}{2 * d_{\perp}} \; [mm]$$



with: R = radius of deformed glass sheet [mm]

L = length of glass sheet [mm]

d_{II} = in-plane displacement [mm]

$d_{\perp}$ = lateral displacement [mm]

In the case of a perfect circular shape, this formula can be used to derive the deformation of glass sheets of every size. However, as seen in Figure 80, the glass does not exactly form such a shape. Therefore, an analytical approach to find out the deformation of different sheet sizes over the radius may require some caution. To investigate the difference further, another numerical calculation was performed with a different sheet size to compare the stress development over the change of the radius. This time, a sheet of the size 710 x 450 mm was chosen. The reason for the selection of that particular size is that it is the available size for a possible physical experiment in case of a doubt about the numerical results. Apart from the sheet size, every other property such as the total thickness and stiffness remained untouched. Figure 81 shows the radius-stress curves of the two sheet sizes plotted on a graph. It is visible that the two curves overlap during the entire process and the deviations are minimal. The conclusion from this graph is, that the radius applies to all sheets regardless of their size. Therefore, instead of the deformation in mm, the radius in mm will be used to compare the stresses of the different glass laminate configurations.

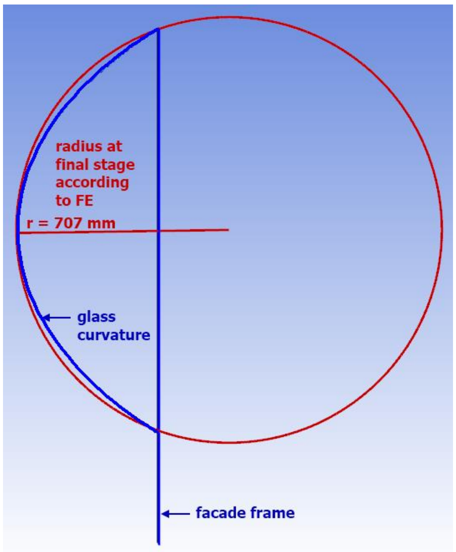


Figure 80 Geometrical shape of the deformed glass sheet at 600 mm in-plane deformation

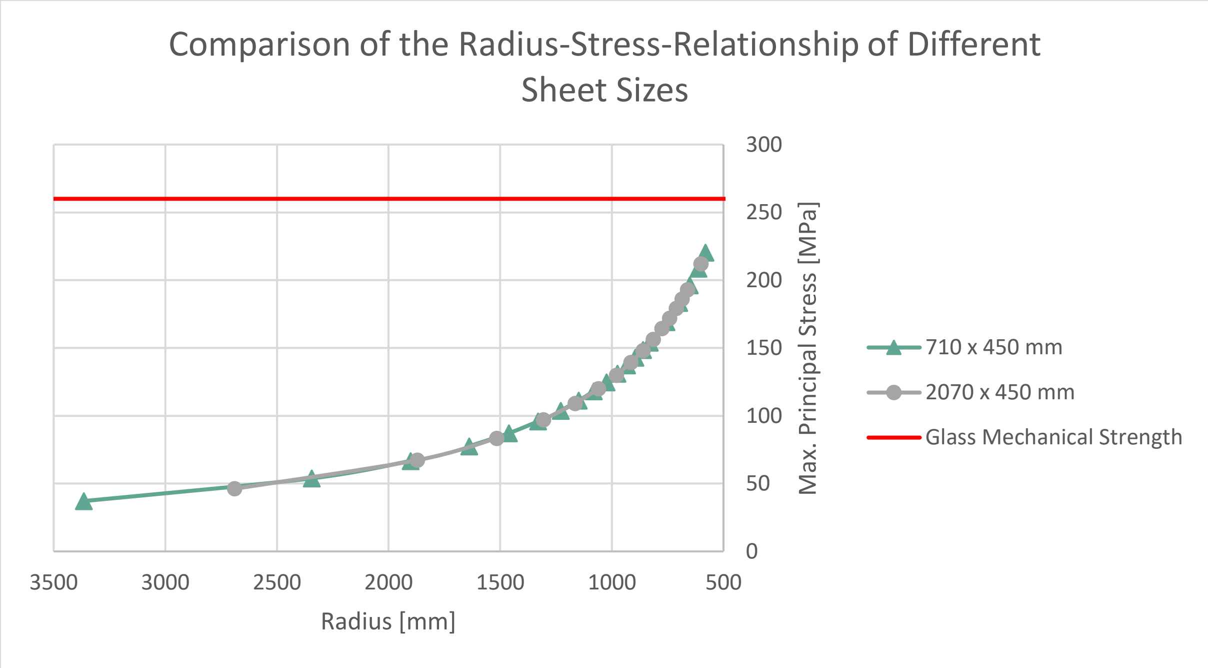


Figure 81 Comparison of the radius-stress-relationship of different sheet sizes

Further observations resulting from the comparison of the results of the two sheets sizes that may not play a significant role but are worth mentioning are as follows:

- the resulting maximal principal stress is not dependent on the sheet width or the length-to-width-ratio but solely on its length
- glass sheets with a larger width require a larger total force [N] to bend, however, if distributed along the edge length [N/m], the values are equal
- sheets with a larger length in the direction of the in-plane displacement require less force for bending
- the central nodes of sheets with a larger length in the direction of the in-plane displacement deform quicker laterally, leading to larger ventilation openings with the same in-plane displacement (Figure 82)

Considering all the listed observations, it can be concluded that large glass sheets, especially in length, are more suitable for cold bending as they are easier to bend and allow for more in-plane deformation with the same bending radius, which increases the opening for ventilation. However, it should still be kept in mind that larger sheet sizes are affected more by external wind loads, which can be a limiting factor for the sheet size.

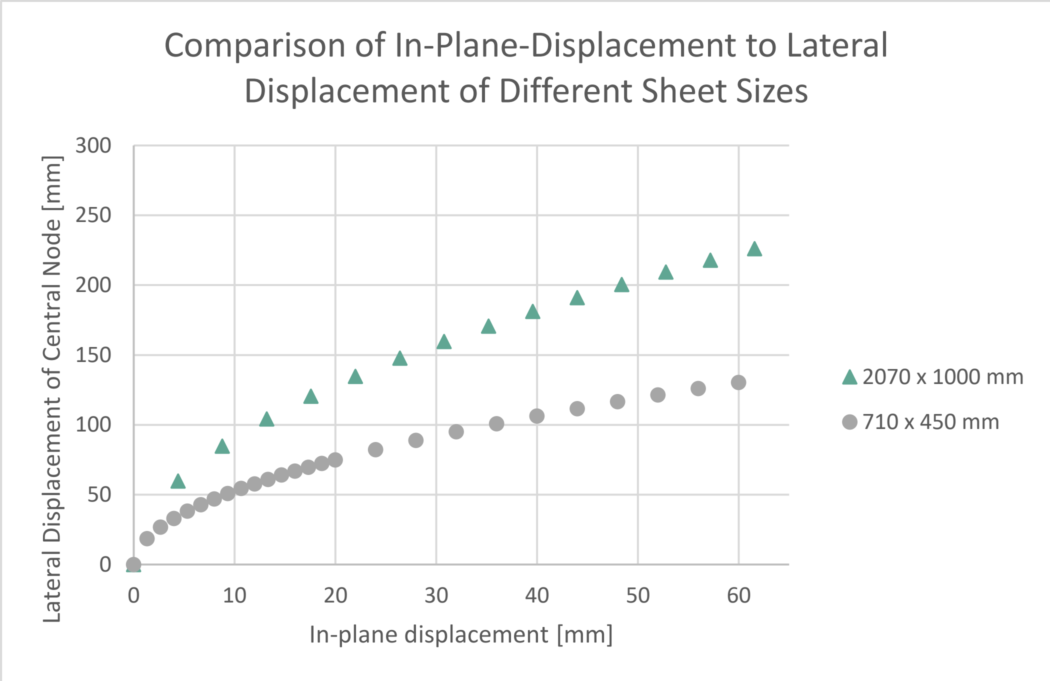


Figure 82 Comparison of in-plane displacement to lateral displacement of different sheet sizes

Next, the maximum principal stress at the final stage for a sheet of the size 2070 x 1000 mm after an in-plane deformation of 600 mm will be considered. As can be seen in Figure 83, the maximum principal stress is located at the edge of the sheet with 181.77 MPa. This is crucial, since the edge of a sheet forms the weakest spot of the entire body after the strengthening process. Furthermore, when a physical experiment is performed, it is usually the stress in the centre that is measured by the device, as it is difficult to place it at the edge. Therefore it is interesting to also regard the maximum stress at the central node of the panel and compare the two values with each other.

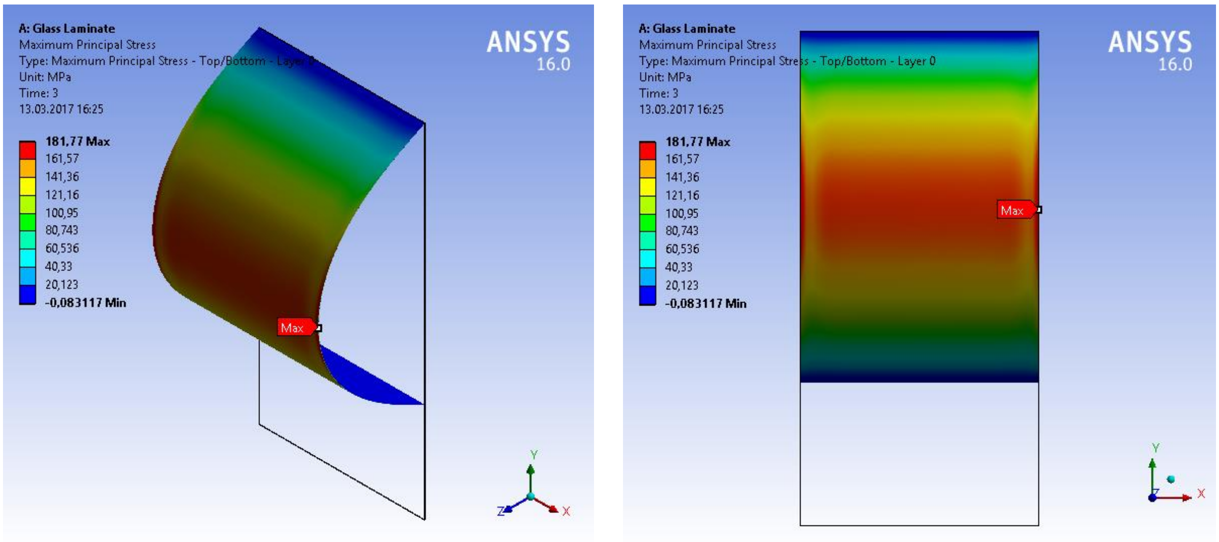


Figure 83 Maximum principal stress at the edge of the reference configuration after 600 mm of deformation

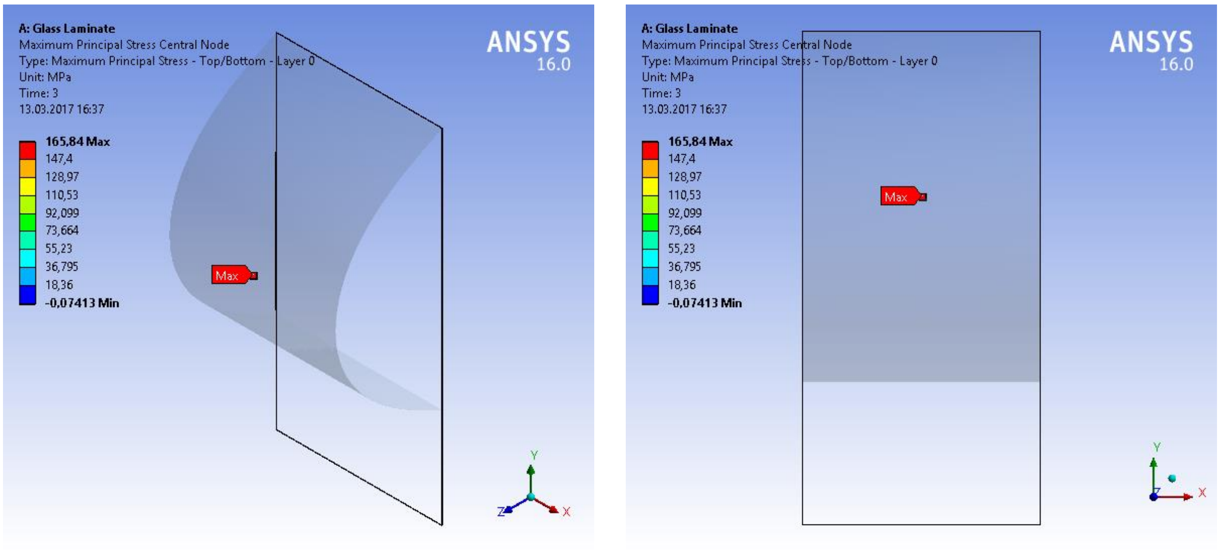


Figure 84 Maximum principal stress at the centre of the reference configuration after 600 mm of deformation

In Figure 84, where the central node is considered, it is visible that the principal stress at this point is lower than at the edge with a value of 165.84 MPa. Figure 85 illustrates the differences in principal stress between the edge and centre of the glass sheet during the course of deformation. From the graph, it can be observed, that the stress in the central node increases with a more gradual increase. The two functions appear to have a similar curvature throughout the bending process.

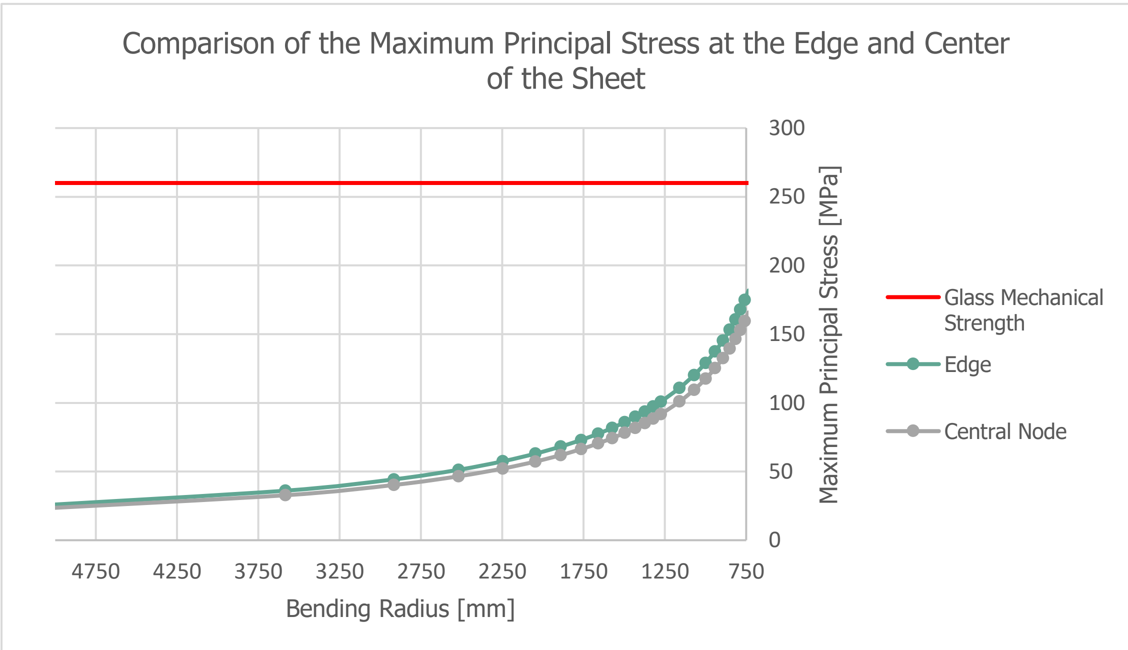


Figure 85 Comparison of the radius-principal stress relationship at the edge and centre of the sheet

For the following comparison of different glass laminate configurations, only the maximum principal stress at the edge will be considered, since it is the significant value for the maximum capacity of the element.

3.4.4. Results – Effects of Changing Variables

After the general observations have been made regarding the relation between bending and stress, the glass laminate configurations can be compared with a better understanding. As shown in Table 17, the comparison will take place in four parts: the effect of altering the glass thickness, the PVB thickness, the PVB stiffness and the effect of an asymmetric configuration respectively.

The glass thickness in a symmetrical configuration has two variations apart from the reference; 0.55 mm and 1.1 mm on both sides (Figure 86). First, the maximum principal stress at the edge of the glass will be examined at an in-plane deformation of the earlier mentioned 600 mm for each configuration. In Figure 87, the graph comparing the results for all variations can be seen.

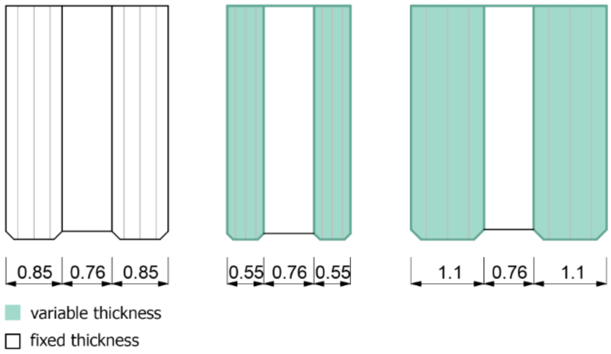


Figure 86 Glass thickness variations, varying properties in green (left to right: reference configuration, 2x0.55 mm, 2x1.1 mm)

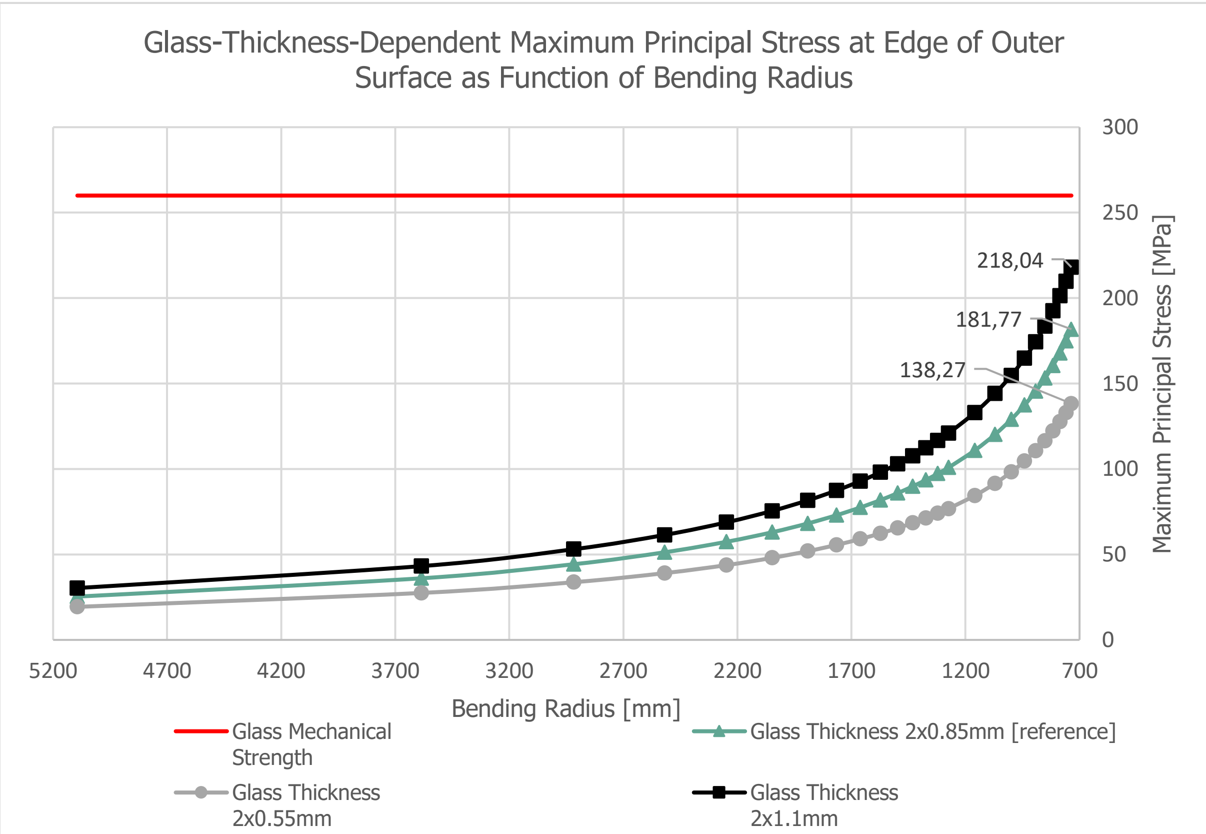


Figure 87 Glass-thickness dependent maximum principal stress at edge of outer surface as function of bending radius

It is visible that even under the extreme condition of 600 mm in-plane bending, all the configurations stay under the maximum mechanical strength of the chemically tempered glass as specified by the manufacturer. The highest resulting stress occurs at the configuration with 2 x 1.1

mm as expected, with 218.04 MPa at a radius of 707.76 mm (equivalent to the radius at 600 mm in-plane displacement). This value is 19.8% higher than that of the reference configuration, which is 181.77 MPa. The thinnest configuration with 2 x 0.55 mm is 24.2% lower than the reference with a resulting stress value of 138.27 MPa. The reason for the variation of the resulting stresses is easily explained. The higher the total thickness of the sheet, the higher is its moment of inertia, which makes the glass laminate stiffer. In this regard, the results provide no surprise.

The stiffness of the panel also affects the maximum required force for bending it. While this factor plays a more minor role for the selection of the glass configuration, it is interesting to view its effects in this context. To retrieve the required force, the support reactions from the numerical analysis are considered. Figure 88 depicts the applied force for bending the sheets of different thicknesses as a function of the in-plane displacement. In the case of the force, it is more reasonable to plot it against the displacement instead of the radius, as the relation of force to displacement is linear.

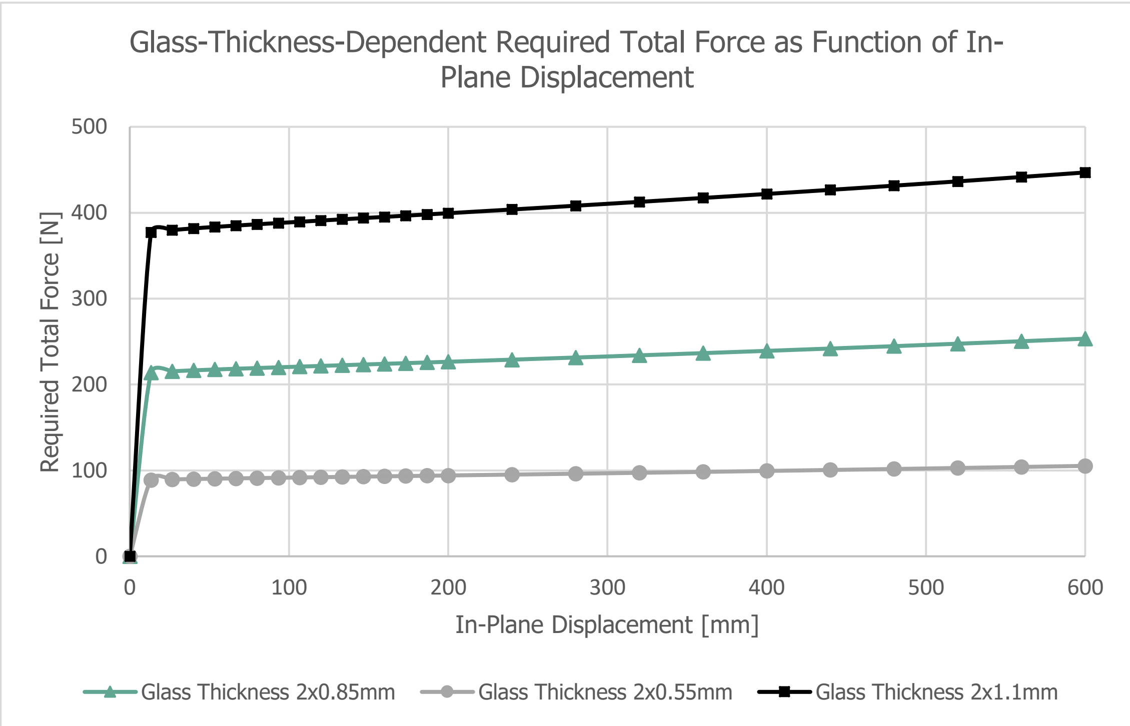


Figure 88 Glass-thickness dependent required total force as function of in-plane displacement

The graph shows the large difference in required force for the three different laminate thicknesses. While the required force for the thick laminate with 2 x 1.1 mm glass is almost twice as much as that of the reference, for the thinner laminate, this number is less than half of it. If the numbers are considered in percentage, it can be concluded that varying the glass thickness has a much larger effect on the required force than on the resulting stress.

While it plays a less significant role for the selection as mentioned earlier, the result for the force affects the required performance of the actuator in case of an electrically controlled façade. If the façade is to be opened and closed by hand, it plays a more significant role for the convenience. After all, 200 N of force is more or less equivalent to lift a weight of 20 kg, which can be inconvenient for the user.

The next variable to be examined is the PVB thickness. Similar to the previous example, there are again two variables other than the reference; A PVB with the thickness 0.38 mm and one with 1.52 mm. The variations are shown in Figure 89, with the changing parameters shown in green colour. Again, the maximum principal stress at the edge of the glass will be examined at the final deformed stage first. The resulting graphs are depicted in Figure 90.

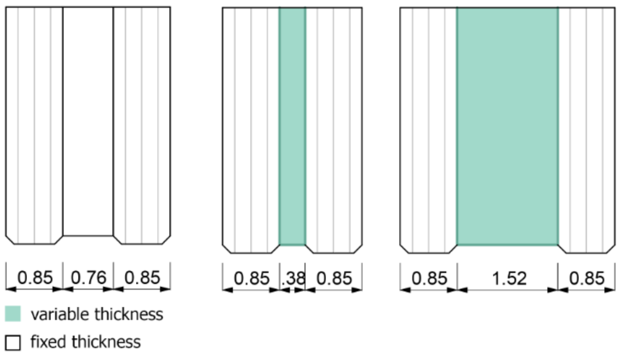


Figure 89 PVB thickness variations, varying properties in green (left to right: reference configuration, 0.38, 1.52 mm)

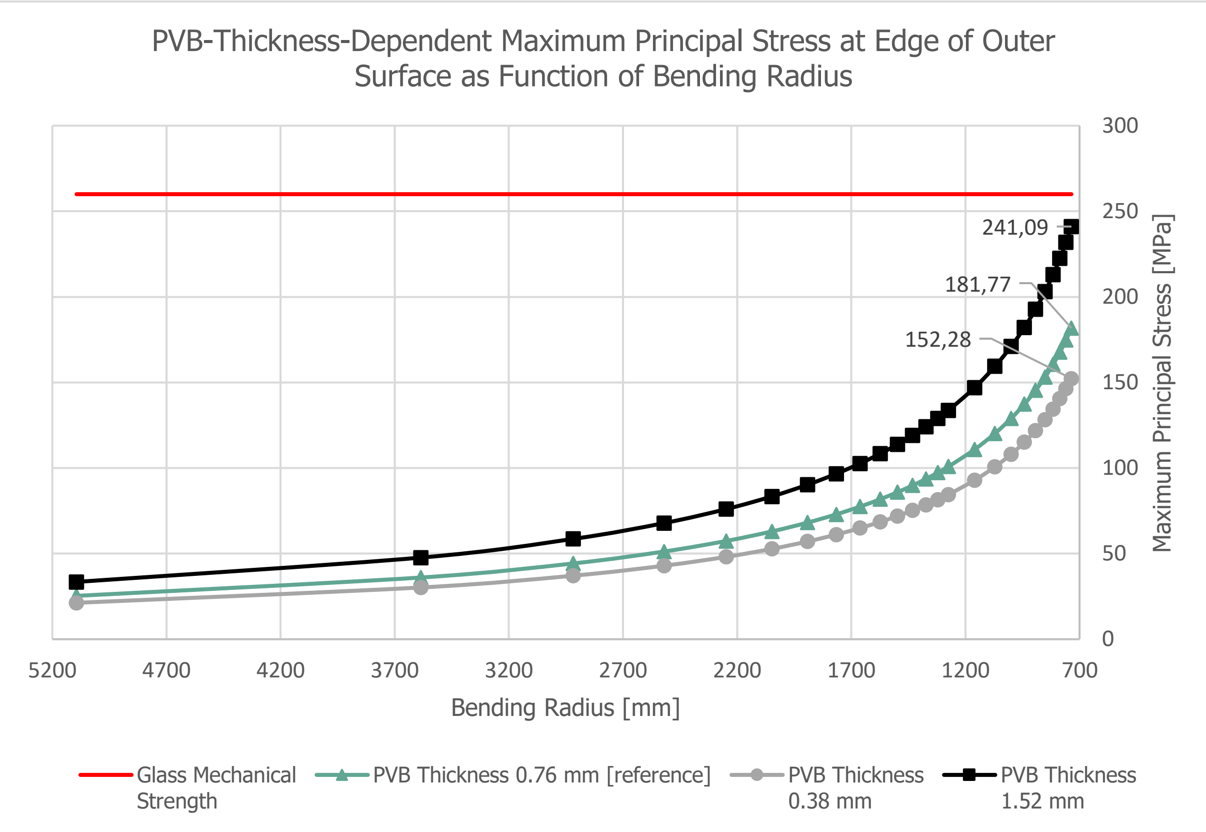


Figure 90 PVB-thickness dependent maximum principal stress at edge of outer surface as function of bending radius

Once again, the reference configuration is located between the two other variations, with the configuration including the thicker interlayer resulting in a higher principal stress than the one with the thinner interlayer.

In chapter 2.4.3, it is mentioned that, in relation to the PVB thickness, the overall stiffness of the laminate depends on two aspects. The first would be the overall thickness of the laminate with a direct relation to its moment of inertia. The second aspect is the ability of the interlayer to redistribute the shear stresses between the glass panels. The latter aspect is both related to the PVB stiffness and the PVB thickness. Since the PVB stiffness is kept the same in this comparison, here has no effect. However, it is a fact that a thinner interlayer transfers more stress than a thicker interlayer, and therefore increases the maximum principal stress. Thus, the change of the PVB stiffness alone has also an effect on its stress transferring ability. In other words, e.g. increasing the PVB thickness would increase the laminate's overall stiffness due to increased moment of inertia but at the same time it would reduce its stiffness due to a better ability to equally redistribute shear stresses between the two glass sheets. The question at this point is, which of the two effects is larger and therefore more decisive. The results of this numerical analysis, showing a higher principal stress for the thicker interlayer, suggest that the moment of inertia is much more influential. Considering the formulae for both aspects, the results make sense. For the calculation of the moment of inertia, the overall thickness has a very large influence, since it is raised to the third power in the formula. As a result, even a slight increase in PVB thickness drastically increases the laminate's moment of inertia, while the shear stress transferring ability is only changed by a relatively low amount.

It is also notable that the thicker configuration clearly deviates much more from the reference (+32.6 %) than the one with lower thickness (-16.2 %). This can be led back to the difference in the total thickness of the laminate. While the difference in total thickness between the reference and the configuration with 0.38 mm variation is 0.38 mm, this difference is doubled between the reference and the variation with a PVB-thickness of 1.52 mm. The larger difference in total thickness therefore leads to a larger deviation in resulting stress. Comparing these percentages to those of the previous configurations with changing glass thickness, it is notable that both variations have a higher resulting principal stress in general. This is again related to the total thickness of the laminate. Even though this time it is the interlayer whose thickness is changing, the total thickness and the resulting principal stress seem to go hand-in-hand.

A similar trend is also visible for the required total force for bending, which is illustrated in a graph in Figure 91. As expected, the required force for bending the composite with the thicker interlayer is at a larger distance from the reference than the thinner interlayer.

