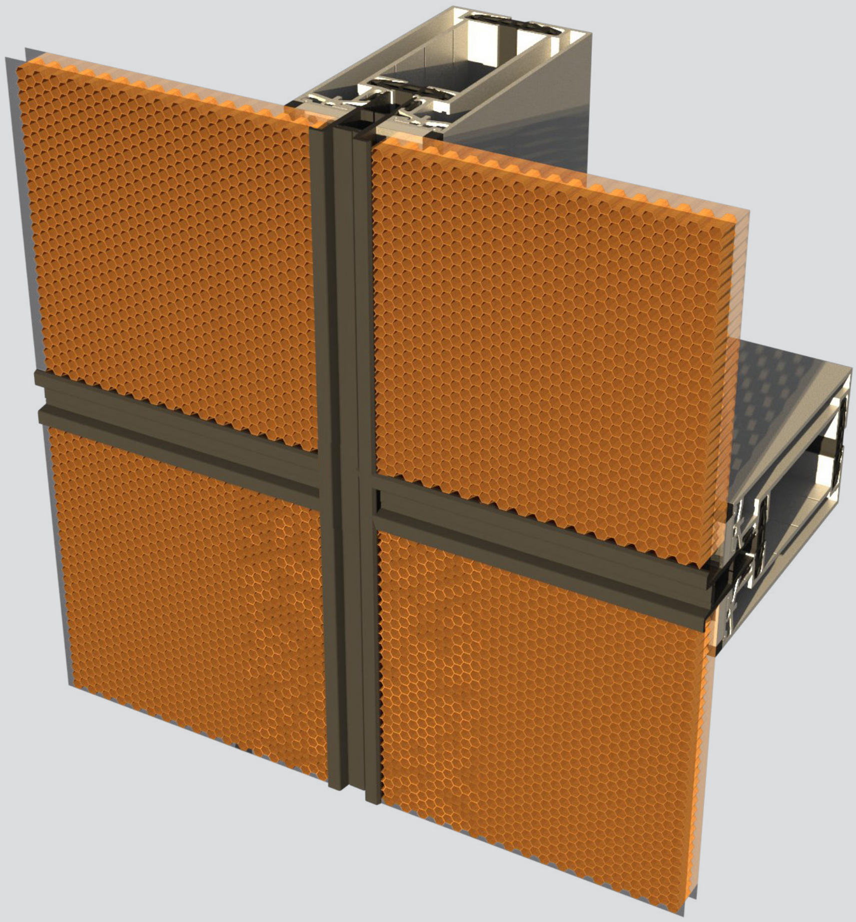
Ultra lightweight, insulating **thin glass** facade panel



TU Delft

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Abstract

Nowadays it is a top priority in the building sector to reduce the energy use and carbon emissions. One of the most important strategies to reduce the carbon dioxide (CO2) emissions in buildings is by increasing the thermal performance of its envelope. To achieve this, a low thermal transmission should be established. Glazed surfaces typically account for about 30 to 50 percent of transmission losses through building envelopes. Improving these products therefore could save an significant amount of energy. Unfortunately, at the moment double and triple glazing is often applied. With each layer of glass, a substantial amount of weight is added. Because of this, the support construction is facing its mechanical limits.Therefore, this thesis focusses on designing an insulating façade system with thin glass.

Thin glass is very lightweight, but also very flexible which is unfavorable in a façade. Inspiration was found by analyzing the stiffening methods that are currently used in the glass industy. But the most suitable stiffening method was found in the industry where lightness matters most, aerospace engineering. A honeycomb sandwich turned out to be most lightweight stiffening method, while also transmitting light and increasing the thermal insulation value.

The result of this graduation project is a thin glass – aramid honeycomb – thin glass sandwich panel. In comparison to the façade of the choosen case study, the weight of the façade and the support construction is reduced substantially while providing integrated sun shading, sufficient insulation (U-value of 1.4 W/m2K) and light transmission.

Acknowledgement

To be able to complete my masters' degree I would first like to thank my family, for their unconditional love, their support and the possibilities they provided for me.
During my studies, I have met lots of people who enriched my study experience in Delft. Some, have become friends for life, to those of you, I would like to say thank you for your presence in my life, your support and the joy you brought into my life.

In addition, I am grateful for my tutors: Christian Louter and Marcel Bilow. Chrisitan has shared his wide knowledge on glass, its possible connections and bonding methods. He helped me with exploring alternatives and eventually make this research reach a scientific level. Marcel has inspired me, gave me great advice and kept me positive during the whole process, therefore I am very grateful.

Also I would like some external professionals who helped me. First of all, I would like to thank INHolland Composites for sharing their knowledge on sandwich panels and bonding methods. Secondly, I would like to thank MCtechnics for providing honeycomb sandwich sheets. Because of their generosity I was able to test the mechanical properties and the physical appearance of the sandwich panel.
Finally I would like to thank AGC for the thin glass samples and Victor Horbowiec, who works at the Aerospace Structures and Materials Laboratory. Without them I would not have been able to create my final model.

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01

Research framework

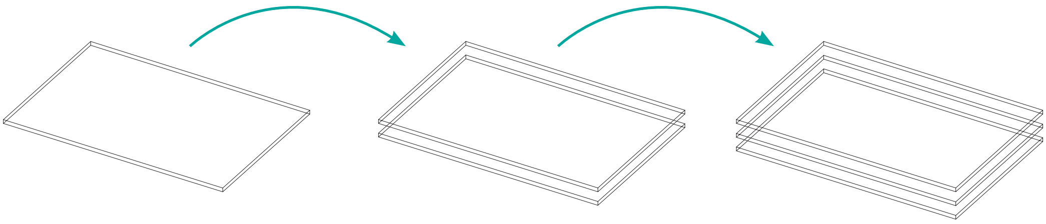
In this chapter, the outline of the research is set out. This includes the problem statement, research objectives, hypotheses, design criteria and research questions. Within this research the option of implementing thin glass in the built environment in explored. First a short introduction of the material will be given, followed by references in which thin glass is implemented. Which will lead to the scientific, environmental and economic relevance of this project.
In order to answer the research questions, the research approach and methodology are explained.


photo: by AGC

1.1 Research outline

Historically, glass has been applied in buildings to provide a view and enable sunlight to enter. At the moment, there are several additional performance requirements for glass surfaces. Thermal insulation regulations are increasing because of comfort and energy saving. Single glass panels are no longer sufficient according to the Dutch building code. According to this code, nowadays an U-value of at least 2.2 W/m2K must be achieved. Therefore double- and even triple glass panels are used in facades, causing the weight of the facade to increase enormously.

Note: Weight is calculated for a thickness of 6 mm



Single glazing	Double glazing	Triple glazing
Insulation value [m^2K/W]	Insulation value [m^2K/W]	Insulation value [m^2K/W]
0.18	0.55 - 0.33	1.25
Weight [per m^2]	Weight [per m^2]	Weight [per m^2]
15 kg	30 kg	45 kg

Figure 1.1: Problem statement, increasing weight glass facades.
Source: by author.

The ratio of glazed versus non-glazed surfaces has increased, plenty of realized buildings show a fully glazed skin. The current tallest building in the world, the Burj Khalifa is an example of such a building, figure 1.2. Especially when it comes to high rise buildings, double- or triple glazing results in a facade with an enourmous amount of weight.

Figure 1.2: Burj Khalifa, fully glazed facade.
Source: A. Lanfermeijer

Facade requirements

Glass facades no longer only provide a view and (sun)light transmittance. Another important requirement of a glass facade is safety. Broken glass pieces could possibly cause a lot of harm, because glass is a brittle material, the scenario of breakage should be considered during transport and use. And finally a glass facade should also provide thermal insulation, as stated above.

Problem statement

While thermal insulation has got inevitable in terms of a building's energy performance it should also be taken into account that glass is a material with a large amount of embodied energy which is due to its production process. The thinner the glass sheets, the less material, the smaller its embodied energy and amount of emission. This leads to the main problem statement of this thesis: Glass surfaces are becoming increasingly heavy in the built environment by inevitable increasing insulation regulations.

The hypothesis is that the usage of thin glass in the built environment could save a substantial amount of weight while complying with the insulation regulations.

Another problem is found in the excessive solar gain of glass surfaces. The transparency of glass creates the possibility for sunlight to transmit though the material and heat the surfaces behind it. Excessive solar gain could result in overheated buildings, thus discomfort for its users. With bright sunlight, this could result in glare. Depending on the function, glare prevention should be taken into account. To do so, either coatings or sunshading should be considered when designing a facade. To provide comfort and reduce energy use, solarshading should be provided within the panel.

Design criteria

The first boundary condition is provided by the location of the project. Especially in temperate climates, such as in the Netherlands, the need for insulating glass is inevitable. For this reason, a case study in the Netherlands is selected as the location for this research. The Dutch building code (Bouwbesluit, 2015) provides the insulation regulations of the panel. In the Netherlands the minimum required U-value is 2.2 W/mK. However, in order to achieve a better competitive position in the market, this project aims to achieve a U-value of at least 1.4 W/mK (figure 1.3).

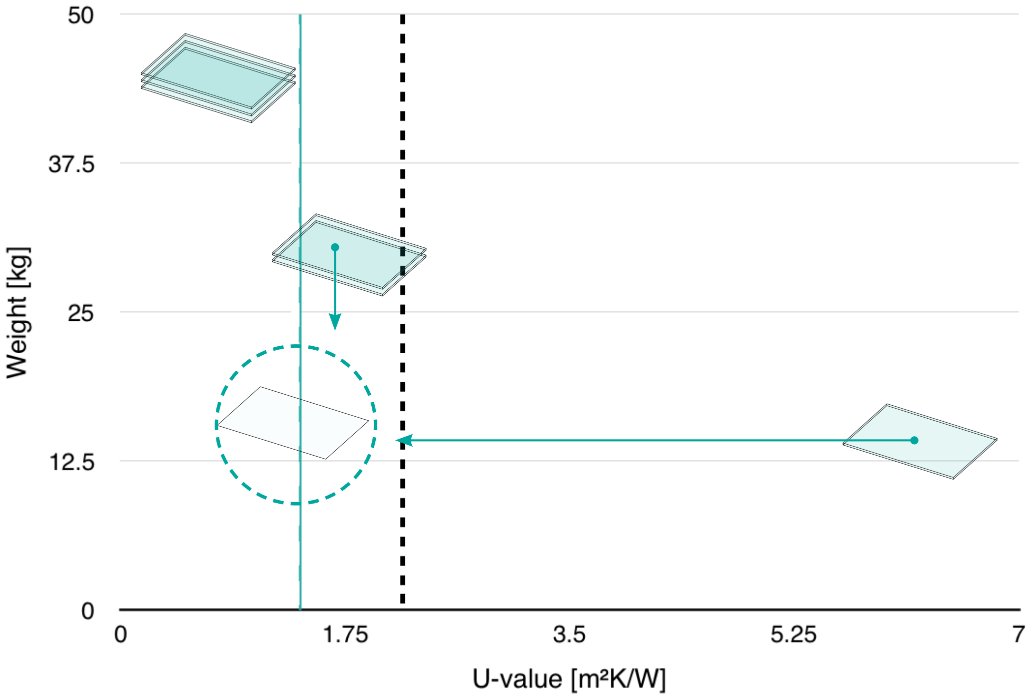


Figure 1.3: Design criteria. Recuding weight while achieving a u-value of 1.4 m2K/W
Source: by author.

The regulations regarding stiffness and safety are provided by the serviceability limit state (SLS) and the ultimate limit state (ULS). Especially when working with glass, the SLS and ULS are very important when designing a facade panel. For glass, both these criteria are defined by the building norm; NEN-2608. It describes the risks and deflecion which are allowed when building with glass. Considering the breakage scenario, the risk of injury, probability, exposure to risk and severity of the consequences of breakage should be considered.

Since thin glass is very slim, it presents flexible behaviour which is inconvenient and unusual in façade panels. In order to apply thin glass in the built environment, a stiffening method must be found in order to comply with the allowed deflection.

The methods used, to manufacture the panel should all be established, meaning that the final design could easily be produced. No experimental methods are therefore explored in this thesis.

1.2 Objectives

Starting with current insulating glass units, several problems have been found. Within this research, the large weight of current insulating glass units and its lack of solar shading are considered to be the biggest challenges.
This leads to the main research question of this thesis: Can thin glass be applied in a facade panel meeting the insulation- and stiffness- and safety requirements?
Supported by the sub-questions:
- What are the material properties of thin glass?
- What are its manufacturing and processing possibilities?
- What glass stiffening- and insulation methods can be found in precedents?
- What sandwich panels are currently on the market?
- What are the Dutch regulations on safety, stiffness and thermal insulation value?
- Can the required insulation value be achieved with a thin glass façade panel?
- Can the required stiffness of a glass panel be achieved with a thin glass façade panel?
- How much is the weight reduction that can be achieved by the of the panels and its support structure in comparison to traditional methods?

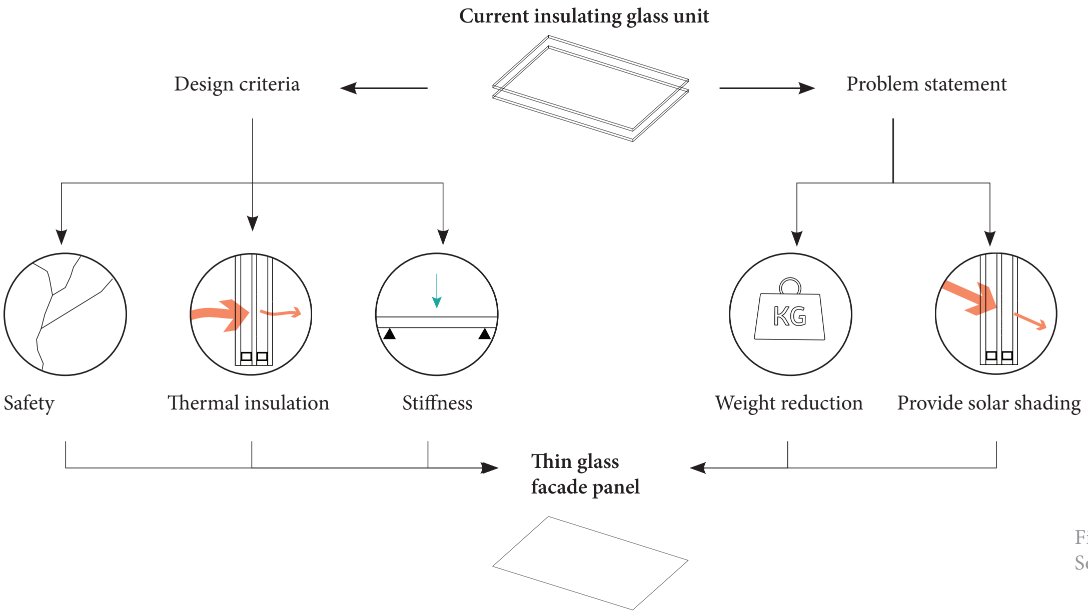


Figure 1.4: Research objectives.
Source: by author.

The general objective of this research is to design a lightweight, façade panel with thin glass complying with the insulation regulations. It should be is safe, provide light transmittance and solar shading. The final product of this thesis is a fully detailed thin glass facade system which could, in theory, be built and applied in the built environment. In order to accomplish this, established methods of designing an insulating panel are to explored.
Because thin glass is quite flexible, stiffening methods are found in order to comply with the regulations. In current applications of soda lime glass and other sheet materials/products stiffening methods can be found.

1.3 Approach & methodology

In order to design an insulating facade panel with thin glass the geometry should be defined. To do so, the material glass, and its processing possibilities are explored. The glass panel should comply with the criteria that is defined by the case study. And, the panel, that will be designed by this research should fit in the architectural concept (figure 1.5).

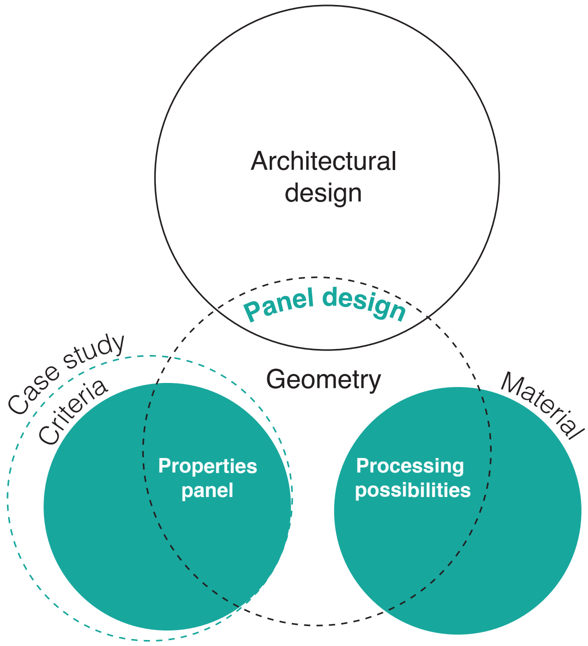


Figure 1.5: Research approach.
Source: by author.

The material properties of both (regular) soda lime glass and thin glass are explored in this thesis. The difference between (regular) soda lime glass and thin glass are set out, and their production and processing possibilities are explored.

Followed by a case study, which fits within the scope of this research. The location of the case study, its performance demands and gridsizes define the requierements for thermal insulation, light transmittance strenght, stiffness and safety the panel. The properties of the panel should comply with both the building codes and the criteria defined by the case study.

Several geometries should be calculated for its mechanical and thermal performance. Suitable configurations and details are explored and calculated for their weight, stiffness (SLS) and strength (ULS). Some geometries are be calculated for its mechanical properties by finite element analysis, some are subjected to actual bending tests. Also other physical tests are performed to explore bonding methods, proper attachment methods and pleasing optical quality.

Results on the stiffness of the panel are to be analyzed, simultaneously with the insulation and light transmittance. When the geometry meets the criteria, the detailing of the panel, the support construction, and interconnections may start in order to come to a panel design which fits within the lightweight concept of this project. A step-by-step overview of the research steps and methodology is shown in figure 1.6. It displays all methods and their corresponding subjects from literature study to final design.

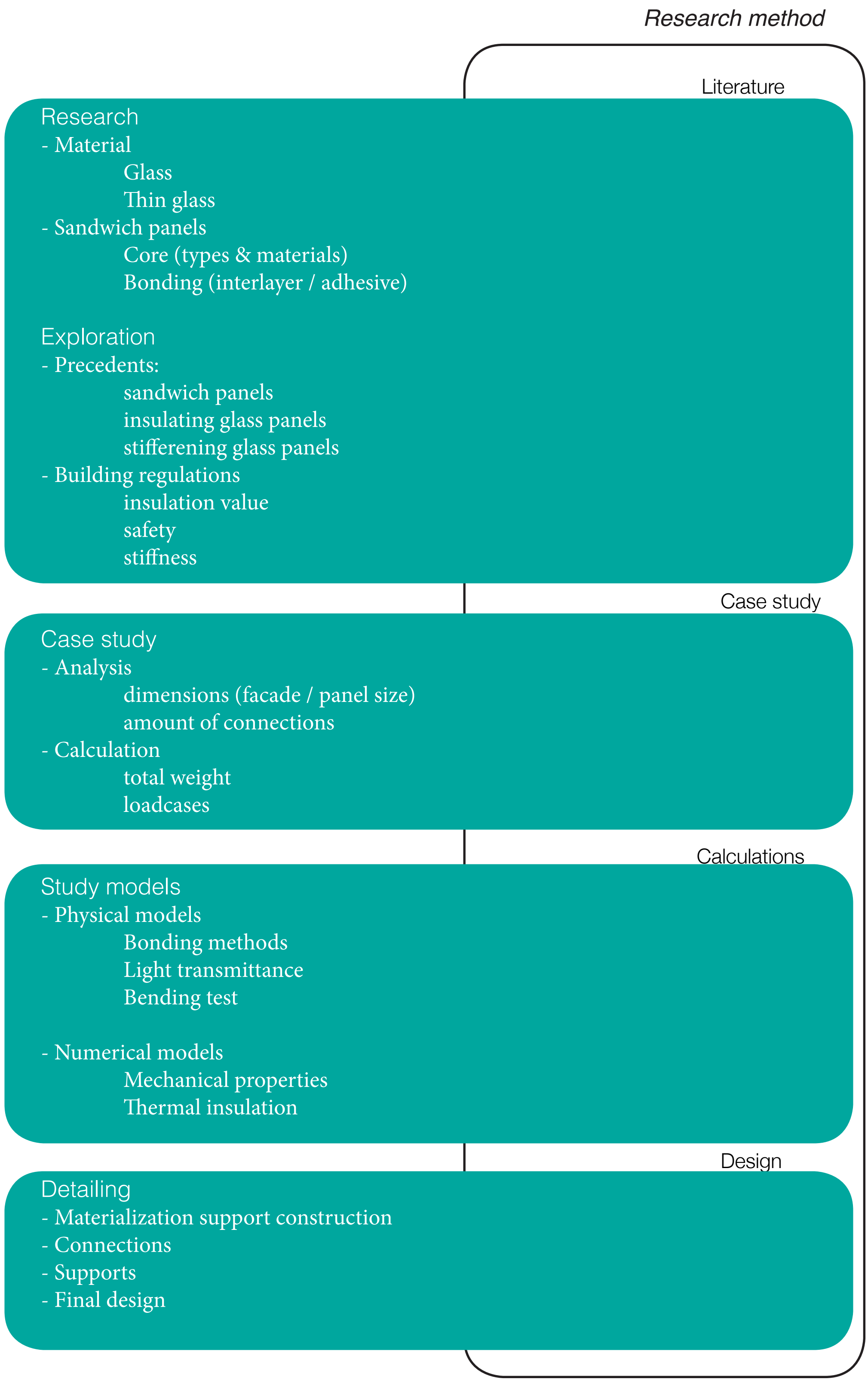


Figure 1.6: Research topics and methods.
Source: by author.

1.4 Material introduction

If a glass sheet is produced thinner than 2 mm it is called thin glass, when its thickness goes below 0.1 mm it may be called ultra thin glass. (Ultra) thin glass has been present in the daily life of people for quite some time. It is a material that is, until now, applied to protect mobile electronics screens from scratches and impact. Only a few thin glass applications and experiments have been done within the built environment, thin glass is still in its first steps.

References

The increasing regulations for low thermal transmittance and development the of passive housing systems increased the demand of high insulating windows. When the insulation value increases by using several layers of glass with a cavity in between, also the weight increases. The demand for insulation caused the European commission to fund a project in which the feasibility of quadruple glass windows, with two thin glass layers, is studied. The panel reaches a U-value of 0.3 W/m2K.

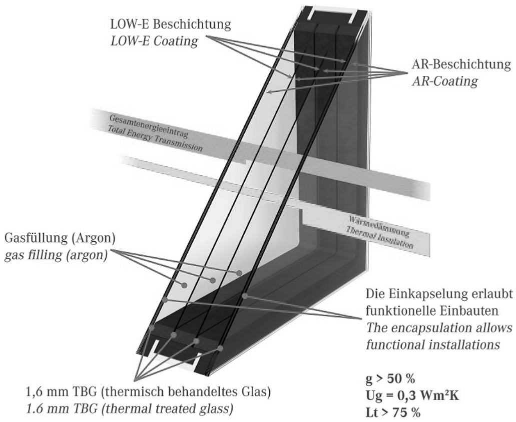


Figure 1.7 (right): insulation glass panel with thin glass sheets.. Source: Glassweb (2016)

Figure 1.8 (left): indoor application thin glass. Source: Corning (2015)

Another application is found by one of the main producers of thin glass: Corning. The impact and scratch resistance of thin glass together with its optical qualities make it possible for usage as a protective layer in interior architecture. By using thin glass as an external layer laminated onto panels the behind it, high optical quality can be achieved, without being subjected to damages. Also, an experimental study has been done by Jürgen Neugenbauer, realized by SFL Technologies. The result was shown at the GlassTec fair 2014 in Dusseldorf. It is a design of a movable glass canopy that is able to expand and contract in two directions showing the adaptability of the material.

Figure 1.9: movable glass canopy. Source: Glassonline (2015)

At the TU Delft there have two students, so far, who have graduated on thin glass.
First there was Carlyn Simoen, her aim was to discover if thin glass could be implemented in a feasible configuration within a building envelope by using the process of cold bending. Feasibility was defined in terms of safety, ecological profitability and the consistence of architectural value. In the end, she achieved to design a curved glass panel that functions as a second skin facade.

Figure 1.10: Thin glass second skin facade.
Source: Simoen, C. (2016)

Rafael Ribeiro Silveira, also designed a second skin facade, his approach was however very different. This main focus has been to embrace the flexibility of the material and using the material in adaptive facade panels. The behavior of thin glass is dependent on its thickness and size, while the bending limits are defined by the desired geometry and movement. Which will affect the stiffness and the visual outcome of the facade.

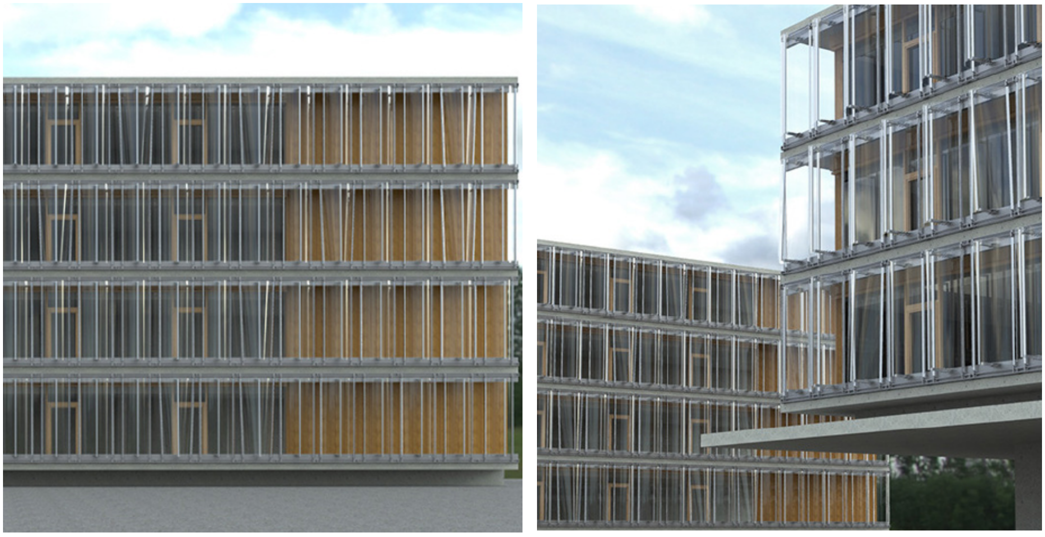


Figure 1.11: Flexible thin glass second skin facade.
Source: Silveira R.R. (2016)

1.5 Relevance

This research is relevant due to the potential scientific, environmental and economic advantages. Until now, there is no precedent in which thin glass is applied as an ultra-lightweight insulating facade panel.

Scientific

Thin glass is quite a new material. At the moment, the main application of thin glass is electronic devices like smartphones and television screens. For the built environment, thin glass is still in its first steps. However, thin glass has a big potential for application on buildings. Some uses are explored, but an insulating façade panel in which only thin glass is applied is not developed yet.

Environmental

The main argument to use thin glass, instead of the conventional soda-lime glass, is its thinness. This thinness and the lightness of this product could have huge environmental advantages. Lower thickness means less material and thus fewer resources required. Also, this could mean less emitted pollution while the glass sheets are produced.
Due to the thinness there will be some advantages when it comes to transport. More glass sheets could fit in a truck which will result in fewer required trucks and less pollution.

Also, the building speed could increase enormously and heavy equipment might not be for assembly. For these reasons a lower environmental burden could be achieved when thin glass is applied instead of the conventional insulating panels.

Economic

Because thin glass is available from 0.025 - 1.1 mm (AGC, 2015) it can save enormous amounts of weight when applied in facades. Due to this lightness there will be transportation benefits. The glass is thinner, meaning that it requires less space when transported and secondly, it has a larger impact resistance leading to a reduced risk of breakage while transported.
Another interesting possibility of thin glass is the fact that it could be cut after strengthening, so minor mistakes could possibly be fixed on site. Cutting could be done without enormous reduction in strength. This should, however, further be explored (Silviera, 2016).
Also, the lightness reduces the required capacity of the lifting equipment of the panels on the building site. Normally a crane and/or forklift is required for placement. With a thin glass facade panel, the weight reduction might result in the redundancy of this heavy equipment.
And last but not least, in the case a thin glass sheet breaks, the lightweight has advantages in terms of replace-ability, again because less, or no, heavy equipment is required on site.

Embedded research programs

The Glass & Transparency Research Group at the TU Delft in the Netherlands focuses on the development of innovative glass solutions for structures, buildings and facades. The research group is based at the Chair of Structures at the Faculty of Architecture and the Built Environment and has
strong links to the Faculty of Civil Engineering and Geosciences.
The topics that are addressed within the research group range from material investigations, via investigations into new connection technologies to the development and assembly of full scale glass structures. Several topics are currently under investigation, such as:

- Strength of structural glass components
- Innovative facade constructions by means of cast glass bricks
- Innovative bridge design making use of dry assembled glass bricks
- Production and residual stress investigations for glass bricks
- Safety performance of structural glass components
- Reinforcement technologies for optimized safety performance
- New glass material compositions
- Other glass applications

02

Glass

Glass is a material that is present in almost everybody's life. In every building there is a need for daylight and a view. This chapter discusses the development of glass constructions over the last century, the chemical composition of glass, the differences of regular soda-lime glass sheets and thin glass. Also the manufacturing and processing methods of (thin) glass is discussed in order to gain information on what the possibilities are in order to design an ultra lightweight thin glass facade.

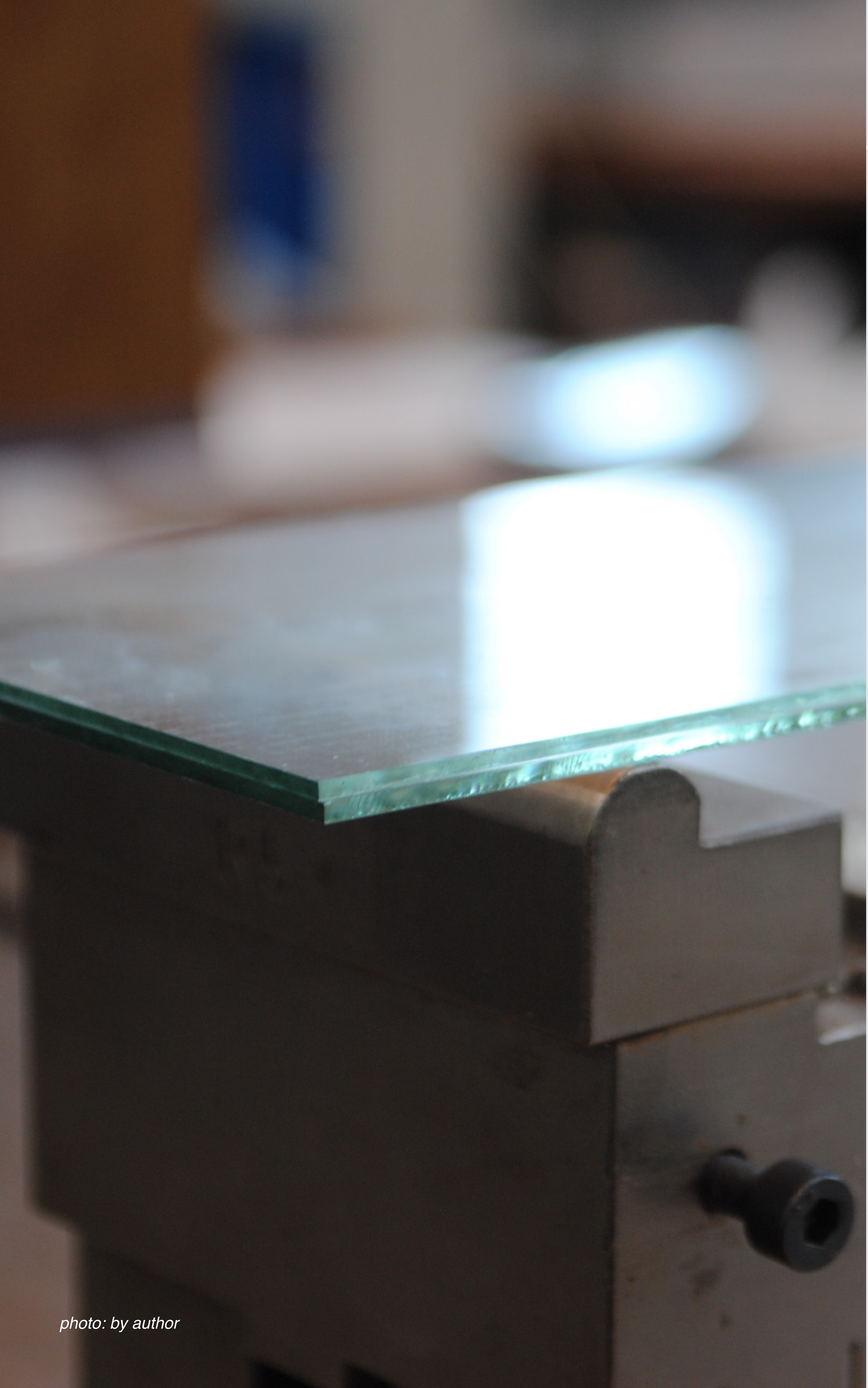


photo: by author

2.1 Development of glass constructions

The last century a lot of glass development has taken place. Of all traditional major building materials (wood, stone, masonry, metals and concrete) glass is the one material where significant technological advantages are still being made. For a long time, glass has been used as a transparent infill panel, providing daylight and view, for quite some time. More recently is the development of glass as a structural element, this is one that shaped the appearance of contemporary architecture unlike any other. Glass is no longer just providing shelter from the elements.