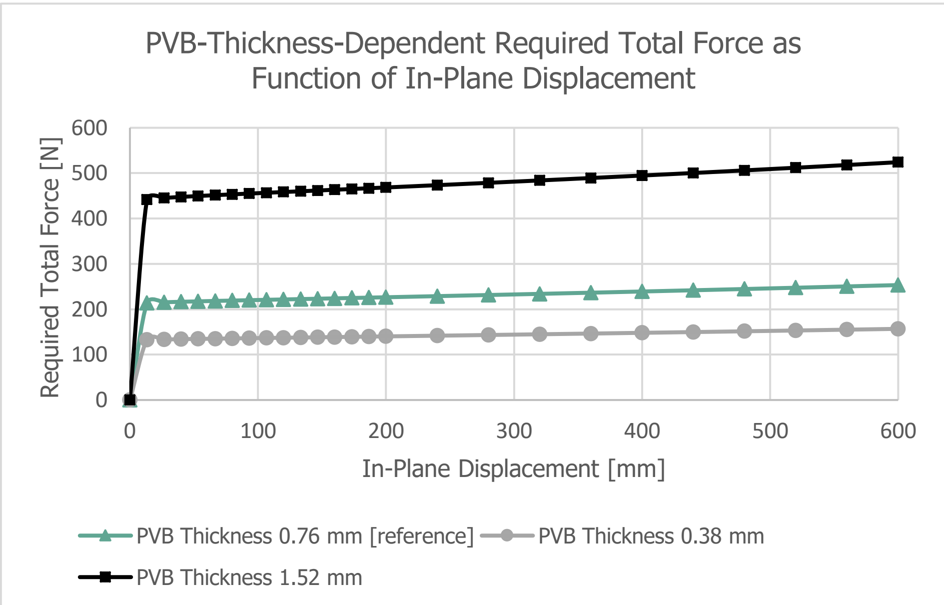


Figure 91 PVB-thickness dependent required total force as a function of in-plane displacement

The next parameter to be tested is the PVB stiffness with fixed thicknesses for both glass and interlayer. As described earlier, for this parameter, a range of Young's and shear moduli has been set according to manufacturer specifications. This range includes the PVB in its softest and stiffest forms. The used Young's moduli are listed in Figure 92.

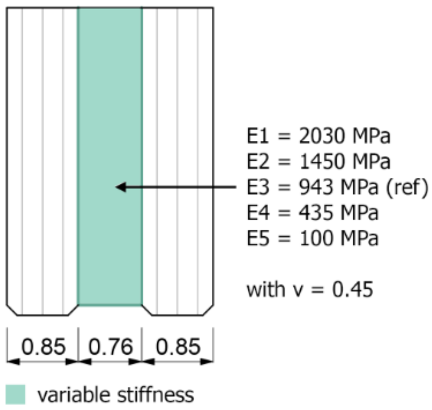


Figure 92 PVB stiffness variations

Since a minimal difference between the variations was detected, the curvature for this comparison was even more increased to get a clearer view of the stress differences. The bending radius in this case goes as low as 370 mm, where the stress exceeds the maximum mechanical strength of the glass. The graph is shown in Figure 93.

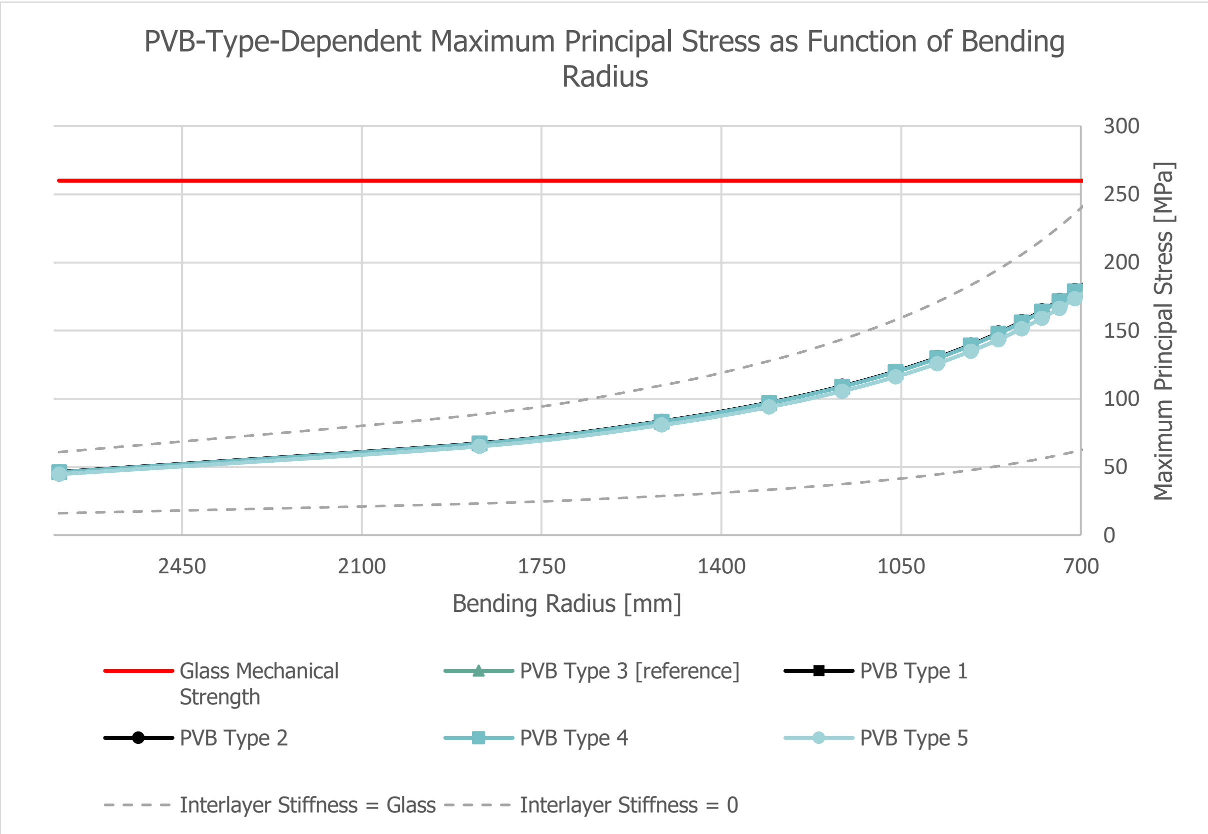


Figure 93 PVB-stiffness dependent maximum principal stress as function of bending radius

Since the curves are very close to each other, a zoomed-in version of the graph is shown in Figure 94, which focuses on the point, where the principal stresses exceed the mechanical strength capacity of the glass.

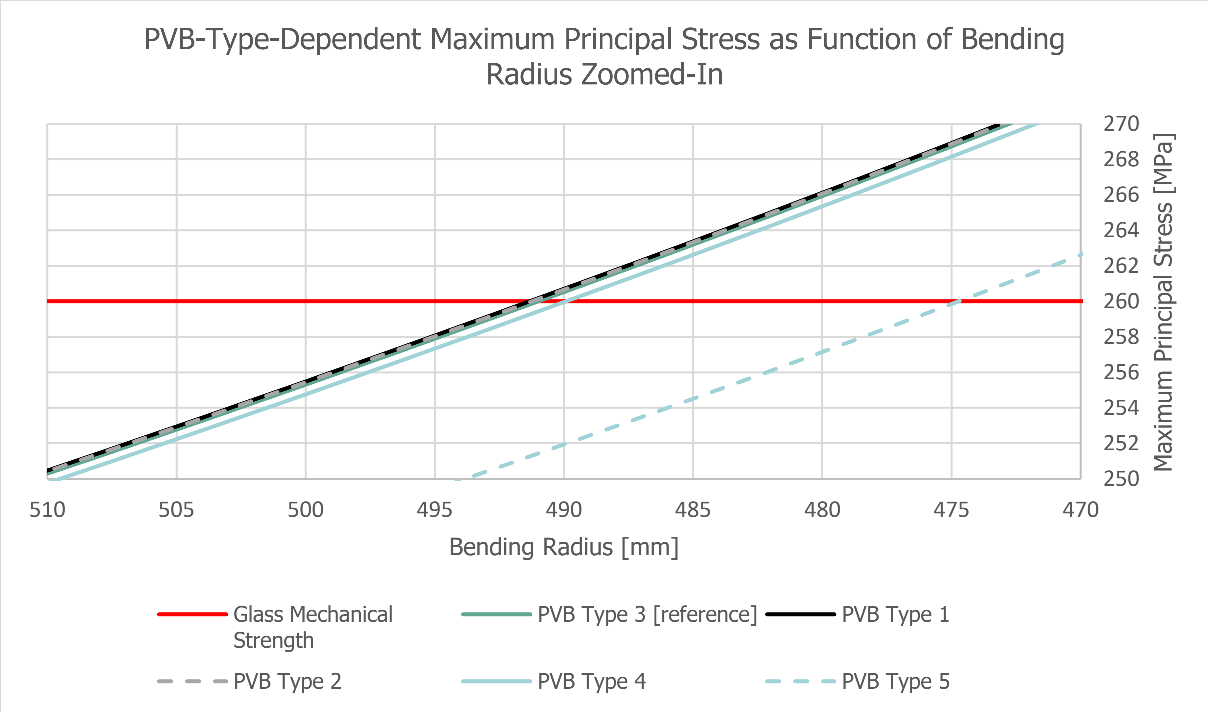


Figure 94 PVB-stiffness dependent maximum principal stress as function of bending radius zoomed into mechanical strength limit

As can be seen in the two graphs, even with a decreased bending radius and by zooming in, the stress difference is still too low to distinguish the curves from each other. An exception is PVB Type 5, which has the lowest stiffness. Compared to the other stiffnesses, which exceed the strength limit of 260 MPa at around 491 mm of bending radius, this one meets the limit at 475 mm. The other four PVB types also follow the expected pattern, with the stiffer interlayers resulting in higher stresses. However, the difference between the stresses are too low to be representing the truth. It is assumed that this occurred due to the use of a sheet model in Ansys. In order to get results for a composite element that are as accurate as possible, a 3D model would be necessary with a mesh size of one fourth of the PVB thickness up the PVB thickness itself. In this case, the mesh size would be as small as 0.2 – 0.8 mm. Given the size of the model to be analysed, the thinness of the interlayer, the necessity for a non-linear analysis and the complexity of the support conditions, this could not be done due to technical limitations. Therefore, based on theoretical knowledge, for the final choice of the most suitable configuration, the softest PVB will be regarded as the first choice for easy bendability. Even if the differences are extremely low in the numerical analysis, this theory is still supported by the ranking of the resulting stresses respective to the PVB stiffness.

The last option to be examined is the asymmetric configuration of glass thicknesses. This relates to the effect of the asymmetry possibly reducing the maximum tensile stress on the side of the thinner glass that is placed on the side with the larger bending radius. The theory behind this effect is explained in chapter 2.4.3 and illustrated in Figure 23. Three configurations were numerically ana-lysed. These include combinations of glass thicknesses of 0.85-1-1 mm, 0.55-1.1 mm and 0.55-0.85 mm with the thinner layer always forming the side with the larger bending radius (Figure 95). The results of the analysis are shown in the graph in Figure 96. Figure 97 shows a zoomed-in version for a clearer distinction.

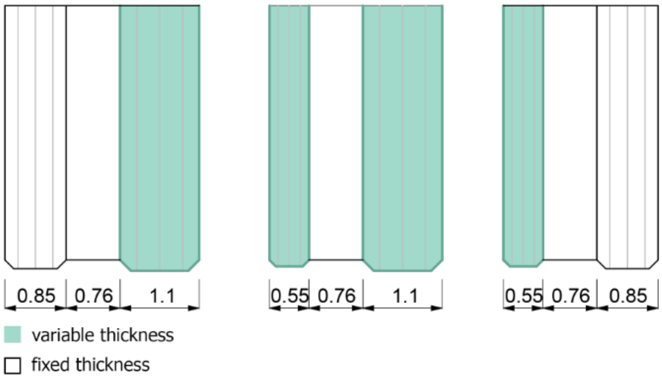


Figure 95 Asymmetric glass thickness variations, varying properties in green (left to right: 0.85-1.1, 0.55-1.1, 0.55-0.85 mm)

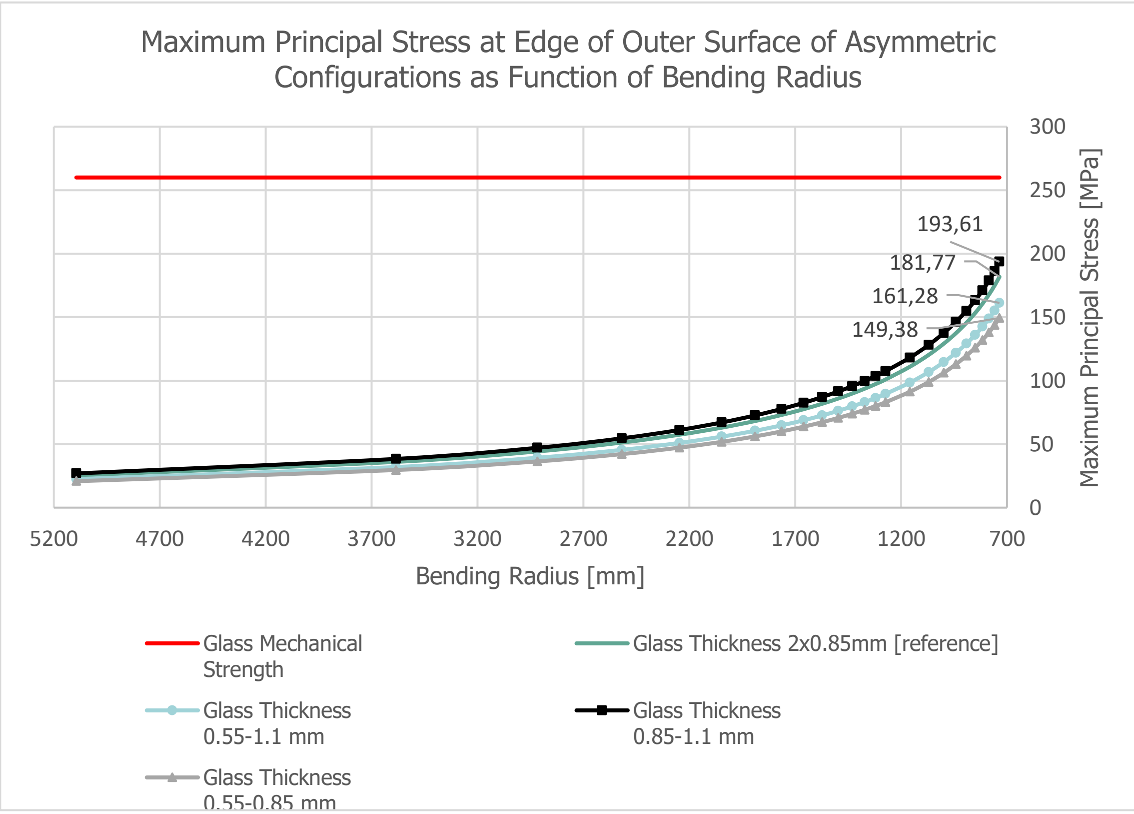


Figure 96 Maximum principal stress at edge of outer surface of asymmetric configurations as function of bending radius

The graphs show small differences between the results in general. It is possible to get a clearer idea, whether the asymmetry reduced the maximum stress or not, by comparing the results to those with symmetric configuration. For this purpose, another graph has been created that compares the maximum principal stresses at 600 mm in-plane deformation including the three symmetric configurations and the three asymmetric versions. The graph also includes a trend line of the total thicknesses of each laminate configuration. This way, the relation between total thickness and maximum principal stress can be observed. The graph is shown in Figure 98.

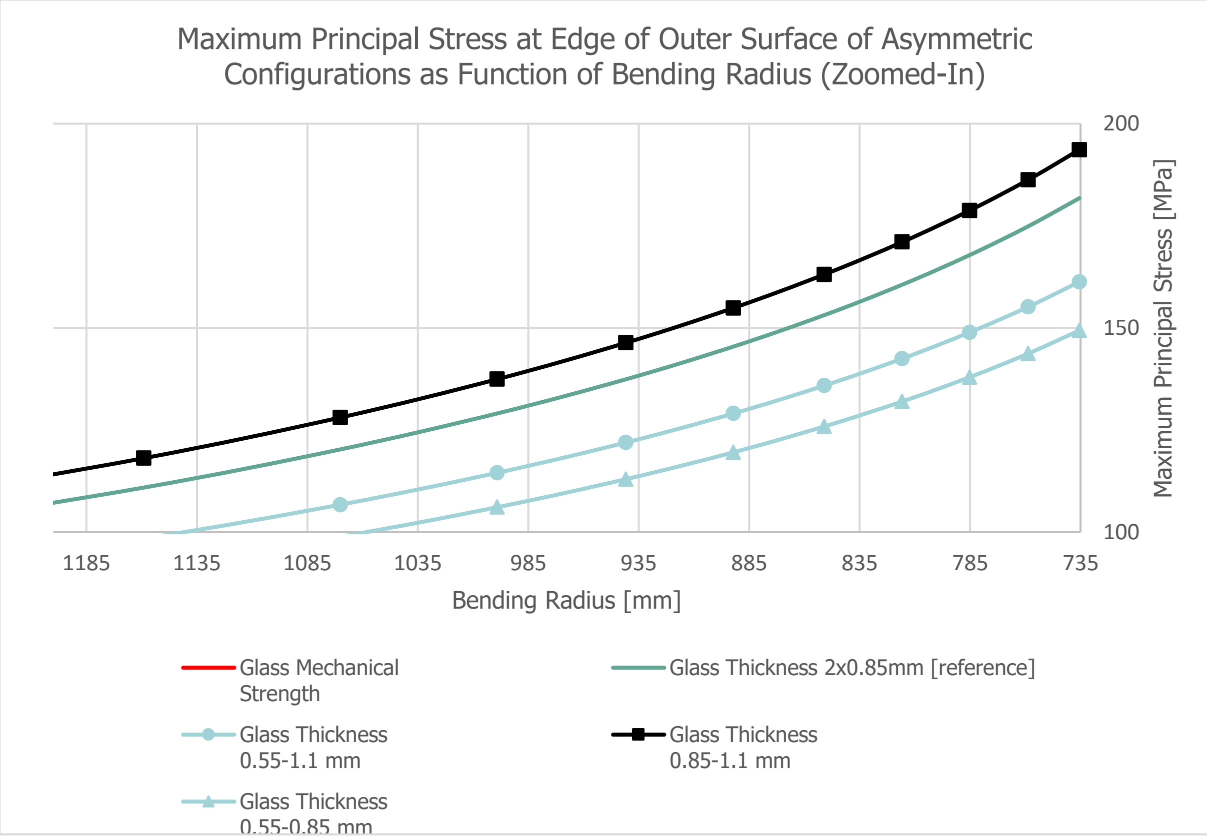


Figure 97 Maximum principal stress at edge of outer surface of asymmetric configurations as function of bending radius zoomed into smallest bending radius

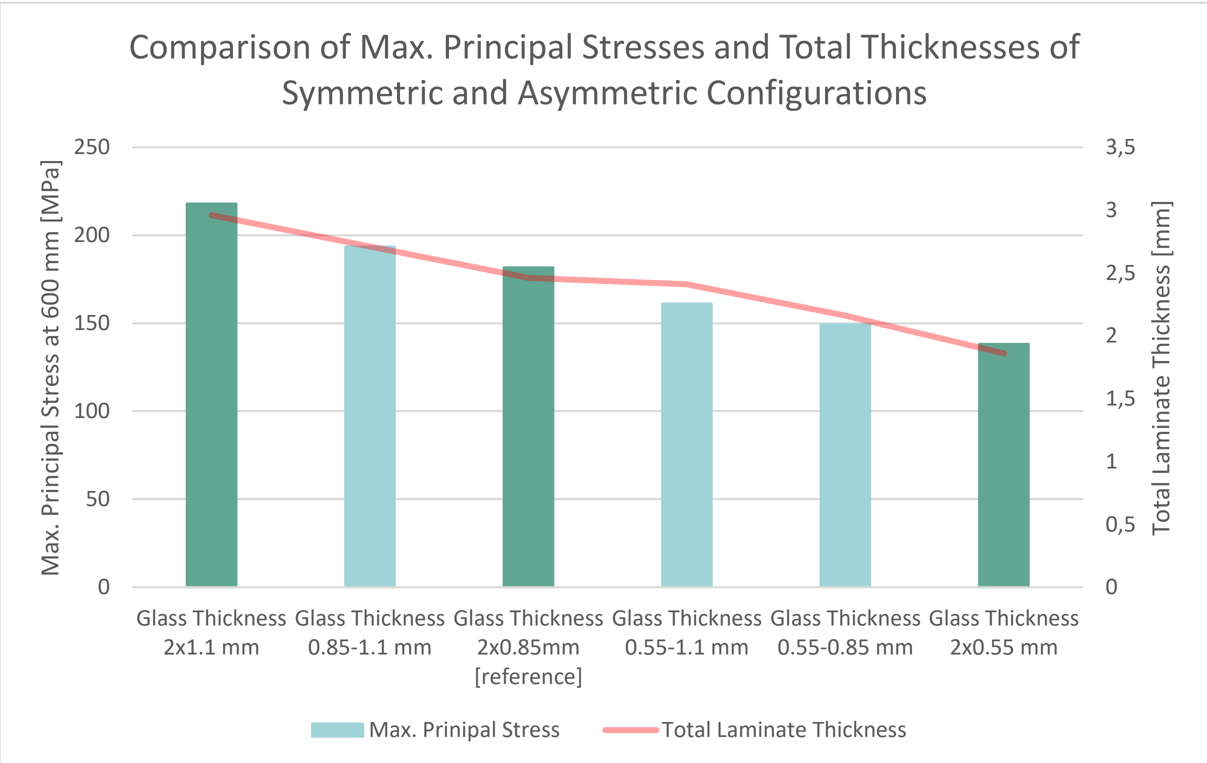


Figure 98 Comparison of the maximal principal stresses and total thicknesses of symmetric and asymmetric configurations

The dark green columns in the graph in Figure 98 represent the maximum principal stresses of the symmetric configurations, while the light green columns stand for those of the asymmetric versions. The columns are ranked according to the total thickness of the laminates including that of the interlayer. The red line illustrates the total laminate thickness of each configuration.

As can be seen on the graph, the columns and the line do not decrease with the same tendency, but rather depict a different trend. The difference is particularly visible between the reference thickness and the 0.55-1.1 mm combination. What is worth mentioning at this point is that it is the only transition where the inner plate's thickness increases, while the total thickness decreases. Therefore, it is safe to assume that, unlike laminated glass elements with regular glass thicknesses, in thin glass laminates, the tensile stresses in the inner plate can exceed those of the outer plate. The reason for this is most likely the small difference between the bending radii of the two plates. Therefore, using an asymmetric configuration does not provide any advantage in the case of thin glass laminates apart from offering optional total thicknesses, located between those of the symmetrical configurations.

3.4.5. Validation of the Numerical Results

The results achieved by numerical calculation cannot be taken for granted as they are. The reason therefore is that often, the results of a FE-analysis can deviate largely from the reality, due to irregularities in the FE-model but also the experiment setup. The initially planned physical experiments to validate the previously presented numerical results were not carried out due to the limited timeframe and in order to prevent the scope of the research to be further widened. Thus, another method must be used to verify the numerical results.

For the validation of the numerical results, a different shell model will be created, equal to a previously executed physical experiment whose results are available. This model will then be fed into the ANSYS software to calculate the resulting stress levels, which will then be compared to those retrieved from the physical experiment. The deviation in percentage between the two sets of results will provide an idea about the accuracy of the numerical calculation. At this point, it is vital that the numerical results remain on the conservative side, i.e. the calculated stress levels are higher than those measured during the physical experiment.

The experiment in question consists of a single glass sheet with a thickness of 2 mm and is tested under bending. The measured values are the vertical displacement, required force and the stress on the glass surface. The trigger for the bending movement is similar to that of the proposed design of this thesis, with the glass being clamped into two linearly moving and simultaneously rotating shafts at its two short edges. The most remarkable difference of the physical experiment case to that of this thesis is undoubtedly that it only comprises a single glass sheet, which is not laminated. Furthermore, with its thickness of 2 mm, it does not fall into the thin glass category. In contrast, the total thickness of the laminates tested in the previous sub-chapters ranges from approximately 1.5 to 3.7 mm, including the interlayer. This makes the thickness of the experiment similar to the average total thickness of the glass laminates. The differing factor, however, is the stiffness, the monolithic glass sheet being a single stiff solid body with E = 74 000 MPa and ν = 0.23 and the laminate, a sandwich with the outer two layers' stiffness being E = 74 000 MPa and ν = 0.23 and the inner layers' stiffness ranging between E = 0.3 and E = 2030 MPa, ν = 0.45 (PVB, SentryGlas). Additionally, the sandwich has the characteristic of a bonded material as shown in Figure 22. Thus, it cannot be assumed that the comparison that is made in this chapter depicts the exact same case as that of a laminated glass element. However, it gives a general idea about the deviation range and how carefully the numerical results should be approached.

The graph in Figure 99 illustrates the differing stress results between the physical experiment and the numerical analysis under the same conditions. As can be seen, the stress that results from the numerical analysis is much higher. The deviation in percentage equals 11.8%. This is a relatively high number to be accepted as a validation. The possible reasons for this difference are numerous. Differences can occur due to inaccuracies both during the physical experiment and in the development of the numerical model. In the former case, the inaccuracies can contain e.g. the misplacement of the strain gauge (even if very small), a different bending radius than planned, irregular movement of the bending mechanism, irregularities in the material etc., whereas in the former case, differences can be the result of rough meshes, inaccuracies due to the nature of 2D-shell-models not depicting the exact situation even in thin materials, and so on.

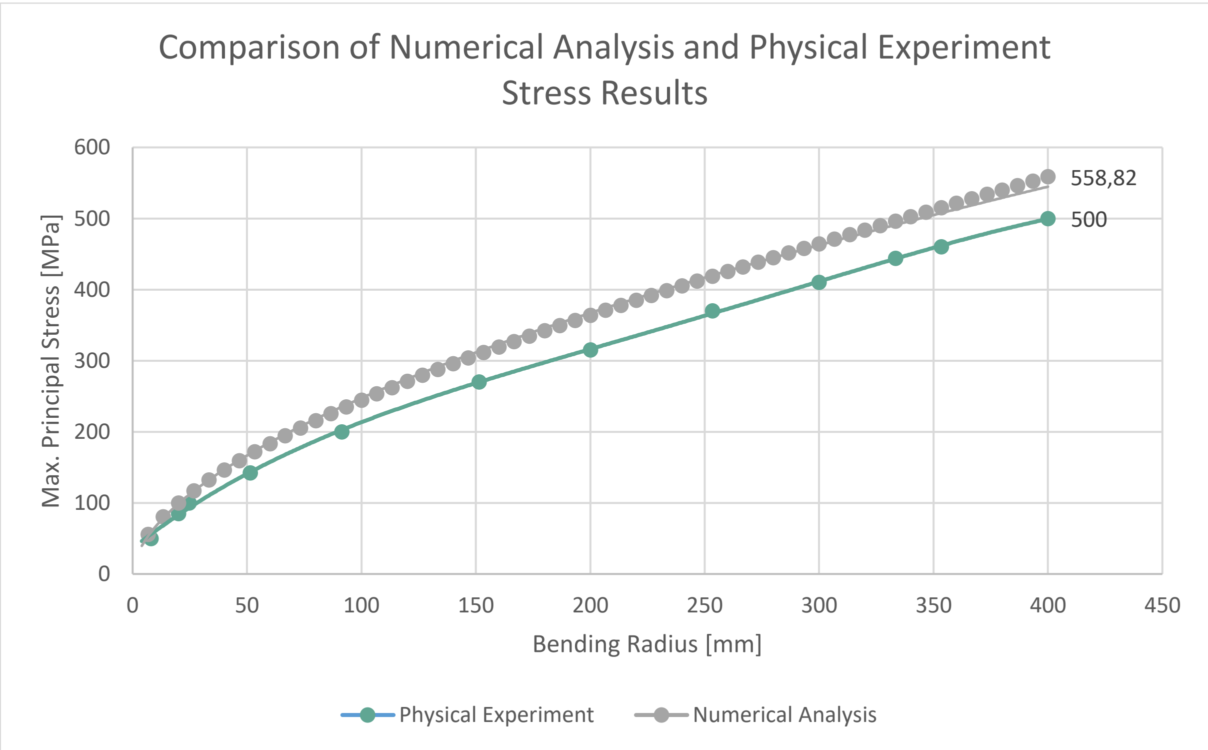


Figure 99 Comparison of Numerical Analysis and Physical Experiment for Validation

With the deviation being too high for an accurate assumption, this result still shows that the numerical result is on the conservative side, with higher stress levels at the same bending radius. Therefore, the additional stress can be regarded as sort of a safety factor for the results achieved in the previous sub-chapters.

3.4.6. Conclusions Drawn From Numerical Results

Following the numerical calculations numerous conclusions were drawn from the results. This chapter is meant to sum up all the conclusions drawn regarding the structural behaviour of the analysed geometry due to cold bending and subjection to external loads. The conclusions are listed in bullet points.

- The relation between the in-plane deformation of a node at the top or bottom edge and one in the centre of a cold-bent sheet are non-linear. Initially, a small in-plane translation of the top or bottom node results in a relatively large out-of-plane translation of the central node, which then slowly declines during the bending process.

- The shape of the cold-bent sheet is not equal to a segment of a circle. The resulting shape resembles more that of a parabola, with the two ends being more flat shaped.

- The radius-stress relationship of different sheet sizes is equal, meaning that two sheets of different sizes bent with the same radius are subjected to the same stress

- The resulting maximal principal stress is not dependent on the sheet width or the length-to-width-ratio but solely on its length

- glass sheets with a larger width require a larger total force [N] to bend, however, if distributed along the edge length [N/m], the values are equal

- sheets with a larger length in the direction of the in-plane displacement require less force for bending

- The maximum principal stress is located at the edge in the centre of the bent glass sheet, which also forms the weakest spot of the chemically tempered glass. The stress inclination between the edge and the centre nodes are different, with relatively small deviation

- The maximum principal stress under the same bending radius is increased with a larger glass thickness, a larger interlayer thickness and a stiffer interlayer

- According to the numerical calculations, even the glass laminate with the highest resulting stress remains under the marginal strength value of the glass as specified by the manufacturer within the required bending radius limits. Therefore, the bending alone does not pose any threats regarding failure of the glass

- The amount of required force for bending according to the glass laminate configuration goes hand-in-hand with the resulting stress values. Thus, a configuration resulting in high stresses also requires high forces for bending

- An asymmetric configuration of glass thicknesses is not very helpful towards reducing the maximum principal stress in the glass. The assumption for this result is that the tensile stress of the inner glass plate can exceed that of the outer plate due to the low overall thickness of the lamination.

3.4.7. Most Suitable Configuration

Now that the effects of altering the single properties are analysed, a ranking can be created that lists the most suitable configurations in terms of minimum stress and minimum required force. This ranking will then be used to numerically test the laminate configurations under wind load starting with the most suitable configuration. If it is determined that the first choice is not stable enough under wind load, the second configuration will be tested. This will go on until a configuration is found that is strong enough to withstand wind loads and still as flexible as possible. The methodology for the determination of the most suitable configuration is shown in Figure 100.

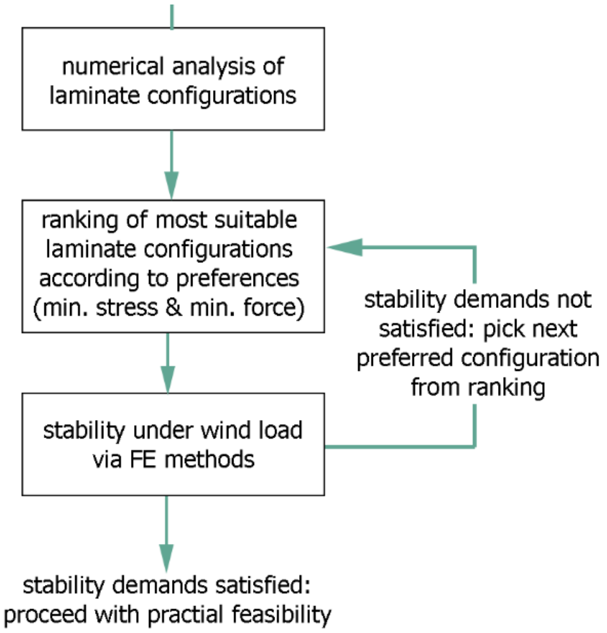


Figure 100 Methodology for determination of most suitable glass laminate configuration

The ranking is created according to the resulting maximum stress differences each variable change has had in comparison to the reference configuration. In chapter 3.4.4. Results – Effects of Changing Variables, these differences are expressed in percentage, with the properties used for the reference configuration forming the basic value. The differences are listed in Table 18.

glass thickness [mm]	**0.85**	**0.55**	**1.1**		
stress difference [%]	-	-24.2	+19.8		
interlayer thickness [mm]	**0.76**	**0.38**	**1.52**		
stress difference [%]	-	-16.2	+32.6		
interlayer type	**E3**	**E1**	**E2**	**E4**	**E5**
stress difference [%]	-	+0.07	+0.05	-0.2	-3.4

Table 18 Stress differences in comparison to reference after each variable change

Using these values, a formula was created in excel that automatically calculated a final value for each configuration and sorted them in ascending order. This way, the "softest" configuration would be listed on top, followed by the others with a stepwise increasing stiffness. The ranking of the test specimens used in the numerical calculations is shown in Table 19. The table also includes the most desirable configuration on top. The first column shows the specimen number as specified in Table 17. The preferred configuration, which is first on the list does not have any specimen number, since it is a combination of the standard configuration. The second column indicates the choice number, which is the position of the configuration in the ranking. The next columns are dedicated to show the glass and interlayer thicknesses, as well as the interlayer type. The last column shows the total value, after which the configurations are ranked. Hereby, a negative final value represents a soft laminate that is the most desirable in terms of stress, while a positive value indicates a stiff one. This table only contains a selected number of configurations. The full list can be found in Appendix 8.

Specimen No.	Choice No.	1st glass thickness t_1 [mm]	interlayer thickness t_2 [mm]	2nd glass thickness t_3 [mm]	interlayer Type p_2	final value [%]	
-	1	0.55	0.38	0.55	E5	-43,8	preferred
1	18	0.55	0.76	0.55	E3	-24,2	
11	24	0.85	0.76	0.55	E3	-17,8	
3	28	0.85	0.38	0.85	E3	-16,2	
10	34	1.1	0.76	0.55	E3	-11,3	
8	41	0.85	0.76	0.85	E5	-3,4	
7	42	0.85	0.76	0.85	E4	-0,2	
0	43	0.85	0.76	0.85	E3	0	reference
6	44	0.85	0.76	0.85	E2	0,05	
5	45	0.85	0.76	0.85	E1	0,07	
9	54	1.1	0.76	0.85	E3	6,5	
2	69	1.1	0.76	1.1	E3	19,8	
4	78	0.85	1.52	0.85	E3	32,6	

Table 19 Ranking of test specimens and most desirable configuration

As can be seen, the first choice is a laminate composed of two thin glass layers of 0.55 mm each, bonded by a 0.38 mm-thick interlayer of the type E5, which is representing an acoustic interlayer. This means that this configuration will be first tested on wind stability in the following chapter.

3.5. Structural Suitability

Now that the most suitable glass laminate configuration has been determined, it can be used to decide which of the three proposed designs is the most favourable in structural terms.

As mentioned in chapter 2.7. Active Bending and Elastic Kinetics, multiple support conditions need to be considered to test the behaviour of each option under the influence of wind load. The reason for this is that in each option, the glass is supported by different means and with different support types. Furthermore, some of the options have additional materials attached to them, such as a metal strip or fabric. In this chapter, for each option, a scenario involving wind load is created that could pose a problem in each specific support and load case. These are presented along with the evaluations respective to their order in chapters 3.2. Design Proposals and 3.3. Practical Feasibility

3.5.1. Support Scenario: Option 1

As presented in chapter 3.3.1. Practical Feasibility: Option 1, the water- and airtightness in this option is provided by a frame composed of four magnet strips (Figure 60). Apart from creating pressure between the glass and the gasket, the magnet also has a holding effect acting against wind suction. This way, the glass will be supported linearly against any kind of large deformation due to external load conditions. This way, the only deformation will occur within the flexibility range of the glass laminate. The four supported edges will not deflect.

To see the effects of this theory, a numerical analysis was created in which a load case for the wind load was implemented. As mentioned in chapter 3.3.1. Practical Feasibility: Option 1, for the wind load, a magnitude of 1 kN/m^2 is assumed for both suction and pressure. In this case, a wind suction is assumed, as it presents the worst case scenario. The glazing will consist of the selected laminate configuration with two glass sheets with a thickness of 0.55 mm bonded by a 0.38 mm-thick acoustic interlayer. The mesh size remains the same with 25 mm. For this analysis, the glass will be tested in the closed condition. Hereby, two scenarios will be tested; a) an unbent straight glazing with no initial curvature and b) the slightly bent version as described in chapter 3.3.1. Practical Feasibility: Option 1 with an initial curvature with a bending radius of 2626 mm. In the following pages, the results are discussed.

a) No initial curvature

The first scenario, namely the one without initial curvature, has the same initial shape and size as the model in chapter 3.4. Glass Laminate Configuration (Figure 101 and Figure 102, left). Also the supports are the same, with the support shown as support A in the same figure being the remote displacement that is movable in the Y-axis and B a simple support, both allowing rotation around the X-axis. The only added support is the rectangular frame (support C) representing the magnet frame. This linear support restrains translations in the lateral direction (Z-axis), while allowing in-plane deformations (X- and Y-axis). The in-plane deformations are made possible due to the possibility of the magnet strip slightly sliding inward under the impact of wind load. Also rotations at this support are allowed, even though it is rather unlikely that a magnet strip of a few centimetres would rotate. However, a slight degree of rotation may still be expected and allowing rotation would be the more conservative choice for the numerical analysis. The wind load (D) is modelled as a linearly increasing pressure and is applied to the entire face of the shell. The pressure graph and its values are shown in Figure 102, right.

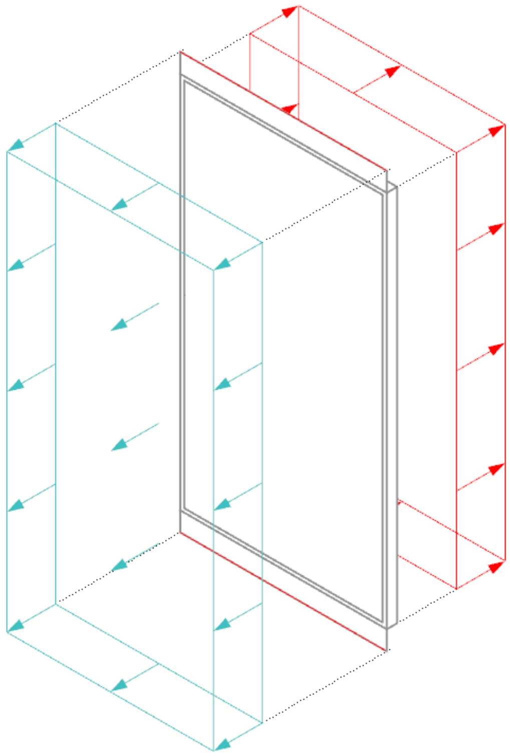
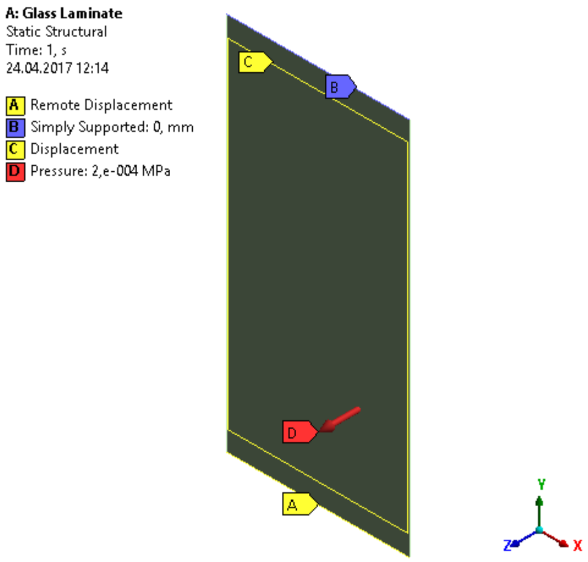
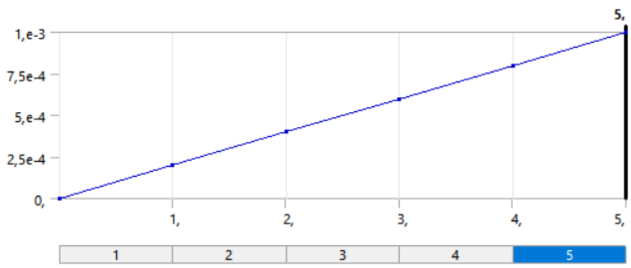


Figure 101 Conceptual illustration of wind and support conditions for a) no curvature





	Steps	Time [s]	X [MPa]	Y [MPa]	Z [MPa]
1	1	0,	0,	0,	0,
2	1	1,	0,	0,	2,e-004
3	2	2,	= 0,	= 0,	4,e-004
4	3	3,	= 0,	= 0,	6,e-004
5	4	4,	= 0,	= 0,	8,e-004
6	5	5,	= 0,	= 0,	1,e-003

Figure 102 Left: support and wind load conditions for a) No initial curvature; top right: linearly increasing wind pressure subdivided into five steps; bottom right: tabular data showing pressure according to direction

The result of interest in this analysis is the deformation in Z-axis, lateral to the plane of the glazing. Figure 103 showcases the outcome of the analysis. As can be seen on the visualizations, the deformation takes place symmetrically, with the maximum being located right in the centre of the glass. The maximum lateral deformation amounts 19.4 mm. The deformed shape in the figure is shown with 10 times the true scale.

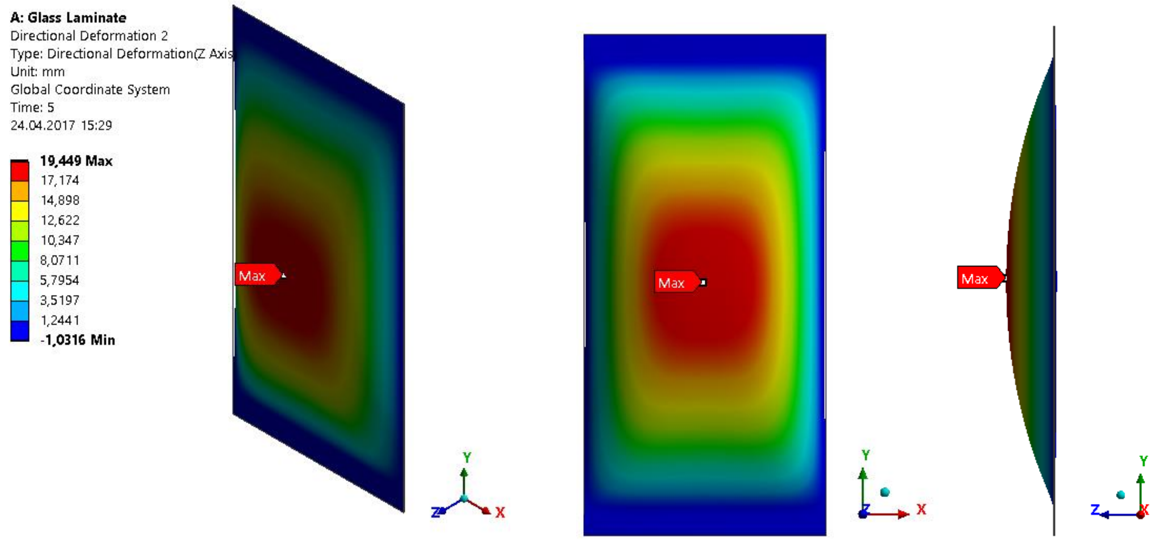


Figure 103 Lateral Deformation of straight glass sheet in Z-Axis under wind load (left: isometric, centre: front view, right: side view, 10 x true scale)

Regarding the maximum stress occurring under the same wind load condition, the maximum appears on the rear side of the glazing right next to the linear supports provided by the magnetic strips. This is due to the abruptly increasing curvature as a result of the wind force directly after the linear support. However, the peak stress amounts to slightly less than 20 MPa, which does not pose any threat regarding the failure of the glass and is therefore negligible.

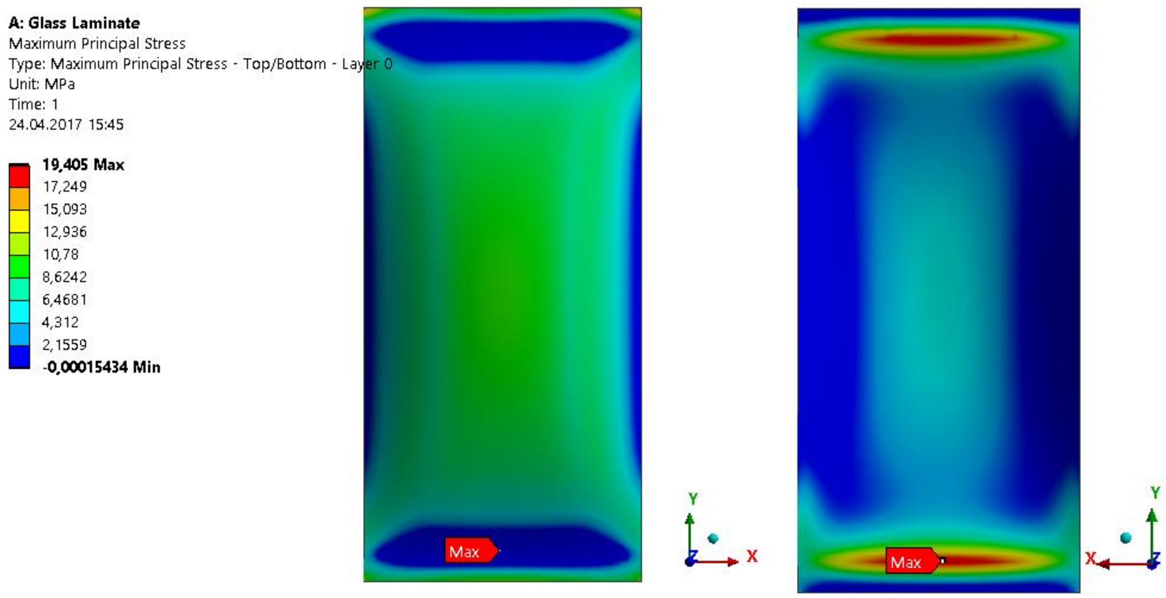


Figure 104 Maximum principal stress under wind load of a) No initial curvature (left: front view, right: rear view)

b) With initial curvature

In this scenario, the same supports and forces are kept as in the first scenario, except that the initial curvature of 2626 mm is added (Figure 105 and Figure 106).

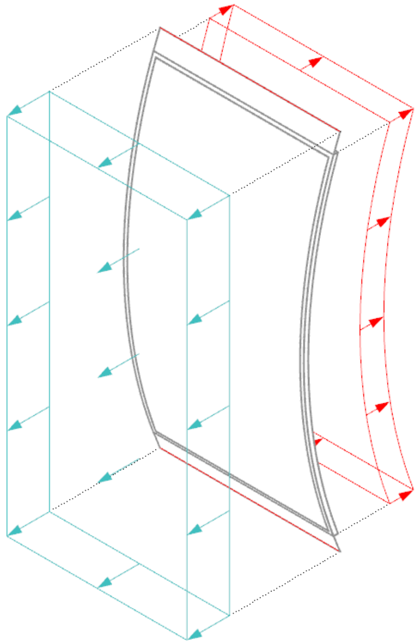
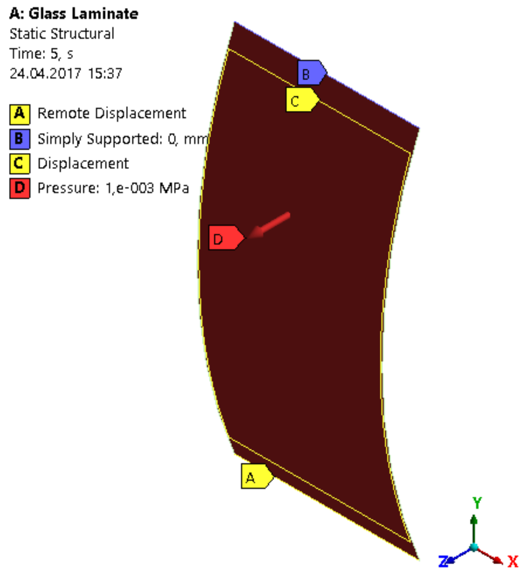
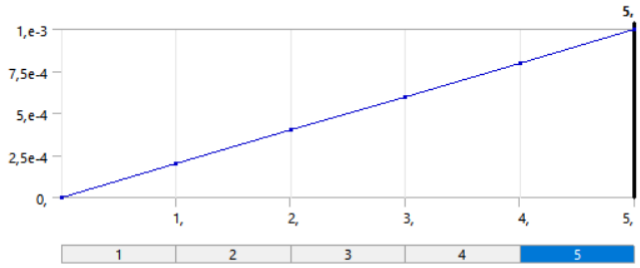


Figure 105 Conceptual illustration of wind and support conditions for b) initial curvature

The result of this analysis shows a much lower maximum deformation in the Z-axis and also in general. The maximum deformation in Z-axis equals 0.15 mm (Figure 107), which shows a drastic decrease in comparison to the straight sheet without initial curvature. It should be mentioned that although the deformation of the curved geometry was expected to be lower, this result appears to come out even lower than the expectations, with only a fraction of a millimetre of deformation. Several attempts were made to investigate whether the results would come closer to the expected values with changed conditions, such as using local coordinate systems that are different at each support due to the curved shape, or even eliminating the magnetic pulling force in the corners of the frame. However, each of these trials resulted in minor differences and sometimes even lowered the value of the resulting deflection. Therefore, whilst the exact magnitude of the resulting values remain arguable, it is still safe to assume that the curved geometry drastically increases the stability of the glass laminate against the impact of wind load. This analysis also shows that, given the magnetic holding force is enough to withstand the suction, this method offers a promising solution for both water- and airtightness and wind stability.





	Steps	Time [s]	X [MPa]	Y [MPa]	Z [MPa]
1	1	0,	0,	0,	0,
2	1	1,	0,	0,	2,e-004
3	2	2,	= 0,	= 0,	4,e-004
4	3	3,	= 0,	= 0,	6,e-004
5	4	4,	= 0,	= 0,	8,e-004
6	5	5,	= 0,	= 0,	1,e-003

Figure 106 Left: support and wind load conditions for b) initial curvature; top right: linearly increasing wind pressure subdivided into five steps; bottom right: tabular data showing pressure according to direction

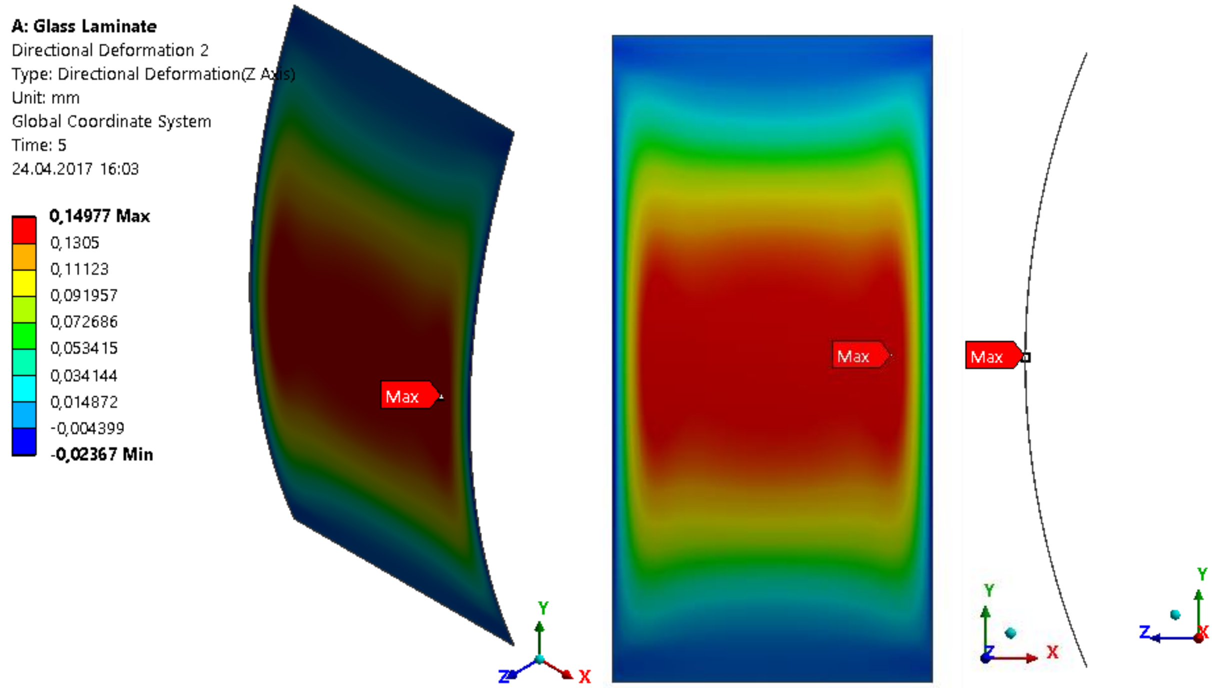


Figure 107 Lateral Deformation of curved glass sheet in Z-Axis under wind load (left: isometric, centre: front view, right: side view, 10 x true scale)

Since the deformations are minimal, locally occurring principle stresses in the corners of the sheet exceeded the global stresses by far with values as low as 4 MPa. Therefore, the illustrations regarding the principal stresses are not included.

Based on these results, it can also be concluded that the preferred glass laminate configuration of 0.55-0.38-0.55 with acoustic interlayer can withstand the wind load and is therefore kept as the final selection.

3.5.2. Support Scenario: Option 2 + Option 3

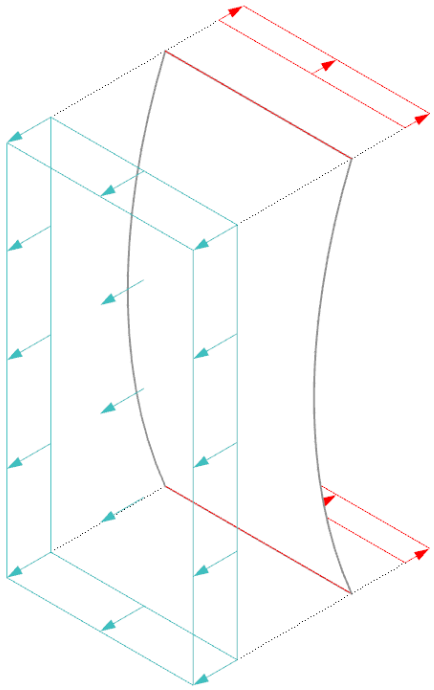


Figure 108 Conceptual illustration of wind and support conditions for Option 2 and Option 3 with no fixation of the shafts

Option 2 and 3 are both expected to possess similar support conditions as both of them do not feature the rectangular magnetic frame to counteract the wind suction and are therefore summarized in a single sub-chapter. The only difference between them is the fabric that is attached to the edges of the glazing in Option 3. However, the tensile force of the stretched fabric is expected to be very low and should therefore make a minimal difference that is negligible. With the glazing resting on gaskets on four edges that act as linear supports, wind pressure is expected to have a similarly minor effect in this case as in Option 1 and is therefore not considered. Wind suction, in contrast, will have a much stronger effect on the glazing in terms of deformation, since the supports on the long edges only act in the other direction. Assuming, no precaution is taken to act against the wind, the load case shown in Figure 108 will apply. As can be seen, the two short edges are only supported against the wind direction, with no support reaction acting up- or downwards. Here it is assumed that the two shafts holding the glass are not secured against movements and can therefore change their position. It is expected that in this case, the thin glass laminate will bend under the suction due to its low stiffness, as it was being bent on purpose for ventilation. A numerical analysis of this situation is made to examine the impact of the wind load on the geometry of the glass laminate without fixation of the shafts. Figure 109 illustrates the deflection under wind suction.

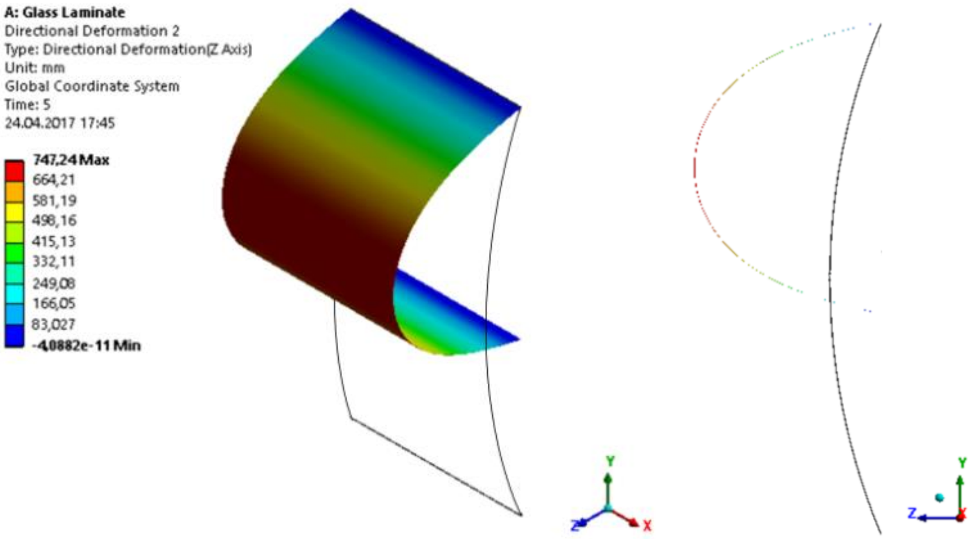


Figure 109 Deformation of Option 2 and Option 3 under wind load without precaution (left: isometric, right: side view, true scale

As can be seen, the shape resembles the same as if the glass was deformed by controlled bending. Under a wind suction of 1 kN/m², the maximum deformation in Z-axis amounts 747 mm. This level of deformation can even lead to failure of the glass. In Figure 110, the resulting principal stress after bending under wind load is shown. The maximum stress equals 246 MPa, which comes quite close to the marginal strength of 260 MPa.

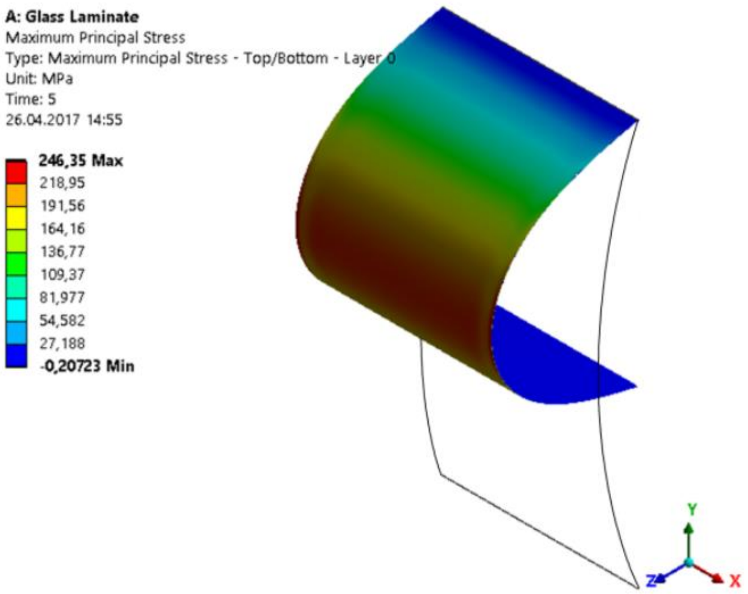


Figure 110 Maximum principal stress of Option 2 and Option 3 after bending under wind load without precaution

The deformation caused by the wind suction can be counteracted by the application of a tensile force to keep the linear supports in position (Figure 112). For this, the two shafts holding the glazing need to be prevented from moving by means of springs or a mechanical device fixing its position. This way, the glazing can be prevented from deforming while in closed condition. To find out the required force to keep the glazing shut under high wind suction, a gradually increasing force in Y-direction was introduced to the two supports at the short edges of the previous analysis. Meanwhile, the wind force of 1 kN/m² will be applied in full from the beginning (Figure 111). The force at the point where the glazing returns to its original shape will be considered as the required force.

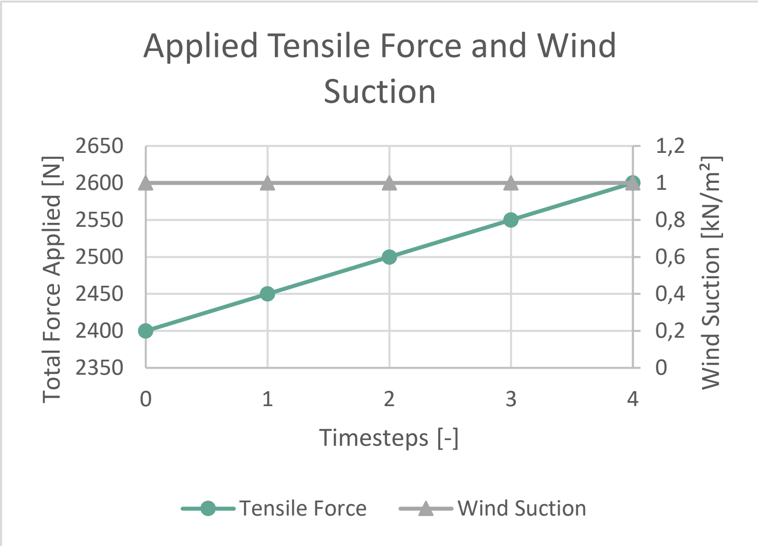


Figure 111 Applied tensile force and wind suction in timesteps

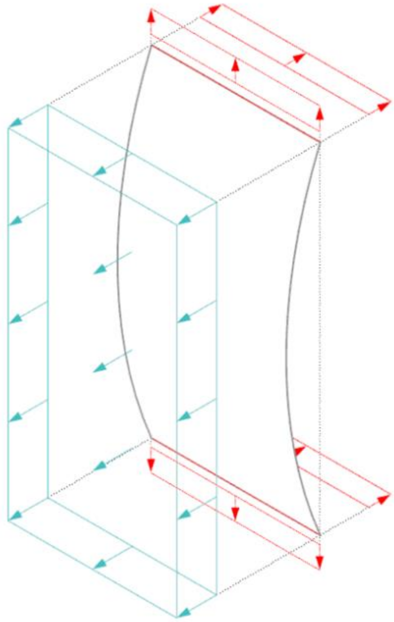


Figure 112 Conceptual illustration of wind and support conditions for Option 2 and Option 3 with fixed shafts

As the movement of the glazing is simulated with only one moving support (Figure 113, support A) with the other one being a simple support that is fixed in Y-direction (support B), the entire force is applied onto support A. In reality, the resulting total force from the numerical analysis would be divided into two separate forces which are applied to each support as shown in Figure 112.

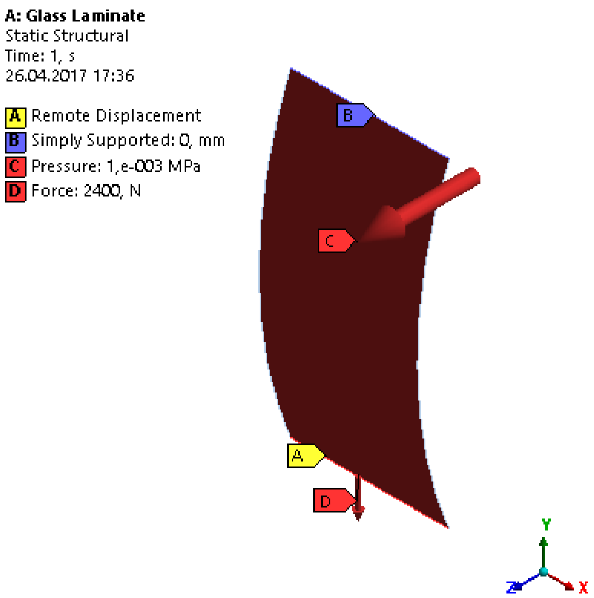


Figure 113 support and wind load conditions for Option 2+3, fixed shaft

The deformation is measured parallel to the y-axis on a node located on support A. The initial starting position of the node is its distance to its original position without the application of any tensile force to support. Following the analysis, the results show that the node reaches its original position at the force magnitude of 2550 N (Figure 114). Converted into kilograms under the influence of gravity, this amounts to 260 kg, which demonstrates how large the required amount of force is. This raises the question, whether the springs or other mechanical devices are strong enough to withstand that load and how long their lifetime will be. Additionally, when divided into the two supports, the force equals to 1275 N for each support. As the force would be applied to each end of the shaft, the shaft would act as a simple beam, which can result in a high deflection, which could create an unpleasant view or even damage the glass.