Roots of this contemporary glass construction reach back to early 19th century greenhouses in England where Joseph Paxton pioneered this new development. The desire to cultivate exotic plants under controlled conditions proved ideal for the experiment of building with glass and iron. In this construction, glass panels were first used as a load-bearing structural element. After completion of this structure, similar ones followed quickly (Wurm, 2007).

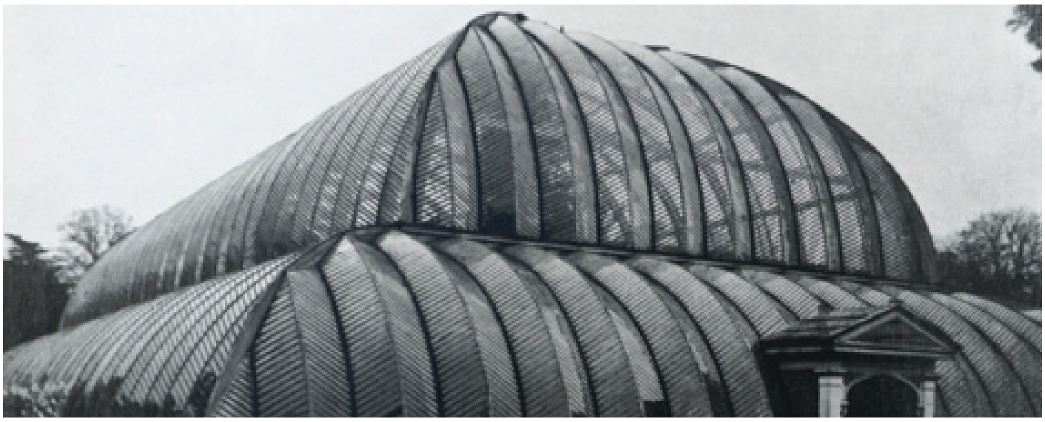


Figure 2.1: Chatsworh by Joseph Paxton. Source: Tristotrojka.com

In the 20th century, a new generation of architects stood up and recognized the visual potential of glass as a new construction method, the openness of large glass surfaces became increasingly appealing. Nowadays, Sadeghi et. al (2015), states that the invisible material, glass, has become a material that is a symbol of openness, democracy and modernity. What used to be a very defined wall, is now no longer there.'

The last decade the usage of curved glass panels has also been further developed, bent glass sheets are shown in several buildings worldwide like the Casa da Musica Porto by OMA and MAS (Museum Aan de Stroom) by Neutelings Riedijk.

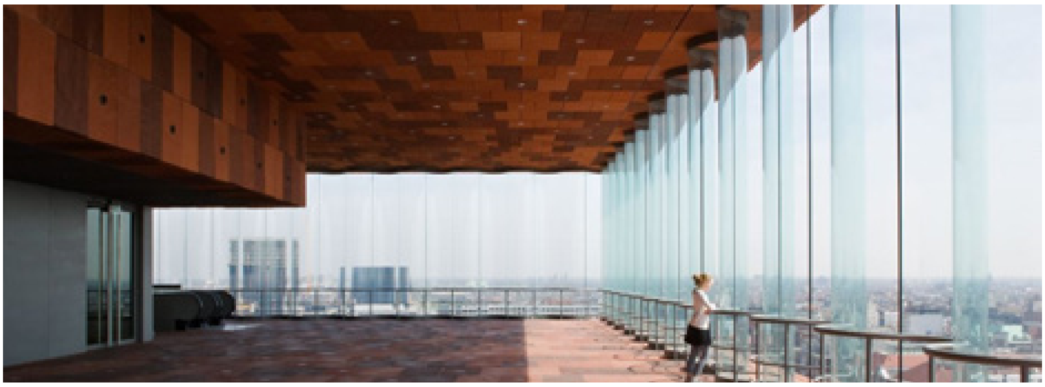


Figure 2.2: Museum aan de Stroom by Neutelings Riedijk.
Source: Dezeen

The approximation is, according to glassglobal.com (2016), that the demand of glass usage will continue to increase in the future. Nevertheless, it must be mentioned that there are two disadvantages of using glass in architecture: energy considerations and costs. Both should be considered when designing.

In terms of energy, there are a few things to acknowledge. The melting point of glass is quite high (approximately 1800 °C) and in order to produce glass, the base materials have to be heated for quite some time. This results in a lot of embodied energy in the material caused by its production process.

Secondly, the insulation value of single glazing is, in general, not sufficient according to building regulation codes for new construction, meaning that a lot of heat will be lost through the glass surface in winter. And a lot of heat in summer could accumulate behind the glass' surface. This is due to the transparency of glass, which allows for sunlight to enter. Both heat loss and gain will influence the costs of the building once in it is use. To prevent heat loss, insulated glass units can be applied. When avoiding solar gain, glass panes can be coated. Both these methods will be further explored in this chapter.

2.2 Chemical composition

Glass is a material which is made out of minerals, its base material is silica (sand), combined with soda and lime. In order to gain glass, these minerals should be subjected to a relatively long heating process in order to become transparent.

To obtain glass in the preferred form and size, silica sand should be molted. The rise in temperature causes the silica to undergo an irreversible physical and chemical transformation. When it is solid is heated to approximately 1400 °C to 1600 °C it reaches its melting point, meaning it will liquefy. If the temperature goes below its melting point, the liquid will become solid once again. Glass is in its solid state solid at room temperature. However when cooling or heating glass, it can never go back to sand.

In most materials and throughout most of the solid state, atoms are organized according to a very precise arrangement (in crystalline or semi-crystalline structure, for example). This arrangement compresses the material. In the case of molten glass, the liquid sets gradually whilst still keeping its irregular atomic structure (vitreous state).

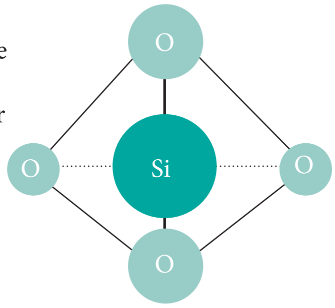


Figure 2.3: Glass atom.
Source: by author.

Glass is therefore said to be non-crystalline or amorphous. A vitreous state is an intermediary state which is just as distinct as the other 'liquid, solid and gaseous' states. Glass is basically liquid silica can be cooled to below its melting point with an increase in viscosity whilst still remaining liquid. Thus glass can be descibed as a solid with the structure of a liquid. It is a brittle and rigid material at ambient temperature and yet extremely plastic when heated (Kula, 2013).

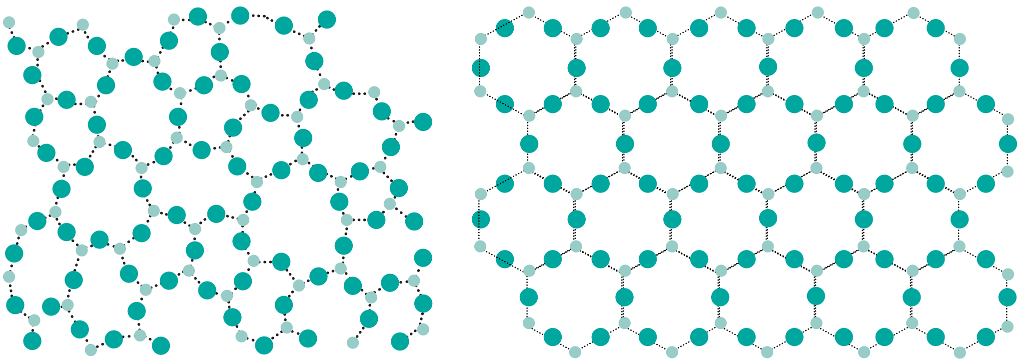


Figure 2.4: irragular atomic structure glass (left) and regular atomic structure quartz (right).
Source: by author.

Basically, all glass types are composed with the same elements: network formers, network modifiers and intermediates. Network formers can be seen as the base constituent, generally this is silica (sand). It provides the structure of the glass, unlike crystals, glass' irregular atomic structure gives scope for the integration of foreign elements. In order to make the production process more efficient, the melting point and viscosity are lowered by the addition of network modifiers. Soda, alkaline oxides and sodium lower the temperature of the melting point. Silica itself melts at 1800 °C, when mixed with modifiers, the melting point can decrease towards 1400 °C. Intermediates, like lime, makes the glass more stable, inert and incapable of being dissolved in water.

The composition and ratio of these elements provide a large variety in the characteristics of glass, the desired optical and physical properties for specific usage can be designed. The malleability, thermal stability, color, optical transmission and refractive index are qualities that can be changed by additives (Callister & Rethwisch, 2011). As a result of this variety, three glass types can be subdivided: borosilicate, silicate and phosphates.

2.3 Glass types

Silicate is the glass type that is mostly applied in the built environment, within this type there are several families like soda-lime and aluminosilicate. (Ultra) thin glass can be produced with both soda lime and aluminosilicate glass. Because the producers (Schott, Corning and AGC) use aluminosilicate glass for manufacturing thin glass sheets, the assumption is made that thin glass consists of the elements described in table 2.1. This table indicates the chemical composition of both families.

Element	function as:	Soda lime	Aluminosilicate
SiO_2 (silica)	network former	73%	62%
Na_2O (sodium oxide)	network modifier	17%	1%
CaO (calcia, lime)	network modifier	5%	8%
MgO (magnesia)	network modifier	4%	7%
Al_2O_3 (alumina)	intermediate	1%	17%
B_2O_3 (boric oxide)	network modifier	-	5%

Table 2.1: Chemical composition.
Source: CES Edupack

When comparing the chemical composition of soda lime- and aluminosilicate glass in a few differences show:
- Soda lime has a much higher percentage of sodium oxide. while aluminosilicate glass has a much higher percentage of alumina.
- Aluminosilicate glass contains boric oxide while soda lime glass does not.However, it must be noted that recent developments show that this element could be excluded from the glass which is preferable since it is a rare and thus an expensive material.

These differences in chemical composition result in different mechanical, thermal and optical properties.

Thin glass

Thin glass sheets are made with aluminosilicate glass. Due to their chemical composition, production process and pre-stressing method, thin glass has become more scratch- and impact resistant, stronger and surprisingly, flexible which is shown in figure 2.5.

Figure 2.5: Bent (ultra) thin glass sheet.
Source: Schott

Currently, there are four glass manufacturing companies that are capable of producing thin glass sheets: ACG, Corning and Schott. All have called their products differently, Leoflex, Dragontrail, Gorilla glass or Xensation. Although they are not showing all details on their products chemical composition and production methods, their thermal, mechanical and optical performance is accessible. Their material properties are slightly different than soda lime glass, but they are very comparable to each other, table 2.2.

The use of (ultra) thin glass offers a lot of opportunities and advantages that could be interesting for architects, structural engineers, clients, and contractors. Thin glass has the potential of offering economic- and ecological benefits when used instead of the conventional glazing. In terms of architectural advantages, the flexibility offers plenty of possible shapes and even allowing for the use of glass as an kinetic element. The thinness allows for lighter facades, less color in the facade and a lighter support structure. Broadly these properties offer the possiblity for a lighter, more sustainable alternative to the current glass industry.

			Any producer	Schott	Corning	AGC
Properties			soda lime	xensation	gorilla glass	leoflex
Mechanical	Density	g/cm3	2.5	2.477	2.39	2.48
	Youngs modulus	GPa	73	74	71.7	74
	Shear Modulus	GPa	30	30	29.7	30
	Poisson's Ration		0.21	0.215	0.21	0.23
	Vickers Hardness, before CT		527	617	625	595
	Vickers Hardness, after CT		580	681	674	673
Thermal	CTE		85	?	?	98
	Tg	°C	550	615	?	604
	Softening Point	°C	733	880	852	831
	Annealing Point	°C	554	635	613	606
	Strain Point	°C	511	?	563	556
	Expansion coefficient	(10-6 1/K)	9	?	?	9.8
Optical	Energy transmission	%	91.1			91.6
	Refraction Index	Nd	1.52	1.51	1.51	1.51

Table 2.2: Material properties
Source: CES Edupack, AGC, Corning and Schott.

2.4 Online production techniques

There are several stages in the glass production industry. The online production stage is the actual manufacturing of the glass sheet. This is followed by offline production processes. These processes include mechanical processing, pre-stressing, lamination, coating, and bending. The order in which the these techniques are applied are shown in figure 2.6.

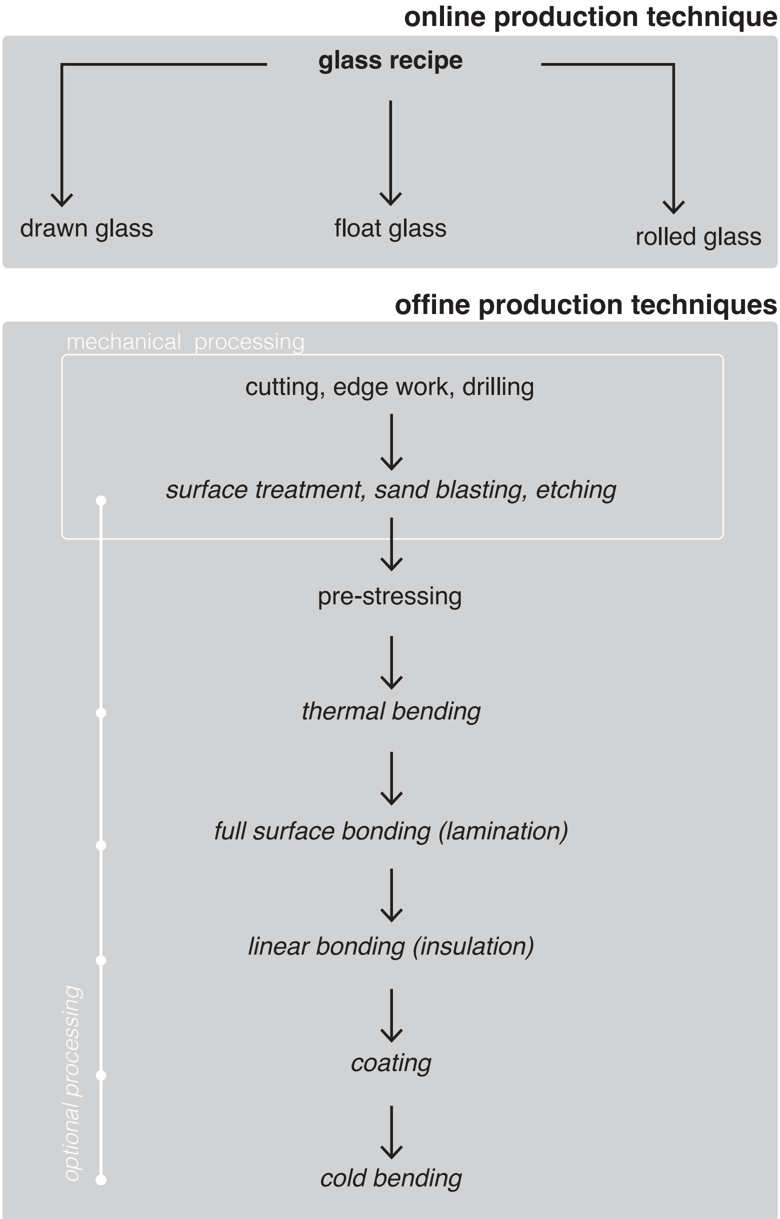


Figure 2.6: Stages of glass production (online and offline).
Source: J. Wurm

There are three methods of manufacturing flat glass sheets, they are called the float glass-, rolled glass- or drawn glass process. The float glass production method makes up for over 90% of the glass sheet production. In this research, which is mainly about thin glass, another slightly different manufacturing method is used.

Float glass

In the late 1950's, glass manufacturer Pilkington invented the floating glass technique. From this moment on, this is the technique that has been the most used method to produce glass sheets. Today, large float glass plants are used for production, a factory like this can produce up to 750 tons of glass per day. This is approximately 50000 m2 glass sheets (Kula, 2013). Float glass is usually produced in thicknesses between 2 to 19 millimeters. The maximum width (3,21 m) is determined by the production equipment and the handling and transportation equipment determine the maximum length (6 m).

The process consists of the following steps: weighing and mixing, melting, floating, cooling, inspection and cutting. Before the cooling process possibly coatings can be applied, this would take place before the cooling.

According to U.S. Patent No. 2911759 (1959) first, the raw materials, silicate, soda and lime, will be captured in silos. Possibly recycled glass can also be included in the raw materials mixture. Within, all will be weighed and mixed together. Then the mixture will be heated in a furnace up to a temperature of approximately 1550°C. When all is melted, the mixture will be kept at a high temperature of approximately 1200°C. After several hours, this process reduces a number of gas bubbles in the melted glass. The mixture will be pushed through a narrow canal on a bath of molten tin. On this molten bath of tin, which is approximately 50 meters long, the liquid glass floats until it solidifies at approximately 600 °C. Due to the tin on which the glass is floating great flatness can be achieved. The thickness of the glass sheet is determined by the speed of the pulling rollers on both sides of the bath. From one side of the bath to the other side, the temperature decreases from 1220 to 600°C. Float glass plants produce a constant thickness since it is economically less convenient to make varying thicknesses in one plant.

In the next stage, there is a possibility to apply hard coating for solar reflectivity or other performance improvements. This can be done by the spray pyrolysis technique.

After, the glass is rolled into an annealing Lehr, where a process of controlled cooling prevents the occurrence of stresses in the glass. Before the glass is cut, it is inspected for flaws by an optical laser. When approved, the long lint of glass goes into the cutting machine. Finally the sheets will be cut to the required size and packaged for delivery.

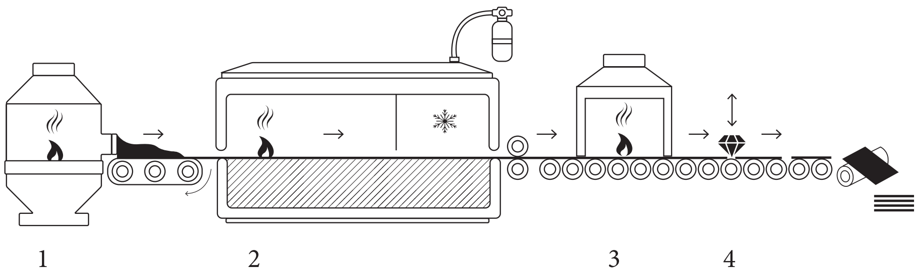


Figure 2.7: Floating technique.
Melting (1), floating(2), annealing (3) and cutting (4).
Source: by author.

The main advantage of the float process is the fact that it is a mass-production method which is optimized economically while it has a high quality and precise manufacture of size and thicknesses. For soda-lime glass sheets with thicknesses of 2; 3; 4; 5; 6, a tolerance of only 0.2 mm should be taken into account (Wurm, 2007).

Rolled glass
Rolled glass is produced by the use of a pair of forming rollers with patterned surfaces. Which continuously pull a glass ribbon out of the melt mixture, after which the ribbon is cooled and cut. This process is based on the so-called “overflowing tub” principle (Wurm, 2007).

Drawn glass
The drawn glass process was developed at the beginning of the 20th century. A wide glass ribbon is drawn vertically out of the melt by a debiteuse (a slotted block of refractory material) and moved vertically up a drawing shaft by rollers, during which it is annealed by cooling slowly to avoid in-built stresses (Wurm, 2007).

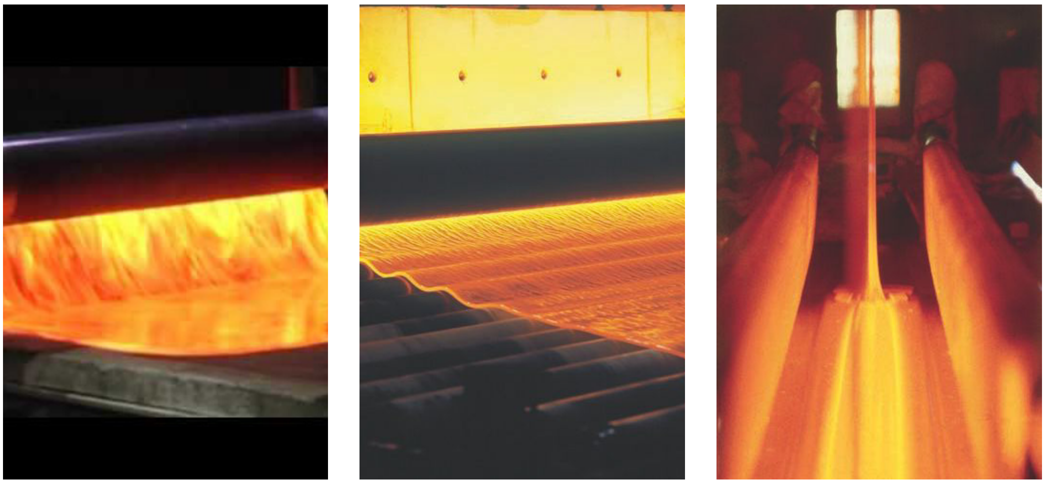


Figure 2.8: Float, rolled glass and drawn glass production.
Source: Wurm

Thin glass production

Thin glass sheets, less than 2 mm thick, cannot be produced in a regular float process. Special production equipment is required, a micro-float process can be used. This float-plant is similar to a regular float process but it can deliver glass sheets down to a thickness of approximately 0.7 mm. Like with the float process, the maximum width is determined by the production equipment.
When producing even thinner glass sheets (below 1 mm thickness), another manufacturing method should be used: the overflow-fusion or the down-draw-process. With these processes, a thickness of 0.025 mm can be achieved. With the overflow-fusion draw process, molten glass is poured into a v-shaped tank, which is filled until it overflows at both sides. At the bottom of the tank, both streams come together and flow down. The down-draw-process is inspired by elder techniques, but further optimized for thin glass. Both Soda lime and Aluminosilicate glass can be produced with these processes (Schneider, 2015).

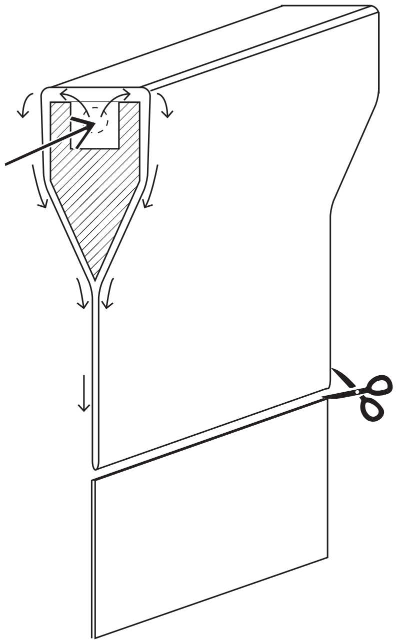


Figure 2.9: Production method ultra-thin glass, down-draw-process technique.
Source: by author.

At the moment, there are four glass manufacturing companies capable of producing thin glass sheets: ACG, Corning and Schott. ACG's thin glass is either called Leoflex or Dragontrail, Corning called their product, Gorilla glass, and Schott called it Xensation. The dimensions of their products are slightly different, in table 2.3 their dimensions are compared to a regular soda lime sheet.

				Schott	Corning	AGC
Properties			**Regular soda lime**	**Xensation**	**Gorilla glass**	**Leoflex**
Size	thickness	mm	12.0, 10.0, 8.0, 6.0, 4.0	2.0, 1.5, 1.0, 0.7, 0.55	2.0, 1.5, 1.0, 0.7, 0.55	2.0, 1.5, 1.0, 0.7, 0.55
	maximum panel size	mm	3210 x 6000	1150 x 950	1250 x 900	1220 x 737

Table 2.3: Producers of thin glass and their production sizes.
Source: by author.

2.5 Offline production techniques

Offline production processes include mechanical processing, pre-stressing, lamination, coating, and bending. Besides the mechanical processing, most of processes are optional. Several methods of pre-stressing may be used, glass sheets may be laminated, coated, and/or bent.

Mechanical processing

Mechanical processing includes sawing, cutting, drilling, edge- and surface grinding. Nowadays these processes are often done by CNC-controlled equipment.
The first stage in this process is the so-called zero-cut. Here the sheets are cut into stock sizes by trimming 5 to 10 centimeter of all edges ensuring the sheet to have right angle. The glass sheets are cut by a diamond tipped cutting arm, which has an accuracy of up to 0.1 millimeters. Cutting of cyclical and conical countersunk holes is often done with a water jet (Wurm, 2007).
The finishing of the edges may be done in a variety of ways. The most simple, normal cut edge, is only sufficient when the edge is placed within a frame. Otherwise, there is a risk of being injured by the sharp edges. In all other applications, the edges should be grounded and/or polished (Schittich, 2001). Grinding and polishing the cut edges are performed using metal tools. These processes take place in several stages with decreasing grain sizes until the desired optical and mechanical properties are achieved. The accuracy in edge treatment is important since it determines the strength of the glass (Kula, 2013).

Figure 2.10: Cut, ground, fine-ground and polished edge.
Source: by author.

The strength of glass is directly related to the shape and the quality of the treated edges and surfaces. Any form of mechanical processing leads to the removal of micro- and macroscopic flakes of material in the area treated and therefore resulting in a strength reduction. For example, surface grinding or sandblasting to achieve a matt finish reduces the strength by up to 50 percent. Pre-stressing a glass sheet after processing can minimize this strength reduction.

Pre-stressing

Because of the large slenderness ratio of flat glass sheets, they will be subjected to bending. Bending a glass sheet will result in tensile stresses which can eventually cause breakage. Pre-stressing of glass is often crucial to increase the tensile strength of glass. Also because when glass sheets are produced, they will be subjected to internal temperature differences. This causes large internal tension to emerge in the glass, which could fracture the glass. Therefore something should be done to rebalance and strenghten the material (Kula, 2013).
Usually, glass sheets are annealed during the online production process. The aim of this treatment is to bring the internal tension down to an acceptable level, by reheating the glass and cool it down to room temperature gradually. When the glass is annealed, it is 10 times stronger in compression (200 Mpa) than it is in tension (20 Mpa). If annealed glass does not offer the required strength, thermal- and chemical tempering are the alternatives. They offer a larger resistance to tensile stess.

Pre-stressing glass creates a compressive stress (CS) in the glass. The magnitude of the CS determines the bending strength of the glass. The CS has a certain depth, the Depth Of Layer (DOL). A larger the CS and DOL are, the higher the impact- and scratch-resistance (Gomez, 2011). Both terms are explained in figure 2.11.

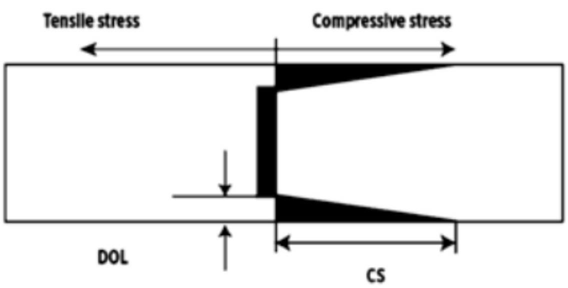


Figure 2.11: Depth of layer (DOL) and compressive stenght (CS).
Source: Gomez et al.

For Soda-lime glass sheets, often thermal strengthening is used, but chemical strengthening is also a possibility. Chemical pre-stressing can reach a higher CS than thermal strengthening.

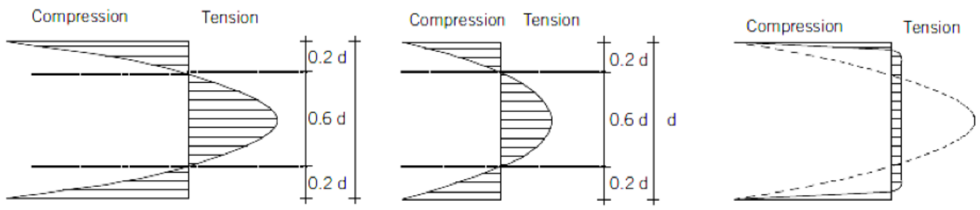


Figure 2.11: Comparison DOL & CS. From left to right: thermally strenghtened and chemically strenghtened glass.
Source: Gomez et al.

Thermal pre-stressing

In this procedure glass is heated to point of annealing (650 °C) and will than be rapidly cooled to 300 °C with draughts of cool air. This cooling process creates an internal state of permanent stress. The surface will cool down quickly resulting in shrinkage of the outer area, while the inside is still hot. When this area cools down the outer surface will the pulled inwards. The DOL is approximately 20% of the thickness of the sheet.
The cooling speed influences the eventual tensile strength. When cooling is done quicker than with annealed glass, a tensile strength of 100 Mpa can be achieved. This strenghtening method creates heat strenghtened glass. A maximum tensile strength of 200 Mpa can be achieved with fast cooling, resulting in fully tempered glass sheets.
Glass must be cut before the thermal tempering process, otherwise the broken internal tension will lead to breakage of the entire glass sheet. The larger the CS, the smaller the fragments in case a glass sheet breaks, figure 2.13. Another important note is that thermal pre-stressing can only be done with glass panels thicker than 2 mm (Schittich, 2001).

Chemical pre-stressing

Chemical strenghtening is suitable for glass sheets with a smaller thickness than 2,8 mm. This pre-stressing process also involves creating compression on the outer surface. With chemical strengthening this is achieved not achieved my thermal treatment but by modifying the chemical composition of the glass' surface. The pre-stressing is realized by placing a glass panel in a bath of molten salt (containing KNO3 and NaNO3) that has a temperature of approximately 500°C, subjecting the glass it to ion exchange, figure 2.12.

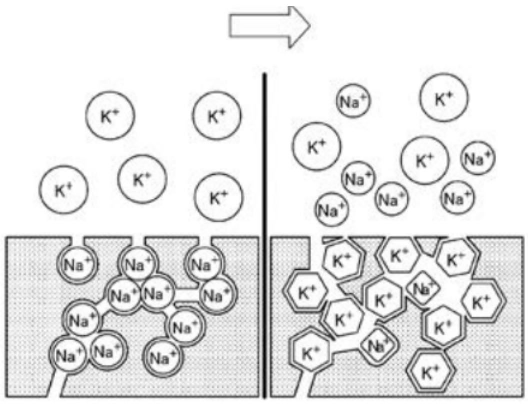


Figure 2.12: Chemical strenghtening process.
Source: Gomez et al.

Aluminosilicate glass contains either Lithium (Li) ions or Sodium (Na) ions. In a salt bath, the Li-ions in the glass will be exchanged with Sodium (Na) ions, which are bigger in volume. In case the Aluminosilicate glass contains Sodium (Na), these Na-ions will be exchanged by Potassium (K) ions in the bath. Due to the bigger volume of the exchanged ions, that are now in the glass surface, a compressive stress layer is created. The DOL and CS of the glass sheet depend on time of ion exchange, temperature of the bath, the composition of the glass and the composition of the bath. Lithium containing Aluminosilicate glass has a higher exchange rate than with the Sodium containing types. The DOL that can be reached with the chemical strengthening of Soda-lime sheets is low. This is caused by the decreased diffusion coefficient created by the availability of non-bridging oxides. Aluminosilicate glass is more suitable for chemical strengthening because it contains large amounts of Alumina which reduces the number of non-bridging oxides (Gomez, 2011).

The effect of chemical strengthening on the toughness, hardness and brittleness in relation to failure is still uncertain. Flexible thin glass sheets, which are chemically strengthened, are currently difficult to test for their strength. Uncertainties arise because the existing standards and methods of strength testing are not suitable for the non-linear effects caused by large deflections (Schneider, 2015).
Also, the knowledge on stress generation and relaxation in the process of chemical strengthening is still in development. This means that the magnitude of compressive- and tensile stresses in the glass is not constant at all times. Therefore chemical strengthened glass sheets are not yet completely reliable (Varshneya, 2010).