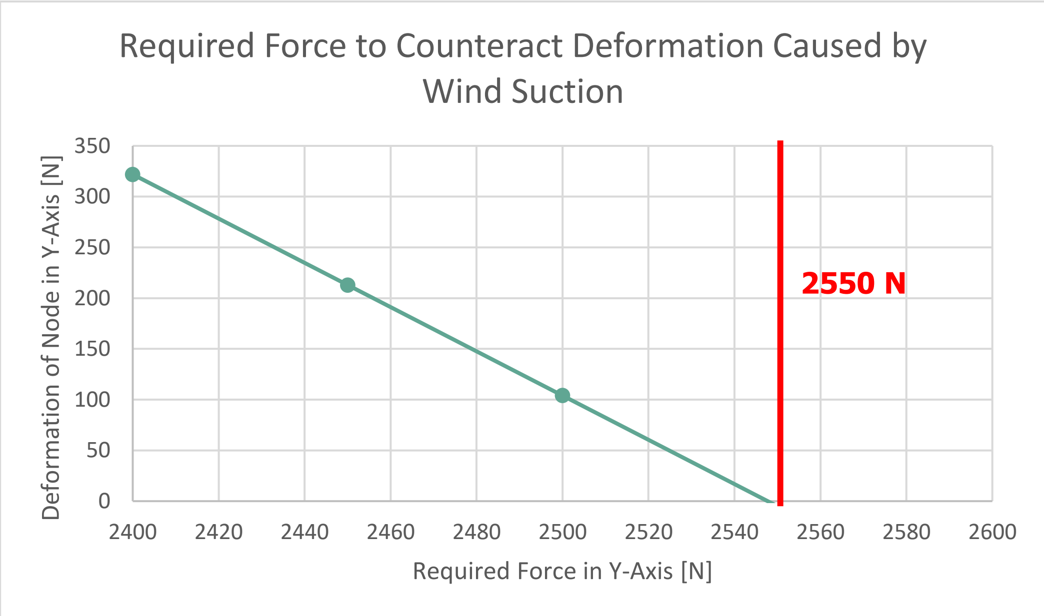


Figure 114 Required force to counteract deformation caused by wind suction

3.6. Conclusions and Selection of the Design

Based on all the findings made in chapters 3.3. Practical Feasibility and 3.5. Structural Suitability, which are related to the practical feasibility and structural suitability of each proposal respectively, a final conclusion can be made and one of the three proposals can be selected for further elaboration. The pros and cons mentioned in those chapters are summarized in Table 20 for a better overview. In this sub-chapter, the pros and cons will be briefly discussed and the selection be made based on the arguments.

At first glance, Option 1 stands out with the little amount of negative aspects in both parts. The most prominent negative aspect is arguably the additionally required horizontal frames, which however, only have an impact on the optics with no negative effect on the structural behaviour. One possible challenge might be the abrupt opening movement of the window that may be caused due to the magnetic holding force acting upon the magnetic strip, which is suddenly released at a certain distance. This may, however, be solved by the use of a switchable magnet or an additional pushing device in the middle of the frame to help opening the window more smoothly. In contrast, the magnet offers a number of perks, such as providing enough pulling force for both, wind stability and water- and airtightness.

The most important positive aspect of Option 2 in comparison to the first one is the possibility for a simpler gasket design, since it does not require the involvement of a magnet into the gasket. However, this option comes with many disadvantages, such as unequally distributed pressure between the gasket and the glazing and extra forces required on the shafts to keep the water- and airtightness, while not eliminating the two horizontal frames of the first option. Therefore, this option seems less advantageous in comparison to Option 1 and will be eliminated.

Option 3 offers the advantage of permanently sealing the bent edges, which eliminates what proved to be the main challenge of the design. However, it seems that this remains as the only advantage, while it brings many disadvantages with it. First of all, the permanently sealed edges drastically reduce the ventilation gap, which forces the glass to be bent with a stronger curvature for ventilation. Furthermore, it leads to leakages in the corners, which is complicated to solve. Another concern is the fabrics elasticity and its possible abrasion due to overstretching. Besides, the fabric can cause an obstruction of the view from the inside. Weighing out the pros and cons of this option, it also does not seem to offer the most suitable solution for the aimed product and is therefore taken out of consideration.

The elimination of Option 2 and Option 3 leaves the first option as the only alternative. This alternative offers a promising prospect towards achieving the goals, if the mentioned obstacles can be overcome. The further elaboration will be focused on Option 1, which is described in the following chapter.

	Option 1		Option 2		Option 3	
	+	-	+	-	+	-
practical feasibility	o magnet can provide enough pulling force for water- airtightness o magnet pulling force adjustable	o additional horizontal frames required o abrupt opening movement due to magnetic holding force (only if permanent magnet)	o simple gasket detail possible	o unequally distributed pressure o additional horizontal frames required o extra force required to keep water- and airtight	o bent edges permanently sealed	o limited ventilation gap o leakage at corners o possible abrasion of fabric due to over-stretching o obstruction of view
structural suitability	o magnetic pulling force can also be used against wind suction			o large force required to keep glazing shut o applied force may result in bending of shafts		o large force required to keep glazing shut o applied force may result in bending of shafts o fabric may pull back edges of glazing with tendency to return to original length

Table 20 Pros and cons of each proposal based on practical feasibility and structural suitability

3.7. Elaboration of Selected Design

In this chapter, the focus will lie on the elaboration of the selected design option, which has been referred to as Option 1 so far. The chapter is subdivided into a number of sub-chapters, each dedicated to a certain aspect that is crucial for the design.

As the design is closely related to the principle of the magnet, the first sub-chapter is dedicated to the selection of the magnet type and the description of its mode of operation. This chapter also includes the gasket design, since both of the designs are closely related to each other and need to be planned simultaneously.

The second sub-chapter explains the mode of operation in terms of kinetics and which products come to use during this process.

The third sub-chapter describes the façade type, including the profile design resulting from the necessities and their influence on the profile shape.

Subsequently, the chapter is rounded off with final technical detail drawings and 3D-illustrations, as well as pictures of the final mock-up.

3.7.1. Magnet-Gasket Design

In chapter 3.3.1. Practical Feasibility: Option 1, some initial presumptions were made regarding the sufficiency of the magnetic force to withstand the wind suction. To sum it up shortly, a wind suction of 1 kN/m² was assumed, which equalled a total of 2 kN on the whole glass surface. The length of the entire magnet frame was approximated to 5.6 m, which would require the magnet to have a holding force of around 0.36 N/mm. The conclusion was that this force could be easily reached. However, several principles exist for magnets. These include permanent magnets, electromagnets, mechanically switchable magnets and electro-permanent magnets. The description for each of these can be found in Appendix 9.

Comparing these principles, the disadvantages of permanent magnets are already mentioned in 3.3.1. Practical Feasibility: Option 1. These included an obstruction of the movement of the glass, possibly an abrupt opening movement and an additionally required force from the actuators for opening the window. Considering these aspects, the permanent magnet remains as a last resort option amongst the principles.

Mechanically switchable magnets offer the option to interrupt the magnetic flux temporarily by activating a mechanical switch. This interruption can be used to switch off the force, each time the window is to be opened. This will prevent the abrupt movement and enable the window to open smoothly, while reducing the required bending force, thus reducing the required performance of the actuators. However, for small-scale applications, mechanically switchable permanent magnets are found to be too bulky and expensive (Knaian, 2010). Besides, their application in form of long strips proves very difficult as they need space for the switches and not to mention inconvenient, since each strip would need its own switch. Furthermore, the curved geometry additionally hinders the feasibility. These arguments make the switchable permanent magnet a less desirable option compared to the permanent magnet and is therefore not considered any further.

In contrast, electromagnets offer a better option, as they can be much thinner and can be executed in form of long strips, as desired for this design. Its execution as a curved frame is also possible, since the entire frame can be switched on and off with a single switch. However, the electromagnet also has its own drawbacks;

"Traditionally, electromagnetic force has three disadvantages at small scales: the need for specialized materials, the need for high-density coiled geometries, and low ratios of force to static power consumption due to the unfavorable scaling of coil resistance in small devices." (Knaian, 2010).

As a certain force is required for stability and given the low ratio of force to static power consumption, this option tends to be less favourable for this application. To maintain the pulling force, a constant flow of electricity needs to be present during the time in which the window is shut. As the window is anticipated to be shut a much longer time than it is opened, this solution would result in a high electricity consumption rate, not to mention the fact that their holding force is much lower than those of permanent magnets.

Electro-permanent magnets can be regarded as a combination of the permanent- and electromagnets. They do not require a permanent electric current for either, the closed or the open condition. The power is only needed once for the switching, which can be as short as a fraction of a second ("Switchable Magnets Explained", 2013). This short current flow will change the two poles of the permanent magnet with lower coercivity, thus steering the magnetic flux towards the two poles of the horseshoe in the "ON" condition, or diverting it away from them in the "OFF" condition (Figure 115).

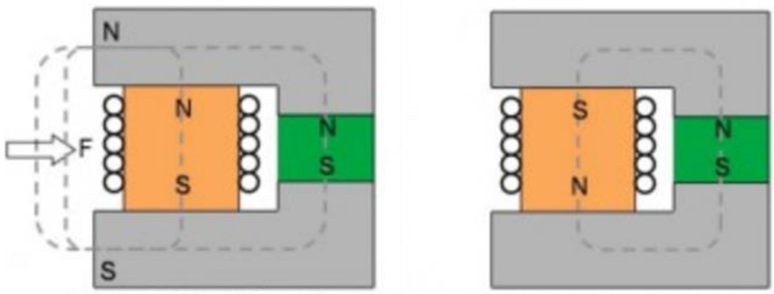
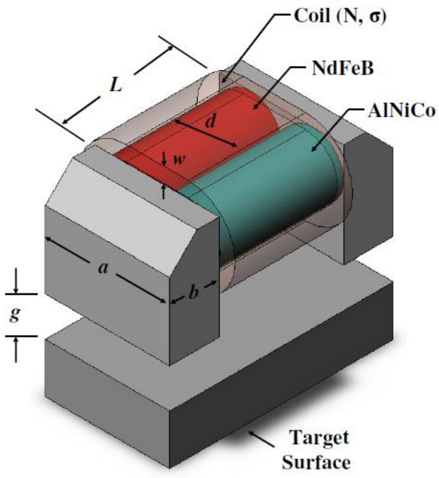


Figure 115 Magnetic flux (dashed line) in a switchable magnet when switched on (top) and off (bottom). Permanent magnet with low coercivity shown in orange with coil wrapped around it ("Switchable Magnets Explained", 2013).

Different configurations are possible within this principle. The coil can be only wrapped around the low coercive magnet with the magnet with higher coercivity is located between the two ferromagnetic materials building the horseshoe as shown in Figure 115. Another option is to place both magnets between the steel parts and wrap the coil around both of them. Since the magnets are made of different materials, one being low coercive, changing its two poles with a low amount of electricity and one high coercive, keeping its pole configuration under the same amount of



	Coercivity	Residual Induction
Grade N40 NIB	1000 kA/m	1.28 T
Sintered Alnico 5	48 kA/m	1.26 T

Figure 116 Switchable electro-permanent magnet construction (top), magnetic properties of NIB and AlNiCo (bottom), (Knaian, 2013)

electricity (Figure 116, top). A good material combination for the magnets is a composition of Neodymium (NdFeB), which is a very strong magnet with a high coercivity and AlNiCo, which is a weaker magnet with a relatively low coercivity (Figure 116, bottom). Thereby, the only purpose of AlNiCo is to switch the poles of the magnet and not to provide any holding force.

As mentioned earlier, only a very short period of voltage is required to achieve a permanent holding force. The force then experiences a sharp incline, which then stabilizes and stays more or less constant, while the velocity slightly increases over time. Once switched off, again a sharp decline appears in the force, with the same voltage required for switching (Figure 117).

This alternative enables the construction of a relatively narrow design with an extremely high holding force. An example of a miniature electro-permanent magnet is shown in Figure 118. The magnet, which is only 3.2 mm long can hold 4.4 N, which is over 2000 times its own weight, switches with a 5 mJ electrical pulse, and holds its state with zero power (Knaian, 2013).

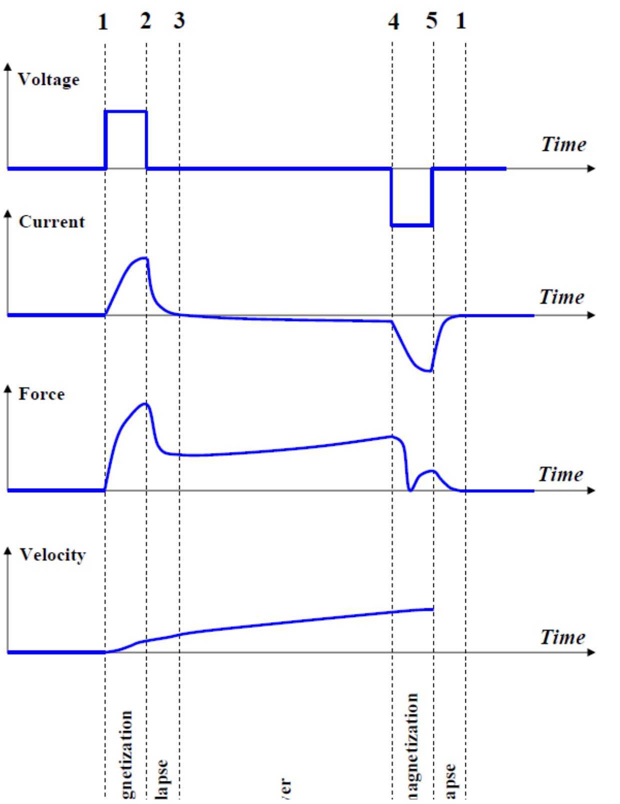


Figure 117 Electro-permanent actuator power variables versus time (Knaian, 2013)

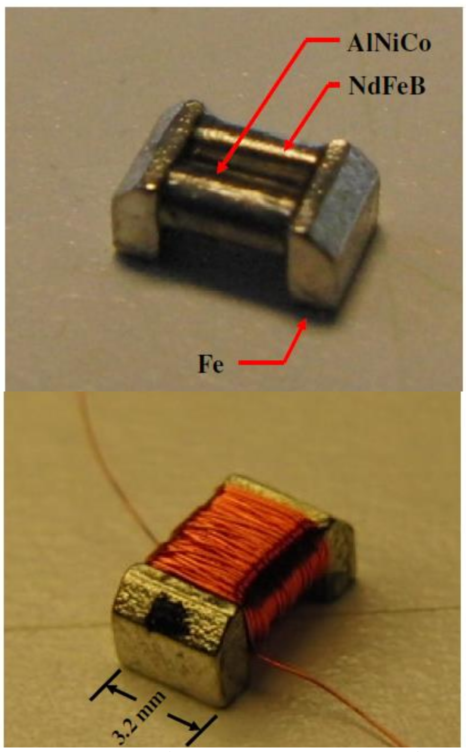


Figure 118 Miniature electropermanent magnet. This magnet is made from cylindrical rods of hard NIB, semi-hard Alnico, iron pole pieces, and a copper wire coil.

A similar product is offered in the market by ThyssenKrupp Magnettechnik (Figure 119). While this design requires a slightly higher thickness than the principle described earlier, it can create stronger magnetic fluxes, which is more preferable in this case. Besides, small sizes are still possible with this configuration. The smallest standard size has a width of 30 mm and a thickness of 25 mm. However, smaller sizes are possible, with the limit of 20 mm width. This size is needed for the steel parts, the permanent magnets and the coils. The length of the magnet can go up to 1000 mm, where it needs to be interrupted by a gap of about 20 mm for the coils. According to the manufacturer, a holding force of 4.6 N/mm is possible with a width of 30 mm, which is more than ten times of the required 0.36 N/mm. Thus, the width can be reduced to 20 mm to allow a narrower gasket design. The ultimate magnet design along with its dimensions is shown in Figure 120 and a 3D-illustration in Figure 121.

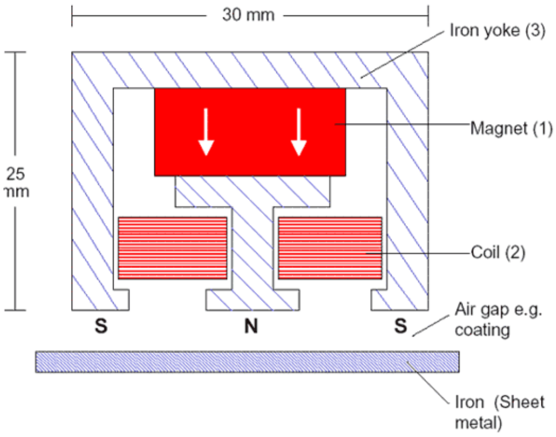


Figure 119 Configuration of an electrically settable permanent magnet strip ("Permanent magnetic strips -/ walking beams", 2014.)

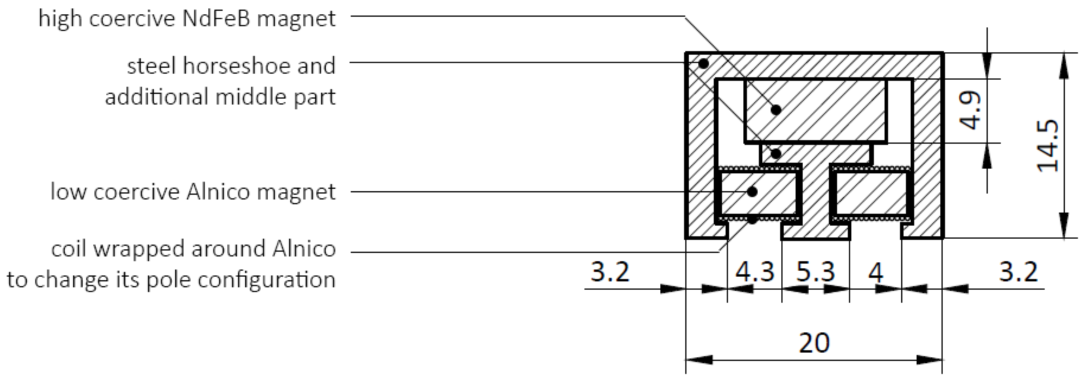


Figure 120 Final magnet dimensions and description of its components

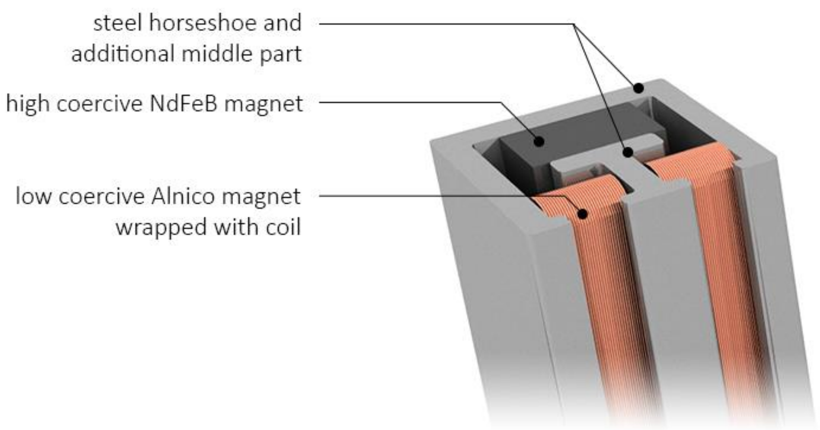
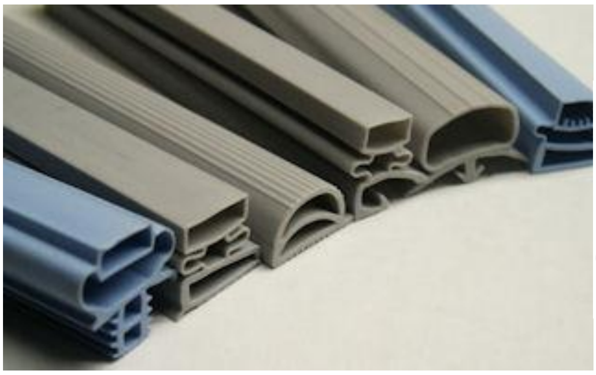


Figure 121 3D-illustration of the magnet strip. The steel horseshoe and the magnets run continiously in a curved line for 1 metre. The coil is wrapped around the low coercive Alnico magnets. The magnet strip needs to be interrupted every metre for the wires leading to the coils for about 20 mm.

There are some factors that influence the holding force of the magnet, apart from the strength of the permanent magnets and the number of turns of the coil. One of these is the thickness of the object of attraction, which in this case is the metal strip attached to the glazing. The thinner the material, the earlier it will be saturated and will therefore provide a lower holding force. Therefore, an application such as a metal coating on the glass does not seem to be feasible. However, a thin metal strip would be enough to provide enough holding force for this application. As it is outside of the scope of this thesis, the calculation to find the exact required thickness of the metal strip will not be performed and the thickness of the metal strip will be set as 1 mm, which is assumed to be on the safe side.

Another influencing factor on the holding force is the distance between the poles of the magnet and the object of attraction. In the case of this design, the distance will be created by the gasket, as the magnet will be placed inside it and will therefore be covered by EPDM rubber. As this material does not block magnetic fluxes, its thickness can be considered the same as an air gap of the same distance. The design of the gasket itself will be strongly influenced by those of refrigerators, since they operate with magnetic force and have proven reliable for decades in terms of airtightness. For the watertightness, it can act as a first line of defence, which is the requirement of the intended design, as it is the outer skin of a double-skin façade, which is not expected to provide total watertightness. There are a vast number of custom gasket cross-section shapes, each designed for their specific purpose (Figure 122). However, in general, all the magnetic gaskets follow the same principle. They consist of a rectangular chamber to house the magnet, a soft chamber to damp the pressure, one or two flanges that rest on a surface, which is the refrigerator door in this case, and in case of a dart gasket, they also comprise a dart to be placed into the door profile (Figure 123). The gasket designed for the façade will follow a similar principle, with each of the mentioned partitions to be customized to fit into the design.



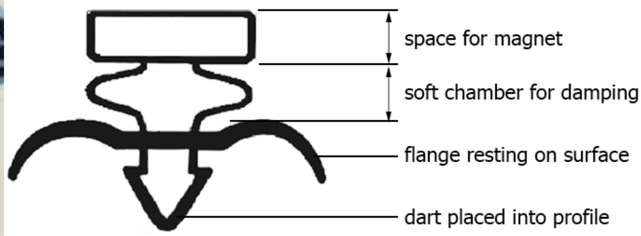


Figure 122 Variety of refrigerator gaskets (www.easterngasket.com) Figure 123 Typical refrigerator gasket design (www.dgk-gmbh.com)

The rectangular space for the magnet of a common refrigerator gasket is obviously too small to fit in an electro-permanent magnet. Therefore, the first customization will take place at this part by being enlarged to create enough space for the magnet. The findings made during the profile design, which will be discussed in 3.7.3. Façade Type and Profile Design, suggest that a symmetric gasket would not fit the detail. Therefore, an asymmetric gasket design is essential. This will be carried out, while keeping the main principles of the refrigerator gasket. The aspects that are changed will be mainly based on eliminating the flange on one side of the dart and add an additional supporting profile on the other side. Furthermore, just as it was done for the rectangular chamber, the dimension of the chamber also needs to be fitted to the aluminium profile. The cross section of the final gasket design along with its dimensions and description of each component is shown in Figure 124. A 3D-illustration of the gasket including the magnet is shown in Figure 125.

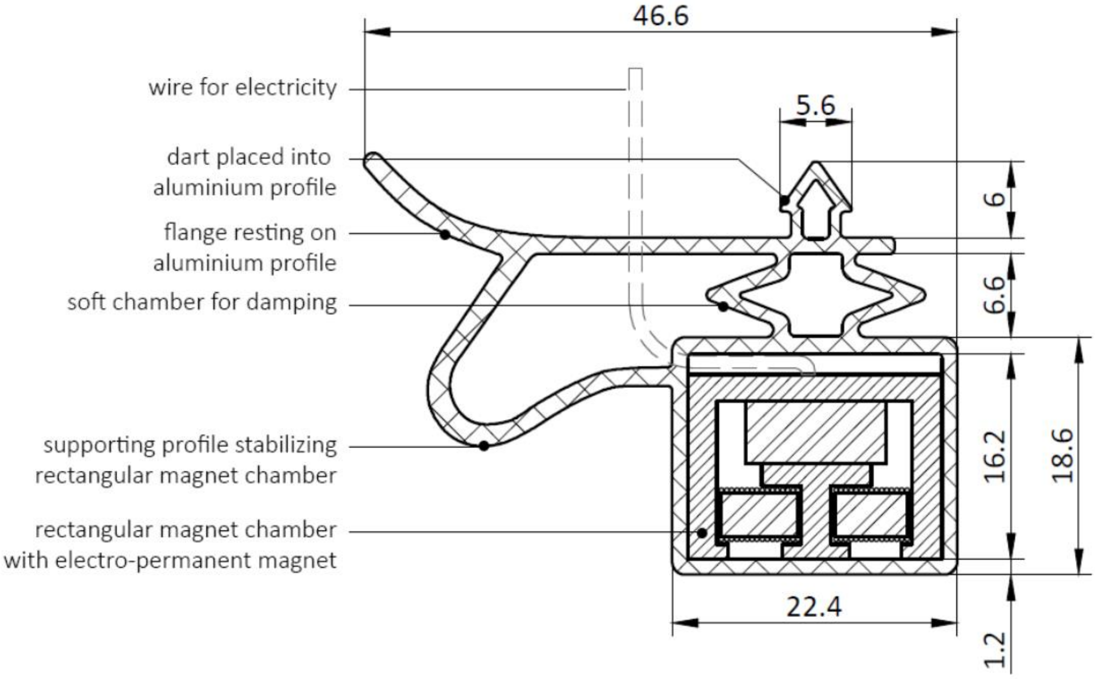


Figure 124 Final gasket design with dimensions and description of each component

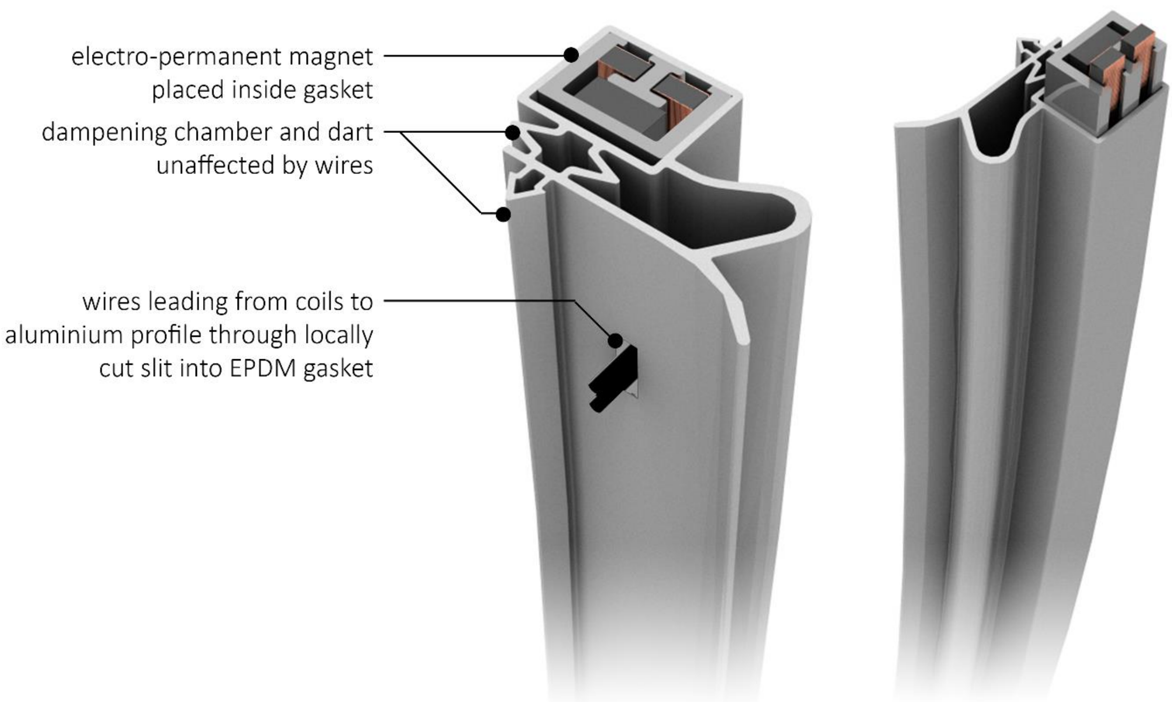


Figure 125 Left: 3D-illustration of gasket at midpoint (wire connection), right: front isometric view

3.7.2. Mode of Operation – Kinetics

In chapter 2.7. Active Bending and Elastic Kinetics the method to be applied in terms of kinetic behaviour was explained. As described in the mentioned chapter, this involves the principle of active bending, in which a simple linear movement can be transformed into a two-dimensional movement, while keeping the required number of mechanical parts and joints to handle the translation and bending at a low quantity. In this chapter, the components that facilitate the movement and the role they play during the process of active bending will be described.

Since the glass will be bent by a movement from both short edges, the number of each required component will be doubled. However, their detailing, mode of operation and therefore also the manufacturing will remain the same, which keeps the method simple. The system is comprised of four major components; a linear actuator to trigger the movement, a rail including the corresponding slider to guide the linear movement, a bearing to enable rotation and a shaft to support the glazing.

The first mentioned component, the actuator's task is to trigger the linear movement. Although the bending can also be carried out mechanically, the use of an electrically controlled actuator will increase the convenience of opening and closing the window, while enabling the synchronisation the movement of multiple windows at once. Linear actuators are available in several sizes and for several types of use. This way a fitting product can be selected for every design. Figure 126 shows an example of a compact model by the manufacturer SKF. As an alternative, rails with integrated actuators are also available. However, the standard ones available in the market tend to be too bulky and aesthetically unappealing, as they are generally meant for use in the production industry.

Figure 126 Linear actuator SKF CAHB-10 (skf.com)

The rail system to be used is the X-Rail product by Rollon. It contains a stainless steel plate on linear roller bearings placed into a stainless steel guide (Figure 127). The standard length of the manufactured steel plate is 71 mm with three rollers. As this length is too much for the intended use, it needed to be customized to create a steel plate with a smaller length. Therefore, one of the rollers was eliminated and the steel plate shortened to 52 mm (Figure 129). An even shorter plate would normally be more beneficial, however, to maintain the stability, at least two rollers are kept. The cross-sectional dimensions are kept as they were (Figure 128).

Figure 127 Linear rail system to be used (rollon.com)

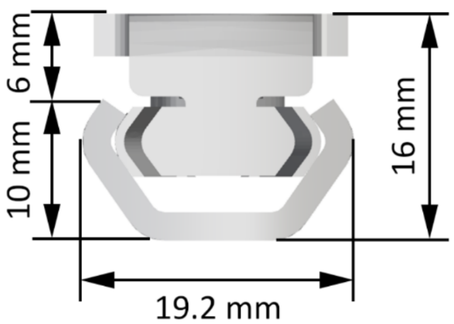


Figure 128 Cross section of rail system

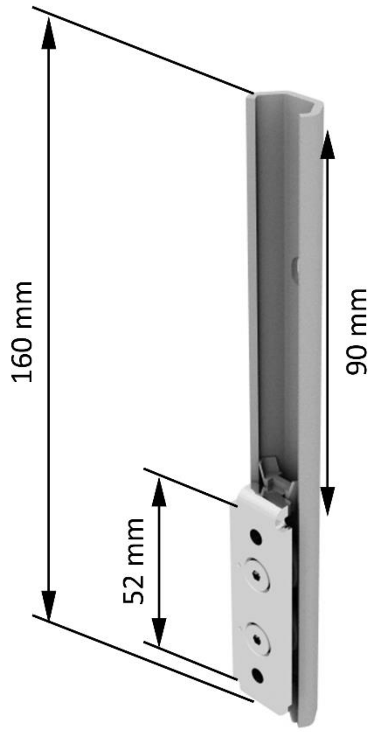


Figure 129 3D-illustration of customized rail system

The laminated thin glass pane will be supported on its both short edges by a stainless steel shaft. Its cross section and dimensions are customized to fit to the total thickness of the laminate as well as to have enough stiffness to prevent large deformations over its length (Figure 130). The glass laminate will be clamped inside the cylindrical shaft and the joint will be sealed with gaskets on both sides to prevent leakages. The shaft's length is 1032 mm, 32 mm wider than the glazing. The reason for this is that the shaft's two ends will be inserted inside the bearing and therefore need to be 16 mm longer on each side (Figure 131).