In contrast to thermal strengthened glass, chemically strengthened glass can presumably be cut, ground and drilled after the the pre-stressing process. The strength near the cut (within a region of 20 mm) will be slightly reduced, it is comparable to that of annealed glass. This should be considered in detailing, if cutting or drilling after chemical tempering is preferred. All this is possible due to the low elastic energy in the core of the glass (Schneider 2015).
When chemically strengthened glass sheets breaks, its fragmentation will be similar to that of annealed glass due to the low amount of tensile stresses in the core of the glass. Although chemical strengthened glass has a large bending strength, it cannot be qualified as safety glass due to its breakage pattern. In architectural application, lamination is therefore mandatory. The glass will not break as fast because the CS on all edges of chemically strengthened glass sheets allows for glass to be flexible.
To summarize, chemically strengthened Aluminosilicate glass can be produced thinner, less fragile and more flexible than Soda-lime glass sheets (Gy, 2008). Nevertheless, safety should still be considered when applied in the built environment because of the breakage pattern.

Designing with glass

The increased strength in both thermal-, and chemical pre-stresses glass shows promising values. Nonetheless, the strength of glass is never secure due to the flaws that are possibly caused during the production process. Research shows that the deviation in strength with multiple glass samples with different cuts, from different floats and are largely varying (Veer, 2007). This makes it difficult to determine the dimensions of glass structures. In order to apply glass safely, in the built environment, relatively low maximum stresses are allowed.

	Annealed	**Heat strengthened**	**Fully tempered**	**Chemical strengthening (Leoflex)**
DOL (mm)	20% of thickness	20% of thickness	20% of thickness	0.015 - 0.04
Compressive strength (Mpa)	200	200	200	550 - 850
Failure strength, tensile (Mpa)	20	40	80	260

Table 2.4: Comparison DOL, compressive strength and failure strenght of several glass types.
Source: by author.

Besides their differing failure strength (table 2.4), there is a difference in the fragmentation pattern. Fully tempered glass breaks into very small fragments, while heat strengthened glass breaks in larger pieces because of its lower level of pre-stress. Heat strengthened - and annealed glass panels allow for post-breakage load-bearing capacity while fully tempered glass doesn't. It depends on the specific application which pre-stressing type is a safer option.

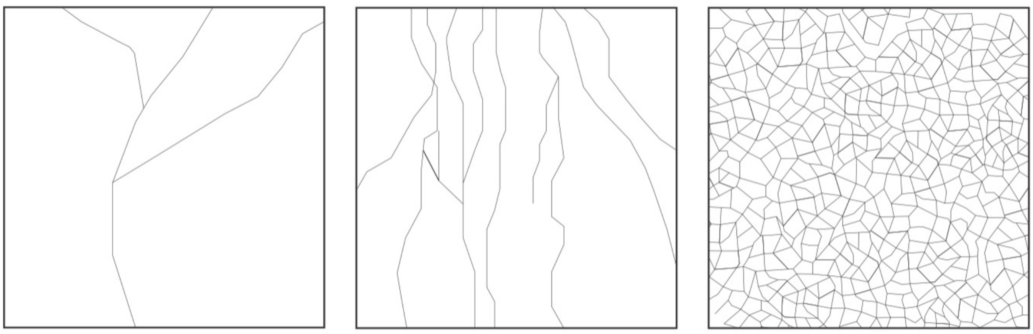


Figure 2.13: Breaking patterns. From left to right: annealed- heat-strenghtened- and fully tempered glass.
Source: by author.

2.6 Laminated glass

Laminated glass consists of two or multiple glass panes and an interlayer in-between, this interlayer provides the bonding of both panes.
Lamination of glass is often done to make glass sheets safer in structural applications. With laminated glass, one panel can break while the other(s) remain. In case of breakage, the interlayer will hold the broken fragments in its place. They will not cause damage to anything/anyone by falling down.

Bonding process

A glass laminate is made several stages. First the individual glass sheets are degreased. Then translucent foil, for example PVB or SG, is placed on one pane after which the next glass pane is put upon. This pre-lamination can be done using the roller process or, in the case of bent sheets and multiple bonded layers, by the vacuum bagging process. The assembly is than put in an autoclave, which puts the glass panels under pressure and raises the temperature to 250 . This is necessary for the interlayer to layer attach to the glass sheets. If done correctly, the foil will become fully transparent. The finished sizes of laminated glass components are normally limited by the dimensions of the heat treatment furnaces (Schittich, 2001).

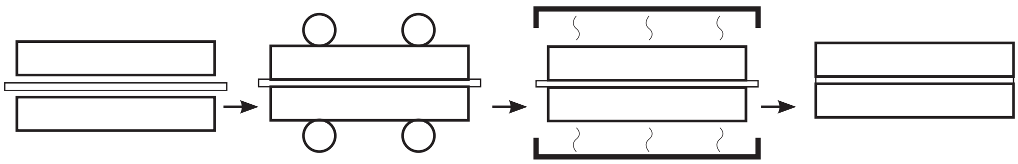


Figure 2.15: Lamination process, from stacking, pre-lamination, autoclave to finished product.
Source: by author.

Load bearing capacity

J.A. Hooper (1972) was one of the first engineers who conducted a study on laminated glass constructions subjected to four-point bending. He concluded that the bending strength of a laminated glass sheet is dependent on the thickness and the Youngs modulus of the interlayer. Meaning, the stiffer and thicker the film, the smaller the resulting deflections.
Secondly, he discovered that laminated glass which is subjected to sustained loads, such as snow or self-weight load, the laminated glass unit should be considered as two glass layers without a bond.
Also the position of the interlayer within the stressed cross section is relevant to its load-bearing capacity. With outer layers of equal thickness in a symmetrical laminated section, the interlayer lies at the neutral axis and in an intact system is subject to shear stresses only.
A laminate can either be elastically or rigidly bonded, when rigid its deflection is much smaller. Like with other forms of composite constructions (plywood, sandwich structures), the mechanical behavior of joined panes is fully dependent on the shear rigidity and shear strength of the intermediate layer. If two slabs are bonded with a rigid, shear-resistant connection, the loads can no longer be split in proportion to the strengths. They will be carried by the complete composite unit instead. In the case of a rigid bond, the maximum stress will be:

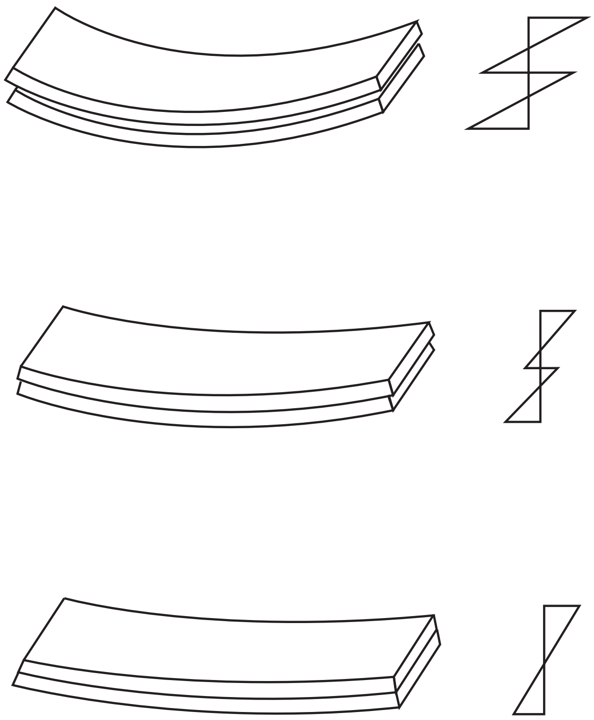


Figure 2.16: Mechanical behaviour of two plates. From top to bottom: two plates laying loosely on top of eachother, flexible adhesive connection, regid adhesive connection.
Source: by author.

Maximum bending stress: σ [N/mm²]
$\sigma = 0.75\, q\, (l/t)^2$ N/mm²
with

q	external load [N/mm2]
t	thickness of composite slab [mm]
l	span [mm]

When two glass sheets are laying loosely on top of each other, each slab carries its share of the total load in proportion to its flexural strength. For instance, two slabs (with thicknesses t1 and t2) spanning one way, would split an external load (q) in the ratio $(t1/t2)^3$. The maximum stress (in a symmetrical arrangement where t1=t2 = t/2) occurring in in the top and bottom of each pane would be (Schittich, 2001):
Maximum bending stress: σ [N/mm²] $= 1.5\, q\, (l/t)^2$
with

q	external load [N/mm2]
t1,t1	thicknesses of slab 1 and 2 [mm]
l	span [mm]

A rigid bond deflects 4 times less than loosely stacked glass sheets. This is an enormous increase in stiffness. However, we meet a contradiction here: maximum rigidity favors the behavior in bending, while if one or more panes are broken, then a more flexible intermediate is advantageous. In the case that happens, a flexible interlayer is much better in holding the fragments together. (Schittich, 2001).

Post-fracture integrity

When an interlayer fulfills certain requirements concerning the adhesion and bonding of broken pieces, we speak of laminated safety glass. Laminated glass has improved post-breakage behavior compared to monolithic glass sheets. The ability of the interlayer to hold the broken glass fragments together and maintain residual strength once the glass is broken is important in terms of safety within building (Schittich, 2001).

The residual strength of laminated safety glass depends on the intermediate film type and thickness, but the residual load-bearing capacity is mainly determined by the fracture pattern (Schittich, 2001.) Larger fragments lead to better post-break behavior of the laminated glass. Annealed glass offers the best performance while a broken fully tempered glass will sag like a wet towel. Its post-breakage capacity relies only on the tensile strength of the interlayer (Fors, 2014). Due to its fracture pattern with very small pieces, the post-failure performance by fully tempered glass is to be avoided.

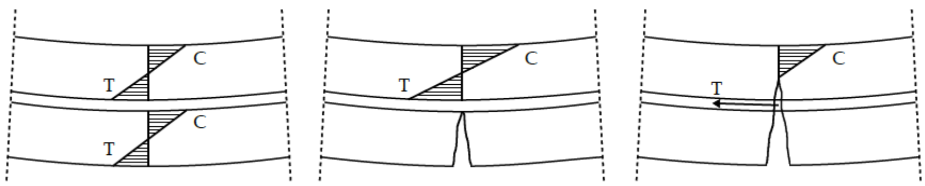


Figure 2.17: Three stages of post breakage behaviour of laminated glass.
Source: Fors.

The residual load-bearing capacity of laminates can be improved by using Sentry Glass (SG). Which is, at the moment, the stiffest interlayer available. It can significantly reduce deformation after breakage.

Once glass sheets are broken, the mechanical behavior can be described in three stages (figure 2.17). Both sheets are intact in the first stage, in stage two, the bottom glass panel is fractured and the top panel is carrying all the loads. In last stage, the top sheet is also fractured; the interlayer is in tension and the glass pieces are locked together in compression (Fors, 2014). When the interlayer is carrying the load, because all glass sheets have broken, there is a risk of glass fragments separating from the interlayer, these are so-called dropouts. This is especially dangerous concerning a glass roof or ceiling. The risk of dropouts is largest for laminated glass units made of fully tempered glass.
Accordingly, it is very important to choose the right type of glass and interlayer when designing with laminated glass in a structural element, the remaining load bearing capacity is dependent on these design choices (Haldimann et. al. , 2008).

2.7 Coating

For glass sheets, many types of coating have been developed to improve its optical-, thermal- or electrical performance. Better solar control and anti-glare, for example, can be achieved by coatings applied on glass sheets. The smooth finish of a glass sheet is ideal for the application of material during or after manufacturing glass sheets.
Glass can be coated either online (during the production of the glass sheet itself), or offline (in the processing phase). By spraying (pyrolysis), magnetron sputtering or dipping a soft coating can be applied. Hard coatings include printed, rolled color coatings and cast laminate layers. There are two types of coatings which can be applied on glass sheets, hard- and soft coatings. Often, the appearance of coated glass is influenced by the coating, this can for example be seen in figure 2.18.

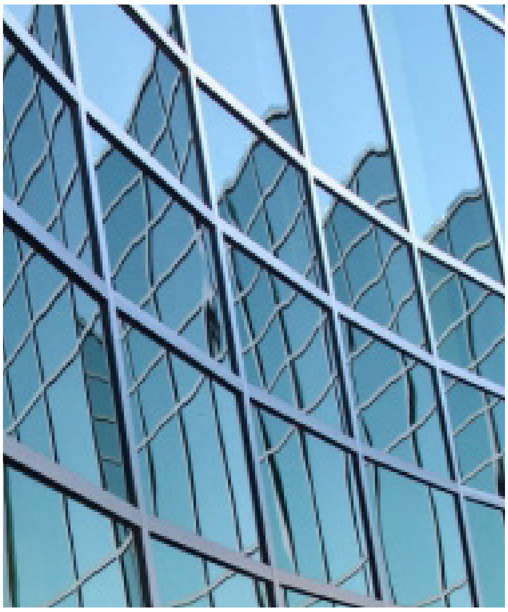


Figure 2.18 (left): Coloured appearance dichroic glass samples. Source: J. Wurm

Figure 2.19 (right): Low-E coating. Source: Vitalglass

Application methods

As mentioned, there are several processes to produce coated glass. Pyrolysis (online), magnetron sputtering (offline) or dipping (offline). Online coating has limitations on the number of coatings materials and they offer limited performance, while the offline coatings offer a large number of available coating materials and a higher performance.

Pyrolysis the method that is most used to bake a hard coating onto glass. By spraying, metal oxide is applied on glass immediately after the forming of the sheet. This coating type allows for thermal processes such as bending and tempering. The method can create a layer that improves solar control and thermal insulation. Some even ensure a glass sheet to become self-cleaning. Self cleaning glass is based on a hydrophilic coating on the outside of the glass allowing for rainwater to flow off evenly.
Reflective or colored coatings can also be applied to reduce the amount of light (thus energy) transmitted through the glass. To improve the heat insulation, for example a tin oxide can be applied (low-E) reducing the emissivity (heat radiation) of the glass from about 90% to 15 percent (Wurm, 2007).

Magnetron Sputtering is a method in which a glass sheet is 'bombarded' with energetic ions, typically inert gas ions such as Argon (Ar+). These ejected atoms reach the substrate and start to condense into a film. As more and more atoms coalesce on the substrate, they begin to bind to each other at the molecular level, forming a tightly bound atomic layer. For this process, solar control and heat resistance are most important. Transmission of light can be 70% while transmitting only 35 percent of the solar energy. The emissivity can be reduced from about 90% to only 2 percent. An important note is that tempering, drilling or cutting must be executed before the coating is applied (Wurm 2007).

The dipping method is self-explanatory. Dip coatings are classed as soft or hard depending on the temperature of subsequent heat treatment (between 400 and 650 °C).
The thermal advantages of coatings are further elaborated upon in the thermal insulation chapter.

Types
For soda-lime glass, there are two types of coatings which can be applied, hard- and soft coatings. Both have to be applied on different positions, this it shown in figure 2.20. Hard coatings can be placed on the exterior of glass sheets (position 1 and 4), they are resistant to heat and mechanical damage. Therefore further processing is possible after application. Low-emission, solar control, mirrors, self-cleaning- and non reflective glass can be produced by hard coatings.
Soft coatings can only be placed between two planes (position 2 and 3), like laminated- or insulated glass panels. They are often not resistant to heat nor to mechanical damage thus has limited suitability for further processing. Soft coatings are used to produce low-emission, solar control and dichroic (multicolored) glass (Wurm, 2007).

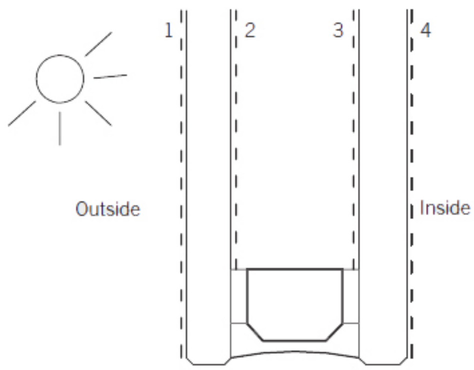


Figure 2.20: Identification of the positions of coated glass surfaces in a double glazing unit
Source: J. Wurm (2007)

Coated thin glass
The improved performances of coated soda lime glass is very promising for a thin glass facade panel. So far, anti fingerprint, anti reflection and Low-E coating has been applied on thin glass successfully. Besides these, no coatings have yet been tested on thin glass, however it seems like it is technically possible to apply any coating (Teper, 2016).

03

Thermal insulation

According to S. van den Berg et al. (2013) it is a top priority in the building and construction sectors to reduce the energy use and carbon emissions. One of the most important strategies to reduce the carbon dioxide (CO_2) emissions in buildings is by increasing the thermal performance of its envelope. To achieve this, a high insulation value in both new and existing buildings should be established. Glazed surfaces typically account for about 30 to 50 percent of transmission losses through building envelopes. Improving these products therefore could significantly save energy.

photo: by AGC

3.1 Heat transfer
An insulating glass unit consists of at least two glass sheets, which are joined linearly along all edges. The specific properties of the insulated glass sheet are dependent on the type of glass that is used, the size of the cavity in between the glass sheets, whether this cavity is filled with an inert gas and if a coating is applied.

Thermal insulation includes conduction, convection and radiation. The insulation value of these factors combined is the described as the U-factor or U-value. This coefficient describes the rate of transfer of heat (in watts) through one square meter of a structure divided by the difference in temperature across the structure. The present day demand on doors and windows is currently < 2.2 W/m2K according to the Dutch building code (Bouwbesluit, 2015). This demand is the maximum value, the lower the U-value the better.

The total heat transfer (q) for cavity constructions can be calculated as follows:

$$
\begin{aligned}
q\ [W/m2] &= qcond + qconv + qrad \\
&= (\alpha cond + \alpha conv + \alpha rad)\ (T1\text{-}T2) \\
&= \alpha tot\ (T1\text{-}T2)
\end{aligned}
$$

Because conduction, convection and radiation occur simultaneously, the combined heat flow is the sum these heat flows, therefore the heat transfer coefficients (α's) must be summed :

$$rcavity = 1 / (\alpha cond + \alpha conv + \alpha rad)$$

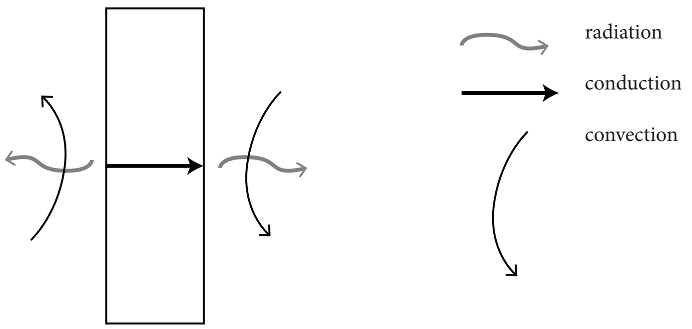


Figure 3.1. The three temperature driven heat transfer mechanisms: conduction, convection and radiation. Source: by author.

Conduction
Conduction is a process in which heat is directly transmitted through a material when there is a difference of temperature between the adjoining regions (figure 3.1). The heat flows though the substance without movement of the material. It naturally flows from the high-temperature location to the low-temperature one (Bokel, 2015).

The heat conduction coefficient (λ) shows how much heat flows through a layer of material of 1-meter-thick and with a surface area of 1 m^2, where the difference in temperature is 1 K (1 °C). The unit in which λ is expressed is: W/mK. The heat conduction coefficient is different for each material. The larger λ, the easier the material can conduct heat. The heat conduction coefficient of glass is around 1 W/mK.

The heat resistance (r) of a layer of material of a particular thickness (d) can be found by dividing the thickness of the material by the heat conduction coefficient:

$$r = d/\lambda\ [m2K/W]$$

The total R-value is determined by the sum of all resistances. The R-value of a single glass sheet can be described in equation form as:

$$R = re + ri + rglass$$

The U-value of the single glazing is the inverse of the total R-value. The total R-value includes the resistance of all materials and the heat resistances from the surface to the inside (ri) and the outside (re) should also be taken into account. The heat resistances for inside and outside are standardized in the Dutch regulations and are:

re = 0.04 m2K/W
ri = 0.13 m2K/W

Heat transport as a result of conduction (qcond) is expressed with the following equation:

qcond = αcond * (T1-T2) = U *(T1-T2) = (T1-T2)/ R [W/m²]

It is not possible to reduce the thermal transport without changing the thickness / composition of the glass (Schittich, 2001).

Convection

Convection can be described as energy transport through a medium(figure 3.1). Within the two glass sheets, this medium is either air or another gas. The gas in the cavity begins to circulate as a result of the different temperatures on both sides (interior and exterior). Causing an energy flow from the hot to the cold surface. The degree in which heat is transferred by convection depends on the speed of the flow of the transport medium (air or wind speed) and the difference in temperature between the object and the medium that is flowing past (R. Bokel, 2015).

By using the following equation, the amount of convection (qconv) can be calculated:
qconv = αconv (T1-T2) [W/m²]
with

qconv	the heat flow density for convection
αconv	the heat transfer coefficient for convection

Common values for αconv are:
- indoors: αconv = 2 to 2.5 W/m²K
- outdoor: average wind αconv = 19 to 20 W/m²K
- outdoor: strong wind αconv = 100 W/m²K

If a cavity has a thickness below 10 mm, no convection will occur. The convective flow increases with the width of the cavity, a very narrow cavity has no airflow in the cavity. The convective heat flow increases until the thickness of the cavity is around 5 cm.

Reduction of the amount of convection is possible by filling the cavity with a gas having a lower thermal conductivity. To prevent convection from occurring within a cavity, a vacuum glass can be created (Schittich, 2001).

Radiation

Because the surface temperatures of the cavity faces (within the cavity) are different, heat transfer also takes place through radiation(figure 3.1). Radiation can be described as the movement of heat energy through space without relying on conduction through the air or by movement of the air. All objects (bodies) radiate heat. It is only at 0 K (around –273 °C) that this is no longer the case. A person will perceive a cold glass surface as cold radiation, but the truth is actually rather different. Cold objects just radiate less heat than warmer ones. People radiate heat themselves, as does the glass. Because glass radiates less heat, the person will experience it as cold (R. Bokel, 2015).

Thus every surface radiates a certain amount of heat. This amount is determined by the temperature of the surface. According to Stefan Boltzmann's law this amount of radiation can be derived from: $E = \varepsilon \sigma T^4$
with
ε = emission constant of the surface [-]
E = radiation heat flow density per wavelength [W/m2]
σ = Stefan-Boltzmann constant (5.67 10-6 W/m2K4)
T = surface temperature [K]

According to Kirchoff's law the emission coefficient ε is equal to the absorption coefficient a. Meaning that a surface that can absorb as much radiation as it emits. In general, the radiation falling on a surface is partly reflected, absorbed and transmitted, so (for both the short and the long wave radiation):

$a + r + t = 1$
with
a= absorption coefficient
r = reflection coefficient
t = transmission coefficient

The heat transfer coefficient for radiation in a cavity construction can be calculated with:
$\alpha res = \varepsilon res\ \sigma\ (T1^4 - T2^4) / (T1 - T2)$
with
T1 = temperature outside [K]
T2 = temperature inside [K]
εres = emission constant [-] which can be calculated with
$(1 / \varepsilon res) = (1/ \varepsilon 1) + (1/ \varepsilon 2) - 1$

With an average temperature of the two surfaces around 300 K (room temperature), this formula can be simplified as:

$\alpha res = 6\ \varepsilon res.$

A so-called black body radiator has ε =1, therefore does not reflect any radiation at a specific wavelength. The name originates from the visible light, because a black surface absorbs all visible light. For most building materials, the emission coefficient (ε) is around 0.9 to 0.95. Which means only 5 - 10 percent of the radiant energy received by the surface is reflected. This value also applies to all paint colors (so white paint, as far as heat radiation is concerned, is just as 'black' as green).

Uncoated glass has an emission coefficient of ε = 0.84. However, there are coatings available with emission coefficients of ε = 0.10 to as low as ε = 0.02 which means 98 percent is reflected.

3.2 Build-up

Generally, insulating glass consists of two, or more, separate panes kept apart by spacers all around the edges. Due to this spacer, a cavity is created in-between the two glass sheets. By adding a second glass sheet, the insulating value (U-value) of the glass is reduced by half. As expected, adding a third or fourth pane of glass further increases the insulating value of the glass product.

Between the spacers and the glass panes, a seal is necessary, which prevents moisture and exchange of gasses in the cavity. This primary seal also ensures protection of the glass. A metal spacer cannot touch the glass sheet; it could create scratches that harm the strength of the glass.

A secondary seal is positioned behind the spacers, between the panes. This serves as a secondary seal, taking a second precautionary measure to prevent moisture as well as an adhesive, keeping the panes and spacer joint together.However, if the cavity does get moist, there is another precaution taken in most spacers. They often contain an absorbent substance that dehumidifies the cavity. This measure reduces the dew point of the enclosed air to below -30 C. It is important to prevent permanent moisture from entering because it could cause condensation in the cavity, which can never be removed.

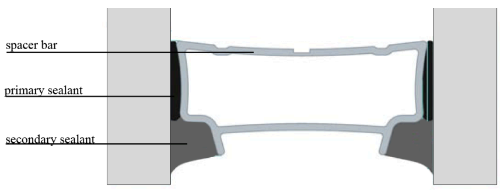


Figure 3.2. Build-up insulating glass facade.
Source: van den Bergh.

Due to the gas in the cavity, the glass panels are subjected to air pressure fluctuations. The air pressure in the cavity corresponds to the atmospheric pressure prevailing at the moment the edges are sealed. When the air pressure rises above the air pressure in the cavity both panes are pressed inwards, when the pressure drops below they will bulge outwards. The in- or outward shaped glass can easily be seen, especially when a reflective coating is applied on the glass. This phenomenon is called barometric pressure (Schittich, 2001).

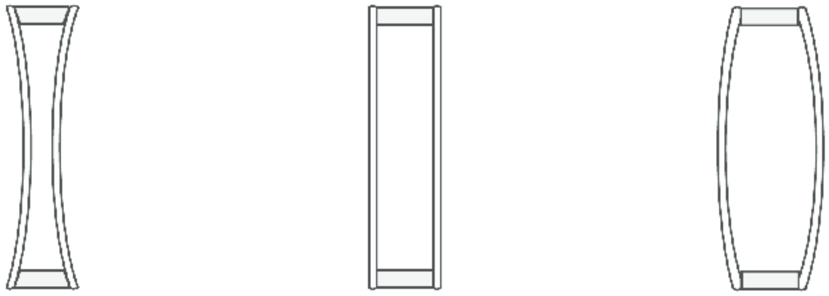


Figure 3.3. Barometric pressure.
Source: researchgate.net

Edges

The main function of the spacer bar is to hold the glass panes at a fixed distance from each other, establishing the size of the cavity space. The typical profile height of spacer bars varies between 4 mm and 8 mm, most common width is between 12 mm and 14 mm.

Spacer bars have traditionally been made of aluminum or galvanized steel. These metal spacer bars have high thermal conductivity and thus create a thermal bridge on the interior glass pane surface in the edge-of-glass area. Thermal performance improved significantly when these traditional metal (aluminum, galvanized steel, or stainless steel) spacers are replaced with spacers (including U-shaped steel profiles, hybrid spacers, and thermally broken aluminum) or non-metal spacers (composite, structural foam, and thermoplastic).

The combined system of spacer bar and sealant should provide sufficient strength to hold two sheets of glass at a fixed distance while the panel is subjected to wind- or other forces. The primary seal does not contribute to the structural integrity of the insulating glass unit. The secondary does, therefore it is essential that it adheres to the glass and spacer bar material. Only than a long service life for the insulating glass unit can be established. The secondary seal must also be flexible to accommodate glass movement under variety of stresses. Pressure fluctuation causes by environmental conditions such as solar radiation, temperature differences, wind loads, barometric pressure, the manufacturing process, transport and the installation, subjects force on the glass panes and cause them to deflect. Often butyl rubber, polysulphide, polyurethane, silicone or polyisobutylene is used as a secondary seal (van den Bergh et. al., 2013).
As a complete vapour seal cannot be guaranteed, most spacers are filled with a fine-grained desiccating agent (molecular sieve) to absorb any penetrating moisture and prevent condensation from forming. To avoid corrosion of soft coatings, the coatings are mechanically removed from the edges of the individual sheets before they are joined (Wurm, 2007).

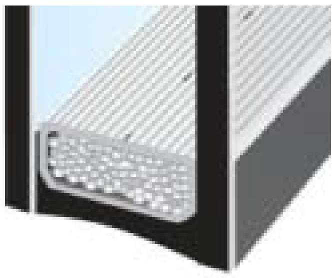


Figure 3.4. Typical spacer.
Source: van den Bergh.

Inert gas fills

The glazing cavity in standard insulating glass may be filled with the gas argon or krypton, rather than dry air, to reduce the thermal conductivity of the cavity. Filling the space with a less conductive gas minimizes overall transfer of heat between two glass layers.
Manufacturers have introduced the use of argon and krypton gas fills, with measurable improvement in thermal performance. Argon is inexpensive, nontoxic, nonreactive, clear, and odorless. The optimal spacing for an argon-filled unit is the same as for air, about 12 mm. Krypton offers better thermal performance, but is more expensive. Krypton is particularly useful when the space between glazing must be thinner than normally desired, for example 6 mm. A mixture of krypton and argon gases is also used as a compromise between thermal performance and cost.

A typical gas fill system adds the gas into the cavity with a pipe inserted through a hole at the edge of the unit. As the gas is pumped in, it mixes with the air, making it difficult to achieve 100 percent purity. Recent research indicates that 90 percent is the typical concentration achieved by manufacturers today. Some manufacturers are able to consistently achieve better than 95 percent gas fill by using a vacuum chamber (Schittich, 2001).

When comparing the u-value of single and insulated glazing units filled with air or argon the difference shows. When coated and gas-filled, the radiation component of heat loss is substantially reduced, the gas fill then has a greater proportional effect on the remaining heat transfer by convection and conduction.

Input	Built-up	Thickness layers [mm]	U-value
Single	Glass	8.00	5.600
Insulated	Glass-air-glass	4 - 16 - 4	3.000
	Glass-argon-glass	4 - 16 - 4	2.700
	Glass-argon-glass with low-e coating applied on 3th position	4 - 16 - 4	1.200
	Glass-argon-glass-argon-glass	4 - 16 - 4 - 14 - 6	0.7

Table 3.1. Comparison insulation values single and insulated glass, with or without gas filling and coating.
Source: by author.

Coatings

Coatings can improve a buildings' thermal properties of insulating glass. Coating a glass surface with a low-emission (low-E) material blocks a significant amount of this radiant heat transfer, thus lowering the total heat flow through the glass unit. The improvement of insulation value due to the Low-E coating is roughly equivalent to adding another sheet of glass (Bokel, 2015).

There are two basic types of Low-E coatings – sputtered and pyrolytic, referring to the process in which they were produced. Preferred is to have a colorless and optically clear coating. Some coatings may have a slight hue or subtle reflective quality, particularly when viewed in certain lighting conditions or at oblique angles.

A sputtered coating is multilayered (typically, three primary layers) with at least one layer of metal. Sputtered coatings often use a silver layer and must be protected from humidity and contact. For this reason they are referred to as "soft coats". While sputtered coatings are not durable in themselves, they should be placed into a sealed double- or triple-glazed assembly. Sputtered coatings typically have a lower emission coefficient (ε) than pyrolytic coatings.

A typical pyrolytic coating is a metallic oxide, most commonly tin oxide, with some additives, which is deposited directly onto a glass surface while it is still hot. The result is a baked-on surface layer that is quite hard, therefore this is referred to as a "hard coat." Pyrolytic coatings can be exposed to air, cleaned with normal cleaning products, and subjected to general wear and tear without losing their Low-E properties. While there is considerable variation in the specific properties of these coatings, they typically have emission coefficient in the range of $\varepsilon = 0.20$ to $\varepsilon = 0.10$.

To describe the position of a pane surface in an insulating glass unit, the surfaces are numbered from the outside (position 1) to the inside (position 4). Soft coatings are only applied in positions 2 and 3, these are protected within the glazing cavity. Solar control coatings are intended for use on the outside, whilst low-E coatings should be applied on the 3th position.

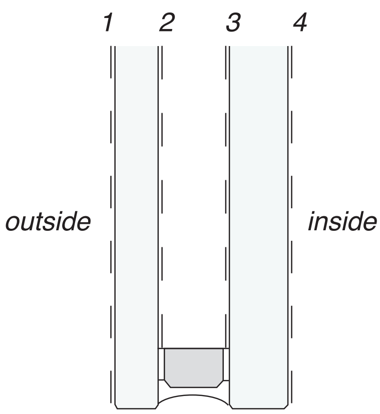


Figure 3.5. Possible positions of coatings.
Source: by author.