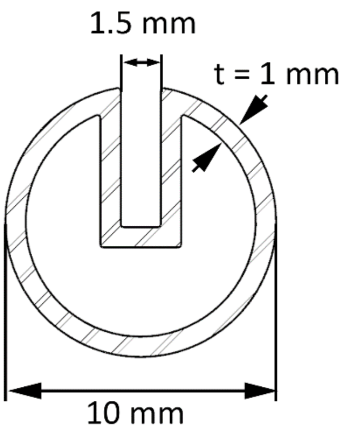


Figure 130 Cross section of steel shaft

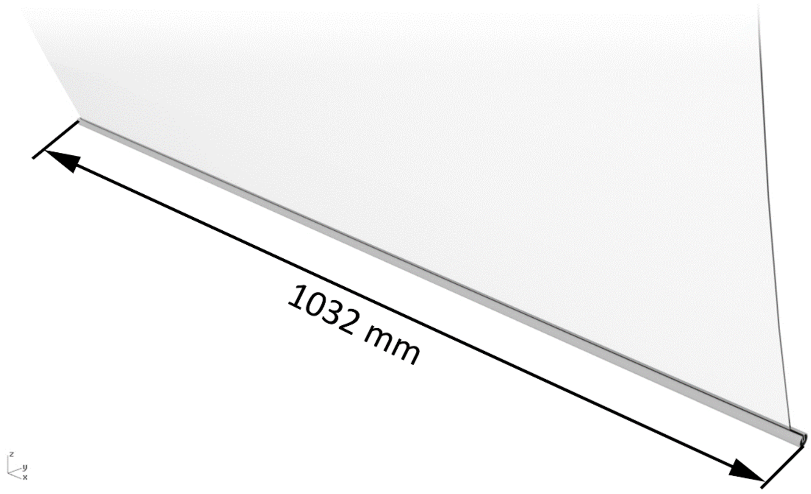


Figure 131 Thin glass laminate clamped into stainless steel shaft

To enable rotation of the shaft, a bearing needs to be placed between the steel plate of the rail and the shaft itself. The bearings size will be the same as that of the steel plate and will have a thickness of 15 mm. It will comprise a hole, the size of the shaft with some tolerance to keep the friction during the rotation at a minimum. An illustration of the bearing is shown in Figure 132.

Making use of the active bending principle, when all the components are put together, they facilitate an active bending movement of the glazing with only one linear motion provided by a linear actuator, which is supported by a rotation that follows automatically. Figure 133 demonstrates an exploded view of the required components for the kinetic behaviour.

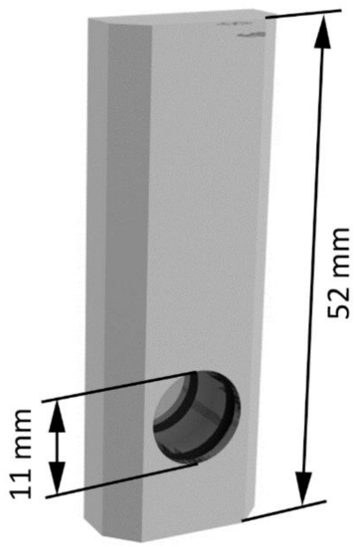


Figure 132 Steel bearing

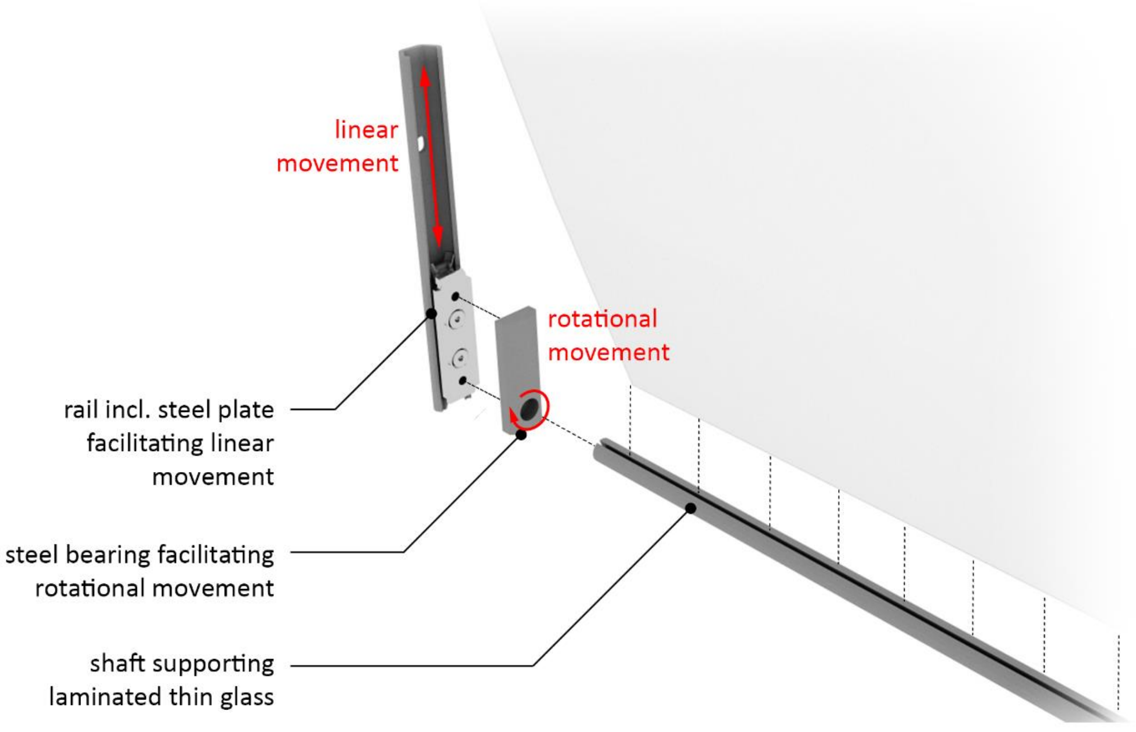


Figure 133 Exploded view of components facilitating active bending

3.7.3. Façade Type and Profile Design

The façade panels are meant to be prefabricated and transported to the site as a finished product. This is necessary because of two reasons; the first reason is that the panel contains many components that need to be fixed into place accurately, as, due to the kinetic property, tolerances are low at some parts of the panel. The best conditions to achieve that amount of accuracy exist in the workshop, as installation on site can be more demanding due to weather conditions and inconvenient positioning during the installation process. The second reason is that the thin glass needs to be treated carefully due to being fragile. Even though chemically treated glass is tougher than regular heat-treated glass, careless treatment on site can cause damages on its surface that may have larger consequences over time. Thus, installation of the single components in the workshop is safer for the glass.

The façade profiles are therefore based on those of standard unitised systems. As a starting point, the USC 65 product by Schüco is adopted (Figure 134, Appendix 10). Since the design in progress is more complex than a regular unitised system, the façade profiles need to be customised. The aspects that distinguish the planned design from regular designs are numerous. In this chapter, the single steps taken in order to create a customised profile as required by the design will be explained.

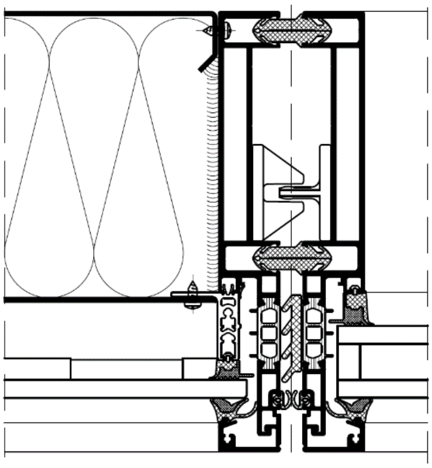


Figure 134 USC 65 unitised facade profile by Schüco

The first and most obvious distinguishing aspect is that the regular glazing units that are clamped between gaskets in standard systems need to be replaced by a single thin glass sheet, which will one-sidedly rest on the gasket presented in chapter 3.7.1. Magnet-Gasket Design. For this, the second gasket, which is placed outside, will be eliminated. Besides, since this design does not have any requirements towards thermal or acoustic insulation, the insulating components will be removed. However, the remaining gasket on the inside will be replaced by a larger gasket incorporating the switchable magnet and will therefore own a larger thickness. Thus, the length of the aluminium profile will be adjusted to fit the design. Another difference is undoubtedly the kinetic property that is integrated into the design. The kinetic movement requires additional components, such as an actuator, a rail and a bearing. This means that the profile shape needs to be customised in order to

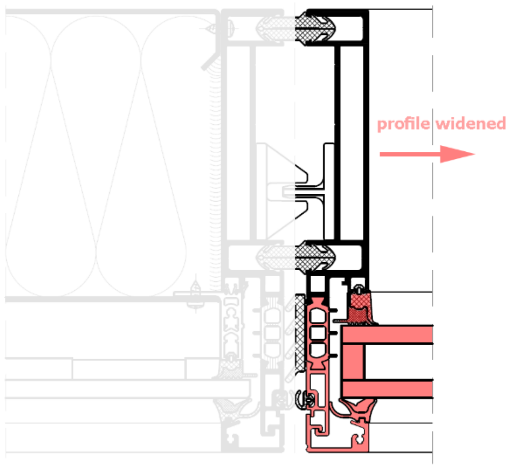


Figure 135 Changes made to standard profile (red: eliminated/replaced parts)

be able to harbour the mentioned components. As a result, the aluminium profile will be widened to offer enough space to those components and the magnetic gasket. Following the changes made, what remains from the standard profile is the structural aluminium component, increased in width. The undertaken changes are shown in Figure 135.

One more additional feature is the curvature the profile needs to own in order to lend stiffness to the glazing through geometry. Therefore, the vertical profiles cannot possess the same cross-section throughout the entire height of the panel. With the glazing having a radius of 2626 mm in closed positon, the front face of the vertical frames need to be offset forward in the centre with a distance of almost 200 mm compared to the bottom and the top. Thus an additional curved profile, where the magnetic gasket will be placed, needs to be attached to the extruded vertical aluminium profile (Figure 136).

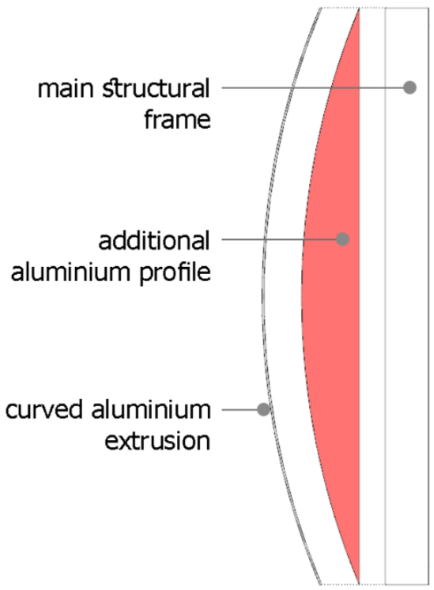


Figure 136 Additional curved profile

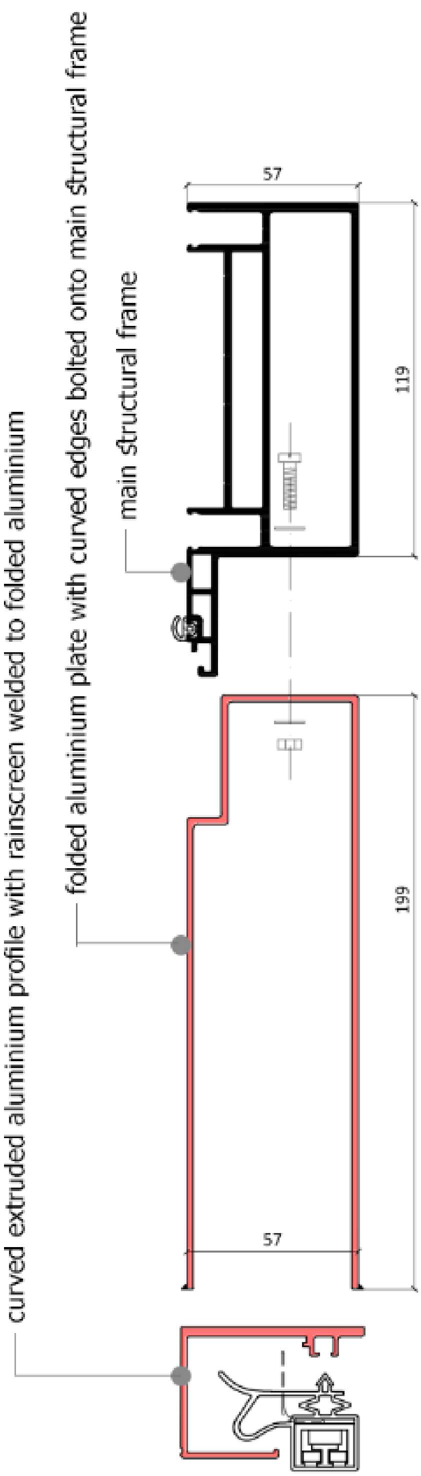


Figure 137 Assembly of vertical profile components shown in a horizontal section in the centre of the profile

The additional vertical curved element will be fixed to the main frame with six bolts throughout the height of the profiles. As the element will be curved at the front face, where special provisions must be taken to attach the magnet, this raises the question how it will be manufactured. The solution lies within manufacturing the extension and the front part separately, and weld them together before fixing them to the main frame. The assembly of the single components of the vertical profile is illustrated in Figure 137.

The last additional feature concerns the addition of two extra transoms to support the magnetic gaskets that have a 20 cm distance from the horizontal profiles of the main structural frame (Figure 138). This gap will also be utilised to create a water- and airtight barrier, since this space is outside the rectangle, the gasket encloses and because there is no provision taken for water- and airtightness, where the shaft meets the frame. The complication related to this matter was described earlier in chapter 3.3.1. Practical Feasibility: Option 1. To close the gap, an aluminium plate will be screwed to the main frame on one side and the additional transom on the other (Figure 139).

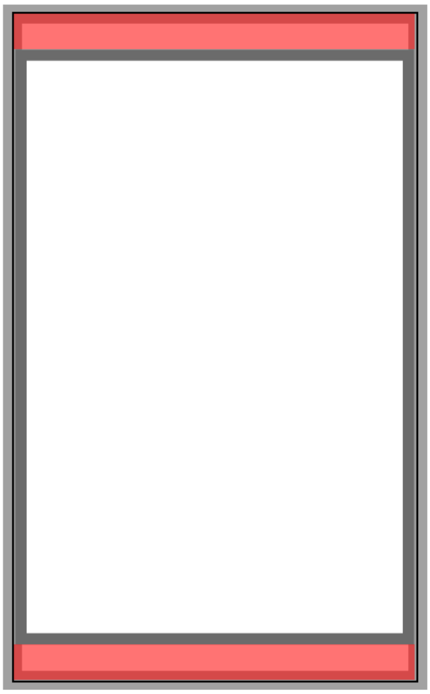


Figure 138 Gaps that need to be covered

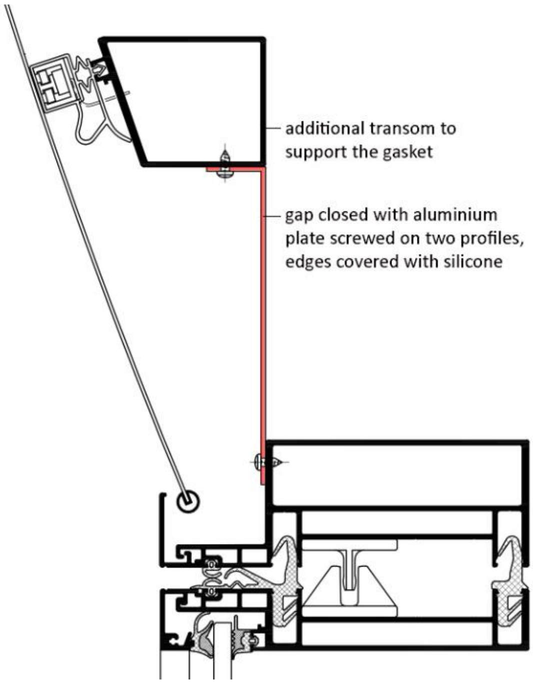
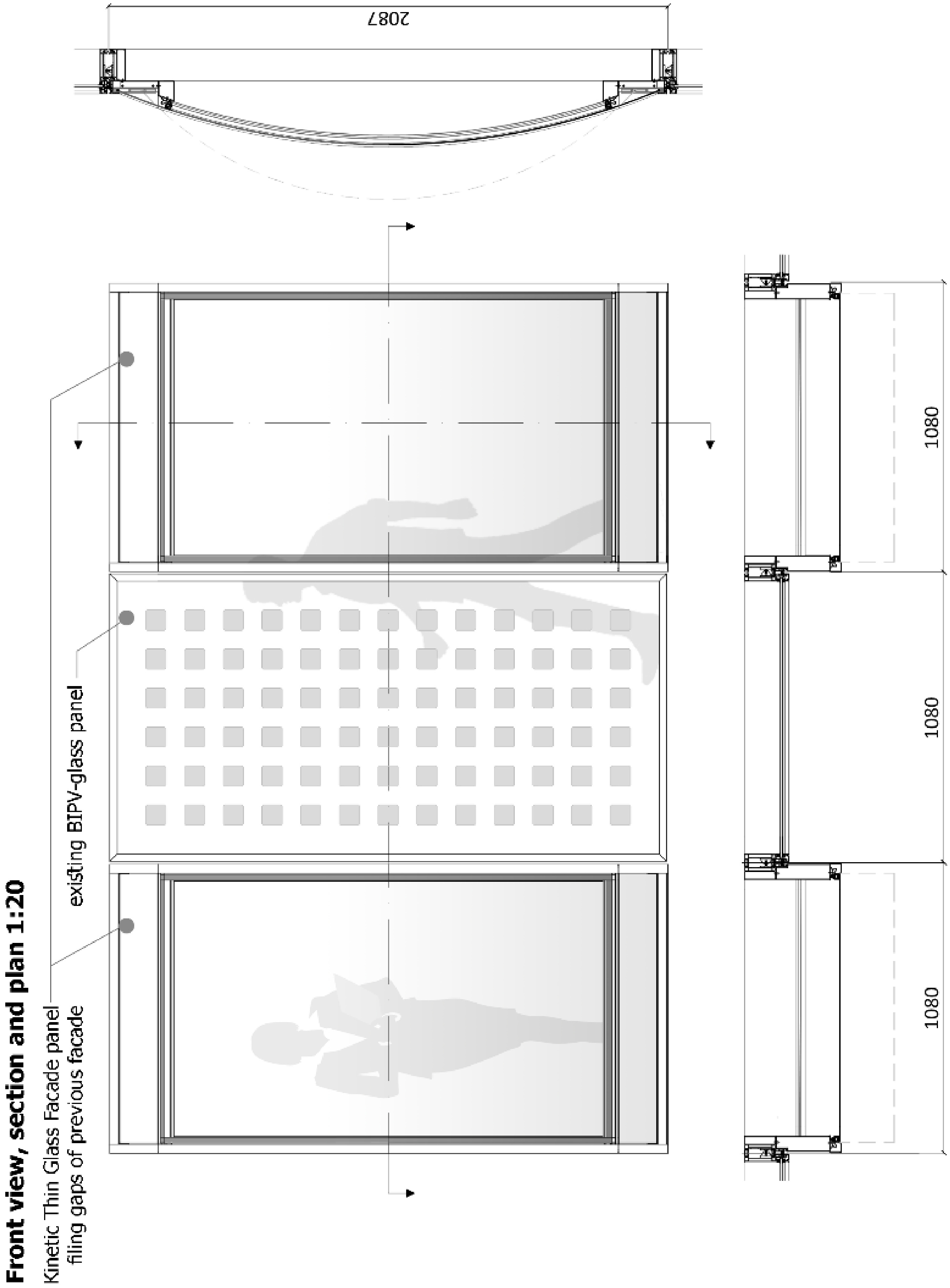
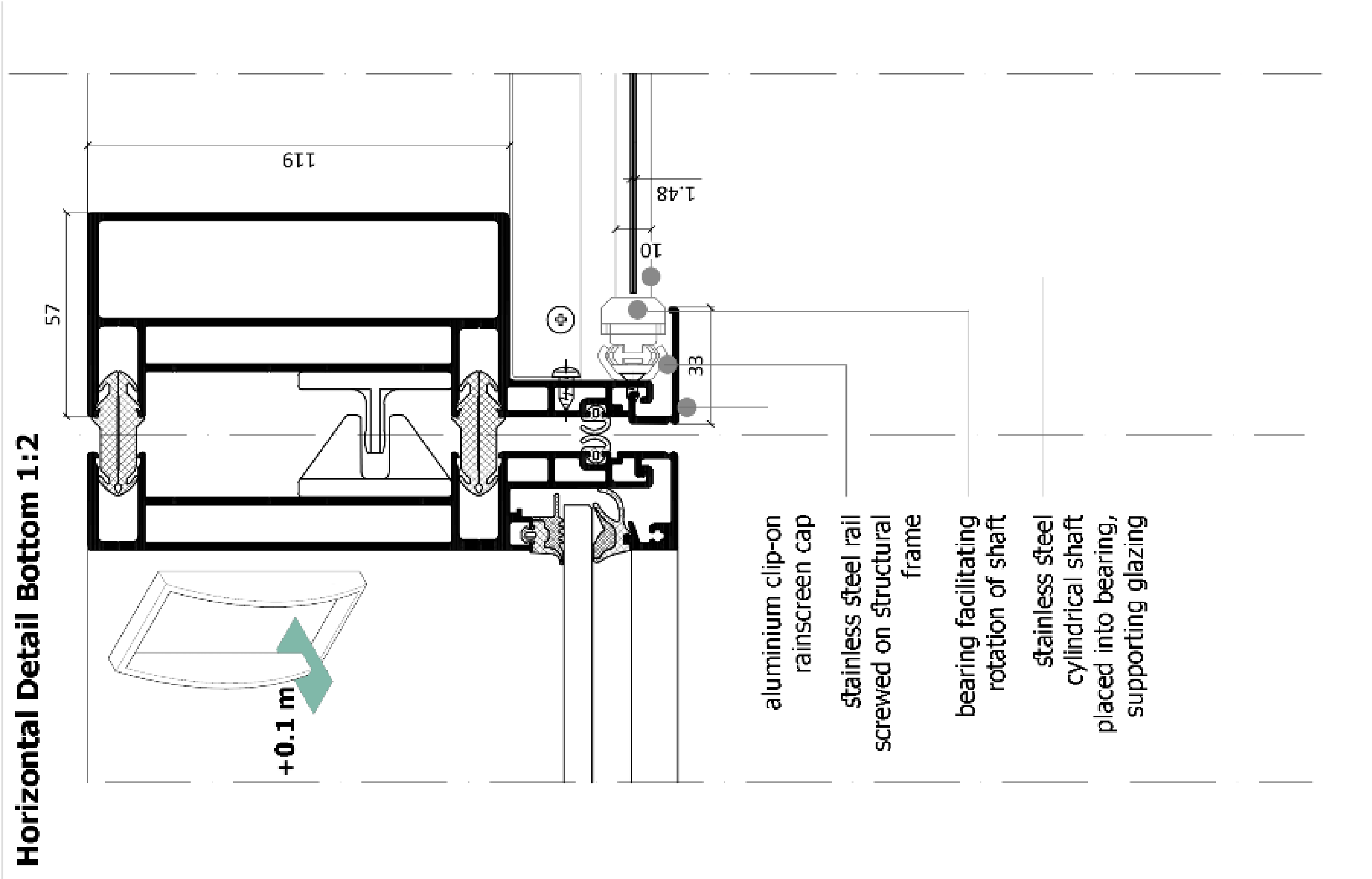


Figure 139 Aluminium plate to cover the gap

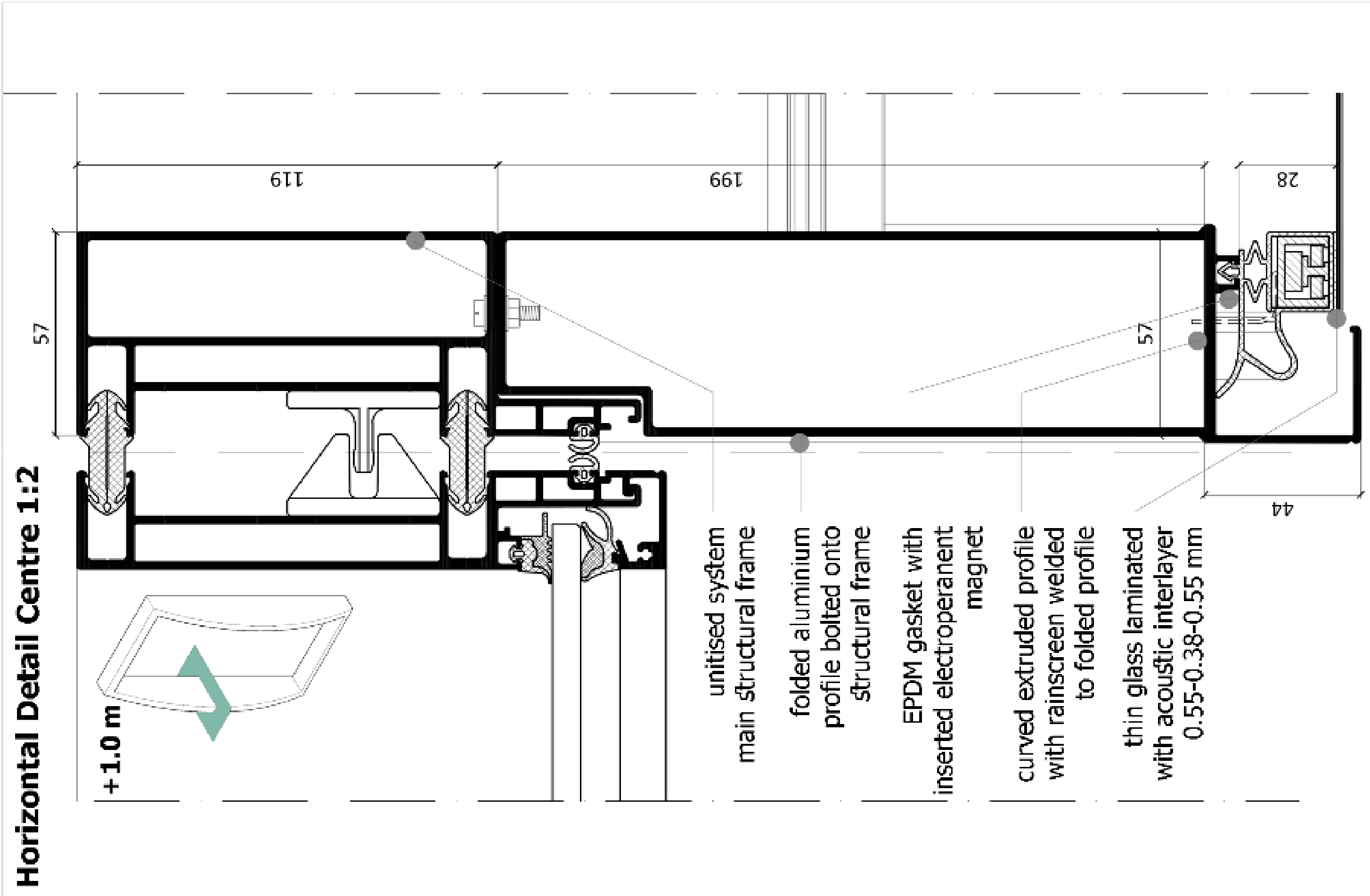
3.7.4. Final Design

After going through the entire planning process, the final design will be presented in this chapter. The result will be first shown with 2D-drawings that present the views and sections in a 1:20 scale and the critical details in 1:5. Subsequently, 3D-illustrations of the entire panel and its sections are presented.

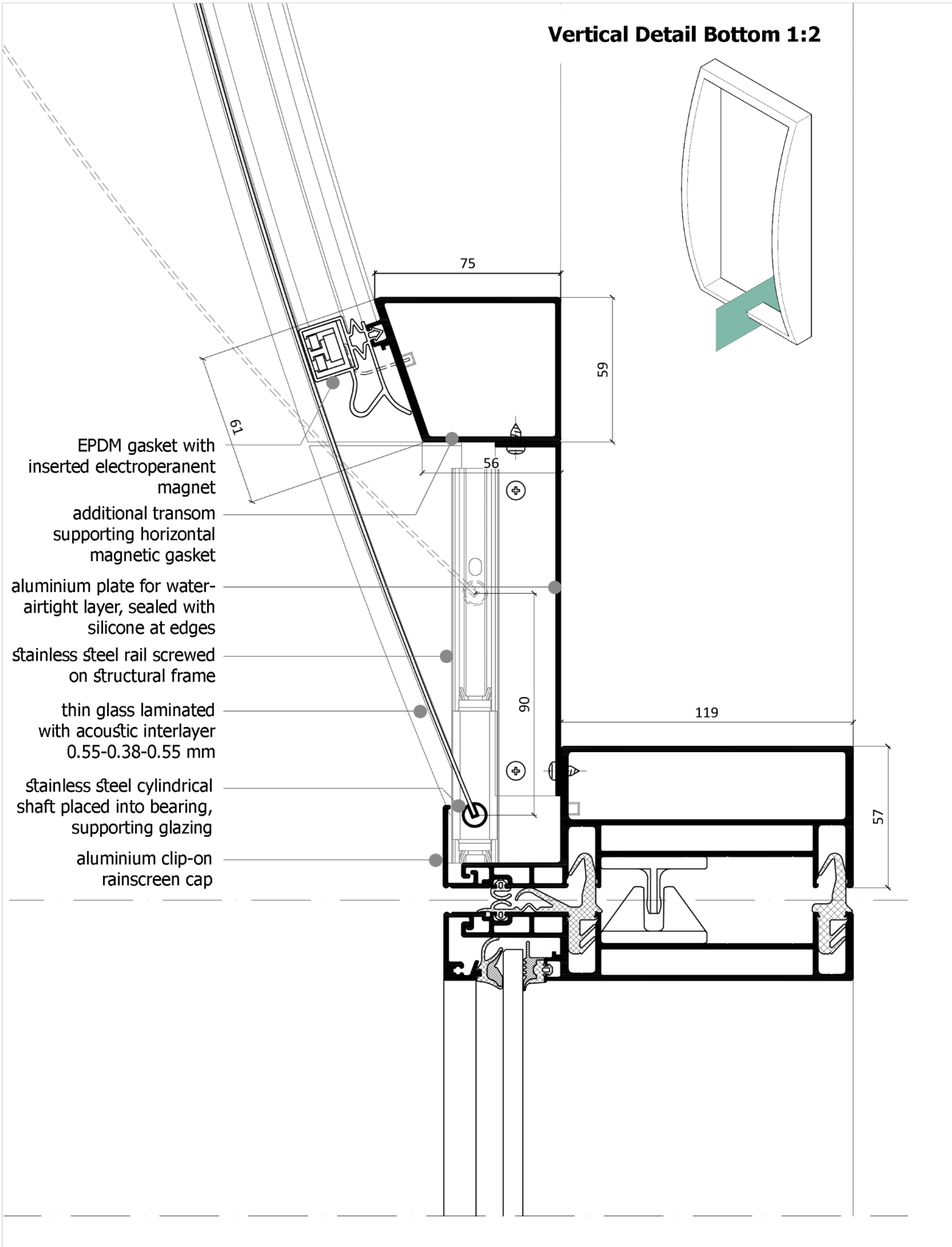

Front view, section and plan 1:20
Kinetic Thin Glass Facade panel
filing gaps of previous facade
existing BIPV-glass panel
2087
1080
1080
1080



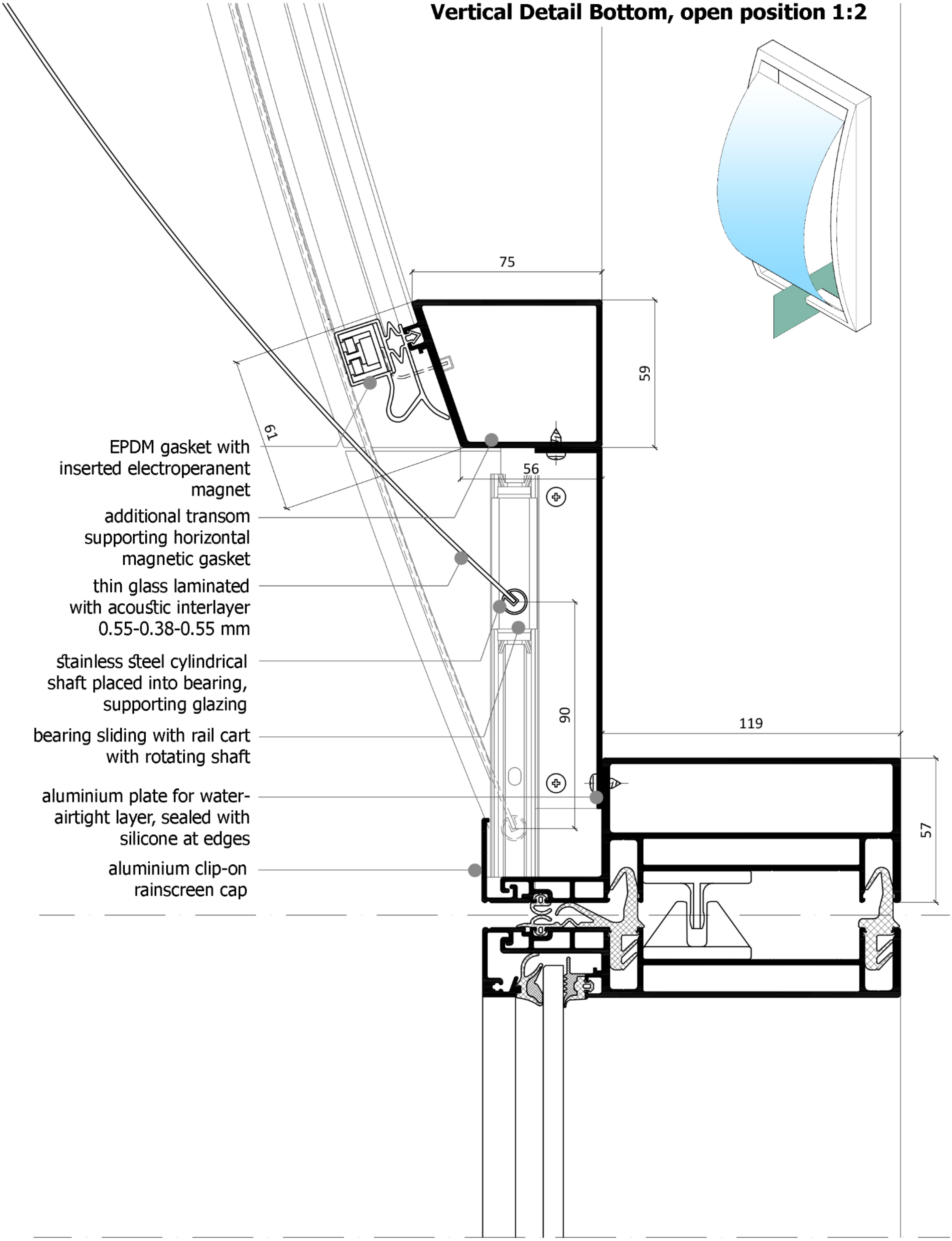
Horizontal Detail Bottom 1:2



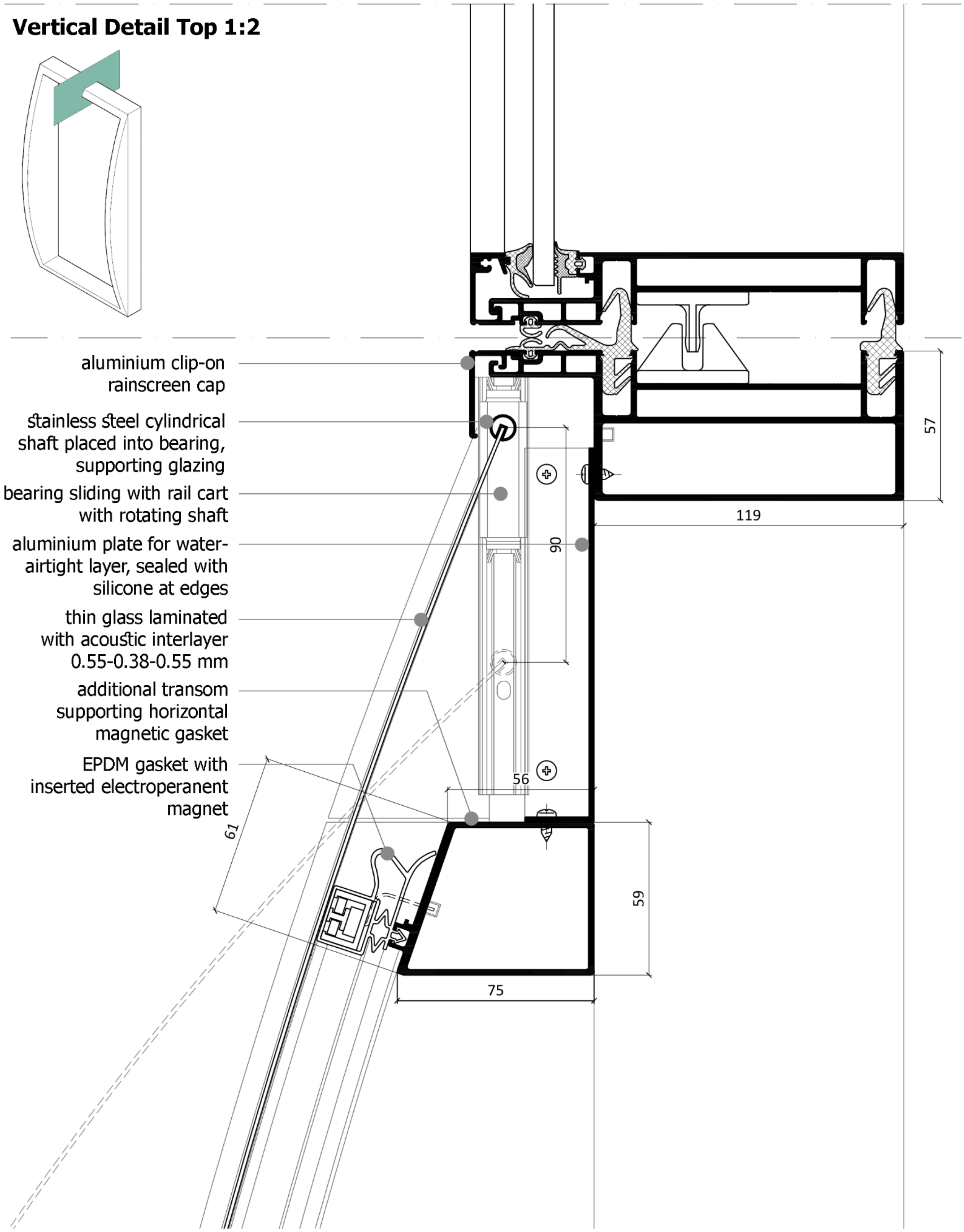
Horizontal Detail Centre 1:2

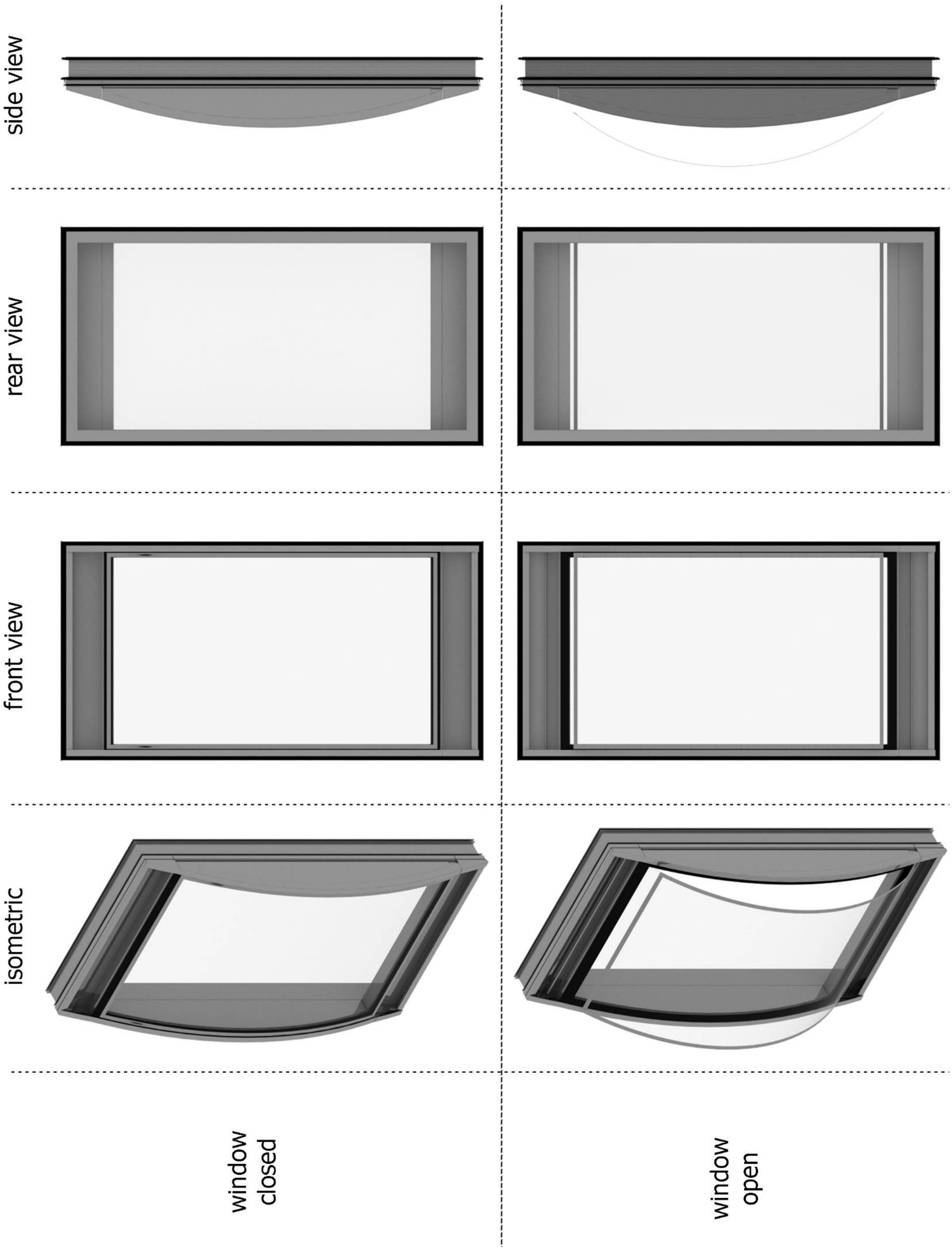

Vertical Detail Bottom 1:2
75
59
61
56
90
119
57
EPDM gasket with inserted electroperanent magnet
additional transom supporting horizontal magnetic gasket
aluminium plate for water-airtight layer, sealed with silicone at edges
stainless steel rail screwed on structural frame
thin glass laminated with acoustic interlayer 0.55-0.38-0.55 mm
stainless steel cylindrical shaft placed into bearing, supporting glazing
aluminium clip-on rainscreen cap

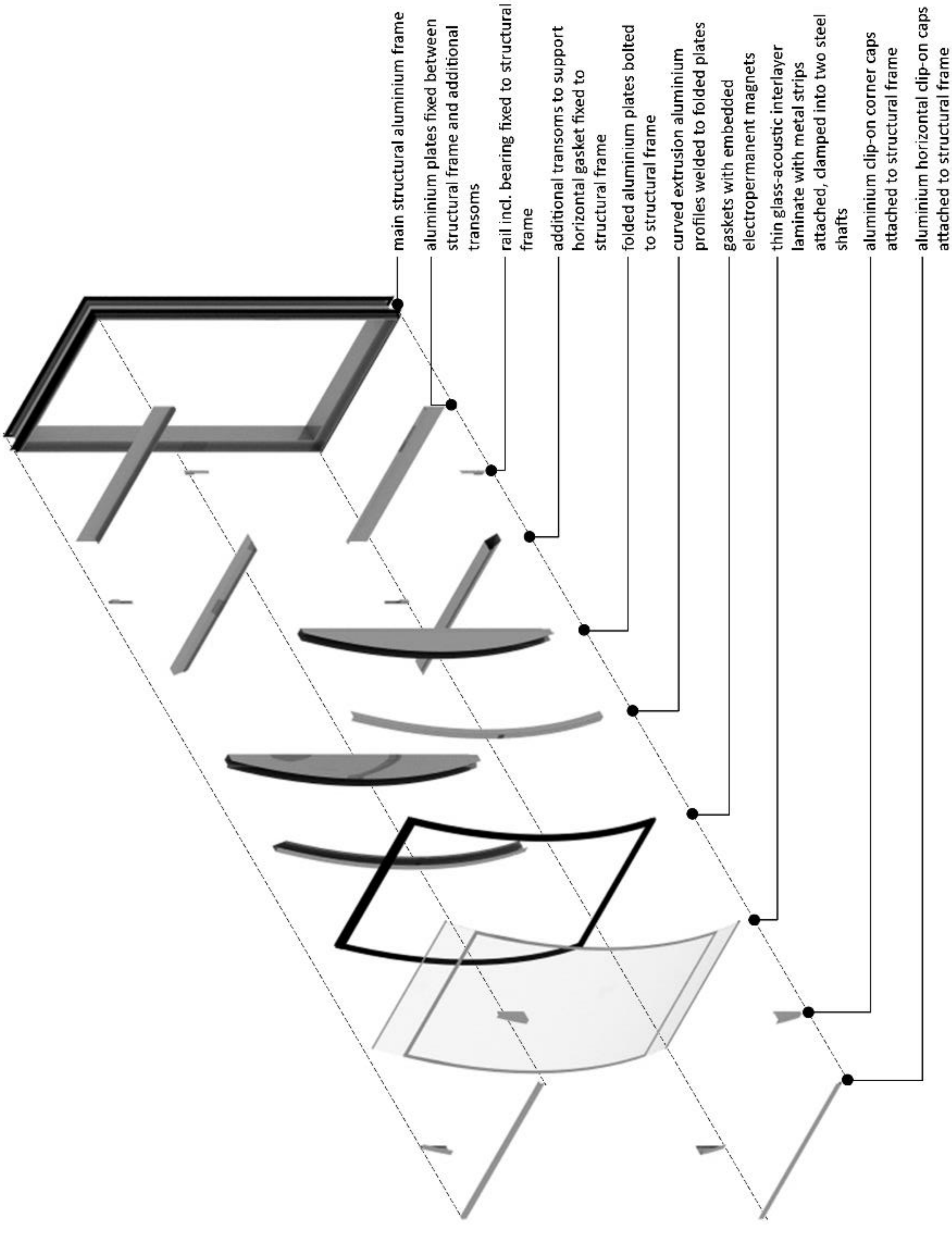
Vertical Detail Bottom, open position 1:2

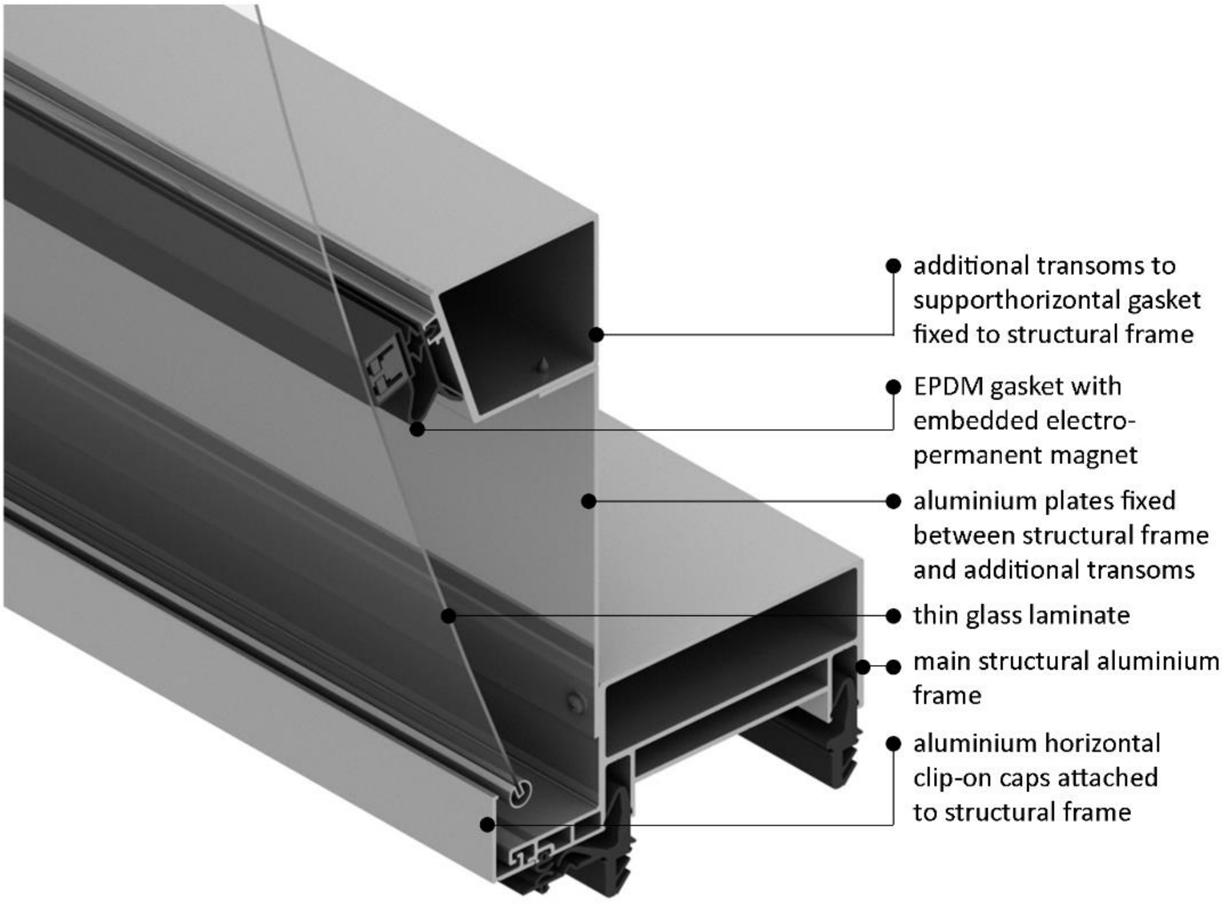


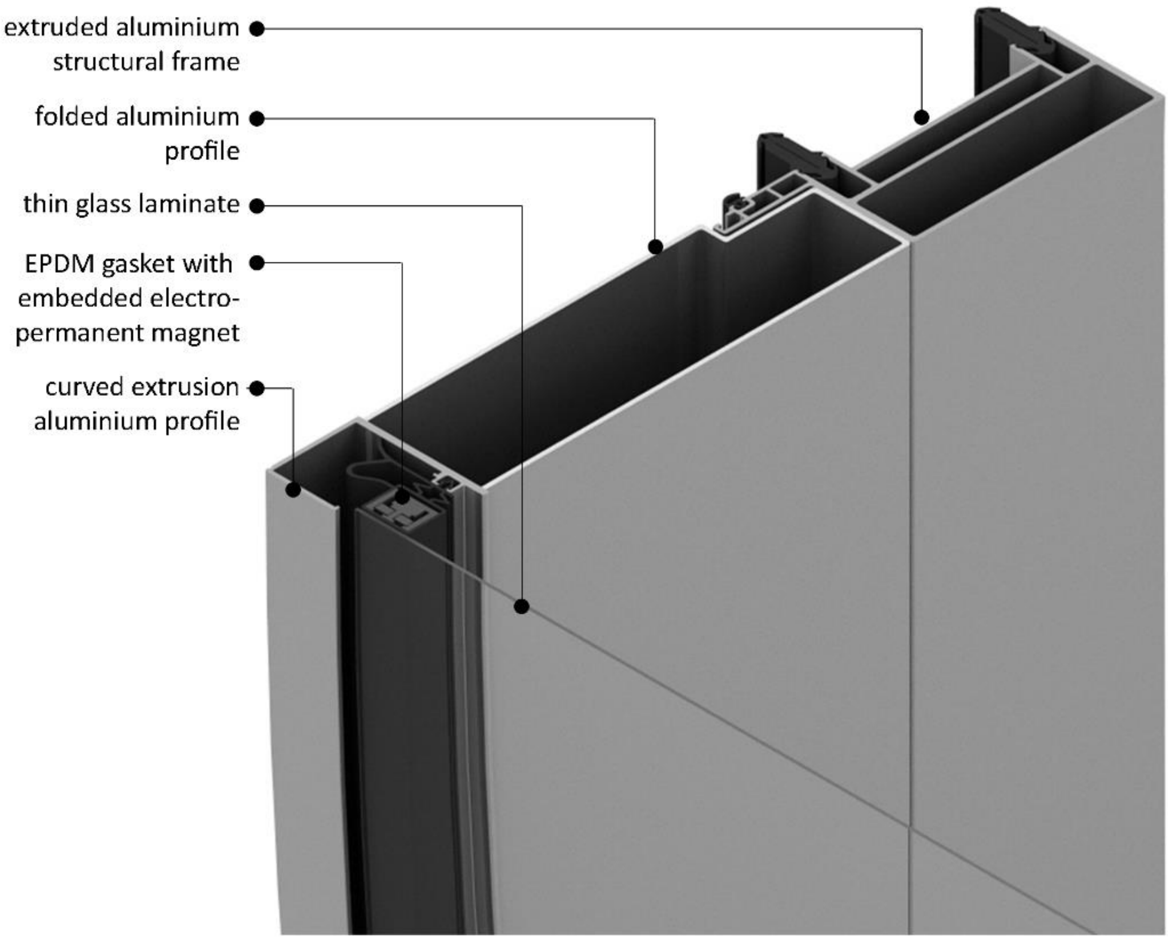
Vertical Detail Top 1:2

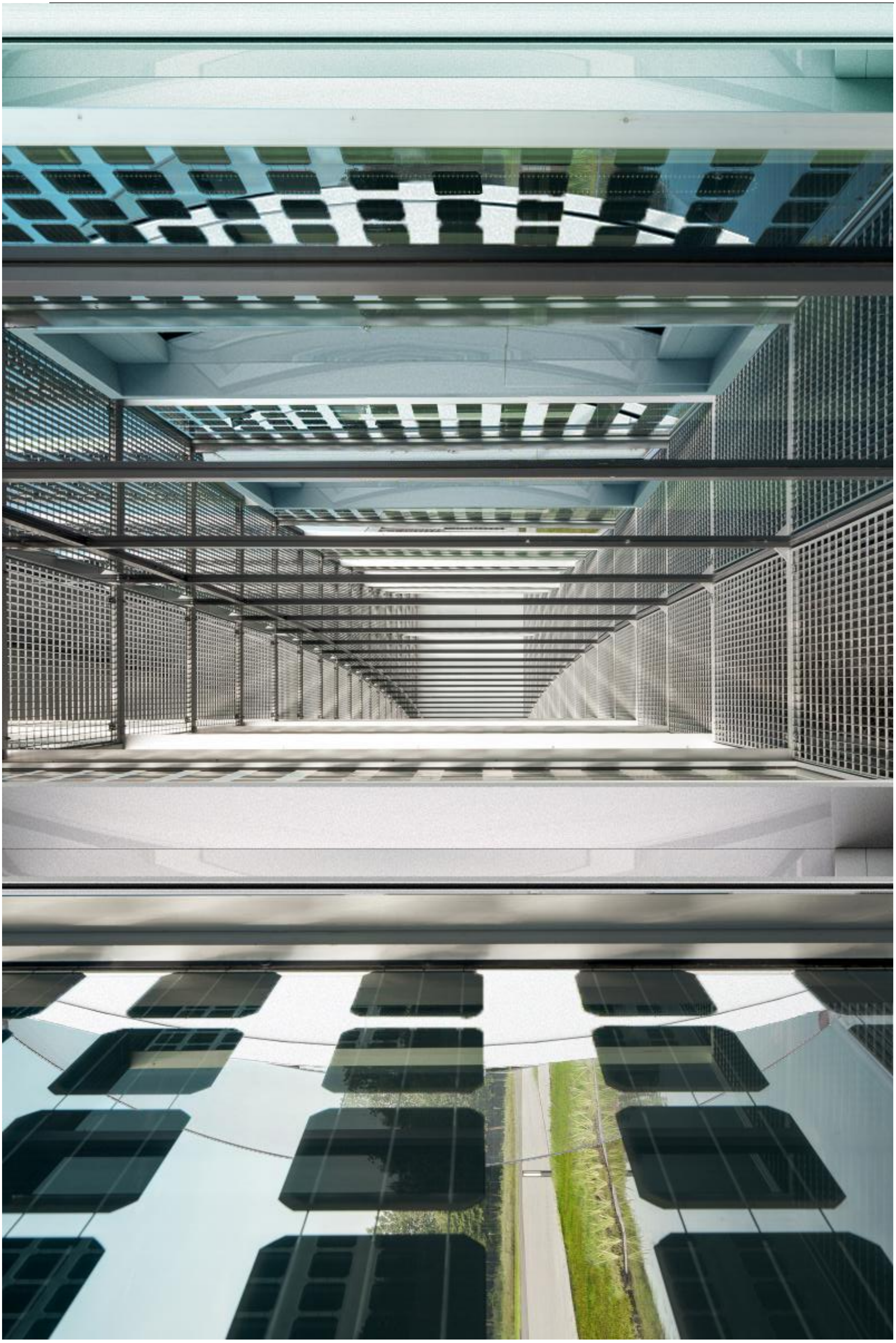



side view
rear view
front view
isometric
window closed
window open


main structural aluminium frame
aluminium plates fixed between structural frame and additional transoms
rail incl. bearing fixed to structural frame
additional transoms to support horizontal gasket fixed to structural frame
folded aluminium plates bolted to structural frame
curved extrusion aluminium profiles welded to folded plates
gaskets with embedded electropermanent magnets
thin glass-acoustic interlayer laminate with metal strips attached, clamped into two steel shafts
aluminium clip-on corner caps attached to structural frame
aluminium horizontal clip-on caps attached to structural frame


additional transoms to supporthorizontal gasket fixed to structural frame
EPDM gasket with embedded electro-permanent magnet
aluminium plates fixed between structural frame and additional transoms
thin glass laminate
main structural aluminium frame
aluminium horizontal clip-on caps attached to structural frame


extruded aluminium structural frame
folded aluminium profile
thin glass laminate
EPDM gasket with embedded electro-permanent magnet
curved extrusion aluminium profile



3.7.5. Final Mock-up

A final mock-up with the use of real chemically strengthened glass of a 1:2 scale was planned to demonstrate the operating principle of the façade element. However, this could not be done, as the manufacturer did not deliver the glass before the final date of the thesis. Nevertheless, this chapter describes the preparations made prior to the arrival of the glass as an example of how the mock-up was planned.

The aluminium frames were planned to be replicated with MDF-plates. The reason for the selection of this material was that it is available in numerous thicknesses and is easily workable. The glass sheet of the size 1260x660 mm would have a thickness of 0.5 mm and was not laminated. Its initial and final bending radii were adjusted according to its scale and were therefore not equivalent to that of the proposed final product. The electro-permanent magnet gaskets would be replaced with a combination of foam strips and a permanent magnet strip due to the unavailability of a gasket fitting this small scale size and the difficulty of acquiring a custom-made electro-permanent magnet. The two shafts were made from a solid PVC-cylinder, manufactured to the required shape on the TU Delft campus.

4. Conclusion

The general aim of this paper was to take the research progress of thin glass, which can nowadays be considered as an indispensable component of numerous products in the electronics industry, one step further towards an application in future buildings. The main idea was to do this in an innovative way, as, along with all the challenges this new product brings with itself, it also has the potential to bring a vast amount of new possibilities into the use of glass in architecture. One of its main features creating the potential is undoubtedly its flexibility. It was exactly this feature that dictated the focus of this research. In pursuit of the adaptation of thin glass into the building industry by making use of its flexibility, the main research question emerged, forming the foundation of this research; *How can a kinetic façade element featuring a bendable thin glass panel be designed to be water- and airtight in closed condition?* Previous researches have already investigated the possibility of bending thin glass and using it in a kinetic application. This thesis aimed to add on top of the foundation set by these previous researches by implementing two additional aspects; achieving water- and airtightness in the façade, as well as the lamination of multiple thin glass elements for improved safety. The water- and airtightness issue is already addressed in the main research question. Finding an answer to this question required several research steps to be taken, which also include the other aspect of lamination of glass amongst other issues. These steps implicated additional questions related to the structural aspect of cold bending a laminated alumino-silicate thin glass element and the implementation of conventional methods to achieve water- and airtightness in façades into a new design that incorporates a bending-active kinetic glass element.

4.1. Results

In this chapter, the sub-questions will be answered individually prior to focusing on the answer to the main research question. Subsequently, the findings will be briefly discussed, addressing whether they meet the expectations from before commencing the study and limiting factors that appeared during the research phase. The chapter will be rounded off with recommendations for further research in this field.

Now, each sub-question asked in the research definition phase will be addressed one by one.

Which is the most suitable application for the proposed façade with regard to its limitations and created possibilities?

This question was dealt with in chapter 3.1. Case Study, before starting with the design process, so that the product could be customised according to the requirements of the specific use. In order to examine which type of use is best suited for this application, first, the expected performance and qualities were assessed, such as tightness, insulation and safety. Once the qualities were defined, the requirements of possible applications such as double skin façade or glass roof were considered under the same categories. The requirements for each use were then compared to the predefined expected qualities of the product and the best fit was selected as a case study. The selected use was the outer skin of a double skin façade due to its relatively low expectations regarding insulation and other aspects. The selected case study was the European headquarter building of AGC, the manufacturer of the glass provided to the university, as its façade was a good match due to being single glazed and the building itself being a showcase for glass innovation.

Which principles can be considered to achieve water- and airtightness in a façade with a bendable glass element?

Three options were proposed to tackle the water- and airtightness issue, which are introduced in chapter 3.2. Design Proposals. Two of them involve creating pressure between the glazing and a rectangular gasket frame to create a water- and airtight barrier. The first of these tackles this by the use of magnetic attraction and the second one by a pressure created by putting tension into the curved glass by means of pulling from two edges, which will then force the glass surface to press onto the gasket. The third option's approach was relatively different in contrast to these two. It aimed to permanently seal the edges against water- and air entrance by the use of a flexible water- and airtight fabric that stretches upon opening the window.

Which of the proposed principles is the most feasible solution with regard to practical feasibility and structural suitability?

Based on the assessments made in chapters 3.3. Practical Feasibility and 3.5. Structural Suitability, a conclusion was drawn and a selection made in chapter 3.6. Conclusions and Selection of the Design. The conclusion was that the first option involving magnetic power was the most suitable alternative due to being the structurally most suitable design with four linear supports supporting the glass from the edges and the practically most feasible one with high possible holding forces through the magnets, enabling a water- and airtight layer. There were too many doubts both structurally and practically about the remaining two options that would overcomplicate the design and were therefore not further considered.

How does lamination of multiple thin glass sheets affect the structural behaviour in a way to find a balance between flexibility and stiffness?

The testing of the structural behaviour of the glass laminates was only carried out numerically. Based on the findings in chapter 3.4. Glass Laminate Configuration and 3.5. Structural Suitability, the glass shows enough stability to withstand wind loads without deforming too much and does not exceed the marginal strength limit of 260 MPa specified by the manufacturer under cold bending up to a relatively small radius. This is still the case after applying a safety factor that is common in regulations. This result is promising towards the application of cold bent thin glass laminates in architecture. However, the numerical results should be treated carefully without being validated by physical testing. The only validation was done with the numerical modelling of a previously carried out physical test that shows a number of differences compared to the case of this research. Therefore, a precise statement about the safety of this application in practice cannot be made purely based on these results until validated by results achieved with physical laboratory tests for this specific case.

What is the effect of changing glass thickness, interlayer thickness and interlayer stiffness regarding the structural behaviour of the glass laminate?

The effect of changing variables of the glass laminate is examined in chapter 3.4.4. Results – Effects of Changing Variables. As expected, increasing the glass thickness resulted in higher stresses under cold bending with the same radius. The same applies for an increasing interlayer thickness, which also leads to higher stresses. These results are linked directly to the increase of the moment of inertia of the glass laminates' cross section regardless of which material's thickness is increased. Therefore, even if slight differences occur in some cases, generally, it can be concluded that the thicker the total thickness of the laminate, the higher will be the peak stresses. The effect of the interlayer stiffness could not be evaluated due to inaccuracies in the numerical model, most likely because it is a 2D-sheet model, not showing the same shear behaviour as the real case. Following the analysis, the configuration involving the thinnest glass thickness of 0.55 mm and an acoustic interlayer with a very low stiffness of the lowest possible thickness of 0.38 mm was selected.