04

Precedents

For applications of thin glass, the flexibility could be a disadvantage in the built environment. When applied, large deflections could occur. This probably will not cause the glass to break, but it would result in fluctuations which could cause noise production and possibly other technical problems. Thus a stiffening solution must be found by optimization the configuration of the glass panel.
The thinness of thin glass introduces another problem, the thermal conductivity is much lower than that of a double glass facade panel. Also, to increase the building energy performance, sunshading methods are explored.
With these challenges should be dealt to design a thin glass facade panel. To find a method to deal with these problems, precedents are found.


photo: by WordPress

4.1 Stiffening

In chapter 2, we learnt that glass has a large compressive strength. Unfortunately, its resistance to tensile forces is low because it causes small cracks in the surface. These small cracks could quickly scatter a whole sheet. Because glass is mostly applied as a sheet in the built environment it does not have a large moment of inertia hence strength by its shape. When increasing the second moment of inertia, the strength of the shape and stiffness could be increased. The second moment of inertia is a measure of the 'efficiency' of a shape to resist bending caused by loading (Wikipedia, 2016). The larger the second moment of inertia, the bigger an objects' resistance to bending.

A precedent study shows this can be achieved by laminating several glass sheets onto each other or increasing the thickness of the glass by adding material onto or in-between the glass sheets. Some of these precedents have been applied in buildings, others are experimental.

Lamination

The lamination of glass sheets is often seen in the built environment, besides stiffening, it also increases the safety of glass sheets. The staircase in figure 4.1, designed by Foster + Partners (with technical support from eoengineers) was completed in 2001. By laminating several glass sheets, the element is stiffened. In total, this staircase consists of 4 pre-stressed glass sheets laminated onto each other. The top- and bottom sheets are thinner, are so called sacrificial layers added for safety reasons.

Figure 4.1: Laminated glass staircase: Apple store Istanbul. Source: EOengineers

Glass fins

Another well-known glass construction is the 5th avenue Apple store in New York City. It was constructed in 2011. Besides laminating glass sheets, glass fins are added perpendicular to the glass to provide stability and stiffness.

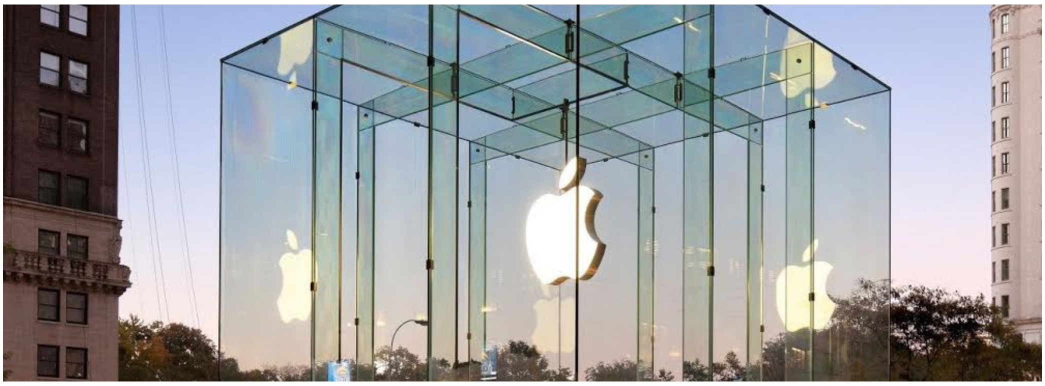


Figure 4.2: Glass fins: Apple store 5th avenue New York City. Source: EOengineers

Additional material

In the Vakko Fashion Center (completed in 2008), the glass in the façade is stiffened in a completely different way. By slumping a structural "X" into each pane the glass's second moment of inertia is increased. The aim of REX architects was to have a transparent façade (without perimeter mullions) with an increased loading capacity.

Figure 4.3: Glass sheets with additional X: Vakko Fashion Center Istanbul.
Source: domusweb.it

Corrugated glass

Another stiffening method is found in the façade of Casa da Musica (Porto). By the technical support of ABT and ARUP, OMA was capable of designing hot bent glass sheets. Due to its curvature, these sheets are far stiffer than a flat glass plate of the same thickness. The load bearing capacity is improved, while the view is enhanced.

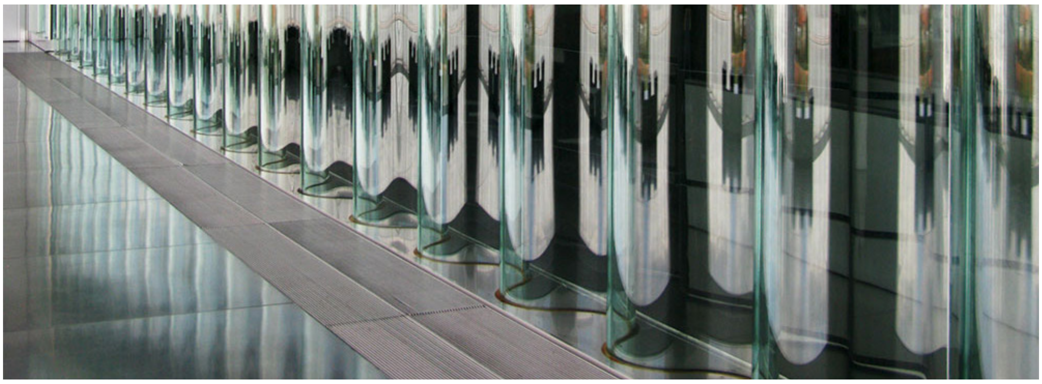


Figure 4.4: Corrugated glass facade: Casa da Musica, Porto.
Source: ABT.eu

Jan Wurm (2012), did several studies on foreign materials that can be laminated in between glass. All reinforce the glass, provide solar shading and thermal insulation. These methods do achieve a larger stiffness, but most are not fully transparent by the intermediate material.

Profiles

In 2002, Jan Wurm, C. Helmus and M. Mevissen developed an insulating glass unit with profiles glued inbetween the face sheets. Solid-, C- and I-profiles can be used but the solid one can withstand most force, moment, stress and deformation. The composite (GFRP) profiles are connected to the glass with a layer of silicon adhesive. Since profiles cannot be regulated according to solar altitude, the system is not very effective in terms of solar shading.

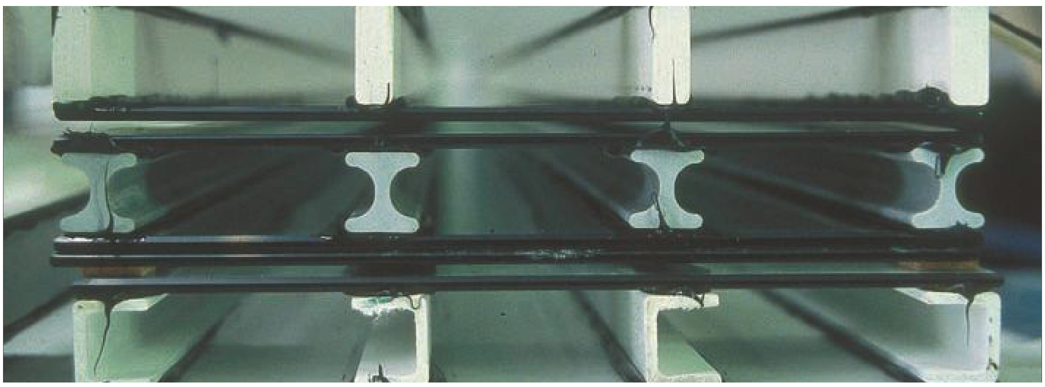


Figure 4.5: GFRP profiles.
Source: J. Wurm.

Aluminum cubes

Another project of Wurm is a glass-aluminum sandwich. In collaboration with E. Acciarito, I. Klockenbusch,S. Riesenkampff, J. Vossebürger and technical support from Institut für Stahlbau (RWTH Aachen), Jan was capable of developing a stiffened, insulating and controlling privacy glass façade element.
The aluminum cubes (4 x 4 cm) are laminated in-between two float glass sheets by the use of high performance, transparent, double-sided acrylate tape.

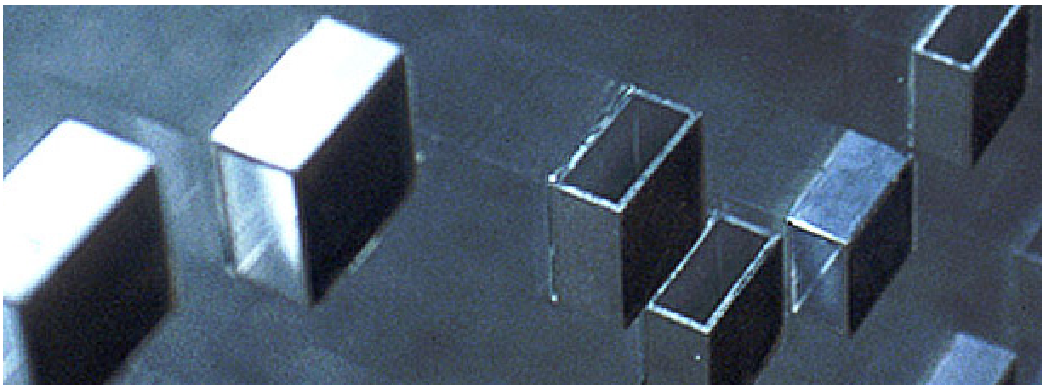


Figure 4.6: Aluminum cubes.
Source: J. Wurm.

Corrugated steel sheet

In 2001, Jan Wurm developed a glass roof construction. In cooperation with A. Hübinger, S. Főrst and Saint Gobain. By supporting the glass sheet with a perforated corrugated steel plate below. In this construction, the glass on top takes compression forces while the steel sheet takes all tensile forces. Besides stiffening and light transmission, the corrugated steel sheet improves the acoustic performance and solar shading.

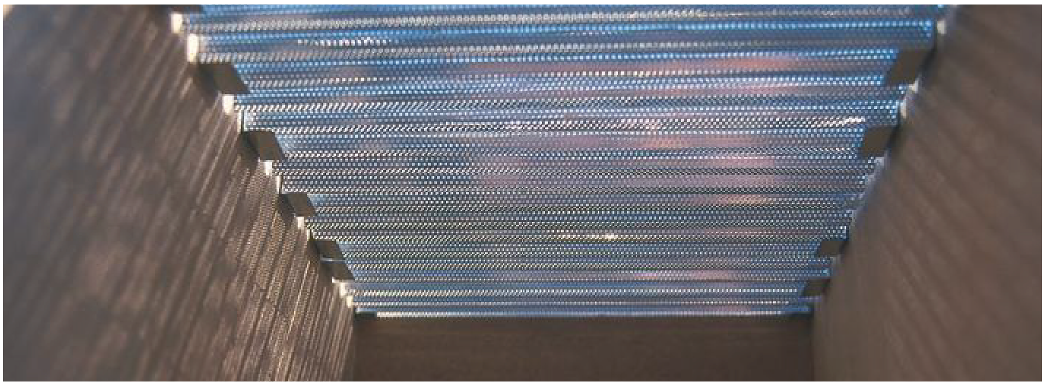


Figure 4.7: Roof structure with a steel glass composite system.
Source: J. Wurm

Honeycomb interlayer

Since 2016, the Berkley Hotel in London has a new entrance canopy. Therefore Rogers Stirk Harbour + Partners designed a glass sandwich panel in cooperation with Arup and Bellapart. The construction consists of glass sheets of 3 mm (4800 x 2300 mm) on top and bottom and an aluminum honeycomb structure bonded onto the glass by UV-curing transparent acrylic adhesive. The honeycomb structure increases the stiffness while few weight is added.

Figure 4.8: Aluminum glass honeycomb sandwich structure.
Source: Bellapart.

Conclusion

Flat glass sheets do not have a large stiffness due to their flat shape. This is easy to understand when comparing glass with a sheet of paper. According to Simoen (2016), there are five stiffening methods which could be applied for thin glass: stretching, bending, increasing the second moment of inertia, inflating or deflating. For soda lime glass, several stiffening methods have been found in this precedent study. All of these methods are based on the principle of increasing the height and thereby the second moment of inertia.

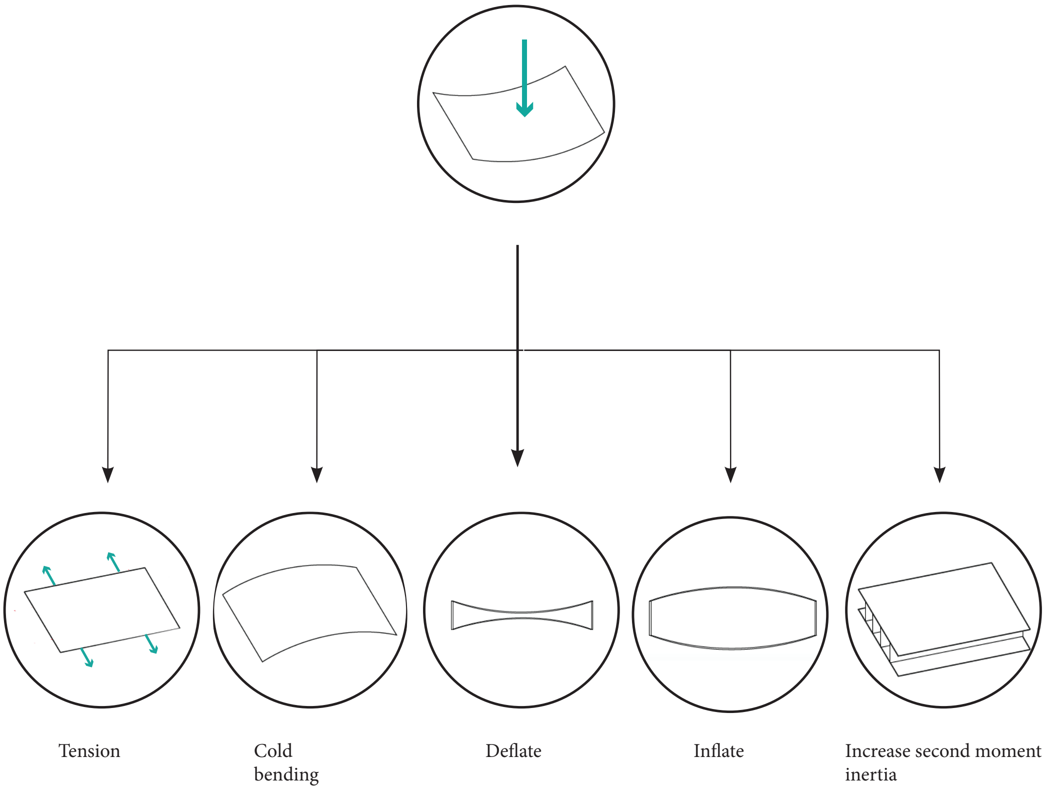


Figure 4.9: Stiffening methods thin glass.
Source: by author.

Lamination, glass fins and additional glass material are stiffening methods that particularly consist of the material glass. These methods provide a large transparency/light transmittance, but they are not insulating by themselves. For that, an additional layer of glass would be needed which creates a cavity. Since glass is a material with a relatively large density, each additional glass layer is detracting from the lightness concept.

Corrugation of glass is not as heavy, since it is just a single glass layer. It is produced by hot bending, this manufacturing method is, so far, not used for thin glass. Whether this is possible should be researched further. Also it is complicated to make a configuration in which the curved glass becomes insulating since the spacers and window frames also need to be curved.

The precedents in which foreign materials (profiles, aluminum cubes and honeycomb structure) are used as interlayers bonded onto the glass can be described as a sandwich construction. The glass sheets are used as the face sheets of the sandwich construction.

4.2 Insulation

Because of its slenderness, thin glass does not have a low u-value (figure 4.10), while it is one of the design criteria to achieve an u-value of at least 1.4 W/m2K.
In order to create a thermally insulating glass panel with thin glass, there several methods. An inventory of current available methods shows several options. As discussed before, generally, insulating glass consists of two, or more, separate panes kept apart by spacers all around the edges creating a cavity. It is possible to create cavities, filled with an inert gass. But it is also possible to fill it with other foreign materials. The most interesting precedents are cavities filled with capillary slab(s), aerogel, PCM plates and vacuum panels.

Most of these methods are not applied regularly because they are either too expensive or not aesthetically pleasing. Some panels, for example, are translucent, which could be very convenient for buildings that should be protected from solar radiation, like museums. However, architects should be willing to accept their aesthetics.

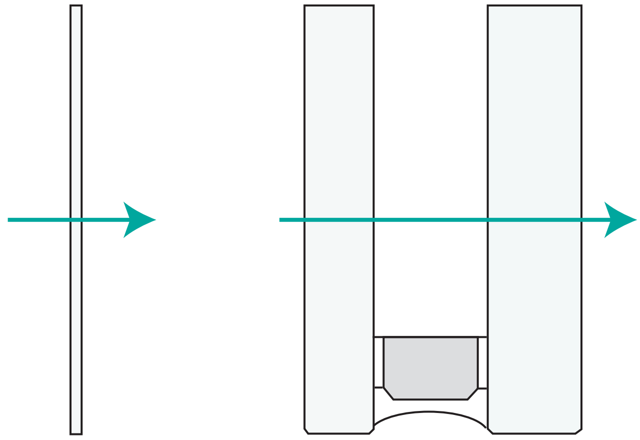


Figure 4.10: Thermal conduction comparison thin glass and
Source: by author.

Capillary slab

Okalux is a company which is specialized in the encapsulation of materials within the cavity insulated glass units. They have developed several products (okalux, okalux +, okalux evo, okalux k and okalux) that consist of glass sheets with a capillary slab in-between. This slab provides diffuse light transmission, thermal- and acoustic insulation.

The difference between these products lies within the built-up. The slabs thickness varies from 8 to 40 mm. The glass can be coated, an additional glass sheets can be added to create an extra cavity and this cavity can be filled with an inert gass. Okalux evo achieves the best thermal insulation value (U = 0.8 W/m2K). It consists of 3 glass sheets of which one is coated with low-e, this creates two cavities. One cavity is filled with Krypton to achieve best thermal insulation. The other cavity contains two capillary slabs with some glass fibre tissue in-between.

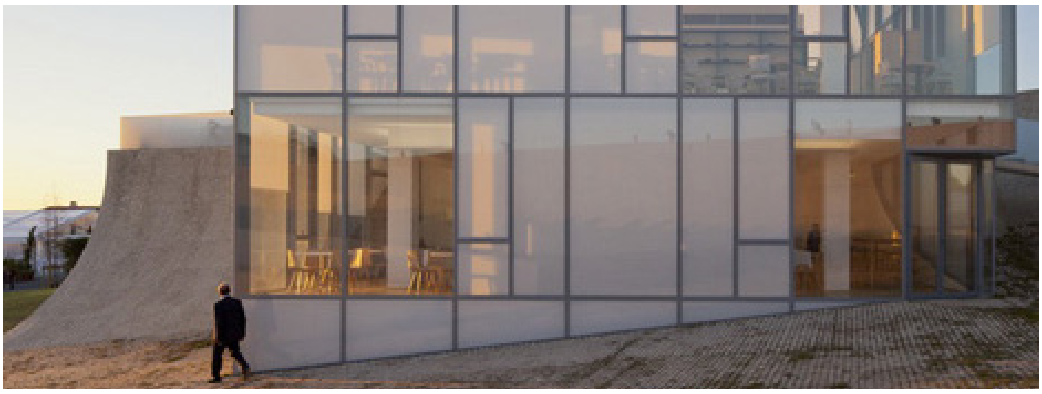


Figure 4.11: Applied cappilary slab panel.
Source: Okalux

Aerogel

In another okalux product, the cavity in-between two glass sheets is filled with aerogel. Aerogel is a synthetic porous ultralight material derived from a gel, in which the liquid component of the gel has been replaced with a gas. It is a material with very low thermal conductivity which also offers outstanding acoustic insulation. The thickness of the aerogel sheet vary from 8 to 40 mm. Best thermal insulation (0.3 W/m2K) can be achieved with the largest thickness.

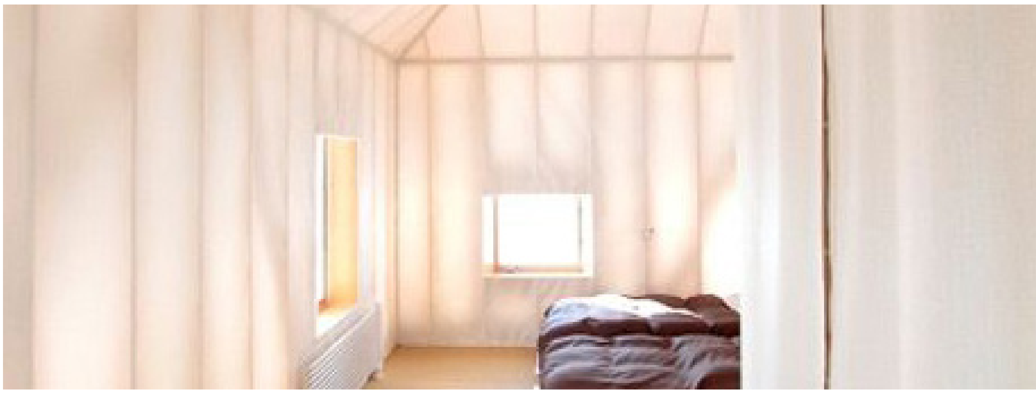


Figure 4.12: Okagel panel. Source: Archdaily.

PCM plate

Phase change materials (PCM) are substances that absorb and release thermal energy during the process of melting and freezing. When a PCM freezes, it releases a large amount of energy in the form of latent heat at a relatively constant temperature. Conversely, when such material melts, it absorbs a large amount of heat from the environment. PCMs recharge as ambient temperatures fluctuate. Glass-x, has a PCM slab integrated in its cavity. Because of that is has become thermodynamic glazing with a storage capacity of 1185 Wh/m².
It is built out of 4 glass sheets, thus three cavities. In the first cavity, a prism plate is placed combines with inert gass. The second is only filled with gass, and the third contains the PCM plate. The second glass sheet is coated. Because of this built-up, an U-value of 0.48 W/m2K is achieved.
Variables in this type are the type of PCM (liquid or crystalline), the thickness of the PCM and the cavities and gass type within the cavities.

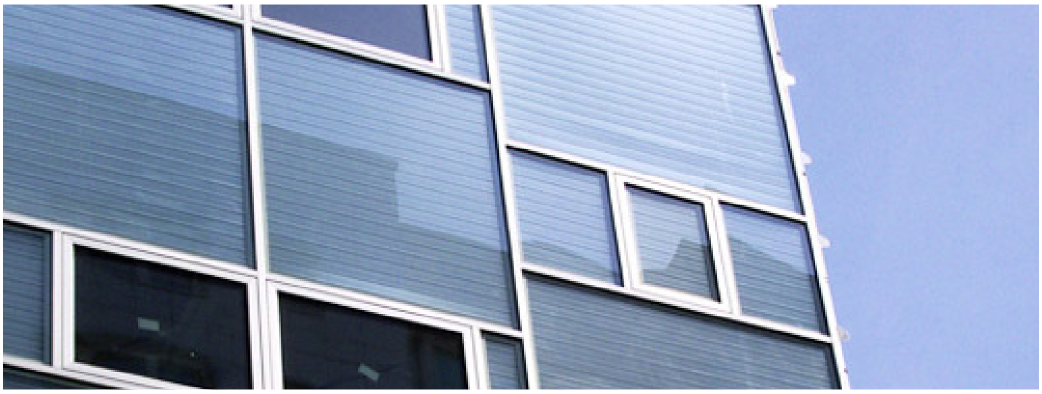


Figure 4.13: Glass-x facade. Source: Greenlite glass

Vacuum panel

Vacuum glazing consists of two glass sheets with tiny distance spacers inbetween them. These are necessary when creating the vacuum. The vacuum cavity eliminates heat transport due to conduction and convection of the filling gas. When coated, it provides a beter thermal insulation (U-value = 0.4 W/m2K) than conventional double glazing with only a quarter of the thickness.

Figure 4.14. Sample vacuum glass panel.
Source: Bine

Conclusion

Without taking cavities into account, there are quite some methods to create insulating glass units. Among the showed insulation methods, very low u-values are achieved (below U=0.5 W/m2K). There are Inserting an interlayer of a foreign material inbetween the two layers can improve the insulation value significantly.

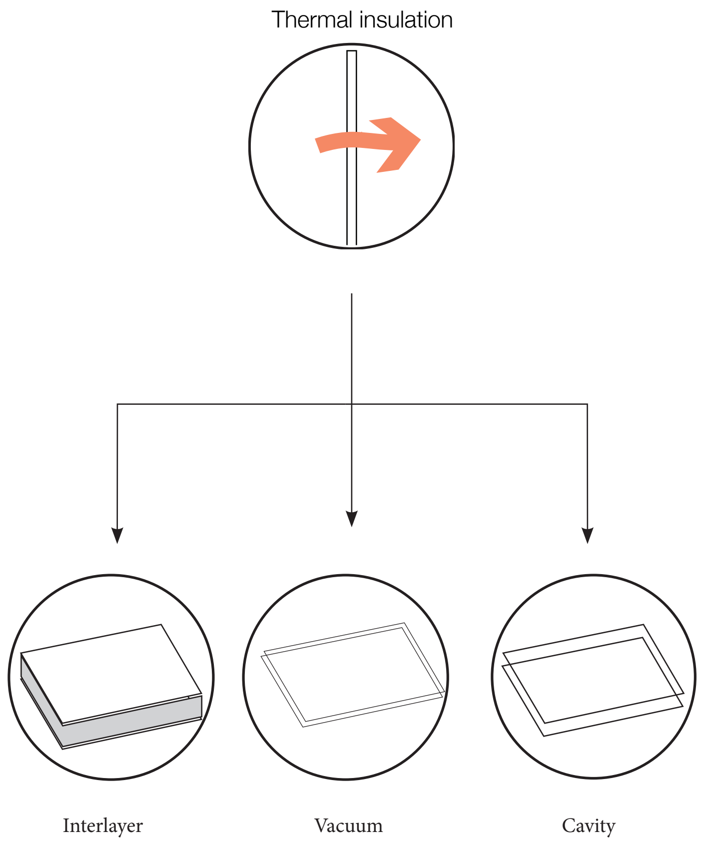


Figure 4.15: Okasolar facade.
Source: by author.

4.3 Sunshading

To prevent excessive solar heat gain, sunshading can be integrated into a facade panel. Again, by integrading foreign materials in the cavity of the glass. All panels, to be discussed, are made of a conventional double or triple glass constructions. In the cavity, louvers, mesh or ion conducting polymers can be added to prevent excessive gain.

Louvres

Okalux has produces a series of panels with integrated louvres in the cavity, called, okasolar. With coated triple glazing, filled with an inert glass, an U-value of 0.8 W/m2K can be achieved. This is the same as can be achieved with insulated triple glass units without louvres. The thickness of the cavities influences the thermal insulation.
There are several types: okawood, okasolar f, okasolar s and okasolar retroflex, which have slightly different louvre-profiles. When disassembled, the louvres can be recycled whether they are made of wood, plastic or metal.

Figure 4.16: Okasolar facade.
Source: Okalux

Mesh

Besides louvers, other semi-transparent materials can be placed inbetween the cavity which can prevent solar gain. Okatech is a product with a metal mesh laminated in-between two glass sheets. The thickness of the cavity and the gass type in it influences the thermal insulation, again, combined with the presence of a coating. The mesh material, type and pattern can vary, although it will not influence the thermal insulation. The best U-value which can be achieved is 1 W/m2K. The metal mesh can be recycled when the panel is no longer in use.

Figure 4.17: mesh integrated facade.
Source: Okalux

Ion conducting polymer

Okatherm swich is an example of a facade panel with electrochromic glass. It changes its brightness at the press of a button. When a small electricalvoltage (approx. 3V) is applied, the glass changes its colour to dark blue, or its turns transparent.
When configured as double insulating glass, using insulated glass, combinations thermal insulation coatings and gas-filled voids, U-values up to U = 1.1 W/m2K can be achieved.

Figure 4.18: Ion conducting polymer.
Source: Obsi.com

4.5 Conclusion

The precedents in which foreign materials (profiles, aluminum cubes and honeycomb structure) are used as interlayers bonded onto the glass can be described as a sandwich construction. The glass sheets are used as the face sheets of the sandwich construction. This sandwich method could be combined with some of the found isolation methods. The found precedents have taught us that, for example, aerogel or a capillary slab could be placed in a cavity. A combination of both stiffening, and thermally insulating properties could be realized with the sandwich construction method. However, the interlayer will reduce the transparency of the panel. This could be seen as a disadvantage, but actually it is beneficial because it reduces solar gain.

Method	Stiffening	Insulating	Sun shading
Lamination	+	-	-
Glass fins	+	-	-
Additional material	+	-	-
Corrugated glass	+	-	-
Profiles	+	+	+/-
Aluminum blocks	+	+	+/-
Corrugated steel sheet	+	-	+
Honeycomb sandwich	+	+	+
Capillary slab	+/-	+	+/-
Aerogel	+/-	+	+
PCM plate	-	+	+
Vacuum panel	+/-	+	-
Louvers	-	+	+
Mesh	-	+/-	+
Ion conducting polymer	-	+	+

Table 4.1: Comparison methods for their stiffening, insulating and sunshading properties.
Source: by author.

In table 4.1, all the found precedents are compared for their stiffening, insulating and sunshading properties. It can be concluded that a sandwich construction is most suitable, it offers stiffening, insulating and sunshading properties(figure 4.19). Several sandwich methods should be explored.

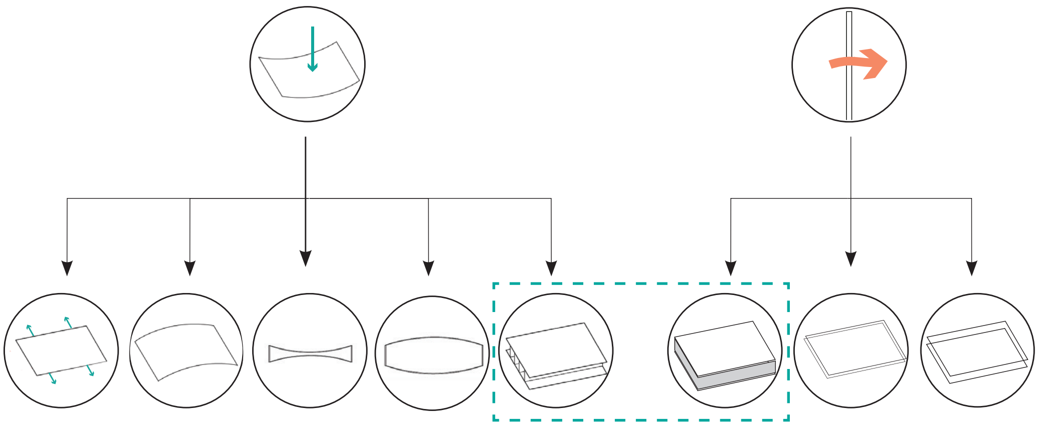


Figure 4.19: Combining stiffening- (increasing second moment inertia) and insulation methods (interlayer). Source: by author.

05

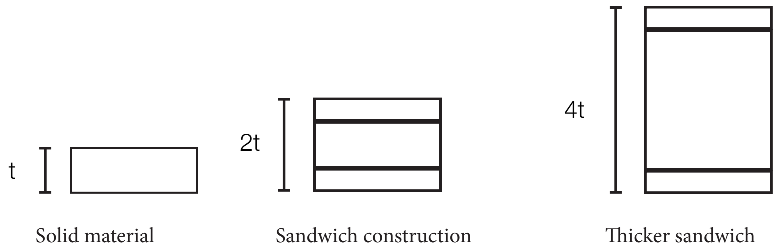
Sandwich panels

Typically sandwich structures have two face sheets, carrying the bending loads (compression and tension) and a core in-between. A sandwich construction, is extremely structurally efficient, particularly in stiffness critical applications. Doubling the thickness increases the stiffness over 7X with only a 3% weight gain, while quadrupling the thickness increases the stiffness over 37X with only a 6% weight gain. This method offers a possibility for lightweight stiffening of thin glass panels.


photo: by author

5.1 Sandwich theory

A sandwich panel is a structure made of three layers: two face sheets and a low density core inserted in between. Generally, sandwich structures have relatively thin face sheets (approximately 0.2 - 3.2 mm) with a lightweight core density in the range of 16 - 480 kg/m3. Core materials include metallic and non-metallic honeycomb cores, wood based materials, open and closed cell foams and syntactics. Because it is an extremely lightweight structural approach that exhibits high stiffness and strength-to-weight ratios, sandwich constructions are extensively applied in both aerospace- and commercial industries. In commercial applications often foam cores are applied, while applications in aerospace use the higher performance but more expensive honeycombs.