The answers to the sub-questions written above, all form the basis for the answer to the main research question; "*How can a kinetic façade element featuring a bendable thin glass panel be designed to be water- and airtight in closed condition?*" The design of a water- and airtight, kinetic façade with a laminated bending-active glass element required all the mentioned sub-questions to be answered beforehand to finally realise the planning and detailing phase of the final product. Knowing the exact type of use of the façade element as the outer skin of a double skin façade, which formed the answer to the first sub-question, helped define the exact requirements for the water- and airtight barriers. Based on this knowledge, it was possible to answer the second and third sub-questions related to the principles to achieve water- and airtightness in the façade. Answering the fourth and fifth sub-questions on the other hand, were crucial to ascertain, whether bending a thin glass laminate to such an extent that makes it possible to ventilate the interior space through the openings was possible in the first place. Only after finding the answers to these questions, it was possible to design the details and make product choices that made the final design complete.

Ultimately, the proposed final design for a product as described in the main research question involves the use of electro-permanent magnets placed inside a gasket similar to that of a refrigerator gasket, forming a rectangular frame. The reason behind the magnet being switchable is based on the convenience during the opening and closing of the window. The glazing, consisting of two layers of thin glass with a soft acoustic interlayer, rests on this fixed gasket frame with a thin metallic strip attached to it, acting as an object of attraction to the magnet. As for the mode of operation, the principle of active bending is applied that allows a two dimensional bending movement caused by a simple linear movement. This way, the number of mechanical parts and actuators could be kept at a minimum. The movement is achieved by linear actuators placed on each corner, causing the bearings to move that are fixed to a rail, which then move the shafts that support the glazing. Matching bespoke façade profiles needed to be designed to fit the configuration of this unique type of movement, which are based on profiles of unitized elements.

4.2. Discussion

As a conclusion, it is well worth mentioning that many choices made during the design process are subjective even though partially supported by numerical data and supporting arguments from previous literature. This work does by no means intend to present the only or the best possibility to achieve the objective, but is rather meant to offer new insights into the field and to form a basis for further research for the development of a similar product. The main objective stated in chapter 1.4 Research Objectives and Final Product at the research definition phase was to investigate possibilities to create a kinetic façade element featuring a bendable thin glass panel that is both air- and watertight upon being closed by examining possible alternative designs. The answers given to the research questions in the previous sub-chapter fulfil their purpose in this respect. There is currently a lack of research for the adaptation of thin glass products into architecture. Few researches have been done before in this regard, which mainly investigated the possibility of bending a single layer of glass and incorporating it into a façade. Requirements that are set to building skins, such as water- and airtightness or thermal- or acoustic insulation were not addressed. The main intent of this research was to add two things on top of what was achieved before; 1) Adding a second layer of glazing to create a laminated glass sheet in order to comply with safety regulations and add some additional stiffness to the thin glass. 2) Investigate possibilities to combine the bending of thin glass with the water- and airtightness properties that form the main prerequisites of a façade. This paper provided some insight into both fields by considering different possibilities and ultimately selecting one that was considered to be the most suitable fit for either of them. The final design presented at the end of the thesis did then propose a possible solution for the execution of the product with the selected principles including complete detail development and a selection of products that are available on the market.

The observations that can be made based on the research results are largely hypothetical. They are mainly based on suggestions and findings from previous literature and on the fact that similar products worked reliably with similar principles, such as the refrigerator gasket for airtightness. However, since these principles have never been tried in construction before, their reliability in this field needs to be tested for the specific use. This was not done within the scope of this research, as many of these tests require a large number of test specimens and very accurate laboratory conditions over long time spans of testing. For testing the structural behaviour of the glass, a range of specimens is required to define the average results. This is especially the case for glass, since the practical strength of glass is largely dependent on the flaws of its surface in micro-scale. In addition, the lamination can also incorporate inaccuracies, such as flaws causing earlier delamination. Only if a sufficient number of the selected glass laminate configuration was present, the tests would provide a reliable result. A similar case applies to the testing of the water- and airtightness properties of the façade. These can only be tested under professional laboratory conditions with accurate tools to measure. Furthermore, running these tests requires a long time, which made it almost impossible to fit into the available time span. One other aspect that can be improved refers to the numerical analysis. The results obtained after changing the interlayer stiffness occurred to be inaccurate. This could be improved by creating a 3D brick model for the numerical calculation instead of a 2D shell.

For this, the scope of the research must be more limited to solely focus on the structural aspect, as the modelling of an accurate 3D finite element model requires a good expertise and is very time consuming.

The last paragraph of this chapter is dedicated to recommendations for further research in this field. As this is a relatively new field in architecture, it offers a large potential for research to improve the applicability of the product and further improve it. The first aspect to mention in this regard is the investigation of other possible uses of bending thin glass in construction. This thesis focused on the purpose of natural ventilation. Other possible applications would include its use as an adaptive sun shading system involving fritted or enamelled glass, increased power generation through adaptive BIPV-glass panels that can be controlled according to the angle of incidence of the sunlight, wind load reduction by adapting the building skin's shape to the current wind condition, or simply for creating visual effects for architectural purposes. One further interesting field to research would be to create an insulating bendable thin glass unit with two or more glazings. Some of the main challenges in this involve the differing radii of the bent glass panels and how to cope with the pressure differences created between the glass sheets and the exterior. Finally, exploring possible other architectural expressions of bent glass could increase the demand for this product in the building industry, which would lead to increased research, which in turn may decrease the price of the product.

5. Reflection

This reflection focuses on the aspects of the social context of the design, as well as on the relationship between the research and the subsequently aimed design as an outcome of the research process. The first part explains the purpose of the design and what it adds to existing applications involving glass. This is followed by the second part, which describes the initially planned steps to achieve the result and what has changed during the progress itself with their corresponding argumentation, mentioning the reason of the choices made.

The Design in the Social Context

With the architectural preferences shifting towards more transparent, open plan designs in our day, glass gains additional importance as a building material. It is not only regarded as a means of admitting daylight into the interior, but is also utilised to add character to the building. This was accelerated, or even made possible by the development of research and production techniques. Thanks to this development, technology has come to a point, where glass can be produced in various types and shapes. These include the relatively new type of glass, namely ultra-thin glass. While this product is nowadays commonly in use in the electronics industry, it is almost non-existent in architecture. One of the main reasons for this is the lack of demand in the market due to many factors such as high costs and therefore also the lack of interest in research, which again prevents its cost from declining. However, this product shows a large potential for use in architecture, provided that sufficient interest is shown in the development. When compared to glass with regular thickness, along with some disadvantages, it also shows many advantages. To name a few, these include the lowered use of raw materials, reduced weight of units containing this type of glass due to its lower thickness, its higher flexibility, allowing for unique types of use, the higher impact resistance of its surface and its excellent optical quality.

This thesis aimed to address some of the existing concerns regarding the use of this product in architecture and to bring it one step closer to realisation by presenting ideas that may inspire future researchers and by analysing the extent of its potential through numerical calculations and possible detail designs.

Initially Planned Approach and Changes During Process

The main focus of the research is divided into one aspect in each part; *a) the structural part of the research will focus on the structural behaviour of the laminated thin glass panels with respect to various parameters such as glass thickness, PVB thickness and PVB type under the controlled bending load as well as the wind load, b) the façade focus will be on the water- and airtightness aspect of the proposed kinetic façade element in the closed condition*. The focuses have not changed since the definition of the research framework and remained to be the main focus points of the research. However, the single steps of the research approach and methodology were subjected to small changes during the course of the research.

The initially planned approaches and the changes made to those later on are discussed in the following section.

a) structural behaviour of laminated thin glass

Initially, it was planned to test possible combinations of glass thickness, PVB thickness and PVB types via numerical analysis. To validate the results of the numerical analysis, one or more physical experiments would be carried out. During the research phase, the physical experiment aiming to validate the numerical results was cancelled. The reason therefore is the normally large number of required physical experiments for an expedient validation. This was not possible due to the limited timeframe and in order to prevent the scope to be widened. Instead of preparing a physical experiment specifically for this research, previously performed physical experiments were modelled using the same software and the experimental results were compared to the numerical results to monitor the deviation. For safety purposes, it was made sure that the numerical results remained on the conservative side depicting higher stresses at certain bending points than the ones measured during the physical experiment.

b) water- airtightness

Initially, it was planned to focus on one of the three potential solutions for the water- and airtightness aspect starting from the P2. Upon consideration of the mentor team, it was decided to further investigate the possibilities of all three proposals and make a final decision until P3, after which the selected proposal would be further elaborated. To conclude, which of the options is the most suitable one, the feasibility of the kinetic mechanism, material capacities, and the simplicity of the details were questioned. As planned in the beginning, the method for this step was to draw conceptual details and experiment with similar materials as those planned to be used in each proposal. Another method to investigate the feasibility was to build smaller scale mock-ups of each proposal. This was however later reduced to only one mock-up of the proposal with the biggest potential, since the other two did not seem to be practicable enough to be realized. Also initially, the option of testing the water- and airtightness of the mock-up was considered, was however later dropped, since an establishment to test this aspect requires very accurate laboratory conditions and a thorough expertise in testing in this particular field for reasonable results.

Also initially, the approaches for structural and façade were planned to be separated, so that at first the focus would be solely on the structural part, which would also play a decisive role in the selection of the most suitable design proposal. Even though, the order was roughly kept, it shifted more towards an approach, where the two focuses of structural and façade would go more hand-in-hand and the final outcome would be drawn from the results of both separately.

Apart from these points, the methodology defined in the research framework was maintained throughout the research process. Hence, research and design went hand in hand from the beginning, with the design purpose influencing the focus points of the research and the results of the research that has been done defining the shape of the final design.

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Standards:

NEN 12152
Curtain walling - Air permeability - Performance requirements and classification

NEN 12153
Curtain walling - Air permeability - Test method

NEN 12155
Curtain walling - Watertightness - Laboratory test under static pressure

NEN 12337
Glass in building - Chemically strengthened soda lime silicate glass

NEN 2608
Glass in building - Requirements and determination method

NEN 2687
Air leakage of dwellings – Requirements

NEN 2778
Moisture control in buildings

NEN 3660
Window frames - Air permeability, rigidity and strength - Methods of test

NEN 3661
Window frames - Air permeability, water tightness, rigidity and strength – Requirements

NEN 572
Glass in building - Basic soda lime silicate glass products

TRLV – Technische Regeln für die Verwendung von linienförmig gelagerten Verglasungen – Schlussfassung August 2006

Appendix

Appendix 1 AGC Leoflex Product Information

AGC Electronics America
(/)

Sitemap (/index.php/product-information2-4) Contact Us

Home (/index.php) Product Information (/index.php/product-information2) Our Global Network (/index.php/2014-03-11-05-22-48)

Home (/index.php) > Leoflex (/index.php/leoflex) > Leoflex Architectural Glass

Leoflex Architectural Glass

Leoflex™
Leoflex Architectural Glass (/index.php/leoflex/37-leoflex-architectural-glass)

Literature
Request Literature (mailto:acrawford@agcem.com?subject=Advanced%20Packagin

Product Features

Leoflex™ Features

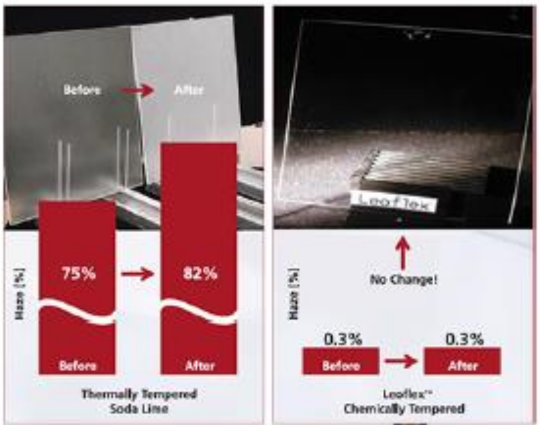
- ✓ 5X tougher than thermally tempered soda lime glass
- ✓ Lightweight
- ✓ Bendable
- ✓ High scratch resistance
- ✓ Outstanding weather resistance
- ✓ High optical clarity
- ✓ High strength compared to soda lime glass

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

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

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

Weather Resistance Test



Leoflex™ Properties

Property	Measurement	Leoflex™	Soda Lime

Available Sizes & Thickness:

Thickness:

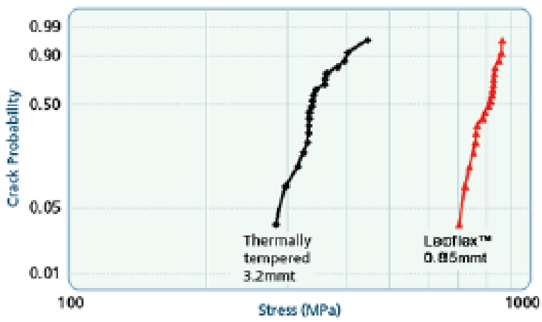
From 0.5mm to 2.0mm

Sizes:

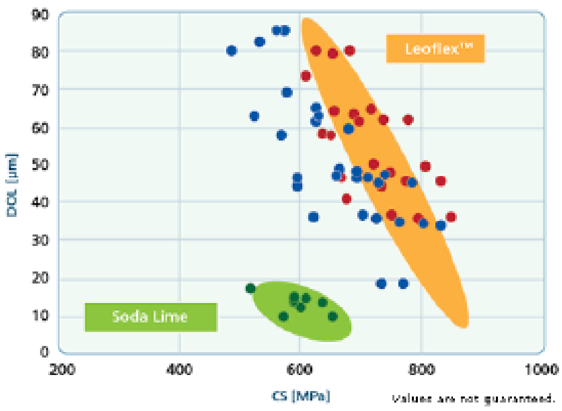
Mechanical	Density	g/cm³	2.48	2.50
	Young's Modulus	GPa	74	73
	Shear Modulus	GPa	30	30
	Poisson's Ration		0.23	0.21
	Vickers Hardness	Before CT	595	533
	Vickers Hardness	After CT	673	580
Thermal	CTE	$[10^{-7}]$(50~200°C)	88	85
	Tg	°C	604	550
	Softening Point	°C	831	733
	Annealing Point	°C	608	554
	Strain Point	°C	568	511
Optical	Refraction Index	Nd	1.51	1.52
	Photoelastic Constant	nm/cm Mpa	28.3	25.6
Electrical	Volume Resistivity	log (Ω·cm)	8.4	8.5

Standard size is 48" x 29".
Custom sizes available.

Toughness Ring-on-Ring Test



Chemical Tempering Performance



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Appendix 2 Structural Properties and Coupling Effect of Kuraray Trosifol Products

STRUCTURAL PROPERTIES AND COUPLING EFFECT

Relaxation modulus (G) as a function of temperature and load duration is shown in the chart below.
As temperatures and load durations increase SentryGlas® will outperform a stiff PVB like Trosifol® Extra Stiff.

Relaxation modulus as a function of time and temperature*

Relaxation modulus G [N/mm²]	Product type	Load duration 3 sec	30 sec	1 min	5 min	30 min	1 hour	1 day	5 days	3 weeks	1 month	1 year
10°C	Trosifol® PVB	-	-	-	-	-	-	-	-	-	-	-
Temperature	Trosifol® Extra Stiff	699	603	573	502	420	388	234	157	95	80	19
	SentryGlas®	236	228	225	220	217	206	190	178	172	171	161
20°C	Trosifol® PVB	8	-	1.6	-	-	0.8	0.5	-	-	0.4	0.3
Temperature	Trosifol® Extra Stiff	342	230	196	122	55	37	5.3	2.8	2.0	1.9	1.6
	Other Stiff PVB	325	-	-	-	-	96	23	-	-	3.0	1.0
	SentryGlas®	211	206	195	188	175	169	146	130	115	112	96.5
30°C	Trosifol® PVB	1	-	0.8	-	-	0.4	0.3	-	-	0.1	0.1
Temperature	Trosifol® Extra Stiff	58	14	9.2	4.0	2.3	2	1.6	1.6	1.5	1.5	1.5
	Other Stiff PVB	97	-	-	-	-	2.4	0.8	-	-	0.5	0.4
	SentryGlas®	141	119	110	82.8	66.1	60	49.7	24.7	12.9	11.6	6.8
40°C	Trosifol® PVB	0.6	-	0.5	-	-	0.2	0.2	-	-	0.1	0.1
Temperature	Trosifol® Extra Stiff	3.4	1.9	1.8	1.6	1.6	1.6	1.5	1.5	-	1.5	-
	Other Stiff PVB	6	-	-	-	-	0.6	0.4	-	-	0.2	-
	SentryGlas®	63	36.6	30.7	19.4	11.4	9.3	4.5	3.6	3.4	3.3	3.1
50°C	Trosifol® PVB	0.4	-	0.3	-	-	0.1	0.1	-	-	0.1	0.1
Temperature	Trosifol® Extra Stiff	1.7	1.6	1.6	1.5	1.5	-	-	-	-	-	-
	Other Stiff PVB	1	-	-	-	-	0.4	0.2	-	-	-	-
	SentryGlas®	26.4	13.5	11.3	7.3	4.9	4.2	2.8	2.4	2.2	2.2	2.1
60°C	Trosifol® PVB	-	-	-	-	-	-	-	-	-	-	-
Temperature	Trosifol® Extra Stiff	1.6	1.5	1.5	-	-	-	-	-	-	-	-
	SentryGlas®	8.2	4.3	3.7	2.6	1.9	1.7	1.3	1.2	1.2	1.1	1.0
70°C	Trosifol® PVB	-	-	-	-	-	-	-	-	-	-	-
Temperature	Trosifol® Extra Stiff	-	-	-	-	-	-	-	-	-	-	-
	SentryGlas®	2.9	2.1	1.9	1.4	1.0	0.8	0.6	0.6	0.5	0.5	0.5
80°C	Trosifol® PVB	-	-	-	-	-	-	-	-	-	-	-
Temperature	Trosifol® Extra Stiff	-	-	-	-	-	-	-	-	-	-	-
	SentryGlas®	1.3	1.0	0.8	0.6	0.4	0.3	0.3	0.2	0.2	0.2	0.2

* Measurements for Trosifol® PVB and Trosifol® Extra Stiff performed by the Fraunhofer Institute, Darmstadt, Germany

Interlayer performance comparison

Properties	Standard PVB	Other Stiff PVB	Trosifol® Extra Stiff	SentryGlas® Ionoplast
Post Breakage Performance at room temperature (21°C/70°F)	🔴	🟢	🟢	🟢
Post Breakage Performance at elevated temperature (50°C/122°F)	🔴	🔴	🔴	🟢
Structural Properties/Coupling effect at room temperature (21°C/70°F)	🔴	🟢	🟢	🟢
Structural Properties/Coupling effect at elevated temperature (50°C/122°F)	🔴	🔴	🔴	🟢
Clarity	🔴*	🔴	🟢	🟢
Sealant compatability/Edge stability	🔴	🟠	🟠	🟢
Product offering	Rolls up to Jumbo 321 cm/126 in	Rolls up to Jumbo 321 cm/126 in	Rolls up to Jumbo 321 cm/126 in	Sheet up to 250 cm/98 in and rolls up to 270 cm/106 in
Calipers	15,30, 60 and 90 mils 0.38, 0.76, 1.52 and 2.28 mm	30 mil/0.76 mm	30 mil/0.76 mm	30, 35, 60, 90, 100, 105 mil 0.76, 0.89, 1.52, 2.28, 2.53 and 3.04 mm
Chemistry	Plasticized PVB	Lower Plasticized PVB	Lower Plasticized PVB	Ionoplast chemistry/ No plasticizer

* Not valid for Trosifol® UltraClear film

04 **BULLETIN**

Appendix 3 Portfolio of Trosifol Products in Architecture by Kuraray

PORTFOLIO

Architecture

Product line	Sub product line/ Sub families	New product name*	Old product name*
Safety	Trosifol® Clear	Trosifol® Clear	Standard Butacite®
	Trosifol® UltraClear	Trosifol® UltraClear	Standard Trosifol® BG
Decorative	Trosifol® Color	Trosifol® Red Trosifol® Light Green Trosifol® Sky Blue Trosifol® Medium Blue Trosifol® Violet Trosifol® Shining White Trosifol® Sand White Trosifol® Coconut White Trosifol® Translucent White Trosifol® Light Blue-green Trosifol® Ocean Blue Trosifol® Bronze Trosifol® Medium Bronze Trosifol® Light Brown Trosifol® Medium Brown Trosifol® Grey Trosifol® Asahi Grey Trosifol® Solar Grey SentryGlas® TW	Trosifol® Colour Red Trosifol® Colour Light Green Trosifol® Colour Sky Blue Trosifol® Colour Medium Blue Trosifol® Colour Violet Trosifol® Colour Shining White Trosifol® BG R15 Sand White Butacite® Coconut White Trosifol® BG R15 White Translucent Trosifol® BG R15 Light Blue-green Trosifol® BG R15 Ocean Blue Trosifol® BG R15 Bronze Trosifol® BG R15 Medium Bronze Trosifol® BG R15 Light Brown Trosifol® BG R15 Medium Brown Trosifol® BG R15 Grey Trosifol® BG R15 Asahi Grey Butacite® Grey SentryGlas® TW
	Trosifol® Opaque Color	Trosifol® Brilliant Black Trosifol® Diamond White	Trosifol® Colour Brilliant Black Trosifol® Colour Diamond White
	Trosifol® Print & Encapsulation	SentryGlas® Expressions™ Trosifol® HR	SentryGlas® Expressions™ Trosifol® HR100
Structural & Security	Trosifol® Structural	SentryGlas® SentryGlas® N-UV SentryGlas® TW Trosifol® Extra Stiff	SentryGlas® SentryGlas® N-UV SentryGlas® TW Trosifol® Extra Strong
	Trosifol® Hurricane Glazing	Trosifol® Clear Trosifol® XT UltraClear SentryGlas® SentryGlas® N-UV SentryGlas® TW	Standard Butacite® Trosifol® XT SP SentryGlas® SentryGlas® N-UV SentryGlas® TW
Acoustic	Trosifol® Sound Control	Trosifol® SC Monolayer Trosifol® SC Multilayer	Trosifol® Sound Control Trosifol® Sound Control+
Specialized Application	Trosifol® UV Control	Trosifol® UV Extra Protect Trosifol® Natural UV SentryGlas® N-UV	Trosifol® Extra Protect Trosifol® UV+ SentryGlas® N-UV
	Trosifol® Autoclave Free	Trosifol® HR	Trosifol® HR100
Recycled		Butacite® G	Butacite® G and Trolen

Automotive and Transportation

Product line	New product name*	Old product name
Safety/Standard	Trosifol® Clear Trosifol® Shadeband Trosifol® Color Trosifol® cPET SentryGlas®	Butacite® Clear & Trosifol® VG Clear Butacite® Shade Band & Trosifol® VG Shade Band Trosifol® VG Colors Spallshield® cPET SentryGlas®
Acoustic	Trosifol® Acoustic	Trosifol® VG SC+
Head-Up Display	Trosifol® The Wedge™	The Wedge™

Photovoltaics

Product line	New product name*	Old product name
Trosifol® Solar	Trosifol® Solar R40 Trosifol® Solar R40 Ultra White Trosifol® Solar UV+ Trosifol® Solar R100	Trosifol® Solar R40 Trosifol® Solar R40 Ultra White Trosifol® Solar UV+ Trosifol® Solar R100

* New product names valid from Q2 2017 onwards

Appendix 4 Test procedure including required pressures in NEN 2778

OPMERKING 3 De toe te passen methode is aangegeven in het volgende overzicht.

Enkelvoudig dichtingssysteem	Samengesteld dichtingssysteem		Scheidingsconstructies of delen daarvan die met toepassing van de betreffende geharmoniseerde productnorm met CE-markering op de markt worden gebracht
	Daken	Gevels	
5.1 of Bijlage E	5.5 (eventueel 5.1 met factor)	5.3.4.2.3	Toepasselijke geharmoniseerde productnorm

OPMERKING 4 Voor de bepaling van de eigenschappen van ramen en deuren is NEN-EN 14351-1 van toepassing met de daarin aangewezen beproevingsmethode NEN-EN 1027. In de prestatieverklaring van het betreffende bouwproduct is aangegeven welke waterdichtheidsprestatie met welk toepassingsgebied uit de CE-markering voortvloeit.

OPMERKING 5 Voor de bepaling van de eigenschappen van vliesgevels die als kit op de markt worden gebracht, is NEN-EN 13830 van toepassing met de daarin aangewezen beproevingsmethode NEN-EN 12155. In de prestatieverklaring van de kit is aangegeven welke waterdichtheidsprestatie met welk toepassingsgebied uit de CE-markering voortvloeit.

5.1 Procedure

De methode bestaat uit het uitvoeren van een proef volgens 5.3 en het verwerken van de resultaten volgens 5.4. De methode mag slechts worden gebruikt als is voldaan aan de in 5.2 gestelde voorwaarden.

Deze methode is niet zonder meer van toepassing op (delen van) scheidingsconstructies die met toepassing van de betreffende geharmoniseerde productnorm met CE-markering op de markt worden gebracht. Voor dergelijke (delen van) scheidingsconstructies geldt dat geacht wordt voldaan te zijn aan de waterdichtheidseis voor die gebruikssituaties waarvoor geldt:

— de gebruikssituatie komt overeen met de door de fabrikant aangegeven beoogde gebruikssituatie; en

— de maximale toetsingsdruk volgens tabel 2 is ten hoogste gelijk aan de maximale toetsingsdruk P_{max} in de bepalingsmethode die in de betreffende geharmoniseerde productnorm is aangewezen.

OPMERKING 1 Aangenomen is dat het betreffende bouwproduct is toegepast en geïnstalleerd conform de meegeleverde voorschriften van de fabrikant.

OPMERKING 2 Voor ramen en deuren is de verhouding tussen de classificatie en de maximale toetsingsdruk P_{max} beschreven in tabel 1 van NEN EN 12208:

Tabel 1 van NEN-EN 12208 – Classificatie

Maximale toetsingsdruk P_{max} (in Pa)	Classificatie (volledig blootgesteld)
150	4A
200	5A
250	6A
300	7A
450	8A
600	9A
750	E_{750}
900	E_{900}

OPMERKING 3 De verhouding tussen de classificatie en de maximale toetsingsdruk P_{max} is voor vliesgevels als volgt volgens tabel 2 van NEN EN 12154:

Tabel 2 van NEN-EN 12154 – Classificatie

Maximale toetsingsdruk P_{max} (in Pa)	Classificatie
150	R4
300	R5
450	R6
600	R7
750	RE_{750}
900	RE_{900}

5.2 Voorwaarden

— Voor de meting moet het beregeningstoestel op de plaats waar de meting zal plaatsvinden worden gekalibreerd volgens 5.3.3.3; het tijdsverloop tussen het voltooien van de kalibratie en de aanvang van de beproeving mag niet groter zijn dan 1 h.

— De temperatuur aan weerszijden van de constructie moet hoger dan of gelijk aan 5 °C zijn.

— Indien de scheidingsconstructie grenst aan een badruimte, mag vanaf 3 h vóór tot aan het einde van de proef geen gebruik van deze badruimte worden gemaakt.

5.3 Proef

5.3.1 Procedure

De proef moet worden uitgevoerd zoals beschreven in 5.3.4 met toestellen en hulpmiddelen vastgelegd in 5.3.3 en onder condities zoals verwoord in 5.3.2.

5.3.2 Condities

De temperatuur van het water moet hoger dan of gelijk aan 5 °C zijn.

De beproevingen mogen niet worden uitgevoerd bij hogere windsnelheden dan die waarbij de kalibratie van het beregeningstoestel heeft plaatsgevonden, tenzij het te beregenen oppervlak en het beregeningstoestel door middel van een hulpconstructie zijn beschermd tegen de invloed van windsnelheden die hoger zijn dan die waarbij de kalibratie heeft plaatsgevonden.

5.3.3 Toestellen en hulpmiddelen

5.3.3.1 Algemeen

De volgende toestellen en hulpmiddelen zijn vereist:

— een volgens 5.3.3.3 gekalibreerd beregeningstoestel;

— vier maatvaten met een volume van ten minste 1,5 l;

Appendix 5 Test procedure for testing watertightness of curtain walls according to NEN 12155

3.5
limit of watertightness
maximum test pressure for which the specimen remains watertight for the specified time (see Table 1, EN 12154:1999).

4 Principle

Application of a constant and specified quantity of water in a continuous film over the outside surface of the specimen with increments of positive static test pressures applied at set time intervals. The test operator shall note when and where any water leakage has occurred.

5 Apparatus

5.1 A chamber with an opening into which the test specimen can be fitted. This chamber shall be of sufficient strength and rigidity to withstand the test pressures likely to be imposed during the tests. It shall not deflect under test pressure to any extent which would affect the performance of the test specimen (figure 1).

Adequately representative structural supports shall be provided to which the specimen shall be attached in accordance with the conditions of use in the works (see also clause 6).

The chamber shall be constructed so that the air permeability through it, at pressures up to the maximum test pressure, does not exceed the permissible air permeability through the specimen at the same pressure.

5.2 A means for applying controlled positive test pressures to the test specimen.

5.3 A means by which rapidly controlled changes of positive test pressures may be produced within defined limits.

5.4 A means of measuring the positive test pressure, steady or fluctuating, calibrated within an accuracy of ± 5 %.

5.5 An adjustable device for spraying water at 2 l/m^2.min so that a constant and continuous film is applied to the outside surface of the specimen.

The water spraying device shall have nozzles spaced on a regular grid and at a uniform distance from the outside surface of the specimen (figure 2 and figure 3).

The local mains water supply will be an acceptable source providing it is clean enough to allow the spray nozzles to function properly throughout the test.

The nozzles shall include the following features:

- circular full cone spray;
- spray angle minimum 90° to maximum 120°;
- working pressure range 2 to 3 bars according to the manufacturer's specification.

5.6 A means of measuring the total amount of water supplied within an accuracy of 10%.

5.7 A drain for the sprayed water which will not interfere with the drainage of the specimen frame.

6 Test specimen

The specimen shall be submitted in a fully operable condition, ready for use. It shall be supplied in a suitable manner for fixing onto a test chamber. The test specimen shall not be less than two typical units wide and shall be sufficient to provide full loading on at least one typical vertical joint or framing member or both. The specimen shall not obtain additional stiffness from the test chamber. The height shall not be less than the full distance between the curtain wall's point of connection to the building structure.

For custom designed curtain walls or special elements, the specimen shall be a size which is adequate to demonstrate its compliance with the specified requirements.

All parts of the specimen shall be full size, using the same materials, details, methods of construction and fixing as intended for use in the works. Conditions for connection to the structural support shall simulate those in the works as accurately as possible (see also 5.1).

This standard does not apply to the perimeter joints between the curtain walling and the test chamber, or to the joints between the curtain walling and the building construction.

7 Test preparation

As this test follows that for air permeability then no further preparatory actions are required.

NOTE The sequence of tests as specified in prEN 13830:2000 should be followed.

8 Test procedure

Select the maximum test pressure (P_{max}) for classification according to EN 12154: 1999.

Apply 3 pulses of positive pressure equal to 500 Pa or 10% greater than the maximum test pressure (p_{max}) whichever is greater. The maximum pressure for each pulse should be reached in not less than 1 s and it should be maintained for not less than 3 s.

Operate the water sprays with 0 Pa test pressure and adjust the total flow to provide 2 l/m^2.m calculated from the area of the specimen under test.

After 15 minutes of spraying apply test pressure in the appropriate sequence specified in EN 12154:1999, Table 1, up to the selected maximum test pressure (P_{max}).

Constantly inspect the inside surfaces of the specimen for water leakage throughout the spraying period and record the test pressure, time and location of any leaks that are observed (figure 4).

9 Results

If water leakage is observed before the required maximum test pressure (P_{max}) has been applied for the specified time, record the test pressure and time for which it has been applied, when the leak is first observed.

Location of leaks (with identifying numbers, if there are more than one) shall be marked on an elevational scaled drawing of the specimen.

10 Test Report

Prepare a report to positively identify the specimen/s and record all parameters checked.

The report shall include the following details:

-Reference to this standard.

-Name of the testing institute.

-Persons or persons requesting the test.

-Details of test specimen/s as follows:

- Type/s of construction;
- Profile references ;
- Origin of materials;
- Type/s of materials;
- Date/s of manufacture, (if known).

-Dimensioned drawings of specimen/s;

-The results of the test;

-Product designation from manufacturer's literature;

-Observations as to the condition of the specimen/s;

-Date of test;

-Date of calibration of test chamber and equipment;

-Date of report;

-Signature of person preparing the report.

Appendix 6 Test procedure for airtightness of window frames according to NEN 3660

NEN 3660 – Blz. 2

3.10 *luchtdoorlatendheid*: Eigenschap van een te beschouwen object om lucht door te laten, indien over beide zijden een luchtdrukverschil aanwezig is.

Opmerking

De luchtdoorlatendheid wordt gekenmerkt door een volumestroom en wordt uitgedrukt in m^3/h als functie van het drukverschil.
Deze stroom kan worden gerelateerd, voor wat betreft de beweegbare delen, aan de lengte van de kieren en, voor de vaste delen, aan de lengte van de naden.

3.11 *naad*: Plaats tussen twee tegen elkaar aangesloten bouwdelen.

3.12 *niet-blijvende vervorming*: Verandering van vorm of afmetingen die ontstaan is door belasting en die herstelt nadat de belasting is weggenomen.

3.13 *toetsingsdruk*: Het drukverschil uit een reeks waarbij wordt bepaald of aan een gestelde eis wordt voldaan.

3.14 *verplaatsing ten opzichte van het vlak van het gevelelement*: Plaatsverandering van een punt van het gevelelement, gemeten loodrecht op en ten opzichte van het vlak van het gevelelement.

3.15 *voeg*: Al dan niet gevulde ruimte tussen twee aangesloten bouwdelen.

4 Beproevingsmethoden

4.1 Toestellen en hulpmiddelen

De beproevingsapparatuur bestaat uit:

a. een beproevingskast met een uitsparing in een van de wanden waartegen het te beproeven element wordt geplaatst, die zo stevig is, dat het de beproevingsdruk kan doorstaan zonder dat vervormingen ervan aanleiding kunnen geven tot beschadigingen van verbindingen of tot beïnvloeding van de meetresultaten;
b. een inrichting waarmee een gecontroleerd drukverschil tussen de beide zijden van het te beproeven element tot stand kan worden gebracht;
c. een inrichting waarmee wisselingen van het drukverschil tot stand kunnen worden gebracht, zoals in de figuur aangegeven;
d. een apparaat voor het meten van de volumestroom van de lucht;
e. een apparaat waarmee het verschil van de druk aan weerszijden van het proefelement kan worden gemeten.

4.2 Beproeving op luchtdoorlatendheid

4.2.1 *Gereedmaken van het proefelement*

Plaats het proefelement tegen de beproevingskast. Indien bekend is op welke wijze de gevelvulling op zijn plaats van bestemming zal worden verankerd, dient de verankering van het proefelement zoveel mogelijk de montagevoorschriften te volgen.
Indien onbekend is hoe de gevelvulling in het bouwwerk zal worden bevestigd, dienen de aanbevelingen van de fabrikant te worden aangehouden. Het proefelement moet te lood, haaks, vrij van scheluwte en doorbuiging worden opgesteld.
Het proefelement moet geheel worden gereinigd en gedroogd.
Voor de glasdikte, het soort glas en de wijze van beglazing dienen de aanbevelingen van de leverancier van het glas te worden gevolgd.
Indien voorschriften of aanbevelingen ontbreken ofwel de kans aanwezig is dat er verschillende ruiten in het proefelement zullen worden gebruikt, dient de proef te worden uitgevoerd met de minimum glasdikte die volgens NEN 2608 bij de oppervlakte van de gevelvulling behoort.

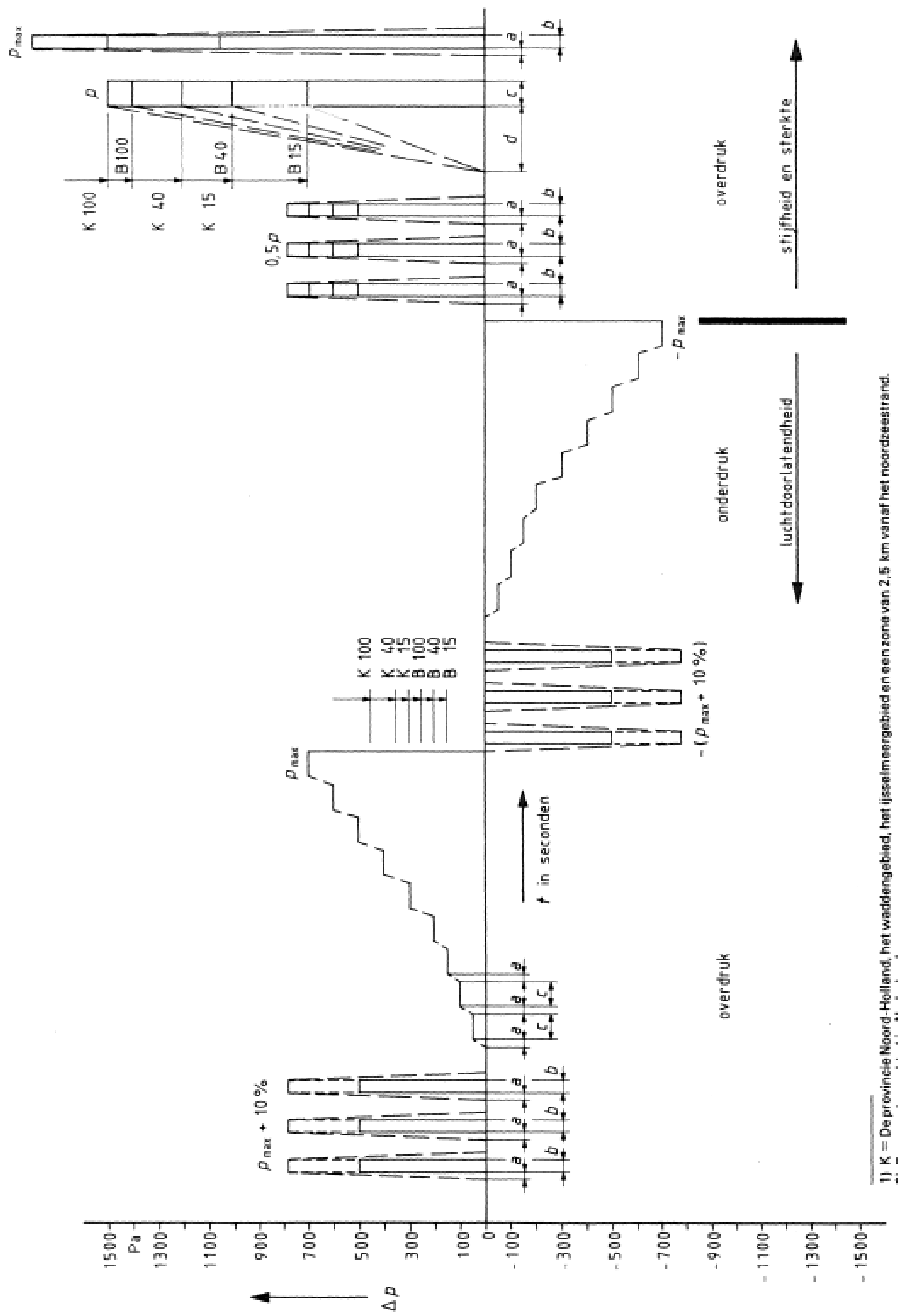
4.2.2 *Voorbereiding van de beproeving*

Meet de luchttemperatuur van het laboratorium en in de beproevingskast en vermeld deze in het rapport.
Belast het proefelement driemaal pulsgewijs met een positieve druk.
De gewenste druk mag niet binnen 1 s worden bereikt.
Deze druk dient gedurende 3s te worden gehandhaafd.
De druk van de pulsen, bedoeld om het proefelement zich te laten zetten, dient de toetsingsdruk met 10 % te overtreffen, maar moet ten minste 500 Pa bedragen.
Nadat de druk tot nul is teruggebracht, moeten alle beweegbare delen van het proefelement vijf maal worden geopend en gesloten en ten slotte worden vergrendeld.
Verder dient er aandacht te worden besteed aan de eventuele luchtverliezen van de beproevingskast zelf en van de aansluiting van het te beproeven element aan de beproevingskast.
Deze verliezen dienen, zo mogelijk, te worden voorkomen. Als ze echter wèl optreden, moeten ze worden bepaald door de luchtverliezen te meten nadat de kieren en naden van het proefelement zijn dichtgeplakt.

Opmerking

Bij droogbeglazing wordt de naad tussen glas en rubber en tussen rubber en het (metalen) omrandingsprofiel tot de naad gerekend, zodat bij droogbeglazing het aantal strekkende meter naad gelijk is aan tweemaal de omtrek van de ruit.

NEN 3660 – Blz. 3



Figuur – Het verloop van de drukken (p) bij beproevingen op luchtdoorlatendheid, stijfheid en sterkte

Hierbij dienen die drukverschillen te worden gekozen, waarmee het proefelement tijdens de beproeving op luchtdoorlatendheid zal worden belast. Met de hierbij gevonden waarden moet de oorspronkelijke waarde worden gecorrigeerd.
De apparatuur die dient voor het meten van het luchtverlies door het proefelement kan, eventueel aangevuld met andere meetinstrumenten, ook worden gebruikt voor het meten van de luchtverliezen van de proefkast.
In het rapport moet duidelijk worden aangegeven welke methode voor het bepalen van de luchtverliezen van de proefkast is gebruikt.

4.2.3 *Beproeving*

Onderwerp het proefelement aan positieve drukken, die in stappen van ten minste 10 s worden opgevoerd totdat de toetsingsdruk is bereikt. Ook de toetsingsdruk dient gedurende 10 s te worden aangehouden. De drukken bedragen: 50, 100, 150, 200, 300, 400, 500 en 600 Pa. Wanneer de toetsingsdruk, bij uitzondering, hoger is dan 600 Pa, bedragen de stappen vervolgens maximaal 250 Pa. Daarna dienen de drukken in tegengestelde volgorde te worden toegepast, zie figuur.
Indien het noodzakelijk is een proefelement in twee richtingen te beproeven op luchtdoorlatendheid, d.w.z. bij een negatieve druk, dient dezelfde werkwijze als voor positieve druk te worden toegepast. (Zie negatieve richting van de druk, uitgezet in de figuur).
Indien het noodzakelijk is een proefelement te beproeven op geconcentreerde lekken, dienen alle kieren, behoudens de te onderzoeken kier van 100 mm, luchtdicht te worden afgeplakt.
Meet bij toenemende druk, bij iedere stap de luchtverliezen.

4.2.4 *Weergaven der beproevingsresultaten*

Voor ieder proefelement moet de luchtdoorlatendheid bij de genoemde toetsingsdruk in $dm^3/(m \cdot s)$ worden gerelateerd aan 1 m kierlengte. Deze resultaten moeten in grafieken worden uitgezet. De grafieken moeten bij het rapport worden gevoegd.

4.3 Beproeving op stijfheid en sterkte

Deze beproeving bestaat uit twee aparte proeven met toetsingsdrukken volgens NEN 3661.

4.3.1 *Gereedmaken van het proefelement*

Volg hiervoor de procedure zoals beschreven in 4.2.1.

4.3.2 *Voorbereiding van de beproeving*

Meet de luchttemperatuur van het laboratorium en in de beproevingskast en vermeld deze in het rapport.
Belast het proefelement driemaal pulsgewijs met een positieve druk.
De gewenste druk mag niet binnen 1 s worden bereikt.
Deze druk dient gedurende 3 s te worden gehandhaafd.
De druk van de pulsen, bedoeld om het proefelement zich te laten zetten, dient de toetsingsdruk met 10 % te overtreffen, deze moet ten minste 500 Pa bedragen.

Nadat de druk tot nul is teruggebracht, moeten alle bewegende delen van het proefelement vijf maal worden geopend en gesloten en ten slotte worden vergrendeld.
Indien het wenselijk is de weerstand tegen positieve en negatieve drukken te onderzoeken, zullen de beide proeven achtereenvolgens eerst bij positief en daarna bij negatief drukken worden uitgevoerd.
Aan de meting van verplaatsingen bij negatieve druk dienen drie negatieve pulsen vooraf te gaan.

4.3.3 *Beproeving*

4.3.3.1 *Beproeving op stijfheid*

Breng de apparatuur aan voor het bepalen van de stijfheid.
Belast het proefelement door de druk geleidelijk op te voeren, totdat de maximaal vereiste druk (p) voor deze beproeving is bereikt en meet hierbij de verplaatsing ten opzichte van het vlak van het proefelement op voor dit element kenmerkende plaatsen. Indien de vervorming bij deze maximale druk groter is dan de toelaatbare vervorming, dient de druk met stappen van 100 Pa te worden verminderd.
Bij iedere stap dient de vervorming te worden gemeten. Het verminderen van de druk met stappen van 100 Pa dient door te gaan totdat de gemeten vervorming gelijk is aan of kleiner is dan de hieraan gestelde eis in NEN 3661.

Het vergelijkingsvlak voor de meting is een vlak door de meetpunten bij de opleggingen.
Wanneer de druk tot nul is teruggebracht, dienen de blijvende vormveranderingen te worden vastgesteld.

4.3.3.2 *Beproeving op sterkte*

De vereiste maximale druk (p) dient zo snel mogelijk, doch niet binnen 1 s, te worden bereikt en dient gedurende 3 s te worden gehandhaafd. Iedere waargenomen blijvende vervorming, beschadiging of mankement aan de normale functie van het proefelement dient te worden vermeld in het beproevingsrapport.

4.4 Weergaven der beproevingsresultaten

De meetpunten dienen op een schets van het proefelement te worden aangegeven. De resultaten van de beproevingen op vormveranderingen dienen zo nodig voor ieder meetpunt grafisch te worden uitgezet als functie van het drukverschil. Blijvende vormveranderingen dienen te worden aangegeven.
Bijzonderheden die tijdens de beproevingen worden waargenomen dienen te worden vermeld en bovendien te worden aangegeven op de schets van het proefelement.
De grafieken die het verloop in de tijd van de drukken van de beproeving op sterkte tonen, dienen aan het rapport te zijn toegevoegd.

5 Verslag

Het verslag dient ten minste de volgende gegevens te bevatten:

a. schema van de beproevingsapparatuur;
b. detailtekening van de bevestiging van het proefelement tegen de beproevingskast;
c. temperatuur van de lucht in het laboratorium en in de beproevingskast;
d. korte beschrijving van het proefelement die ten minste de volgende gegevens moet bevatten:
- samenstelling van de gevelvulling met de daarin voorkomende raamtypen;
- materialen en eventueel de oppervlaktebehandeling;
- relevante afmetingen in mm;
- oppervlakte van het beweegbare deel in m^2;
- kierlengte in mm;
- eventueel afdichtingsmateriaal (met opgave van type);
- glasdikte en beglazingssysteem;
- hang- en sluitwerk;

en in een bijlage:
- tekening van het proefelement, inclusief hang- en sluitwerk;
- horizontale en verticale doorsneden, waarin de positie is aangegeven van tochtstrippen en eventueel afdichtingsmateriaal;

e. beproevingsresultaten van de beproevingen volgens 4.2 en 4.3;
f. een verwijzing naar deze norm, door vermelding: "volgens NEN 3660".

Appendix 7 Test procedure for airtightness of curtain walls according to NEN 12153

1 Scope

This standard defines the method to be used to determine the air permeability of curtain walling, both its fixed and openable parts. It describes how the specimen shall be tested under positive and negative air pressure.

NOTE : This standard applies to any curtain walling product as defined in prEN 13830:2000.

2 Normative References

This European Standard incorporates by dated or undated reference, provisions from other publications. These normative references are cited at the appropriate points in the text and the publications are listed hereafter. For dated references, subsequent amendments to or revisions of any of these listed publications apply to this European Standard only when incorporated into it by amendment or revision. For undated references the latest edition of the publication referred to applies.

prEN 12152: 1999 Curtain walling - Air permeability - Performance requirements and classification.

prEN 13119: 1997 Curtain walling - Terminology.

3 Definitions

For the purposes of this standard, the definitions given in prEN 13119: 1997, together with the following, apply:

3.1
test pressure
Differential pressure between the two faces of the test specimen, expressed in Pascals (Pa).

3.2
positive pressure
When outer face is subjected to higher pressure than inner face.

3.3
negative pressure
When inner face is subjected to higher pressure than outer face.

3.4
air permeability
Passage of air through the construction of the curtain walling when subjected to air pressure.

The volume being expressed as a rate in cubic metres per hour (m^3/h), this rate being related to the overall area of the curtain walling. Alternatively, the rate can be related to the metre length of joint.

3.5
fixed joint
All joints except those between openable parts of the curtain wall.

Where a window is incorporated in the specimen it shall be considered as a panel for the purpose of the fixed joint calculation.

3.6 Fixed joint length
Sum of the perimeters of all fixed and openable panels (windows) within the specimen, having regard to the position of the principle air barrier.

3.7 openable joint length
Sum of the perimeters of all moving frames within the test specimen.

3.8 overall area
Sum of the areas of all the faces of the specimen that are enclosed within the test chamber, measured parallel to all fixed and openable panels (see figure 2). It shall be expressed in square metres (m^2).

4 Principle

Application of increasing and decreasing pressure steps (positive or negative) with measurements of air flow at each test pressure.

5 Apparatus

5.1 A chamber with an opening into which the test specimen can be fitted. This chamber shall be of sufficient strength and rigidity to withstand the test pressures likely to be imposed during the tests. It shall not deflect under test pressure to any extent which would affect the performance of the test specimen (see figure 1).

Adequately representative structural supports shall be provided to which the specimen shall be attached in accordance with the conditions of use in the works (see also clause 6).

The chamber shall be constructed so that the air permeability through it, at pressures up to the maximum test pressure, does not exceed the permissible air permeability through the specimen at the same pressure.

5.2 A means for applying controlled positive (or negative) test pressures to the test specimen.

5.3 A means by which rapidly controlled changes of positive (or negative) test pressures may be produced within defined limits.

5.4 A means of measuring the air flow into the chamber within an accuracy of ± 5 % in order to enable the quantity of air permeability through the specimen to be assessed within an accuracy of 10% of the permissible air permeability through the specimen.

5.5 A means of measuring the positive (or negative) test pressures, steady or fluctuating, calibrated within an accuracy of ± 5 %.

5.6 A temporary means of sealing all joints of the specimen during the determination of test chamber leakages.

6 Test specimen

The specimen shall be submitted in a fully operable condition, ready for use. It shall be supplied in a suitable manner for fixing onto a test chamber. The test specimen shall not be less than two typical units wide and shall be sufficient to provide full loading on at least one typical vertical joint or framing member or both. The specimen shall not obtain additional stiffness from the test chamber. The height shall not be less than the full distance between the curtain wall's point of connection to the building structure.

For custom designed curtain walls or special elements, the specimen shall be a size which is adequate to demonstrate its compliance with the specified requirements.

All parts of the specimen shall be full size, using the same materials, details, methods of construction and fixing as intended for use in the works. Conditions for connection to the structural support shall simulate those in the works as accurately as possible (see also 5.1).

This standard does not apply to the perimeter joints between the curtain walling and the test chamber, or to the joints between the curtain walling and the building construction.

7 Test preparation

Build the test specimen into the test chamber.

Fix true to the normal attitude of use in both directions, level, square and without visible twist or bend as a result of the application of fixing devices.

Remove all transport blocks, bracings or packings and protective wrappings.

Tape all openable joints to prevent air infiltration.

Tape seal any ventilation devices, where these may occur.

Ensure any leakage through all points, including frame joints, is readily detectable.

Ensure all joints between the test specimen and the test chamber are sealed.

Ensure the specimen is clean prior to commencing the test sequence.

8 Test procedure

For classification, select the maximum test pressure (P_{max}) according to prEN 12152:1999.

Apply test pressures, throughout the following procedures, in increments of 50 Pa up to 300 Pa and increments of 150 Pa up to the maximum test pressure (figure 3).

Appendix 8 List of Most Suitable Glass Laminate Configurations

Choice No.	1st glass thickness t_1 [mm]	PVB thickness t_2 [mm]	2nd glass thickness t_3 [mm]	PVB Type p_2	final value [%]	
1	0.55	0.38	0.55	E5	-43,8	
2	0.55	0.38	0.55	E4	-40,6	
3	0.55	0.38	0.55	E3	-40,4	
4	0.55	0.38	0.55	E2	-40,35	
5	0.55	0.38	0.55	E1	-40,33	
6	0.85	0.38	0.55	E5	-37,4	
7	0.85	0.38	0.55	E4	-34,2	
8	0.85	0.38	0.55	E3	-34	
9	0.85	0.38	0.55	E2	-33,95	
10	0.85	0.38	0.55	E1	-33,93	
11	1.1	0.38	0.55	E5	-30,9	
12	1.1	0.38	0.55	E4	-27,7	
13	0.55	0.76	0.55	E5	-27,6	
14	1.1	0.38	0.55	E3	-27,5	
15	1.1	0.38	0.55	E2	-27,45	
16	1.1	0.38	0.55	E1	-27,43	
17	0.55	0.76	0.55	E4	-24,4	
18	0.55	0.76	0.55	E3	-24,2	
19	0.55	0.76	0.55	E2	-24,15	
20	0.55	0.76	0.55	E1	-24,13	
21	0.85	0.76	0.55	E5	-21,2	
22	0.85	0.38	0.85	E5	-19,6	
23	0.85	0.76	0.55	E4	-18	
24	0.85	0.76	0.55	E3	-17,8	
25	0.85	0.76	0.55	E2	-17,75	
26	0.85	0.76	0.55	E1	-17,73	
27	0.85	0.38	0.85	E4	-16,4	
28	0.85	0.38	0.85	E3	-16,2	
29	0.85	0.38	0.85	E2	-16,15	
30	0.85	0.38	0.85	E1	-16,13	
31	1.1	0.76	0.55	E5	-14,7	
32	1.1	0.38	0.85	E5	-13,1	
33	1.1	0.76	0.55	E4	-11,5	
34	1.1	0.76	0.55	E3	-11,3	
35	1.1	0.76	0.55	E2	-11,25	
36	1.1	0.76	0.55	E1	-11,23	
37	1.1	0.38	0.85	E4	-9,9	
38	1.1	0.38	0.85	E3	-9,7	
39	1.1	0.38	0.85	E2	-9,65	
40	1.1	0.38	0.85	E1	-9,63	
41	0.85	0.76	0.85	E5	-3,4	
42	0.85	0.76	0.85	E4	-0,2	
43	0.85	0.76	0.85	E3	0	reference
44	0.85	0.76	0.85	E2	0,05	

Choice No.	1st glass thickness t_1 [mm]	PVB thickness t_2 [mm]	2nd glass thickness t_3 [mm]	PVB Type p_2	final value [%]
45	0.85	0.76	0.85	E1	0,07
46	1.1	0.38	1.1	E5	0,2
47	1.1	0.76	0.85	E5	3,1
48	1.1	0.38	1.1	E4	3,4
49	1.1	0.38	1.1	E3	3,6
50	1.1	0.38	1.1	E2	3,65
51	1.1	0.38	1.1	E1	3,67
52	0.55	1.52	0.55	E5	5
53	1.1	0.76	0.85	E4	6,3
54	1.1	0.76	0.85	E3	6,5
55	1.1	0.76	0.85	E2	6,55
56	1.1	0.76	0.85	E1	6,57
57	0.55	1.52	0.55	E4	8,2
58	0.55	1.52	0.55	E3	8,4
59	0.55	1.52	0.55	E2	8,45
60	0.55	1.52	0.55	E1	8,47
61	0.85	1.52	0.55	E5	11,4
62	0.85	1.52	0.55	E4	14,6
63	0.85	1.52	0.55	E3	14,8
64	0.85	1.52	0.55	E2	14,85
65	0.85	1.52	0.55	E1	14,87
66	1.1	0.76	1.1	E5	16,4
67	1.1	1.52	0.55	E5	17,9
68	1.1	0.76	1.1	E4	19,6
69	1.1	0.76	1.1	E3	19,8
70	1.1	0.76	1.1	E2	19,85
71	1.1	0.76	1.1	E1	19,87
72	1.1	1.52	0.55	E4	21,1
73	1.1	1.52	0.55	E3	21,3
74	1.1	1.52	0.55	E2	21,35
75	1.1	1.52	0.55	E1	21,37
76	0.85	1.52	0.85	E5	29,2
77	0.85	1.52	0.85	E4	32,4
78	0.85	1.52	0.85	E3	32,6
79	0.85	1.52	0.85	E2	32,65
80	0.85	1.52	0.85	E1	32,67
81	1.1	1.52	0.85	E5	35,7
82	1.1	1.52	0.85	E4	38,9
83	1.1	1.52	0.85	E3	39,1
84	1.1	1.52	0.85	E2	39,15
85	1.1	1.52	0.85	E1	39,17
86	1.1	1.52	1.1	E5	49
87	1.1	1.52	1.1	E4	52,2
88	1.1	1.52	1.1	E3	52,4
89	1.1	1.52	1.1	E2	52,45
90	1.1	1.52	1.1	E1	52,47

Appendix 9 Magnet Types and Working Principles (docmagnet.com)

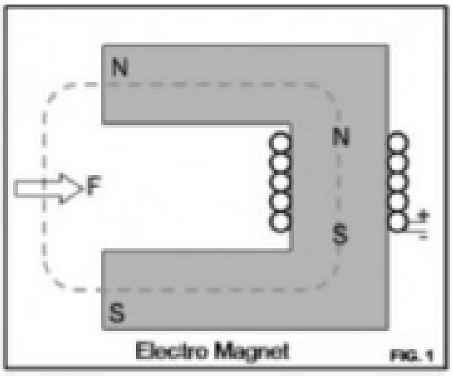
Electro Magnets

A simple electro magnet shown (fig.1) incorporates a coil of N turns wrapped around a ferromagnetic steel horseshoe.

Direct current is applied to the coil which creates a magnetic force perpendicular to the coil.

Magnetic flux passes through the poles of the horseshoe which will then influence any ferromagnetic material that comes within the field area.

Electro magnets can be very powerful, more turns on the coil and or more current generates more force: MMF = I x T.



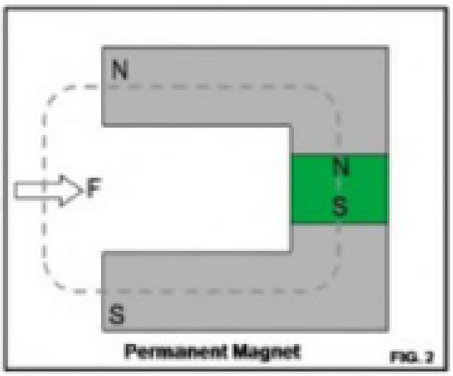
The magnetic field is removed from the poles the moment the current is removed from the coil.

Permanent Magnets

In the case of a simple permanent magnet design, the horseshoe is interrupted with a permanent magnet.

The permanent magnet material would likely exhibit high coercivity (difficult to demagnetize), Rare-Earth, for example.

As its name suggests, magnetic flux is always flowing from north to south. The horseshoe allows the flux to concentrate over the pole areas and influence any ferromagnetic material that comes within the field area.



With permanent magnets, MMF is increased as the magnetic length of the raw material is increased.

In this illustration the magnetic field is always present and cannot be removed*. A high-coercive permanent magnet is very difficult to demagnetize, therefore, if we want to make it switchable, we need some method of redirecting the flux away from the pole surfaces.

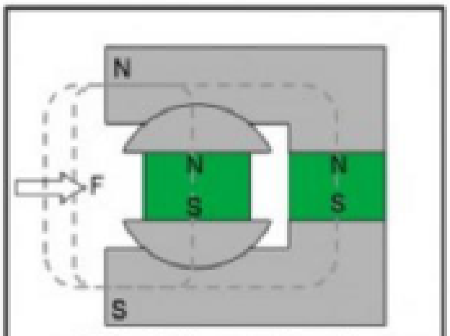
Switchable Permanent Magnets

In Fig. 3 we have introduced a second permanent magnet of equal proportions into the circuit. This has the benefit of providing twice the amount of flux which increases the density of the field, creating an even greater attractive force when in the ON condition.

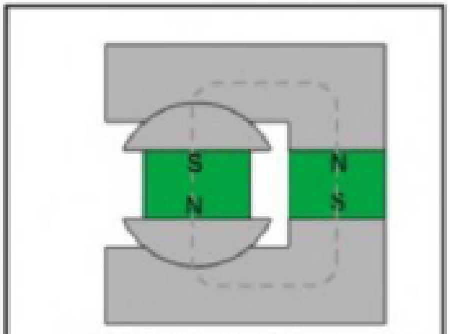
More important, the second magnet is free to rotate which changes the overall state of polarity.

As can be seen in Fig. 4, when the second magnet has been rotated, the flux emanating from both raw magnets has a better route to travel from one pole to the other, and is now diverted away from the pole surfaces placing the unit in an OFF condition.

Switchable permanent magnets can be very powerful and have the benefit over electro-magnets of better safety since there are less external factors that can affect performance*. However, there comes a point when the physical friction of moving a magnet becomes impractical and expensive to solve. Permanent-electro magnets combine the benefits of both electro and permanent magnet technology.



Switchable Permanent Magnet FIG. 3



Switchable Permanent Magnet FIG. 4

Permanent-Electro Magnets

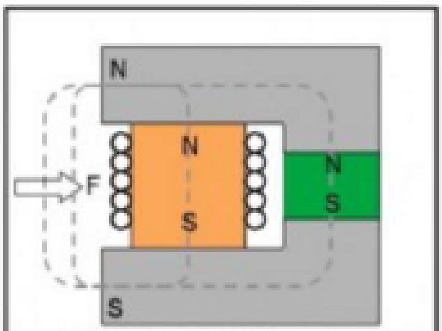
In Fig. 5 we have replaced the moving magnet with a static low coercive one.

By placing a coil around this magnet and using a short electromagnetic field, this magnet can be energized fully.

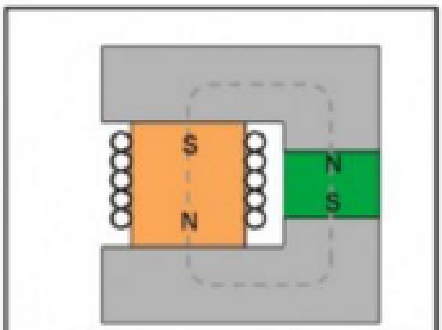
In the ON condition, as with the previous permanent magnet, flux from both magnets are combined and directed through to the poles surfaces. In the OFF Condition, the coil is re-energized in the opposite direction, thus re-magnetizing the magnet to opposite polarity.

Magnetic flux from both magnets is now re-routed internally leaving the pole surfaces free of magnetism.

Permanent-electro magnets, require electricity only for the switching process (<0.5 secs). They can be very powerful, they don't generate heat and have no moving parts.



Permanent-Electro Magnet FIG. 5



Permanent-Electro Magnet FIG. 6

** High Coercive magnets can be influenced externally, either by high temperatures and/or by influence of high electro-magnetic fields.*

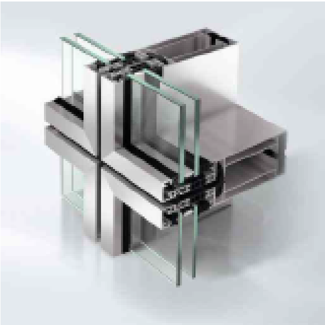
Appendix 10 Schüco USC 65

SCHÜCO

Fabricators › Products › Façades › **USC 65**

‹ Overview Remember product

Schüco Façade USC 65



DESCRIPTION PRODUCT BENEFITS FABRICATION BENEFITS

Unitised curtain wall with high level of cost-effectiveness, functionality as well as an attractive appearance – and façade bracket for universal load connection

The design of the Schüco Façade USC 65 (Unitised System Construction) is flexible and can be fabricated efficiently. With its all-round narrow face width of only 65 mm as well as maximum unit weights up to 500 kg, it enables large architecturally appealing façade constructions. An additional benefit: with the façade bracket made from glass fibre-reinforced plastic, loads such as solar shading systems can be connected safety and without thermal bridges. The approval is pending for this energy-efficient solution, which is free of condensation, on the basis of numerous tests.

With its three design options, Schüco USC 65 offers maximum design freedom to create highly sophisticated architecture: Schüco USC 65 F as unitised façade with framed look, Schüco USC 65 FSG in structural glazing look with horizontal or vertically arranged glazing beads.

For using opening units in unitised façades, there is a wide range of Schüco windows from the AWS to the super-insulated Schüco AWS 114 SG.SI series.

GALLERY +

DOCUMENTATION

TECHNICAL INFORMATION