	Solid material	Sandwich construction	Thicker sandwich
Stiffness	1	7	37
Flexural strenght	1	3.5	9.2
Weight	1	1.03	1.06

Figure 5.1: Stiffening method: sandwich panels
Source: Cambell Jr.

In general, foams have a relatively low crush strength and stiffness, which causes increased stresses in the face sheets. Foam has a limited strength and they are often friable and fatigue. Wood-based materials, such as plywood, balsawood or OSB, have a relatively heavy density in comparison to honeycombs and foams. They also are vulnerable to moisture degradation, to which honeycomb cores can offers excellent resistance (Hexcel, 2016).

According to Campbell Jr. (2011), sandwich panels, especially with a honeycomb core, exhibit high stiffness and strenght-to-weight ratios (figure 5.1). This is proven by Evans (2001), he states that the preferred typology of a lightweight structure depends on the configuration (flat or curved) and the loading (compression or bending). For flat panels subjected to bending, honeycomb cores represent the performance benchmark when it comes to strenght-to-weight ratio. This is shown in figure 5.2 where the weight index, of a flat panel subjected to bending force, is plotted against the load index.

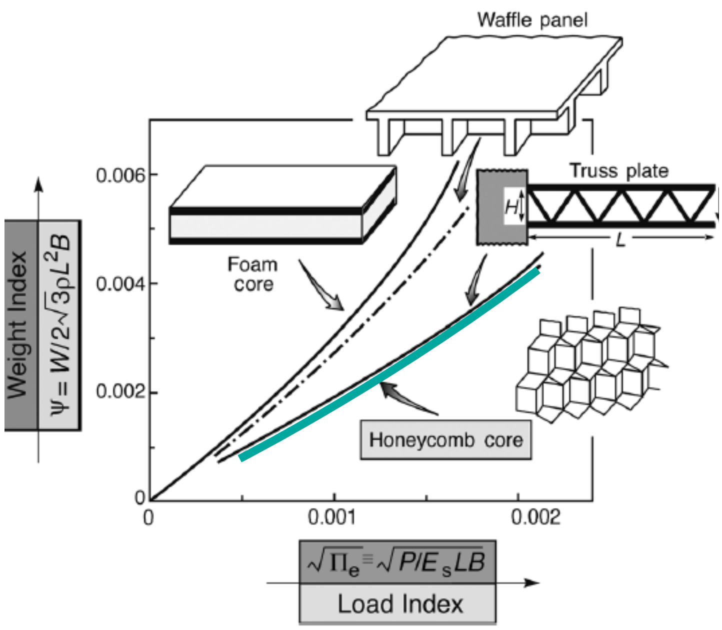


Figure 5.2: Comparison weight/load ratio of a waffle, foam core, truss- and honeycomb panel
Source: Campbell Jr.

5.2 Honeycomb core

As stated before, the core of a honeycomb structure can be made out of metallic or non-metallic material. Most commonly used is aluminum, glass fabric, aramid paper, aramid fabric or carbon fiber. In order to understand how a honeycomb sandwich core should be like, first the basics of the honeycomb core itself should be explored.

How it is made

The corrugated ribbons that create the honeycomb consist of several parameters, as shown in figure 5.3. First, there is the L-dimension which is the length of the ribbon, the W-dimension is the height of all layers on top of each other and the thickness or width of the structure altogether. Final parameter is the cell size in-between the ribbons.

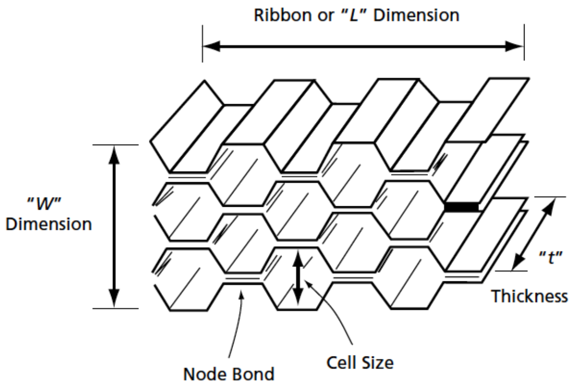


Figure 5.3: Corrugated ribbons that create the honeycomb
Source: Campbell Jr.

Besides the previous shown hexagonal structure, other configurations of the core cells are possible. The hexagonal cell configuration has a limited formability, this leaded to the development of the flexible and the over-expanded (OX) core configuration.The over-expanded configuration has increased shear properties in the W-direction, but decreased shear properties in L-direction when compared to the hexagonal one (F.C. Campbell Jr, 2011).

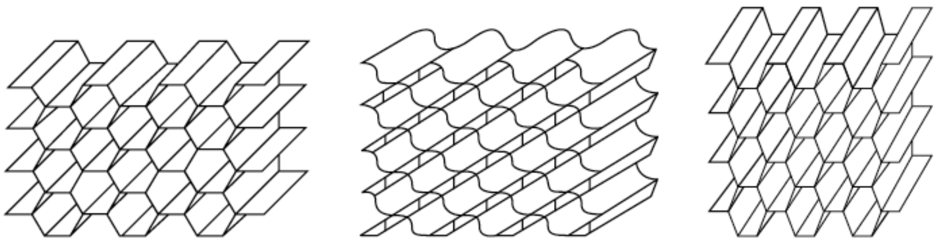


Figure 5.4: Typical core types. From left to right: hexagonal, flexible and overexpanded core.
Source: Campbell Jr.

A honeycomb core can be produced by the expansion or the corrugation method. The expansion method is a fabrication that process begins with the stacking of sheets on which adhesive node lines have been printed. The adhesive lines are then cured, after the block may be expanded to gain an expanded block. Slices of the expanded block may then be cut to the desired L dimension (ribbon direction) and W dimension (transverse to the ribbon).

The corrugated process of honeycomb manufacture is normally used to produce products in the higher density range. In this process adhesive is applied to the corrugated nodes, the corrugated sheets are stacked into blocks, the node adhesive cured, and sheets are cut from these blocks to the required core thickness.
Due to the cured nodes, honeycomb is stronger in the longitudinal ("L") direction than the width ("W") direction (Campbell, 2006). A typical honeycomb panel construction is shown in figure 5.8.

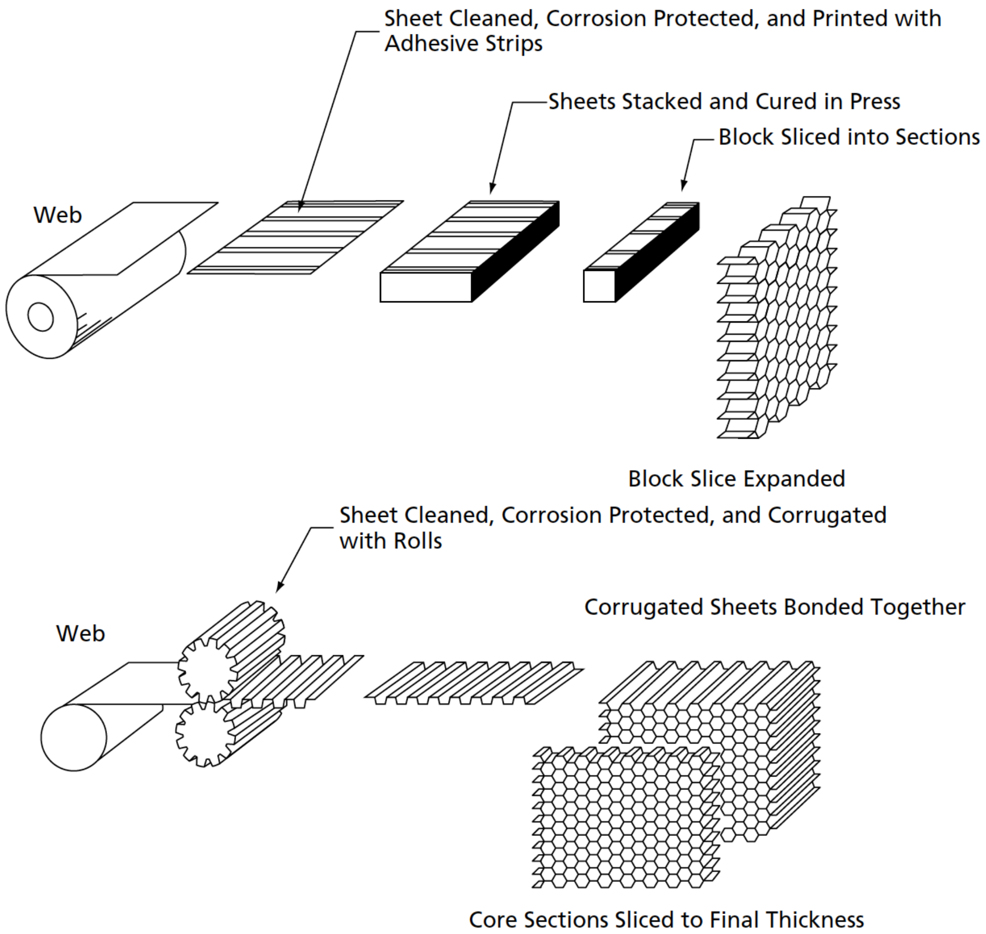


Figure 5.5: Production typical honeycomb core.
Source: Hexcel

Mechanical performance

A sandwich panel, will deflect under (bending) pressure. The top and bottom plate will deflect simultaneously. Meaning that the core will be subjected to tensile forces on top, and compression on the bottom. These different directions create shear forces. A shear force is a force that is acting on a substance in a direction perpendicular to the extension of the substance. These shear forces are explained in figure 5.6, where a force perpendicular to the surface of the sandwich panel results in tension in the top of the interlayer, and compression at the bottom. These forces create internal stresses in the material, they are called shear stresses. Because of this effect, the core material should be able to withstand a certain amount of shear. A materials' shear modulus describes the amount of shear stress a materials is able to resist.

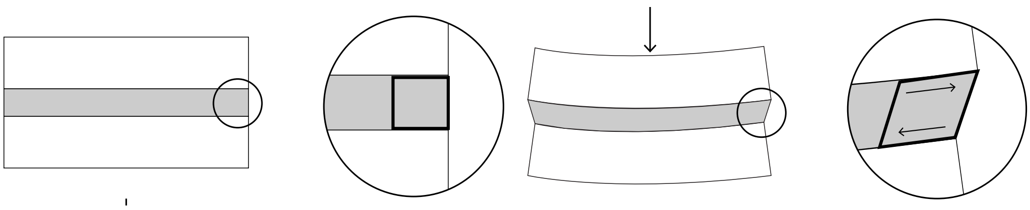
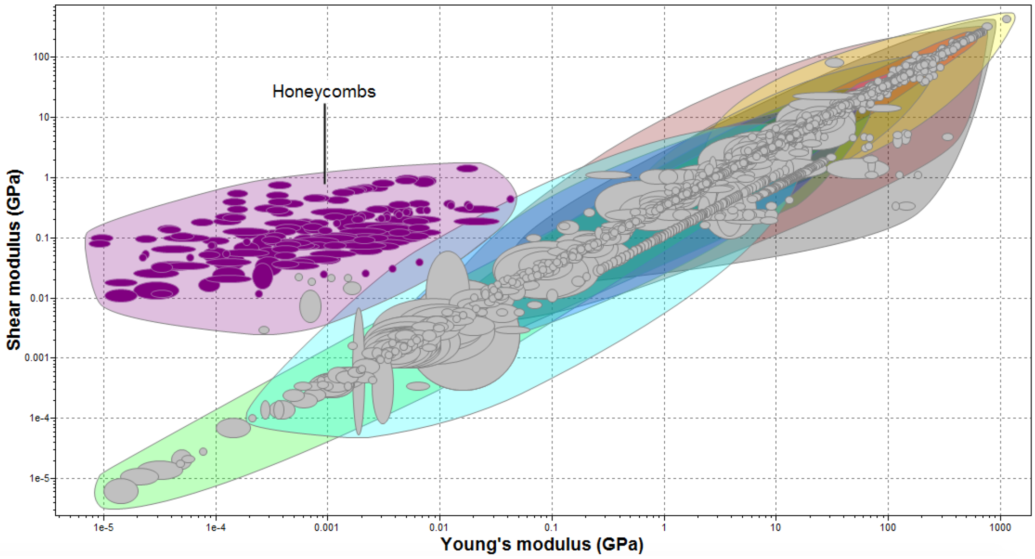


Figure 5.6: Shear force by bending force.
Source: by author.

CES Edupack, is a software which contains a large database of existing materials, production- and joining methods. Within the program, properties and techniques can be filtered, plotted and compared in order to find a material which complies with the requirements. When plotting the shear modulus to the youngs modulus (which provides stiffness), it is clearly shown that, among all materials, the ratio shear/stiffness is highest for all honeycomb types, graph 5.1. This proves a honeycomb core is very suitable as a core material.



Graph 5.1: Plotted shear - and Youngs modulus of all materials. Source: CES Edupack

The graph also shows a relatively low stiffness, which be explained by a phenomenon which is called anticlastic curvature. When hexagonal honeycomb is bent, it exhibits a phenomenon where the honeycomb is forcibly curved around one axis and the core reacts by bending in a reversed curvature along an axis oriented 90°. Once a honeycomb core is used in a sandwich panel, the bending forces will be absorbed by the top- and bottom plate. The anticlastic curvature effect will not occur when the performance of the glass face sheets are sufficient.

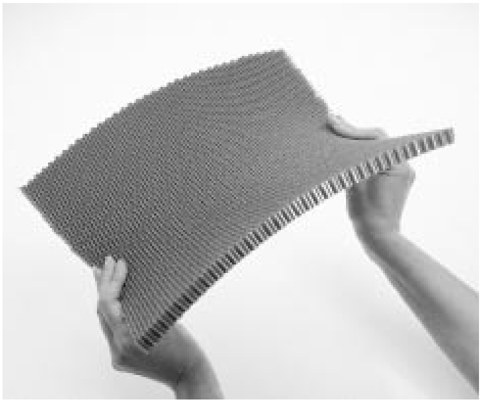


Figure 5.7: Anticlastic curvature. Source: Hexcel.

5.3 Manufacturing a sandwich panel

Usually a honeycomb sandwich construction consists of two corrugated ribbons that are glued onto each other (node bond adhesive) in order to make the hexagonal shape for the core. The core is glued onto the face-sheets, to do so, it is very important that the applied adhesive provides a good fillet at the honeycomb core to skin interface (face bond adhesive). According to Hexcel (2016), a honeycomb sandwich components may be produced using three alternative well-established methods: the heated press, vacuum bag processing, and matched mould processing.

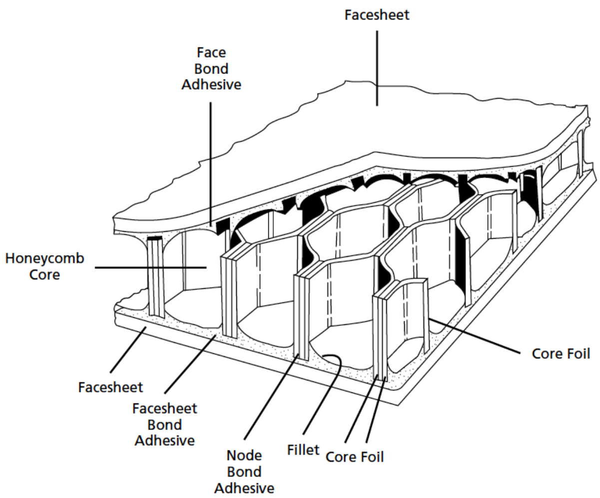


Figure 5.8: Typical honeycomb core. Source: Campbell Jr.

Heated Press

This method is generally used for the production of flat board or simple preformed panels. Ideally the panels should be assembled ready for curing as a single shot process. This method is suitable for metallic and pre-impregnated facing skins. Alternatively pre-impregnated facing skin materials may be pre-cured by using a press, and subsequently bonding with a film adhesive layer.
Integrally bonded items such as extruded bar sections and inserts may be included and located by the honeycomb core or with simple tooling.

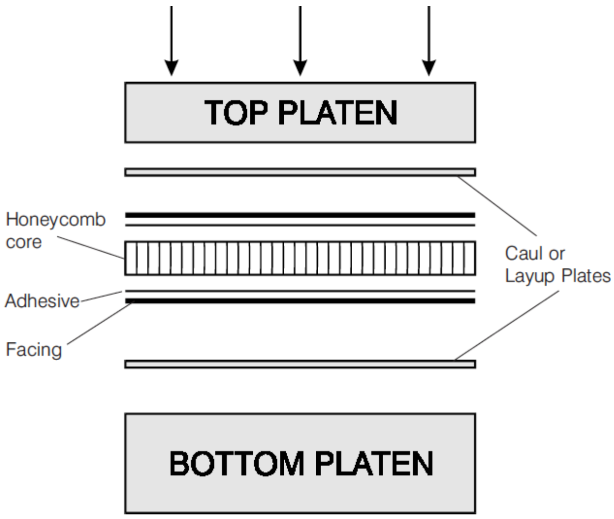


Figure 5.9: Production typical honeycomb core, heated press.
Source: Hexcel

Vacuum Bag Processing

When making curved and complex form panels this method is often used.
The component should be assembled for cure as a single shot process, the necessary consolidation is obtained using a vacuum. This can be cured in an oven or an autoclave, where additional pressure can be applied. This method is suitable for items with pre-impregnated or preformed composite or metallic facing skins. When a flexible or formed honeycomb core and film adhesives are used complex items, such as double curved surfaces, may be produced (figure 5.10).

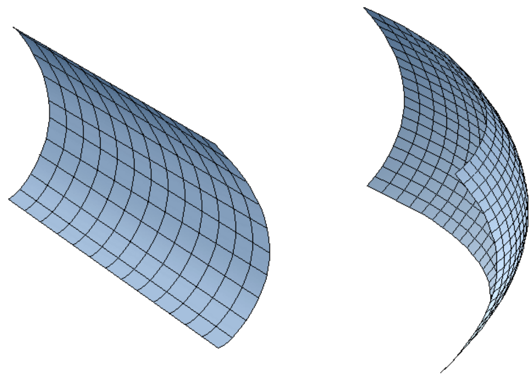
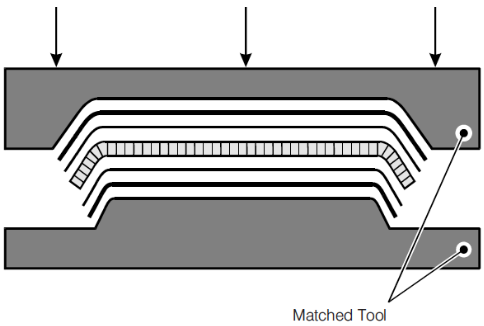


Figure 5.10: Complex geometry, single and double curved surfaces.
Source: Radar.eu

Match Mould Processing

This method is used generally for batch production of finished panels, it is most suited to the single shot cure process where a key objective is to achieve production items with high levels of tolerance and surface finish. The heat and pressure cure cycle in this case is applied using a variety of methods. Typical methods are the use of heated tools with external mechanical pressure or non heated tools placed in a press or oven to achieve the full cycle. Using a room temperature curing adhesive cold bonding may be considered if the sandwich construction is too large to be processed using the above methods, or if heating equipment is unavailable.



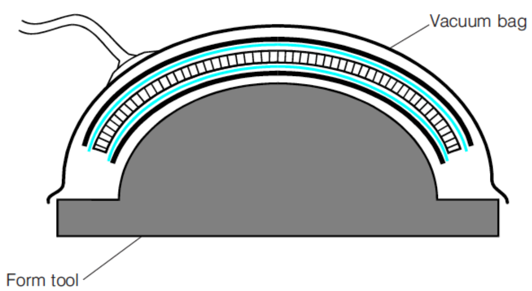


Figure 5.11 (left): Production typical honeycomb core, match mould processing.
Source: Hexcel

Figure 5.12 (right): Production typical honeycomb core, vacuum bag processing.
Source: Hexcel

5.4 Mechanical testing methods

To test the mechanical properties of a sandwich panel, several testing methods are available. The compressive strength, crush strength, L- and W-shear properties, flatwise tensile and beam flexure (or bending test) can be tested. For these tests, the facings must be adhesively bonded to the honeycomb material in stabilized condition.

The compressive strength represents the ultimate compressive strength, expressed in Newton per square meter, of the honeycomb when loaded in t-direction. The standard specimen size for the stabilized compressive tests is 76.2mm x 76.2mm x 15.875 mm. After honeycomb has exceeded its ultimate compressive strength, it will continue to deform plastically and crush uniformly. The load-deflection curve shows such a typical response. The average crush load per unit cross-sectional area is defined as the crush strength, expressed in N/m2. Fixed loading and bearing plates are used for crush strength tests and a deflectometer is employed to measure the travel of the crosshead of the test machine. In order to obtain a meaningful crush load deflection curve, a minimum core thickness of 0.625 inches (15.875mm) should be used.

The shear strength of a honeycomb refers to the ultimate stress in N/m2 when a shear load is applied parallel to the L–W plane. The specimen size for aluminum honeycomb is normally 190.5 mm x 50.8 mm x 15.875 mm. Non-metallic honeycombs test sample size is 152.4 mm x 50.8 mm x 12.7 mm. The specimens are bonded to steel loading plates and then tested. The loading rate used produces a failure in three to six minutes. Shear deflections are measured with a displacement transducer that senses the relative movement of the two plates.

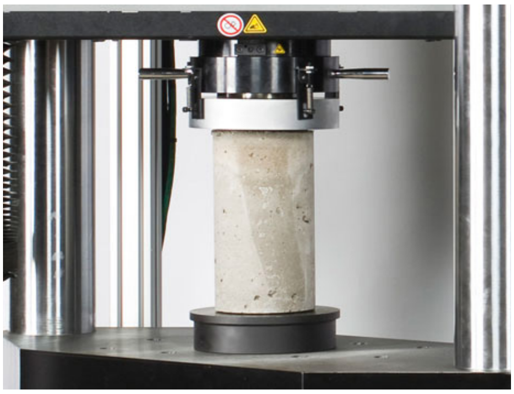


Figure 5.13 (left): Compressive test.
Source: SANS.

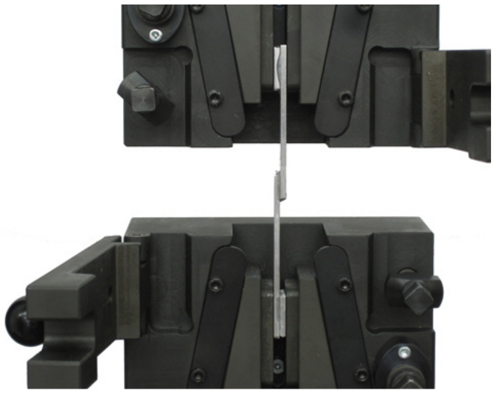


Figure 5.14 (right) : Shear strength test.
Source: Wyomingtestfixtures.

Flatwise tensile is used to measure bond strength of adhesives and/or the tensile strength of the honeycomb core. This test is most useful in determining skin preparation, bonding conditions, and prepreg adhesions.

Although the plate shear method is preferred for obtaining actual honeycomb shear strength and modulus results, the beam-flexure test is often used to evaluate overall sandwich panel performance. Experience indicates that since these values are very much dependent on the facing thickness, facing material and loading conditions. The preferred specimen size is 203.2 mm x 76.2 mm. The span between supports is 152.4 mm and either one or two point loading can be used. The distance between the load pads for two point loading is normally 1/3 the span.

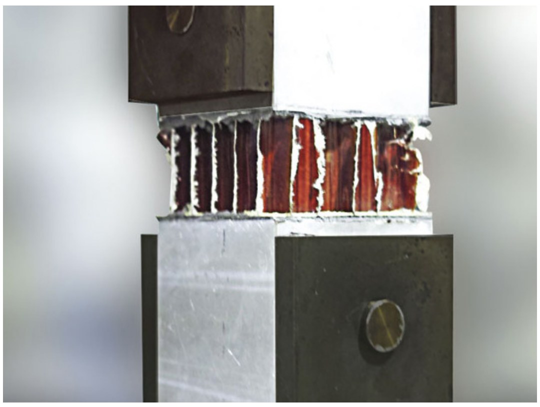


Figure 5.15 (left): Flatwise tensile test
Source: Wyomingtestfixtures.

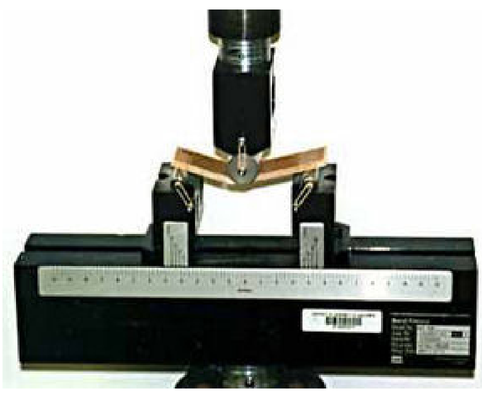


Figure 5.16 (right): Beam flexure / 3 point bending test.
Source: Hexcel

5.5 Honeycomb materials

As aforementioned, most commonly applied materials for honeycomb cores are aluminum, glass fabric, aramid, paper and steel. Most producers of hexagonal honeycomb cores (like Hexcel and Plascore) also produce polyurethane honeycomb structures, however, this material is not a common material for application in any industry. In this paragraph, their properties are compared.

Aluminum

According to CES (2106), among all core types the expanded aluminum cores offer the lowest density. It has the greatest strenght/weight ratio, which is due to the cell wands that are the thinnest among these materials (Hexcel, 1999). Like all metals, aluminum has the property to allow for conductive heat transfer.
An aluminum core is relatively low in cost therefore, it finds its typical usage in building cladding, commercial vehicle panels, railway floors and doors, boat hulls, interior panels, motor racing chassis. Energy absorbing structures, air and fluid straighteners (wind tunnel grilles), heat exchangers, skylights (CES, 2016).

Cell sizes [mm]	1.59 - 25.4
Density [kg/m3]	15.7 - 25.8
Price [€/kg]	12 - 13.5

Aramid (para- and paper)

Aramid honeycombs come in many different types. After the paper is manufactured, it is dipped in resin to producte the final product. Their composition can be 18 - 80% paper and 20 - 82 % phenolic resin. Also, many different cell sizes, densities and therefore strengths can be obtained with aramid fiber. Among all materials, aramid-paper offers the lowest thermal conductivity, thus good thermal insulation. Also, it has low dielectric properties (Hexcel, 1999).
Their most typical uses are: helicopter blades, fairings, control surfaces, bulkheads, flooring, interior panels, hatches, high performance boat hulls, automotive body panels, precision optical equipment, radar reflectors, covers and emitters (CES, 2016).

Cell sizes [mm]	3.18 - 19
Density [kg/m3]	23 - 180
Price [€/kg]	27.3 - 56.7

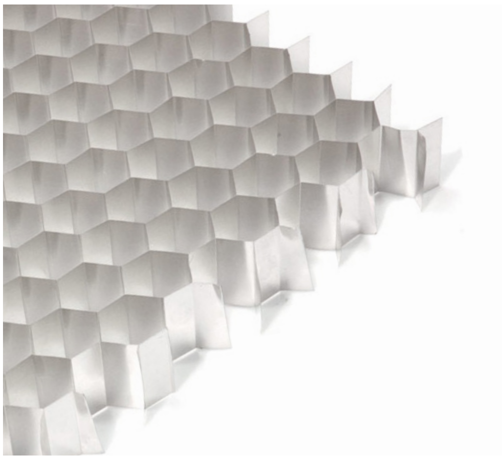


Figure 5.17 (left): Aluminum honeycomb core.
Source: Hexcell.

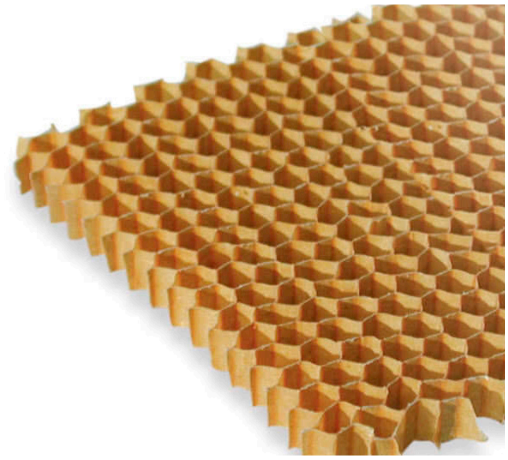


Figure 5.18 (right): Aramid honeycomb core.
Source: Hexcell.

Impregnated paper

Impregnated paper is lightweight and low-cost. Approximately 15% of this structure is resin (polymer) and 85% cellulose (paper). Impregnated paper is not often applied for structural purposes, mostly imgregnated paper is used in interior panels, doors furniture, automotive floor plans, display boards and packaging (CES, 2016).

Cell sizes [mm]	6.35 - 12.7
Density [kg/m3]	24.6 - 25.8
Price [€/kg]	8.74 - 9.61

Glass phenolic/polyimide

Expanded impregnated glass fabric honeycomb offers the multi dimensional strength of a woven structure. Like with aramid-paper, the chemical composition of this honeycomb type can vary, the woven glass fiber reinforcement differs from 30 - 60 percent, thus 40 - 70 % phenolic resin.
It provides thermal insulation and low dielectric properties (Hexcel, 1999). This core material finds applications in structures requiring high temperature resistance and RF transparency, high-energy radomes, aircraft structural parts and engine inlets. It is among these, most expensive and for that reason not applicable in many other products (CES, 2016).

Cell sizes [mm]	4.76 - 9.53
Density [kg/m3]	34.5 - 35.9
Price [€/kg]	60.6 - 140

Stainless steel

Like aluminum, steel has the material property to conduct thermal heat. It is relatively heavy in comparison to the other materials but its UV-resistance is largest among all available honeycomb materials. Also, stainless steel has a large resistance to highly corrosive environments. Typical use of stainless steel honeycomb cores are found in bulkheads, train doors and floors (CES, 2016).

Cell sizes [mm]	9.53 - 12.7
Density [kg/m3]	83.1 - 86.5
Price [€/kg]	37.1 - 61.9

Plastics

Besides polyurethane, a honeycomb structure can also be created by polyetherimide polycarbonate and polypropylene. Polycarbonate can be produced in different colors, translucent or transparent. When designing with plastics, UV-resistance should be taken into account when applied in an exposed facade element (S. Engelsmann, 2010).
The resistance of (polypropene) PP is poor but polycarbonate (PC) offers a fair resistance (CES Edupack, 2016).

When designing with plastics, some possible problems should be taken into account. First its melting and/or yield temperature, which is possibly about the same temperature as the curing process of a film adhesive. When manufacturing the sandwich panel, this could mean the core melts simultaneously with film interlayer.
Another possible problem could occur when using adhesives instead of film interlayers, when an agressive glue type is used it could vanish the plastic.

Additive manufacturing

Also, one could imagine the possibility of creating a honeycomb structure by additive manufacturing. Additive manufacturing (or 3D printing) is a manufacturing method which refers to processes used to create a three-dimensional object in which successive layers of material are formed under computer control to create an object. Objects can be of almost any shape or geometry and are produced using digital model data from a 3D model or another electronic data source such as an Additive Manufacturing File (AMF) file.With this method numerous materials can be used. It is a method which could easily be used to produce honeycomb structures. It offers the possibility to create a honeycomb structure that has equal mechanical properties in L- and W-direction.

3D printing could also produce a honeycomb structure with a variety in cell-wand sizes. Areas in the panel that are subjected to most stresses could be strenghtened by a thicker cell wand size. In this research however, the focus lies on excisting products because manufacturers of excisting products offer factural information on the mechanical and thermal performance of their products. In further research, this method would be worth investigating.

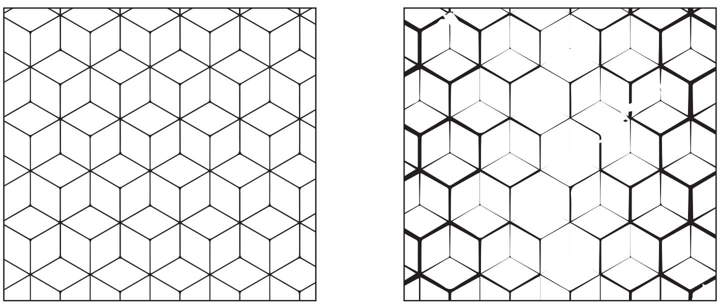


Figure 5.19: Possible configuration honeycomb core by additive manufacturing.
Source: by author.

5.6 Heat transfer of a sandwich panel

To calculate heat transfer of cavity constructions conduction, convection and radiation should be considered. It could be said a honeycomb sandwich panel consists of many small cavities. Therefore, the same calculation method as described in chapter 3 can be used to indicate the overall heat transfer. The only difference is that these small cavities are non-ventilated. Like with insulated glass units, the heat resistance of a sandwich panel can be approximated by the following formula:

Rtotal = 1/(αcond + αconv + αrad)

K.Kantha Rao and K. Jayathirtha Rao (2014) have done research on the heat transfer of honeycomb sandwich structures. They stated, for most honeycomb cores used in the fabrication of sandwich panels, the heat exchange by convection and conduction within the air contained in the cell is negligible compared to conduction in the cell walls and radiation within the cell. They also state that the effect of radiation is much smaller than that of conduction. However, their tests have not been done with glass face sheets, because of this material, radiation might be more important than stated in their paper. This results in an heat resistance calculation with the following formula:

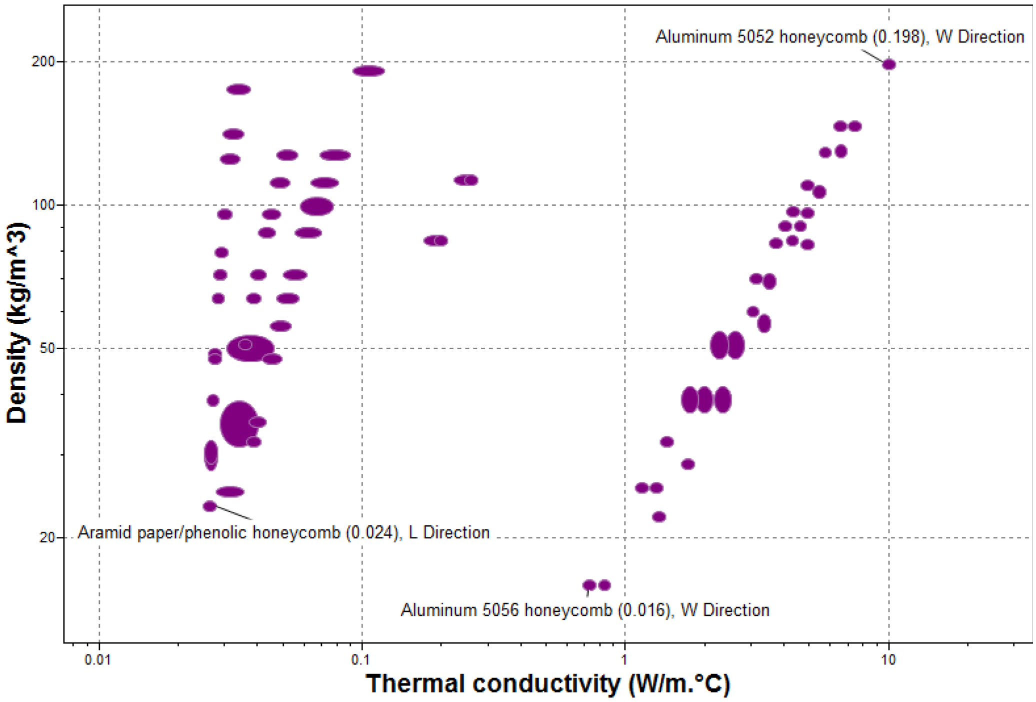
Rtotal = 1/ (αcond + αrad)

Conduction

Hexweb (2000) states that the thermal conductivity of a sandwich panel is influenced by each component in the build-up of the assemble: the facing, core, and adhesive. The resistances of each of these layer can simply be added in order to find the total heat resistance:

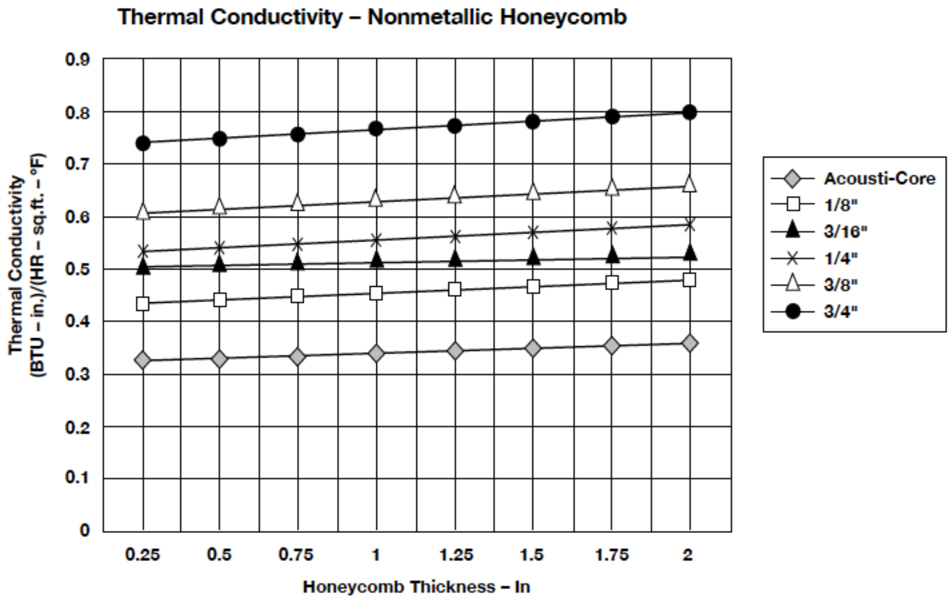
R= re + rglass + radhesive + rcore + radhesive + rglass + ri

The heat resistance of the applied facing material, glass, is a material property. Thermal resistance (r) for typical core-to-facing adhesives are 0.01 - 0.03 m2K/W for film adhesives. The thermal conductivity of the core is dependent on its material, the thickness, the density of the core and its cell size (graph 5.2).



Graph 5.2: Aramid honeycomb core.
Source: CES Edupack

Metallic cores generally have a larger thermal conduction than non-metallic ones. For metal honeycomb materials, the density is the variable that determines the heat transfer, it is nearly independent of the core thickness (Hexcel, 1999).



Graph 5.3. Thermal conductivity of non-metallic honeycomb cores. Source: HexWeb

For a non-metallic honeycomb, the cell size is much more important than core density. A non-metallic core such as aramid (paper) has much lower conduction coefficient than for example aluminum. To determine a core's thermal conductivity, graph 5.3 can be used. In this graph, the thermal conductivity and the honeycomb thickness of a non-metallic core are plotted. It is shown that the thermal conductivity is lowest when a small cell size and a low thickness is used. Higher thermal conductivities can be achieved with larger cell sizes, and larger honeycomb thicknesses.

Radiation

As stated before, most building materials have an emission coefficient (ε) around 0.9 to 0.95. Uncoated glass has an emission coefficient of ε = 0.84, the emission coefficient of the core can be estimated with the coefficient of paper which is ε = 0.93. The resultant, εres, gives the heat transfer coefficient the materials combined. It can be calculated with the following formula:

$1/\varepsilon_{res} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$
$\alpha_{res} = 6\,\varepsilon_{res}$

06

Bonding method

In order to make a sandwich panel, adhesive joints are inevitable. The top- and bottom sheets need to be bonded onto the core for the panel to accomplish structural collaboration. In this case, the top and bottom sheets of the sandwich panel are thin glass.

In general, the material glass faces several major problems. According to Veer, Janssen and Nägele (2005) these problems are as followed: glass is extremely brittle, it has a low strength, it is difficult to join onto other materials and the size of glass sheets are limited due to its maximum production size. Brittleness is in the nature of the material but the low strength can be dealt with by pre-stressing methods.

Joining of glass can be done mechanically (making holes in the glass and the use of bolts), by solding, physically (welding of glass) and chemically (adhesives). Mechanical joining requires drilling holes in glass sheets which is complicated due to its brittleness. In addition, the holes require a high degree of finish along the cut edges because a cut surface severely degreases in strength. Also bolts preferably do not touch the glass surface to eliminate the risk of surface damage. Altogether, this type of construction faces quite some difficulties. Both solding and physical joints cannot by applied in large scale applications thus they are recurrently inconvenient methods in the built environment. Veer (2005) states that chemical joining is the best joining technique for glass. Therefore, this chapter is dedicated to a further investigation of optional chemical bonds and their application.

photo: by author

6.1 Adhesive bonding

There are several structural adhesives types for bonding glass, according to Louter, Veer and Belis (2008) the most common ones within the built environment are epoxy, acrylate, polyurethane and silicon.

Epoxy

Epoxy is in general a two-component adhesive. Their curing process can vary, it is either done by UV, cold or heat. Most are two-component systems, curing at temperatures between 20-172 C. Its optimal thickness is generally less than 0.5 mm, it has a high strength and stiffness but it must be taken into account that epoxies are brittle. Among all structural adhesives, epoxies provide the highest overall strength, heat- and chemical resistance. Most epoxies are grey colored, but transparent ones are also available. Epoxy adhesives currently find structural applications in aircrafts, boats and metal structures (CES, 2016).

Acrylate

Acrylate adhesive consists of a resin which is to be applied on a surface and an activator responsible for the curing. Acrylate adhesives cure at room temperature; however, this process should be activated chemically (two components) or electromagnetic light or UV-radiation.
A huge advantage of this adhesive is its short curing time. Another advantage is the easy adherence; acrylates can be applied without special preparation they can even attach to oily surfaces. Disadvantages are its brittleness and its low viscosity which causes that acrylates cannot compensate for uneven surfaces. Another disadvantage is its unpleasant and possibly even toxic smell (CES, 2016).
Besides liquid, acrylate can also be is applied in structural double-sided tape which can be used for indoor applications like for example door hinges.

Figure 6.1 (left) epoxy adhesive.
Source: 3m solutions.com

Figure 6.2 (right) acrylic adhesive tape.
Source: 3m solutions.com

Polyurethane

There are several types of polyurethane, one- and two component variants and physical-, chemical curing types. Polyurethane offers a great flexibility and good peeling resistance. They can be applied using a brush, spray or tapes. Because of its flexibility the load bearing capacity of polyurethane is limited. This adhesive is generally stronger than silicones, less brittle than epoxies and acrylates but it has a lower UV resistance. For this reason, it finds applications in the automotive industry and bonding of non-transparent facade panels. Because of its low UV-resistance, this adhesive type cannot be applied in an exposed façade (CES, 2016).

Silicone

Silicones are capable of enhancing mechanical connections. In general, they are applied as a sealant, to even out tolerances and deformations. Normally silicones are black but nowadays also Transparent Structural Silicone Adhesive (TSSA) is available unfortunately, the costs of this silicon type is extremely high. Silicones are flexible and therefore its load-bearing ability is limited, TSSA is an exception it offers high strength and stiffness. When applied, its thickness should be more than 6 mm in order to achieve the correct amount of strength (CES, 2016). There are several types of silicones, all have different curing procedures. One component (air curing), two component (chemical curing) variants and hot curing film (TSSA), they can be used as a structural sealant. Generally, silicones have a high durability for UV as well as humidity.

TSSA is an elastomer produced by Dow Corning which can be applied in laminated connections in structural glass applications (Santarsiero, 2015). TSSA is developed especially for metal-to-glass connections. TSSA adhesive differs in many aspects from conventional silicone sealants by combining excellent transparency and better mechanical performance (Hagl, Dieterich, Wolf, & Sitte, 2012). It exhibits high stiffness and strength, which makes it suitable for structural applications (Hanenberg, 2015).
Unlike most silicons, TSSA is is produced in foils of 1mm thickness. The foil is delivered with protective films on both sides, that have to be removed before lamination. The optimal curing process is achieved in an autoclave, where the film adhesive is cured at temperatures of 120°C to 130 °C and a pressure of 0.15MPa to 1.3MPa, for a period of 20 minutes to 30 minutes.

Figure 6.3(left): point connection
Source: glasstec-online.com

Figure 6.4 (right): Silicon joint.
Source: planetpartitioning.co.uk

Use of adhesives

Advantages of the use of adhesives, described by Veer (2005) are:
- No holes thus avoiding stress concentrations in the glass.
- More reliable and safer failure behavior, tempering is not required.
- 100% transparency can be achieved.
- Applicable on small and large areas.

Bonding glass with adhesives also has its advantages and disadvantages. The conventionally considered disadvantages are:
- Low water resistance.
- Difficulty to apply evenly.
- Unsuitable to apply on a large surface, unless autoclaved.
- Difficulty to control the curing process with two component adhesives.
- Creep under sustained load.

When designing with adhesive glass joints, there should be dealt with these five problems. The mentioned adhesive types vary in curing time, color, strength and gap-filling properties. Table 6.1 shows an overview of the aforementioned types and their properties.

Adhesive type	Shear strength [Mpa]	Curing time	Color	Gap-filling capacity [mm]
Epoxy	18	> 10 hours	Grey	Up to 5
Acrylate	23	30-60 seconds	Transparent	< 0.1
Polyurethane	7	> 8 hours	Transparent	0.05 – 0.1
Silicone	1.06	> 7 days	Black	6 - 15

Table 6.1: Adhesive types and their properties
Source: Louter et al.

Properties which are not mentioned in this table are the effects of direct sunlight, such as UV-radiation and increased temperatures, water resistance and the influence of loaded time, these properties are investigated by Louter (2008). In his paper 'Redundancy of reinforced glass beams; temperature, moisture and time dependent behavior of the adhesive bond' bending tests of a reinforced glass beam are compared with elevated temperature (60 C), exposure to moisture (8 weeks of salt water (WS) spraying) and load duration (at least 72 hours). Displacement and crack propagation has been monitored. A summary of the results is shown in table 6.2.

Adhesive type	Test type	Failure cause	Initial failure load [kN]	Post initial failure load [kN]	Remaining load carrying capacity [%]
Epoxy	20	Glass	7.9-10.8	12.0 – 13.5	126 – 153
	60	Adhesive	6.7 – 7.2	5.1 – 7.9	75 - 111
	WS	Glass	8.9 – 11.7	12.0 - 13.5	111 - 147
Acrylate 1	20	Glass	6.4 – 8.7	11.7 – 13.4	142 - 184
	60	Adhesive	7.3 – 9.3	9.5 – 11.8	102 – 156
	WS	Glass	9.1 – 12.3	10.9 – 12.8	115 – 124
Polyurethane	60	Adhesive	6.6 – 8.4	4.5 – 5.5	59 - 83
Silicone	60	Adhesive	5.2 – 9.0	0	0

Table 6.2: Adhesive types and their mechanical performance.
Source: Louter et al.

The results of this research show, considering temperature, acrylates generally perform better than the rest. Moisture does not have significant negative effects on the residual strength of reinforces glass beams. All specimens ultimately failed due to glass failure without showing any slip. This means that the glass is weaker than the adhesive. All tested specimens showed comparable post-failure loads as the specimens tested at room temperature. Another conclusion from this research is that a key aspect in structural bonding is not only selecting the proper adhesive but also controlling the bonding process to be able to repetitively ensure a high quality bond. UV-acrylates show an advantage since their applicability is relatively easy to control. This enhances the realization of even adhesive thicknesses. Which is important to provide even stress distributions in the glass.

6.2 Laminated bonding

A transparent, full surface bonds can be achieved by foils such as polyvinyl butyrate (PVB), SentryGlas (SG), TPU and EVA. For structural glass application PVB is mostly used. Although SG has the highest stiffness and strength. Due to the large bonded surface often low material strength is needed for structural collaboration. A property of these plastic interlayers is its visco-elasticity, meaning that its strength is time- and temperature-dependent. The structural applications that can be obtained by these interlayers are laminated glass sheets, splice lamination, hybrid components and experimental point fixings. It should be considered, when designing with a laminated sheet that the interlayer has a different thermal expansion coefficient than the glass (Louter, 2015).

Assembly of this connection should be done in a dust-free environment where humidity and temperature can be controlled. The glass plate and SG-foil should be placed in a vacuum bag, than with the use of an autoclave, the laminate connection can be made. The SG should be

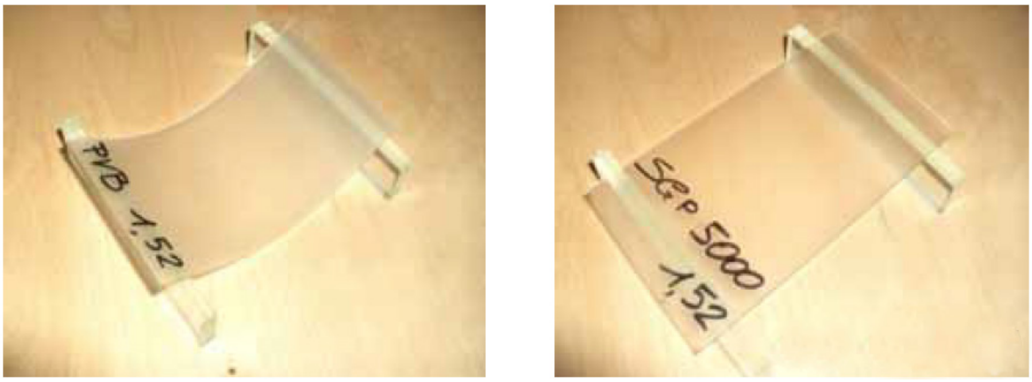


Figure 6.5: PVB and SG samples with a thickness of 1.52 mm
Source: Belis

subjected to a temperature of 135°C and a pressure of 12 bar for at least an hour. The cooling phase should be performed with a minimum rate of 2°C/min or 3°C/min. At the end of this process the SG should be fully transparent (Santarsiero, 2015).

It should be noted that thin glass is not yet applied in the built environment. Due to its failure pattern, safety in case of breakage should be considered. Lamination can increase the safety of thin glass elements. Fortunately, every interlayer (PVB, EVA, etc.) that can be applied in Soda-lime glass can also be applied for chemical strengthened Aluminosilicate glass (L. Taper, 2016). Nonetheless, further research is recommended to understand what can be expected and assured regarding safety.

PVB

The PVB interlayer is tough and ductile, so brittle cracks will not pass from one side of the laminate to the other. As PVB is a visco-elastic thermoplastic, its shear modulus is largely dependent on the ambient temperature and the load duration. At temperatures below 23 °C, a section of laminated glass achieve with partial composite stiffness. But above 80 °C the PVB film starts to separate from the glass (delamination). EVA and CIP have similar material properties to PVB. But their stiffness at room temperature is only about half that of PVB, although at temperatures of 60 °C the reduced stiffness is substantially higher (Schittich, 2001).

PVB interlayer can be purchased in colored sheets, such as for the blue or green “shade band” at the top edge of many automobile windshields. PVB interlayers can also be purchased in many different colors for architectural laminated glass manufacture. These interlayers have a standard thickness: 0.38 mm or multiples. PVB slowly degrades over time within laminated windows.

SG

A structural interlayer of SG, originally developed to laminate glazing in hurricane-prone areas, is five times stronger and has a stiffness up to 100 times higher than that of PVB. SG has a significantly improved shear strength and the flow characteristics are much better during the lamination process (O’Callaghan, 2012). Full composite action can be assumed even for permanent loads and thus the glass thicknesses and weights can be substantially reduced. Sheets of SG come in standard thicknesses of 0.72, 0.89 and 1.52 mm. SG interlayers retains its clarity, even after years of service, unlike other interlayers, SG is not vulnerable to moisture exposure or yellowing over time. High permanent temperatures (up to 70 °C) are supposed to hardly change its mechanical properties. It does affect the thermal expansion, the expansion coefficient of SG is a number of times that of glass. Therefore, it is necessary to consider long-term temperature stresses when designing with SG (Schittich, 2001).

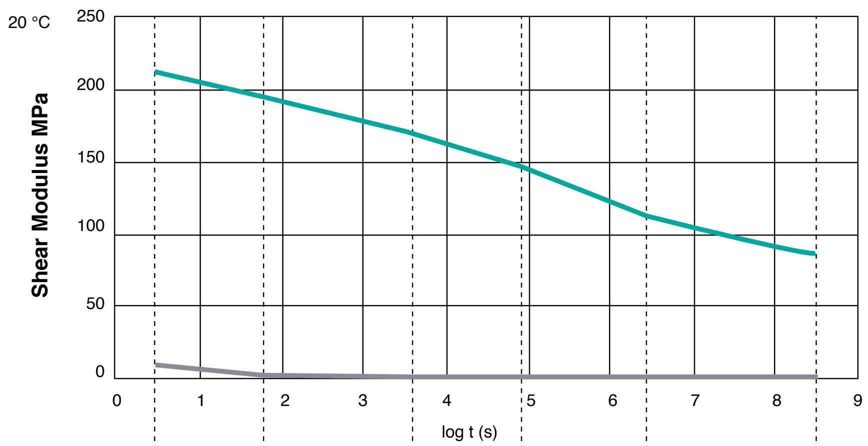
Comparison

As mentioned before, SG has a much higher strength and a larger stiffness than PVB. The mechanical properties of both interlayers are described in table 6.3.

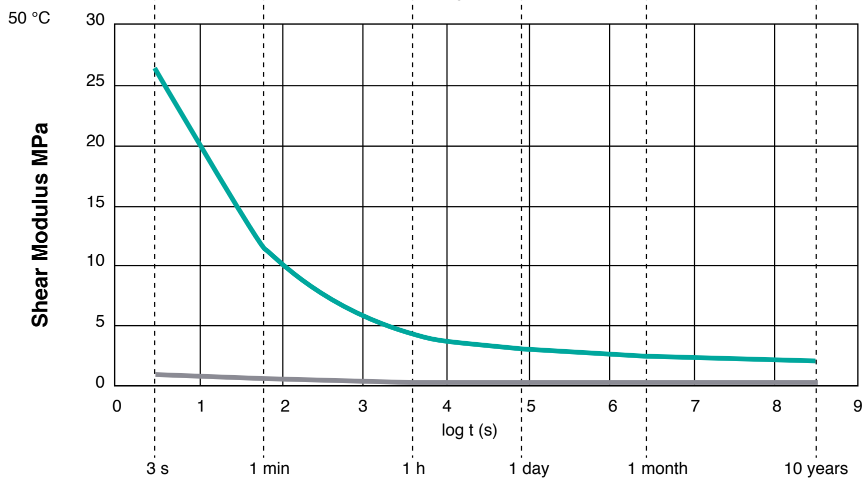
Properties	SGP	PVB
Density [g/cm3]	0.95	1.07 – 1.08
Thickness [mm]	0.72, 0.89, 1.52, 2.28	0.38, 0.76
Tensile Strength [MPa]	34.5	20
Shear modulus [Gpa] Time and temperature dependent	80 - 200	0 - 4
Poisson ratio Time and temperature dependent	0.44 – 0.5	0.45 – 0.49

Table 6.3: Material properties SG and PVB
Source: Santarsiero

The stiffness of the interlayer at room- and elevated temperature over a certain amount of time, the viscoelasticity, of both materials is plotted in the graphs below. Exposure to an elevated temperature during longer period of time decreases the shear modulus enormously. When designing with an SG or PVB interlayer, there should be kept an eye on the temperature of the materials which are bonded.



Graph 6.1: Shear modulus of SG (green)and PVB (grey) at 20 C
Source: Santarsiero



Graph 7.2: Shear modulus of SG (green)and PVB (grey) at 50 C
Source: Santarsiero

6.3 Physical tests

There are several methods to apply a honeycomb structure onto a glass face sheet. Among the described bonding options (epoxy, acrylate, polyurethane, silicon, PVB, SG) so far, only acrylate has been applied on glass in order to bond a honeycomb structure onto a glass sheet. This sandwich panel has been made for a lightweight canopy above the entrance of the Berkley Hotel in London which is designed by Rogers Stirk Harbour + Partners, engineered by ARUP Facades and manufactured by Bellapart.

Figure 6.6. Canopy of the Berkley Hotel, Londen.
Source: J. Souza

The sandwich panel is produced by applying an evenly distributed layer of acrylate adhesive on the full surface of the glass. Subsequently the honeycomb structure is positioned in a controlled manner, this process is shown in figure 6.7.

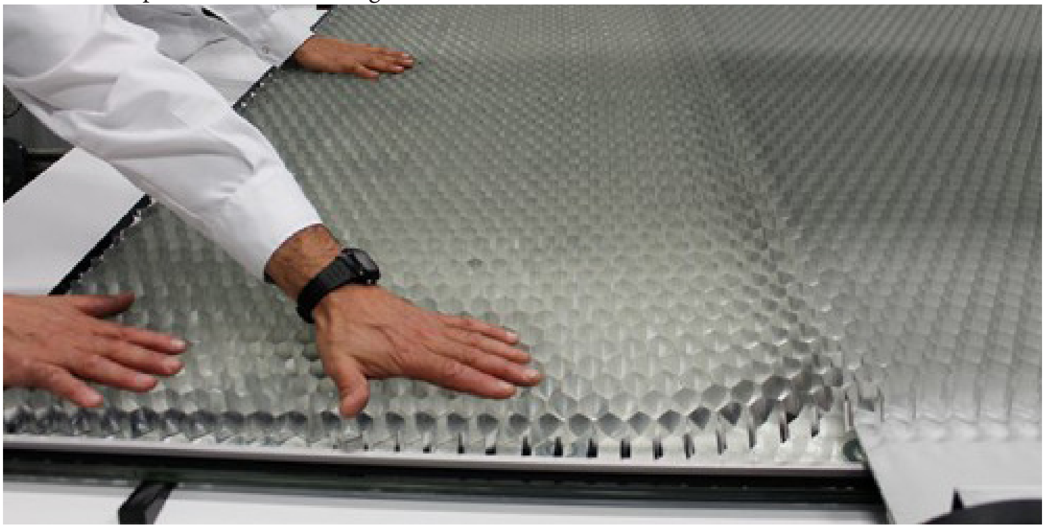


Figure 6.7. Positioning of the honeycomb structure after application of acrylate adhesive.
Source: Bellapart

The optical effect of this panel is quite good, light easily transmits through the panel and slight transparency is created. Silhouettes are clearly visible behind the panel.

Figure 6.8 (left). Visual effect honeycomb glass canopy.
Source: Bellapart

Figure 6.9 (right). Visual effect honeycomb glass canopy.
Source: Bellapart

In order to find out what type of adhesive works best for this facade panel, mechanically and visually, several physical tests need to be done. Hexcel (1999) describes what important aspects are to create a good honeycomb sandwich bond. First, to achieve a good attachment to an open cell core such as honeycomb, the adhesive should flow sufficiently to form a fillet without running away from the skin to core joint. Every endeavour should be made to ensure intimate contact between the parts during bonding, as the adhesive needs to fill any gaps between the bonding surfaces. By testing, hopefully the question if this bonding material provides a proper bonding and sufficient transparency will be answered.

The objective of this test is to discover what material and their associated application method provides the best bonding while offering most transparency for the façade panel. The hypothesis of the test is that every adhesive will create a fillet bond, which will create the visual effect of a lens. Because of this phenomenon, small cell sizes will have a decreased transparency. It ia also expected that the fillet bond of the adhesives will be less than with film interlayers both will be tested.

Test 1: acrylic adhesive bond

This test is inspired by the bonding method of the Berkley Hotel, which is a layer of acrylate adhesive on the full surface of the glass. A transparent 2-component acrylate adhesive is applied onto one side of a glass sheet. In order to properly inspect the visible effect of this adhesive, only one glass to honeycomb connection is made.
In order to find out what the visual quality of this bond is.

Necessities:
- Honeycomb structure (cell size: 3.2 mm)
- Acrylate 2-component adhesive
- Glass sheet
- Stirring rod
- Roller
- Alcohol-based cleainging product

Method:
An important first step of this test is to clean the glass, because of a few reasons. First, greasy spots might block a clear view and the glass can never be cleaned again after it is attached. Another reason is that the bond with the surface is usually is better when the surface is degreased. The used two-component adhesive contains two tubes, when pressing out the adhesive on a clean tray (without and dirt or dust) it should be properly mixed with the stirring rod. Mixing is important because the two components should blend as evenly as possible in order to achieve good adhesion. When the mixture is ready, it can be applied onto the glass sheet, this is done by using the stirring rod as a spatula and a roller. When the adhesive is visually about evenly distributed the honeycomb is placed on top of it.

Results:

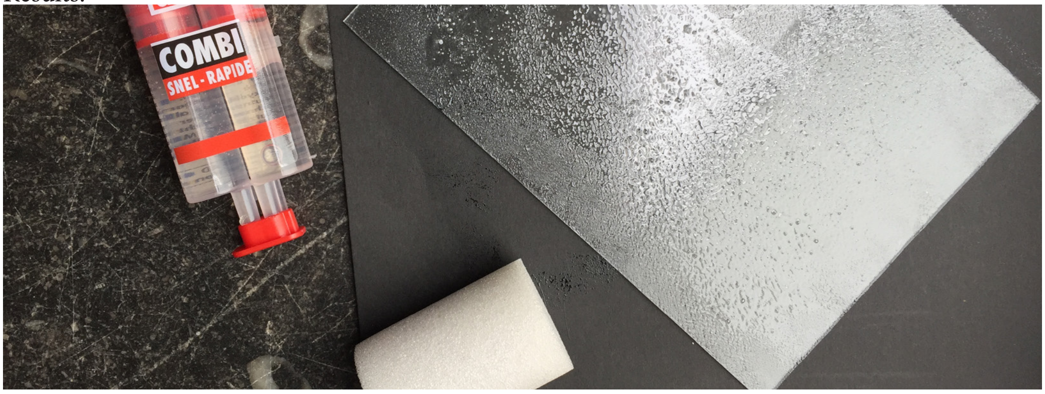


Figure 6.10: Application method.
Source: by author.

Figure 6.11 shows a photo of the outcome of the test. A few things can be noted:
First finding is that a minor fillet (bond) is created between the glass sheet and the honeycomb. However, this bond is not the same in every cell, which is shown by the presence of adhesive in the cells. In some cells, the adhesive is visually more present than in others.

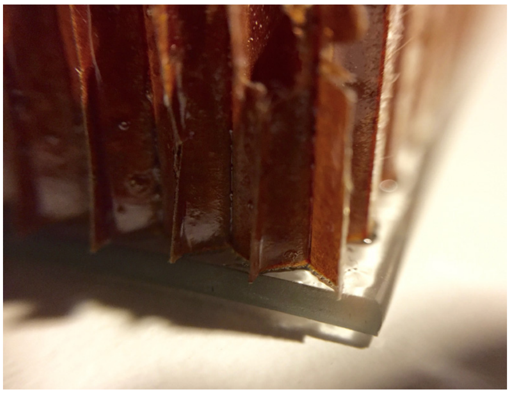


Figure 6.11(left): Fillet bond adhesive.
Source: by author.

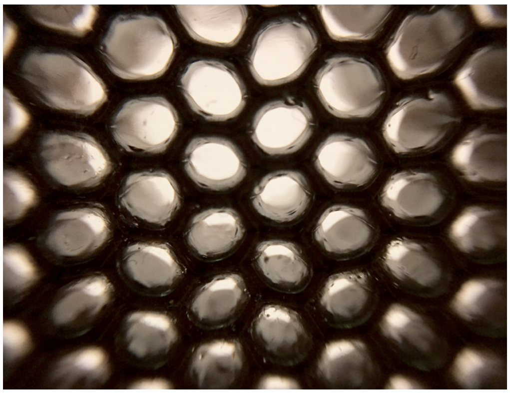


Figure 6.12(right): Adhesive causes lens effect in some cells.
Source: by author.

None of the cells provides a clear view however the adhesive does transmit diffuse light. As expected, a lens effect is created within the cells. The amount of adhesive clearly has an its influence on the lens effect. The more adhesive, the more this effect is visible.

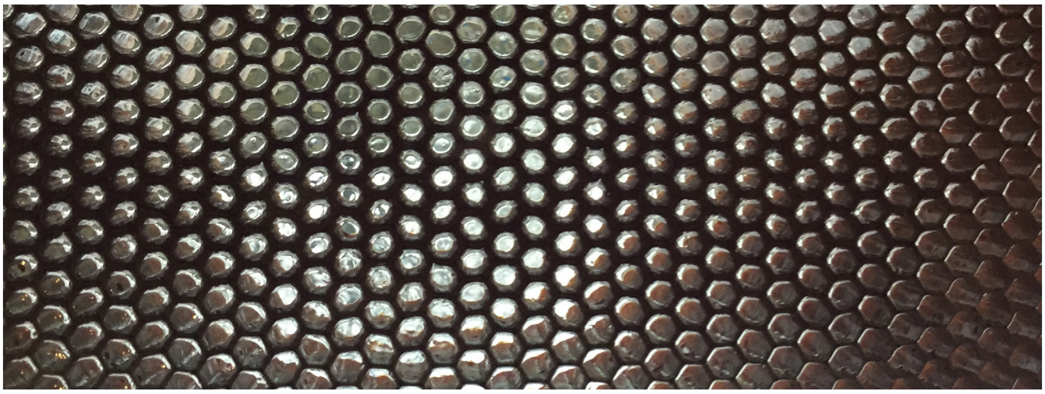


Figure 6.13: Uneven distribution adhesive.
Source: by author.

Test 2: acrylic adhesive bond, larger cell size

To find out difference another cell size could make, the exact same test is done with a aramid core that has a cell size of 5 mm.

Necessities:
- Honeycomb structure (cell size: 5 mm)
- Acrylate 2-component adhesive
- Glass sheet
- Stirring rod
- Roller
- Alcohol-based cleainging product

Results:
In comparison to test 1, it is clearly shown that overall, the distribution of the adhesive seems to be more transparent, unfortunately the fillet is still not good (figure 6.15).

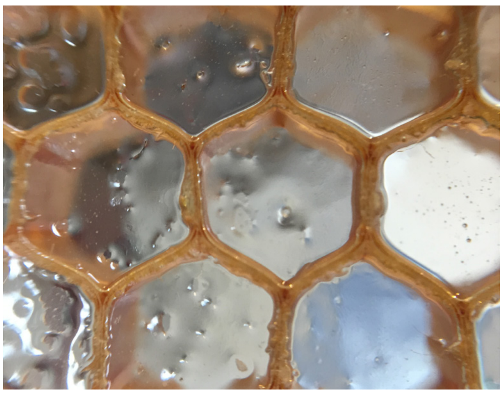


Figure 6.14 (left): Transparency acrylate adhesive.
Source: by author.

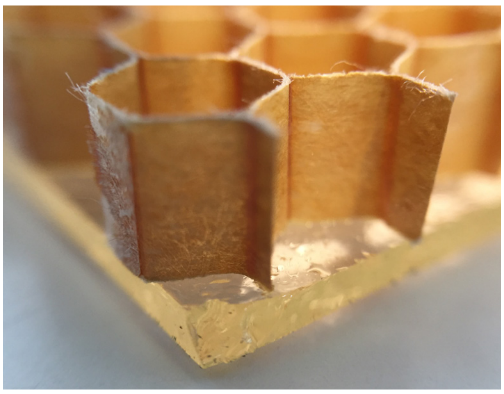
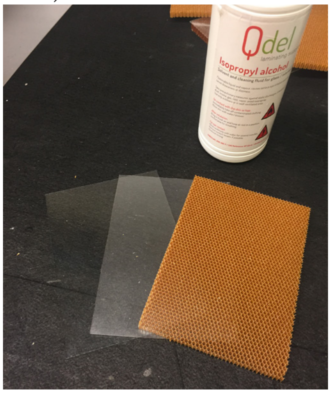


Figure 16.5 (right): Fillet bond acrylate adhesive.
Source: by author.

Test 3: SG laminated bond

Now conclusions can now be drawn upon the optical quality of acrylate adhesive. Another test is required to learn what optical quality a transparent interlayer, such as SG, could achieve.

Necessities:
- Aramid honeycomb structure (cell size : 3.2 mm)
- SentryGlass (SG) interlayer (1 mm)
- Glass sheet (2 mm)
- Oven (+ oven tray)
- Cling film
- Isopropyl alcohol
- Additional weight to pressurize the whole in the oven (in this case a glasss sheet of 12 mm was used).



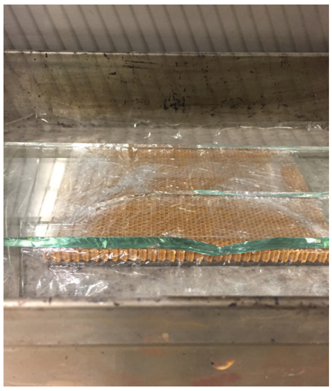


Figure 6.16(left): Necessities laminate bonding. Glass, SG film and a core.
Source: by author.

Figure 6.17(middle): Stacked layers in cling film.
Source: by author.

Figure 6.18(right): Stacked layer in oven, pressurized.
Source: by author.

Method:
First the glass- and SG sheet need to be cleaned with the alcohol. Than the glass, SG and honeycomb can be stacked onto eachother. A SG interlayer is to be attached onto the honeycomb structure by reaching the melting point of SG (135 C) and pressurize the assembly. To do this, an autoclave is normally required. Unfortunately, using an autoclave was not possible within the time span and economic possibilities of this research. Therefore, an oven has been used to create the adhesive bond with an additional weight on top (12 mm glass sheet). To check if this method works, first one sheet of glass, SG and honeycomb is tested. Because SG becomes liquid when it reaches its melting point, the package is covered in cling film. The oven follows a program in which it slowly heats to a temperature of 135 degrees than remains constant on this temperature for an hour. After one hour, the oven slowly cools to a temperature of 20 degrees Celcius.

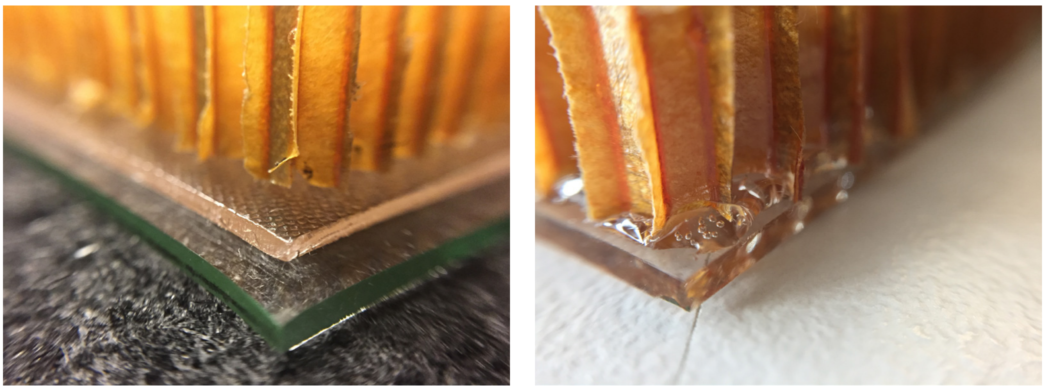


Figure 6.19: Stacked layers of test sample 3 before and after oven.
Source: by author.

Results:
The SG interlayer has melted in the oven and created a fillet which bonds the glass and honeycomb. When looking closely, there are some air bubbles in the SG.
Overall the SG is very evenly distributed over the glass sheet. All honeycomb cells are well connected to the glass. Again, a lens effect is created in the cells by the fillet. And there are some minor irregularities to be found when looking closely to the panel.

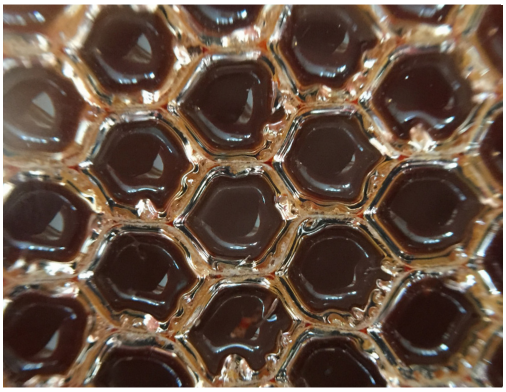


Figure 6.20: Even distribution adhesive.
Source: by author.

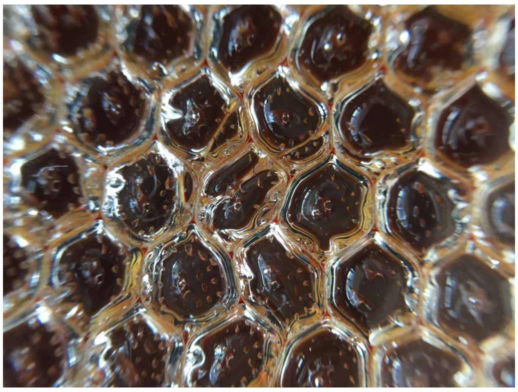


Figure 6.21: Uneven distribution adhesive.
Source: by author.

Another interesting optical effect is that the SG is glistering when it is exposed to light. Which gives the panel a luxurious appearance. Light is transmits though the panel, but transparency is not achieved. All combined, the panel is aesthetically pleasing, especially when compared to the adhesive connection in test 1.

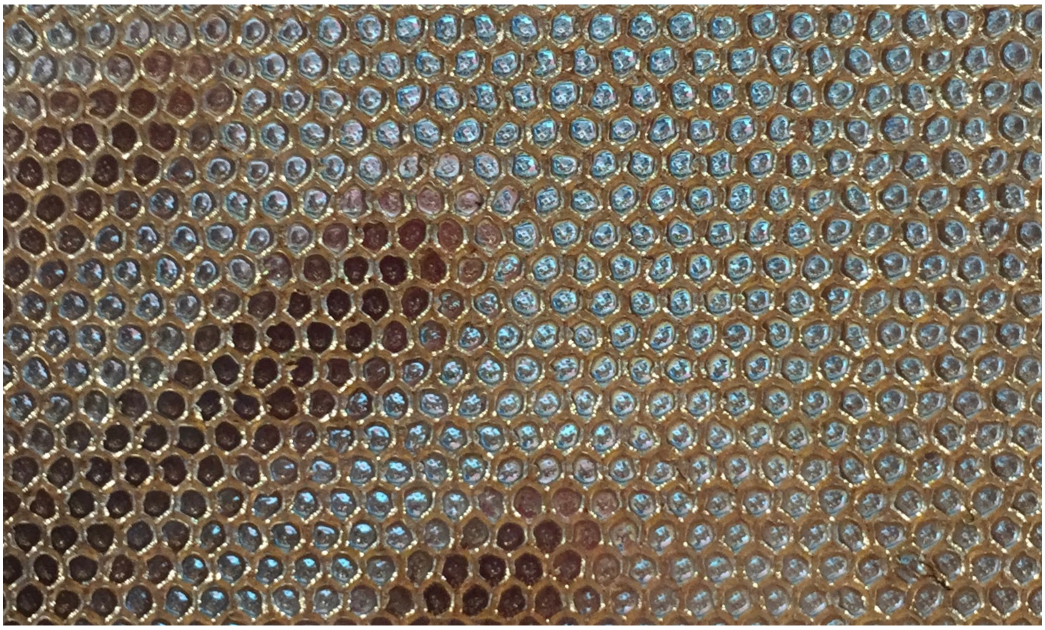


Figure 6.22: Test sample 3, full panel.
Source: by author.

Test 4: SG laminated bond, larger cell size

We learnt that the SG achieves an aesthetically pleasing effect and a good attachment. However, transparency is still not achieved. For this a bigger cell size should be tested.

Necessities:
- Aramid honeycomb structure (cell size : 5 mm)
- SentryGlass (SG) interlayer (1 mm)
- Glass sheet (2 mm)
- Oven (+ oven tray)
- Cling film
- Isopropyl alcohol
- Additional weight to pressurize the whole in the oven (in this case a glass sheet of 12 mm was used).

Method:
The glass- and SG sheet need to be cleaned with the alcohol. Than the glass, SG and honeycomb need to be stacked onto each other in that specific order. An oven is used to create the adhesive bond. The assemble is covered in cling film. In the oven a pressure is applied on the package by putting a weight of a glass sheet on top. Again, the oven follows a program in which it slowly heats to a temperature of 135 degrees than remains constant on this temperature for an hour. After one hour, the oven slowly cools back again to a temperature of 20 degrees Celsius.

Results:
The results of this test are very comparable to the results of test 2a and 2b. An even distribution is, again, created. The cell size is slightly bigger, so this honeycomb structure transmits more light. The overall optical quality is, again, pleasing. and the fillet bond is well created. However air bubbles are clearly visible, possibly, this could be prevented if an autoclave could be used.

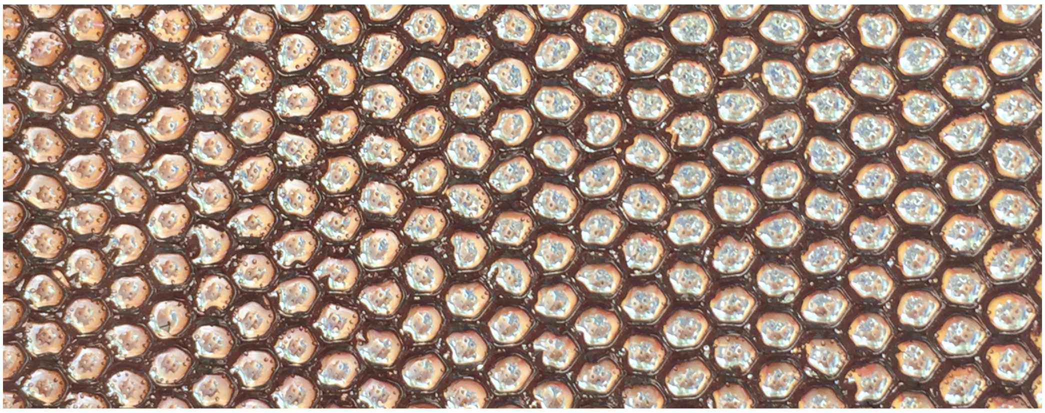


Figure 6.23: Test sample 4, full panel.
Source: by author.

Test 5: SG laminated bond, polycarbonate core

We learnt that the SG achieves an aesthetically pleasing effect and a good attachment. However, full transparency is still not achieved. For this translucent core material is tested, polycarbonate. This, in order to find out if it enables to transmittance of more (sun)light.
Necessities:
- Polycarbonate honeycomb structure (cell size : 5 mm)
- SentryGlass (SG) interlayers (1 mm)
- Glass sheets (2 mm)
- Oven (+ oven tray)
- Heat resistant tape
- Isopropyl alcohol
- Additional weight to pressurize the whole in the oven (in this case a glass sheet of 12 mm was used).

Method:
The glass- and SG sheet need to be cleaned with the alcohol. Than the glass sheets, SG films and honeycomb need to be stacked on top of each other in that specific order. The edges of the assemble is covered in heat resistant tape. In the oven a pressure is applied on the package by putting a weight of a glass sheet on top. Again, the oven follows a program in which it slowly heats to a temperature of 135 degrees than remains constant on this temperature for an hour. After one hour, the oven slowly cools back again to a temperature of 20 degrees Celsius.

Results:
A more or less even distribution is created for the adhesive, the fillet bond that is created is sufficient. The light transmission is very diffuse, and transparency is not yet achieved. The overall optical quality is, luxurous and therefore pleasing (figure 6.24).

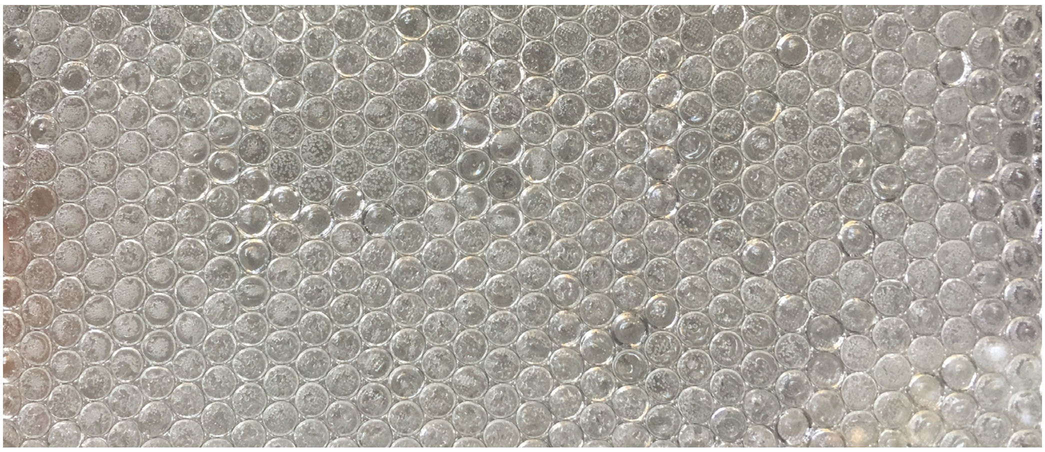
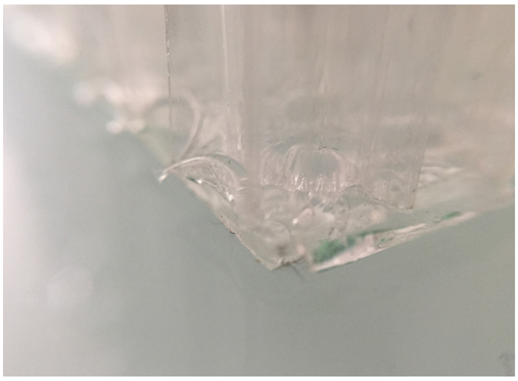


Figure 6.24: Test sample 5, full panel.
Source: by author.



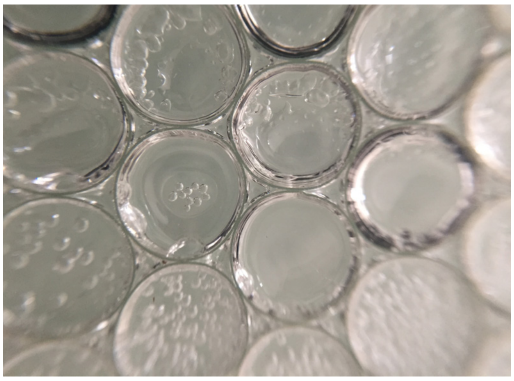


Figure 6.25: Fillet bond test sample 5.
Source: by author.

Figure 6.26: Uneven distribution adhesive.
Source: by author.

But, in one of the corners of the panel, the plastic is affected by the heat, its colour has changed (figure 6.27).

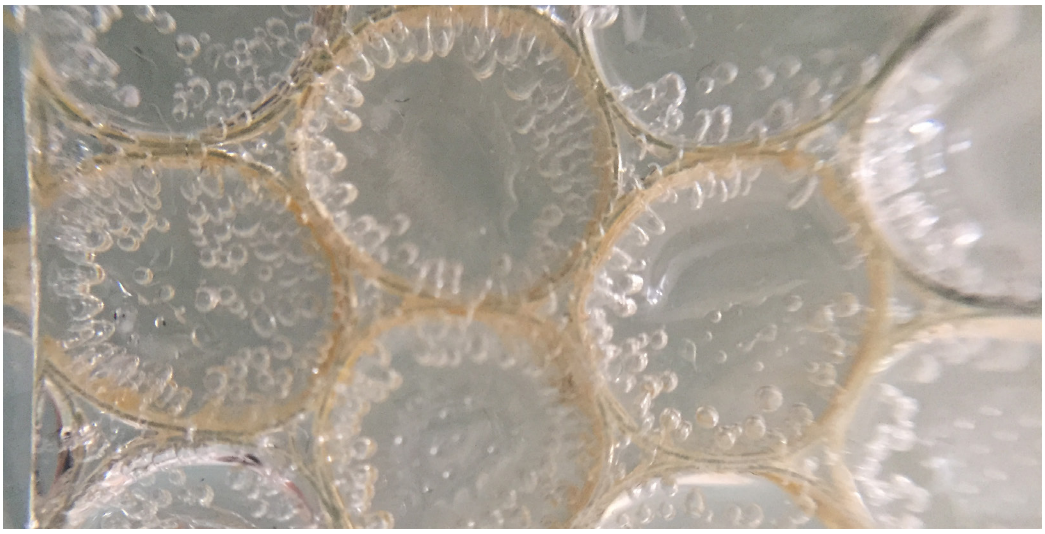


Figure 6.27: Colour change by heat.
Source: by author.

6.4 Conclusion

The objective of these tests were to find out what bonding material provides best adhesion, most transparency and a large amount of light transmission. Findings are that the best adhesion is provided by an laminated bond, it creates the best fillet and even distribution. This even distribution also results in an aestetically pleasing result. In terms of transparency there are several findings. First, the expected lens effect did appear due to the adhesive fillet, this effect prohibits full transparency in all cell sizes that were tested.

07

Validation method

A bending test (also flex or flexural testing) is commonly performed to evaluate the mechanical performance of many types of materials and products. Bending tests are done, mainly to determine a beam's stiffness. By pressing a force onto a beam, it deflects. During the test, data of the amount of force, as well as the deflection is collected. With this data, an analysis can be done which can validate the strength and the stiffness of a glass sandwich panel.
A bending test can be done with both monolithic- and composite materials. The mechanical values of composite materials are dependent on the thickness and material of the facing material, interlayer material, and the core.

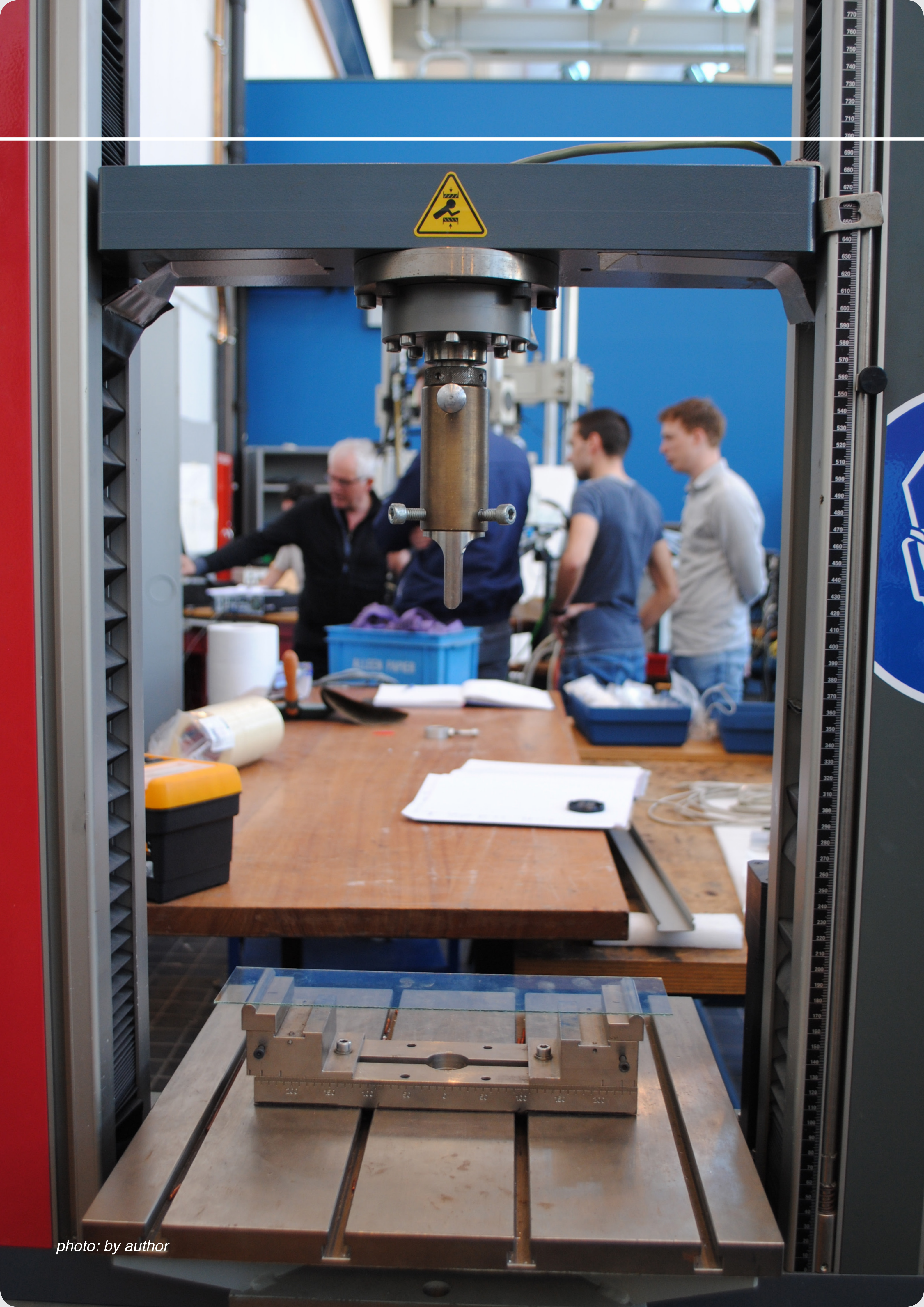


photo: by author

7.1 Theory

The three-point bend test is a classical experiment in mechanical science, which is used to determine the stiffness of a material in the shape of a beam. The beam, with length L, is simply supported on two supports. The center of the beam is subjected to a concentrated load (P).

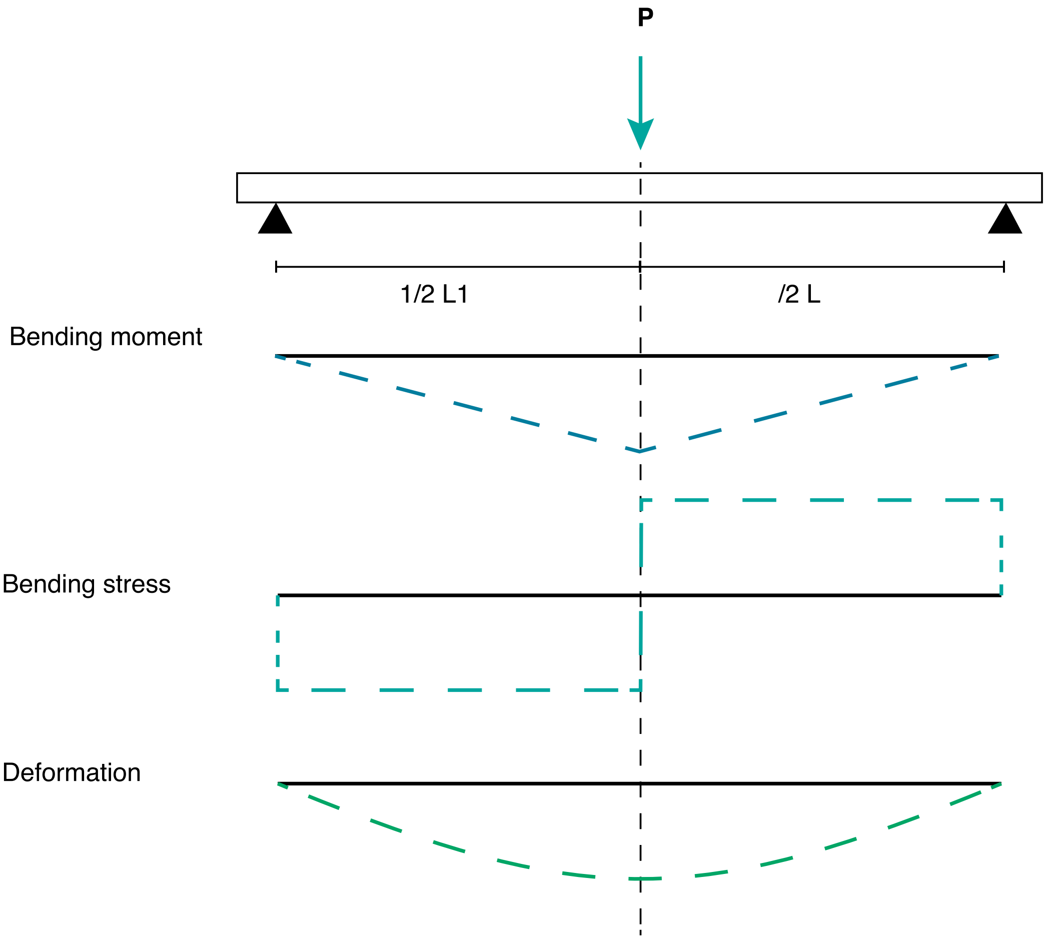


Figure 7.1. Schematic of the three-point bend test, with graphs of bending moment, bending stress and deflection.
Source: by author.

In order to do calculations, the three-point bending test can be schematized (figure 7.1). A beam will be subjected to a bending moment, bending stressed and deflection. All of these find their maximum value in the center of the beam.

These maximum values indicate whether the material is sufficiently stiff and strong, for the force that it is subjected to. When the stress in a material is larger than it can withstand it could deform to a point of no return but depending on the material it can also break. The maximum bending moment, bending stress and deformation can be calculated with the following formulas. By using these formulas the materials bending stiffness can be determined.

Maximum bending moment: M (Nmm) = (Pl)/4
with
P force (N)
L span length (mm)

Bending stress: σ (Mpa) = M/W
with
M maximum bending moment (N)
W span length (mm)

Section moment: W (mm3) = (w t^2)/6
with
w width section (mm)
t thickness section (mm)

Deflection: δ (mm) = $(PL^3)/(48\ EI)$

E	Young's modulus (Mpa)
I	second moment of Interia (mm4)

Second moment of inertia: I (mm4) =$(wt^3)/(12)$

Sandwich theory

A sandwich panel consists of several layers. In general, they have two face sheets, carrying the bending loads (compression and tension) and a core in-between which carries the shear forces.

Like a monolithic beam, a sandwich panel can also be tested with a flexural test. However, the calculation of the mechanical properties of a sandwich beam, is a bit different. As a composite plate or beam, all layers have different mechanical properties. Without taking the adhesive film layer into consideration, these are the formulas that can be used to calculate the stiffness of the assemble. This calculation method is described by Hexweb.

Bending stiffness: D (Nmm2) = $(Ef\ tf\ h^2\ w)/(2)$
With
Ef	Young's modulus facing material (Mpa)
tf	thickness facing material (mm)
h	thickness core + thickness facing (mm)
w	width (mm)

Shear stiffness: S (N) = Gw h w
with
GW	shear modulus of the core in W-direction (Mpa)

Deflection: δ (mm) = δbending+ δshear = $(1/48\ P\ l^3)/D + (1/4\ P\ l)/S$

Facing stress: σ (Nm) = M/(h tf w)
with
M	maximum bending moment (Nm)

The maximum bending moment (M) is defined by the span and the subjected load:
M=(P l)/4

Core stress: T (Mpa)
T =F/(h w)
With
F	Maximum shear force (N)

The maximum shear force (N) is defined by the loading type and the subjected load:

F=P/2

With these formulas, an assumption of the mechanical properties of a sandwich panel can be made.

Determining stiffness

The main goal of performing a bending test, is to determine a products' Young's-, flexural- (or bending) modulus, flexural strength, yield point and bending stiffness by the deformation.

Young's modulus, also known as the elastic modulus, is a measure of the stiffness of a solid material. It is a mechanical property of linear elastic solid materials. Not to be confused with the geometric stiffness. The Young's modulus can be derived from the slope of a stress/strain curve.

The flexural modulus or bending modulus is an indication of the beams' stiffness. The flexural modulus can be explained by the tendency for a material to bend.

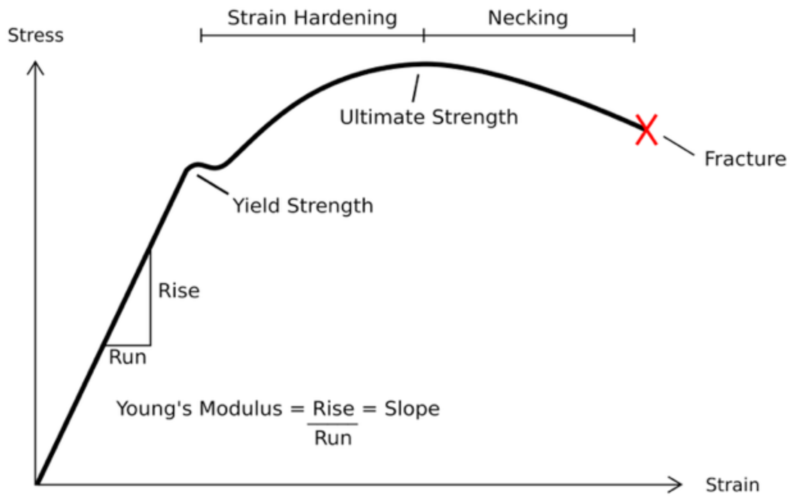
Another indication of the stiffness is the bending stiffness (K). Which is the resistance of a material (or product) to bending deformation. It is a function of elastic modulus E, the area moment of inertia of the beam cross-section about the axis of interest, length of the beam and beam boundary condition. Bending stiffness of a beam can analytically be derived from the equation of beam deflection when it is applied by a force.

$K=P/\delta$

with

p	applied force (N)
δ	deflection (mm)

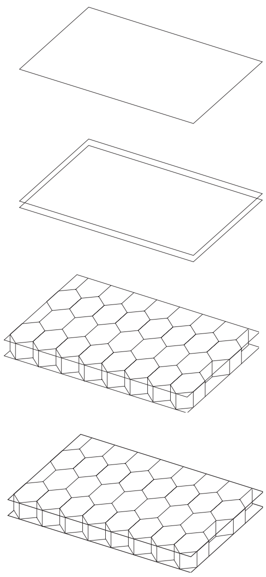
The flexural strength is the maximum force that a material can withstand before it breaks or yields (yield is where you have pushed a material past its recoverable deformation and it will no longer go back to the shape it once was). This point is also called yield point. If you were to continue to bend a product, from this point, the force will not continue to increase and will then start to decrease or break. This phenomenon is shown in graph 7.1, the stress and strain are plotted against each other.



Graph 7.1: Stress-strain curve for a ductile material.
Source: Wikipedia

7.2 Tests

In order to find out what the stiffness is of a glass-aramid-glass sandwich panel in comparison to a single glass sheet, and to determine what the mechanical improvement of chemical strengthened glass is in comparison to annealed soda lime glass.
Several bending tests have been done, first a single glass sheet has been tested. Secondly, two (non-laminated) glass sheets stacked loosely on top of each other are tested. This is necessary to find out what the difference is between these two glass sheets and a sandwich construction. Then two glass-aramid-glass sandwich panels are tested. Two samples are tested so the values can be compared. Until this point, all tests are done with (1 mm) annealed soda lime glass. The final sample is also a sandwich panel; the difference is that this panel is built out of slightly thicker chemically strengthened aluminosilicate glass (2 mm).



Test 1:
1 mm annealed glass

Test 2:
2 x 1 mm annealed glass sheet

Test 3 & 4:
Sandwich panel annealed glass (1 mm) & aramid honeycomb (10 mm)

Test 5:
Sandwich panel chemically strengthened glass (2 mm) & aramid honeycomb (10 mm)

Figure 7.2: Bending test 1 - 5. Single glass sheet (1), two glass sheets(2), annealed glass sandwich panel (3 & 4) and chemically strengthened sandwich panel (5).
Source: by author.

According to the theoretical research, several things can be expected:
- Among all samples, the single glass sheet (test 1) has the lowest flexural strength, meaning it will break easiest.
- The annealed glass sandwich panel will break when subjected to a stress of 40 MPa, while the chemically strengthened sandwich panel will not break up until a stress of 260 MPa is achieved.
- In the stacked glass sample (test 2), the bottom plate will break first, due to the tensile stress that it is subjected to. Also, with the sandwich panels (test 3, 4), the bottom plate will break first, because of tensile stresses that glass cannot withstand.
- In the second test, after breakage, it is expected that the top plate will have a flexural strength and bending stiffness which is comparable to that of the first sample when the bottom plate is broken.
- The sandwich panels in test 3, 4 and 5will be much stiffer than the single- and stacked glass sheets.
- The interlayer of the samples further increases the stiffness of the sandwich panels.
- In test 1 and 2 the annealed glass will break into several pieces, while in test 3 and 4 the glass will be held into its place by the interlayer, resulting in a safer failure scenario.

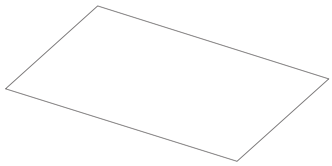
The question is, whether these assumptions can be proven my doing actual bending tests. In order to check if the test results are valid, they are compared to manual calculation.

Preliminary calculations

In advance of the actual tests, the discussed formulas are used to make a theoretical assumption of the test results.

Test 1

Input:



Material	annealed soda lime glass
Thickness	1 mm
Geometry	300 x 70 mm
Effective span	250 mm
Young's modulus	73000 Mpa

By knowing the maximum stress of the material it is possible to calculate the force at which the sample is expected to break and determine the maximum deflection. For annealed glass, this maximum stress is 40 MPa. The maximum allowed deflection is determined by NEN2608 (2014) in this document it is described that a glass sheet in the built environment cannot deflect more than its span devided by 65. The result of 250/65 is 4.6 mm.

Criteria:

Bending stress	40 Mpa
Deflection	4.6 mm

Results:

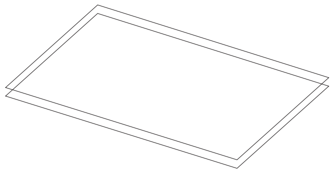
Section moment	
$W = w\,t^2 / 6$	$= 70 * 1^2 / 6$
	$= 11.67$ mm^3
Maximum bending moment	
$M = \sigma W$	$= 40 * 11.67$
	$= 466.67$ Nmm
Maximum force	
$P = M4/l$	$= 466.67 * 4 / 250$
	$= 7.46$ N
Second moment of inertia	
$I = w\,t^3 / 12$	$= 70 * 1^3 / 12$
	$= 5.83$ mm^4
Deflection	
$\delta = P\,l^3 / 48\,E\,I$	$7.46 * 250^3 / 48 * 73000 * 5.83$
	$= 5.7$ mm
Bending stiffness	
$K = Fmax / \delta max$	$= 7.46/5.7$
	$= 1.3$ N/mm

At a force of 7.46 N, it is expected that the single glass sheet in test 1 will break. When subjecting the glass sheet to this load, the deflection exceeds the allowed amount.

Test 2

Input:

Material	annealed soda lime glass
Amount	2 sheets
Thickness	1 mm each
Geometry	300 x 70 mm
Effective span	250 mm



NEN 2608 (2014), describes that in the case of multiple glass sheets, its structural performance is usually calculated by defining its effective thickness [t*]: This is the thickness of a monolithic glass element with equivalent bending properties in terms of stress and deflection. The equivalent thickness (t*) of a laminated glass composed of laminates (of t1, t2, t3, etc.) thicknesses respectively is calculated by the following formula: $t^*=\sqrt{(t1^2 + t2^2)}$

Criteria:

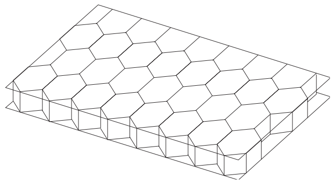
Bending stress	40 Mpa
Deflection	4.6 mm

Results:

Equivalent thickness	
$t^*=\sqrt{(t1^2 + t2^2)}$	$t^*=\sqrt{(1^2 + 1^2)}$
	= 1.41 mm
Section moment	
$W = w\, t^{*2} / 6$	$= 70 * 1.41^2 / 6$
	$= 23.19\ mm^3$
Maximum bending moment	
$M = \sigma W$	= 40 * 23.19
	= 927.6 Nmm
Maximum force	
P = M4/l	= 927.6 * 4 / 250
	= 14.8 N
Second moment of inertia	
$I = w\, t^3 / 12$	$= 70 * 1.4^3 / 12$
	$= 16.01\ mm^4$
Deflection	
$\delta = P\, l^3 / 48\, E\, I$	$= 14.8 * 250^3 / 48 * 73000 * 16.01$
	= 4.12 mm
Bending stiffness	
$K = Fmax / \delta max$	= 14.8/4.12
	= 3.59 N/mm

When the load reaches 14.8 N, it is expected that bottom single glass sheet will break. The glass sheet on the bottom is expected to break first, due to tensile forces. Once this sheet is broken, the leftover glass sheet on top will have a stiffness which is comparable to the single glass sheet in test 1. When subjecting the glass sheets to the calculated maximum load, the deflection does not exceed the allowed amount of 4.12 mm.

Test 3 & 4



Input:

Geometry	300 x 70 mm
Effective span	250 mm
Effective height (h)	11 mm

Face sheets:

Material	annealed soda lime glass
Thickness	1 mm each
Young's modulus	73000 MPa

Core:

Material	aramid
Thickness	10 mm
Young's modulus	73000 MPa
Compressive strength	0.9 MPa
Shear strength L	0.5 MPa
Shear strength W	0.35 MPa
Shear modulus L	25 MPa
Shear modulus W	17 MPa

Criteria:

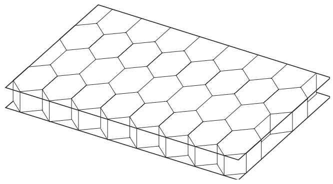
Bending stress glass	40 Mpa
Deflection	4.6 mm
Shear stress core	0.35 Mpa

Results:

Maximum bending moment	
$M = \sigma\ h\ tf\ b$	$= 40 * 11 * 1 * 70$
	$= 30800$ Nmm
Maximum bending force	
$P = M4/l$	$= 30800 * 4 / 250$
	$= 492.8$ N
Maximum shear force	
$P = T\ h\ b * 2$	$= 0.35 * 11 * 70 * 2$
	$= 539$ N
Deflection	
$\delta = (P\ l^3 / 48\ (Ef\ tf\ h^2\ w / 2)) + (P\ l / b\ h\ Gw)$	$= (493 * 250^3 / 48\ (73000 * 1 * 11^2 * 70 / 2)) + (493 * 250 / 70 * 11 * 0.35)$
	$= 0.5 + 2.4$
	$= 2.9$ mm
Bending stiffness	
$K = Fmax / \delta max$	$= 539/2.9$
	$= 185.8$ N/mm

Besides the bending force, now also the shear force plays a role in determining the maximum allowed force. When the load (P) is 492.8 N, it is expected that the glass sheet on the bottom will break. This is, again, due to the tensile forces. The maximum shear load will occur at 539 N, this means that the glass will break before the core will fail. The yield point will not be reached before the breakage of the glass. When subjecting the glass sheets to the maximum bending force of 492.8 N, the deflection does not exceed the allowed amount of 4.12 mm.

Test 5



Input:

Geometry	300 x 80 mm
Effective span	250 mm
Effective height (h)	13 mm

Face:

Material	chemically strengthened aluminosilicate glass
Thickness	2 mm each
Young's modulus	73000 MPa

Core:

Material	aramid
Thickness	10 mm
Young's modulus	73000 MPa
Compressive strength	0.9 MPa
Shear strength L	0.5 MPa
Shear strength W	0.35 MPa
Shear modulus L	25 MPa
Shear modulus W	17 MPa

Criteria:

Bending stress glass	260 Mpa
Deflection	4.6 mm
Shear stress core	0.35 Mpa

Results:

Maximum bending moment	
$M = \sigma\ h\ tf\ b$	$= 260 * 12 * 2 * 70$ $= 436800$ Nmm
Maximum bending force	
$P = M4/l$	$= 436800 * 4 / 250$ $= 6988.8$ N
Maximum shear force	
$P = T\ h\ b * 2$	$= 0.35 * 12 * 80 * 2$ $= 672$ N
Deflection at maximum shear force	
$\delta = (P\ l^3 / 48\ (Ef\ tf\ h^2\ w / 2)) + (P\ l / b\ h\ Gw)$	$= (672 * 250^3 / 48\ (73000 * 2 * 13^2 * 80 / 2))$ $+ (672 * 250 / 80 * 13 * 0.35)$ $= 0.3 + 2.6$ $= 2.8$ mm
Bending stiffness	
$K = Fmax / \delta max$	$= 672/2.8$ $= 240$ N/mm

In this test, the maximum bending force (6988.8 N) is very high because the chemically strengthened alumino silicate glass can withstand a large bending stress. This results in such a large allowable bending force that the tested panel will first fail by exceeding the maximum shear forces. The maximum shear force of 672 N is now leading to determine the deflection. Exceeding the maximum shear force will cause the panel to reach its yield point.

Hypothesis

The expected maximum forces and deflection in the tests are summarized in table 7.1. As expected, the single glass sheet in test 1 has the lowest flexural strength. Followed by the stacked glass sample in test 2. It is predicted that the sandwich panels in test 3, 4 and 5 have a much larger bending stiffness than the glass sheets. After doing these theoretical calculations, it is clear what forces to expect during the actual bending tests.

Expected		Test 1	Test 2	Test 3	Test 4	Test 5
Fbreak	[N]	7.46	14.80	492.800	492.800	6988.8
δmax	[mm]	5.70	4.12	2.900	2.900	-
Fyield	[N]	-	-	539.000	539.000	672
δyield	[mm]	0.00	-	-	-	2.8
Bending stiffness	[N/mm]	1.30	3.60	170	170	236.3

Table 7.1. Expected results bending tests.
Source: by author.

7.3 Test results

In advance of the bending tests, all samples have been prepared. The glass sheets have been cut to a size of 250 mm by a glass cutter and the edges have been slightly grinded. The sandwich honeycomb panels have been laminated with a SG interlayer sheet in an oven, without creating vacuum in advance. When the interlayer is heated to 135 degrees (for at least an hour), it melts and creates a fillet which connects the honeycomb onto the glass sheet.

Test 1: annealed glass sheet

The test setup is shown in figure 7.3. The sample has a length of 30 cm, however the span in-between the supports is 25 cm, so the sample is placed in the middle.

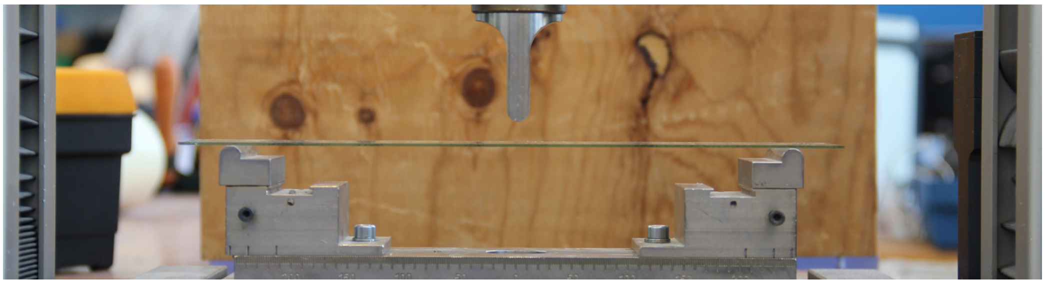


Figure 7.3: Test sample 1, annealed glass sheet.
Source: C. Louter

When glass sheet was subjected to force of 18.98 N, it deflected 5.7 mm. The deflection is more than the expected amount. The force is more than twice the expected maximum force of 7.46 N, the glass did not yet break. At this point, the force was released so the glass sheet could be re-used in test 2.

Test 2: 2 x annealed glass sheet

The glass sample from test 1 was re-used in this test, a greasy layer is applied on both glass sheets to avoid friction with the glass sheet placed on top.

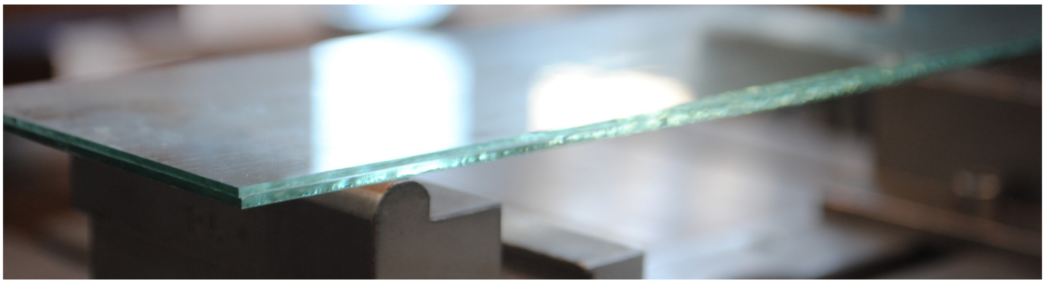


Figure 7.4: Test sample 2, two annealed glass sheets.
Source: by author.

The compiled glass sheets deflected 6.78 mm when subjected to a force of 22.6 N, at this moment the bottom glass sheet broke. This, again happened at a larger force than expected (14.8 N).

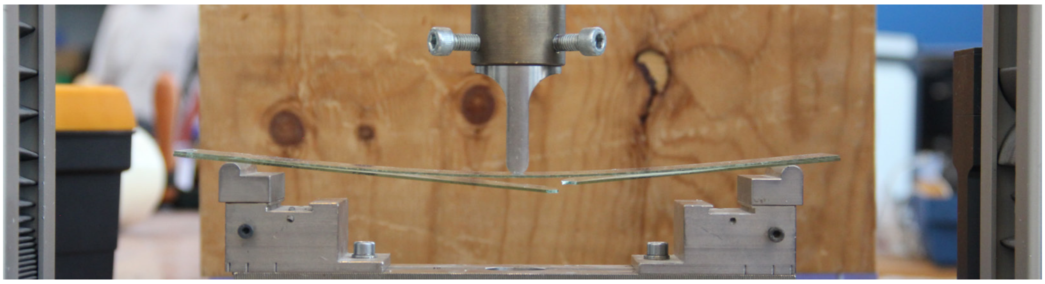
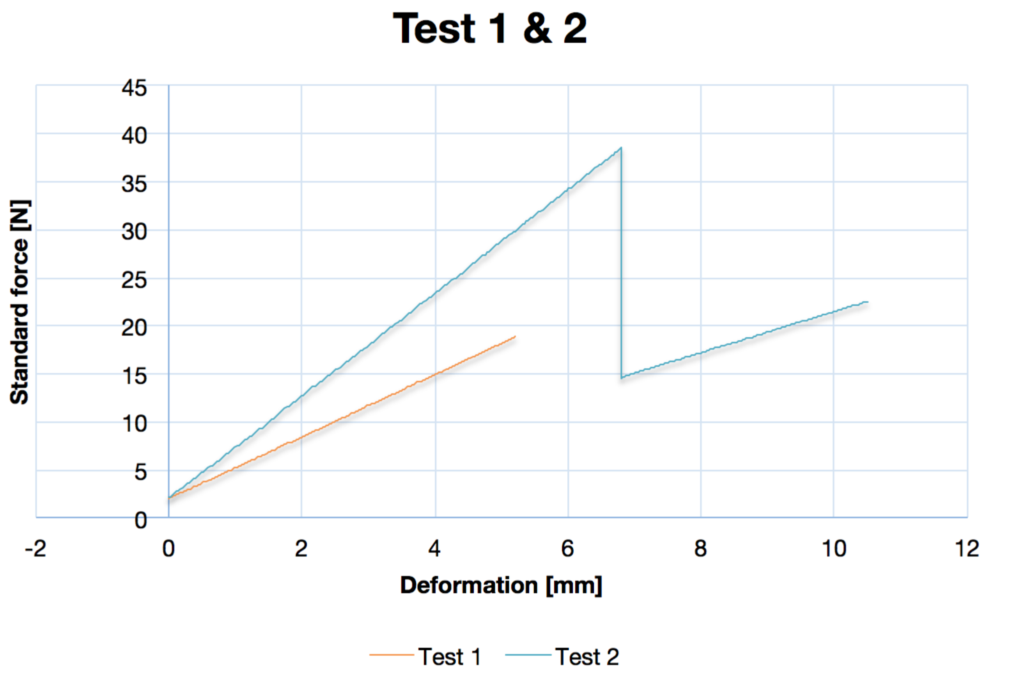


Figure 7.5: Test sample 2, broken bottom sheet.
Source: C. Louter

The force was not released from the remaining glass sheet until the second sheet also broke, this happened when a force of 38.57 N was achieved. In total, the deflection of this sheet is 10.51 mm. This is a much larger force and deflection than in test 1.

The testing software provided data about the force (N) and the deformation (mm) that the samples were subjected to. The bending stiffness of a 'beam' can be derived from the division of the applied force and the deflection of beam. When plotting the applied force and deformation from the data, the slope of the graph represents the bending stiffness.



Graph 7.2: Applied force and deformation in test 1 and 2. Source: by author.

Graph 7.2 shows the results of test 1 and 2. Test 1 stopped when the panel was subjected to a force of 18 N. In test 2, a drop is shown in the graph, this drop represents the breakage of the bottom glass sheet (at 38 N). The slope of test 1 and test 2.2 (after the break) is comparable to eachother.

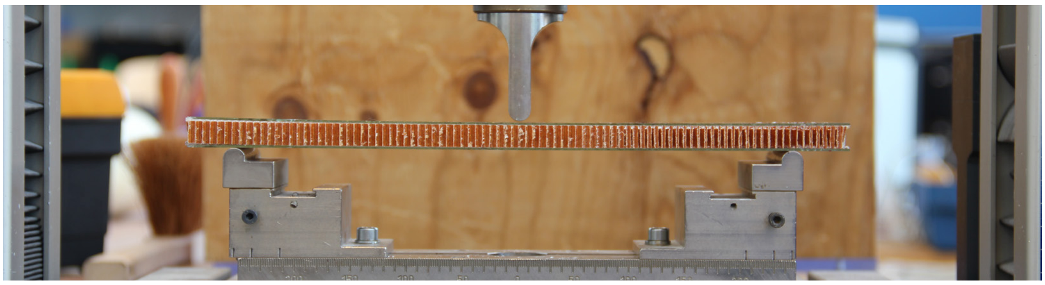


Figure 7.6. Test sample 3 annealed glass aramid sandwich panel. Source: C. Louter

Test 3: Annealed glass aramid sandwich panel

Like in test 1, the prepared annealed glass honeycomb sample was placed in the middle of the bending test. When a force of 582.63 N was achieved breakage occurred in the bottom glass sheet, at this moment the deflection was 2.05 mm. The breakage of the glass sheet is clearly shown, but all glass fragments are held into its place by the SG layer. In other words, this panel is very safe in case of breakage.

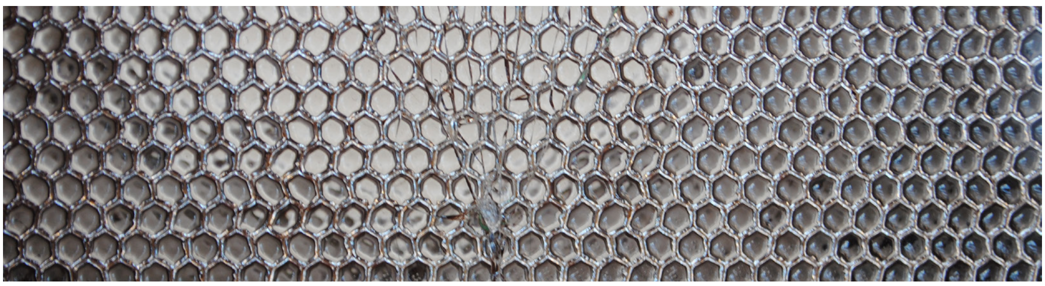
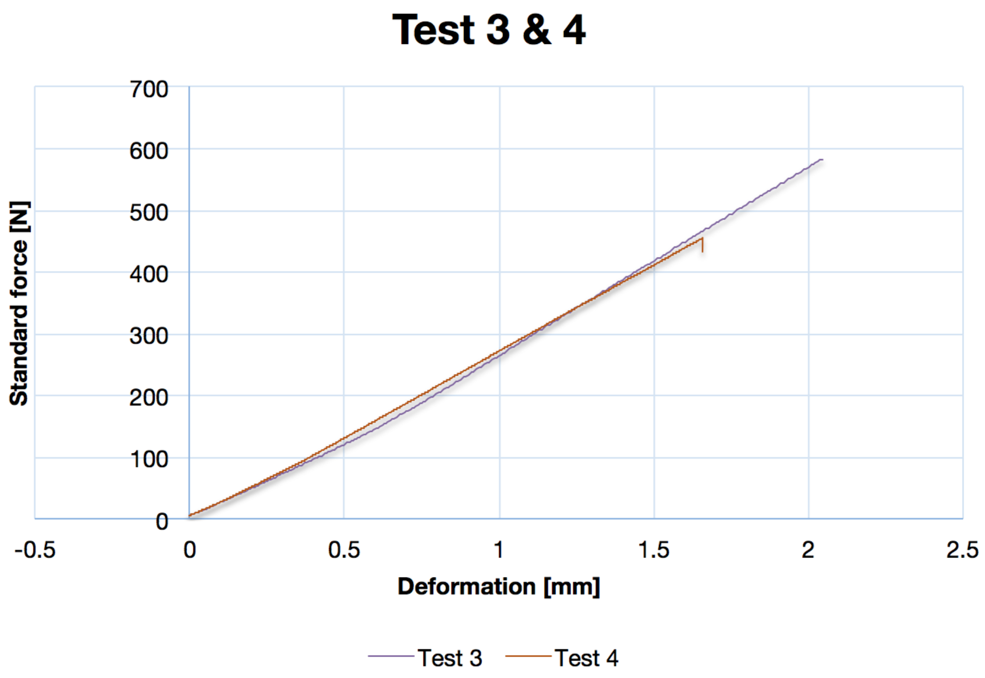


Figure 7.7. Breakge pattern test 3 Source: C. Louter

Test 4: Annealed glass aramid sandwich panel 12 mm

To properly compare the stiffness of the stacked glass sheets to an adhesively bonded glass sandwich panel, this test is done. It is exactly the same as test 3. Sample 4 showed the exact same behavior as sample 3. However, the sample broke much sooner, at 434.39 N. As a result of this lower force, the deflection is also less than in test 4 in this test it is 1.65 mm.



Graph 7.3: Applied force and deformation in test 3 and 4.
Source: by author.

Graph 7.3 shows that the samples in test 3 and 4 behave very similar to each other when it comes to bending stiffness (the slope of the graph). The only difference is that test 4 broke at a much lower force (440 N) than test 3 (580 N).

Test 5: Thin glass aramid sandwich panel 14 mm

The sample of test 5 is made with a chemically strengthened glass sheet.

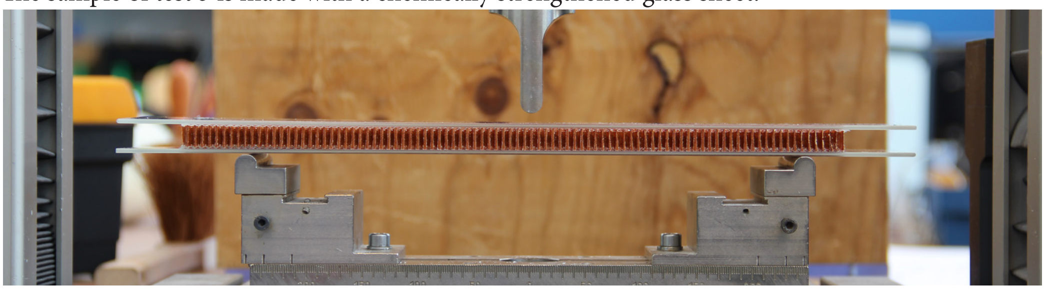


Figure 7.8. Test sample 5: chemically strenghtened aluminosilicate glass and aramid sandwich panel.
Source: C. Louter

Unlike the previous test, breakage did not occur during this test, while subjecting the panel to a force, the core did reduce in its strength. This was not visible, but a soft crumbling sound was heard. This sound can be explained by reaching the maximum shear force that the core could withstand, in other words its yield point.

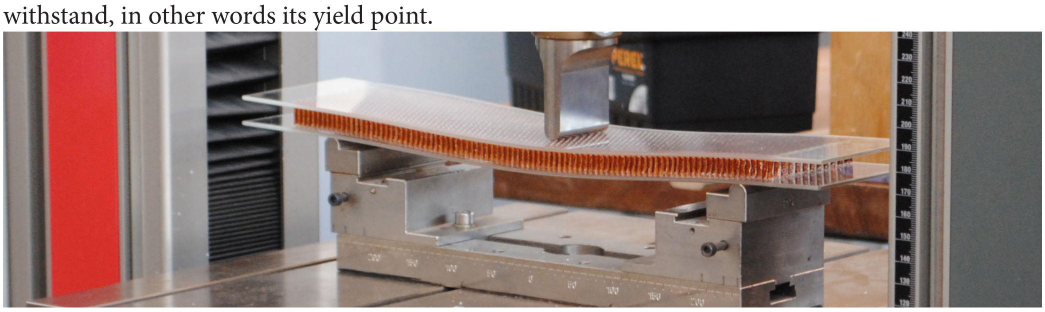
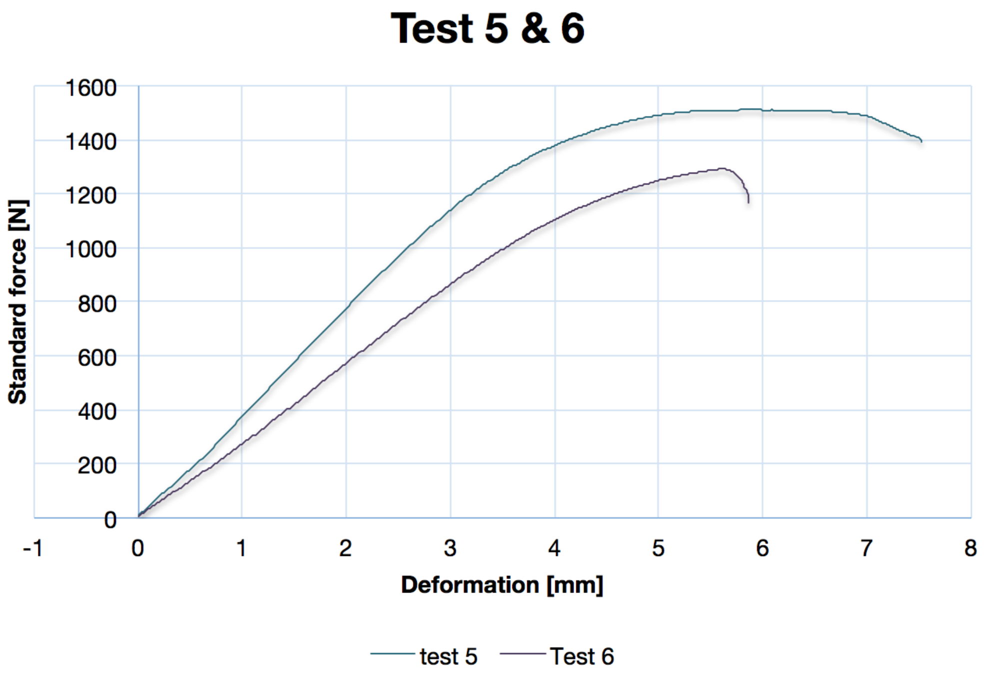


Figure 7.9. Bending test sample 5
Source: by author.

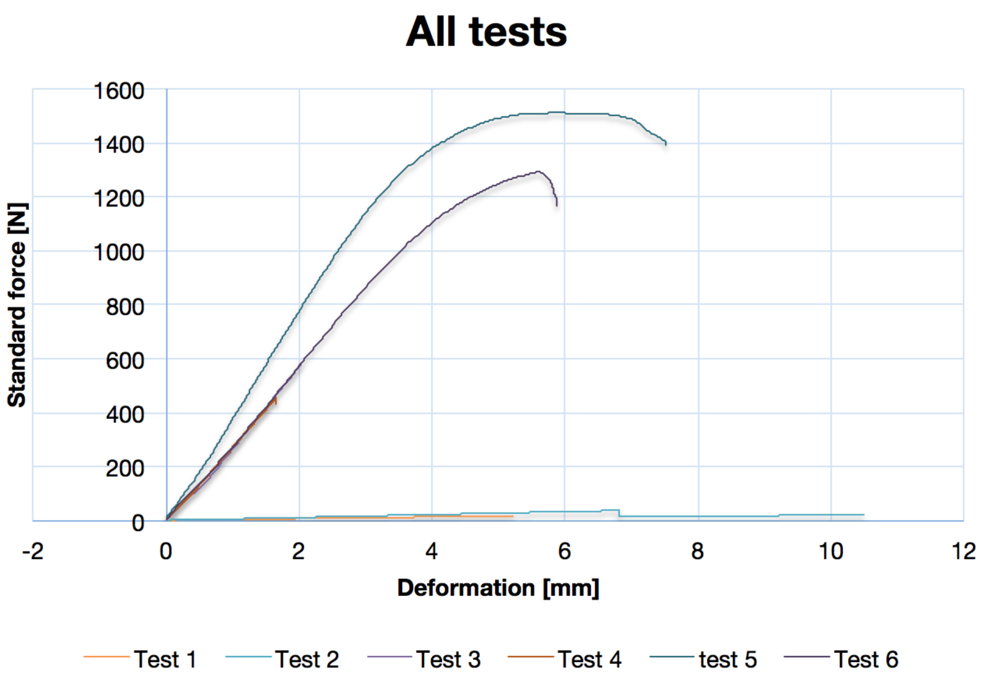
When this sound was observed, the pressure of the machine was released. The sample reached its yield point at 1511 N, at that moment it deflected 5.9 mm.

When the pressure was released, the panel did not show any visible flaws. Because neither the glass nor the core showed any damage, the test was done another time with the same sample, but the sample was placed upside down. The behavior of this test was similar to the previous one. This time the yield point was much lower, it occurred at 1292.42 N. The fact that this force is much lower than in the previous test can easily be explained by the fact that the panel was already damaged by the earlier test. Again, it can be concluded that this panel is safe in use.



Graph 7.4. Applied force and deformation in test 5.
Source: by author.

In graph 4, test samples 5.1 and 5.2 both show a linear curve in the beginning of the test but after some time the slope becomes less steep when the applied force rises above the yield point. It can be noted that test sample 5.2 has a lower bending stiffness than test 5.1, which can easily be explained. Sample 5.2 is the same sample as 5.1, turned upside down. In test 5.1 the yield point was already achieved, meaning that some unrecoverable damage had already been done to the core.



Graph 7.5. Applied force and deformation in all tests.
Source: by author.

7.4 Conclusion

All test results are shown in graph 5, it clearly shows that the bending stiffness of test 1 and 2 is very low compared to the sandwich panels (test 3, 4, 5 and 6), this is also shown in the data provided by the testing software (table 7.2). In this table, the expected results are compared to the actual test results. To calculate the bending stiffness of test 5.1 and 5.2, the linear slope in the

Test			F_{max}(N)	δ_{break} (N)	F_{yield} (N)	δ_{yield} (mm)	Bending stiffness (N/mm)
1	Expected result	broken	7.46	5.7	-	-	1.3
	Test result	not broken	18.9	5.7	-	-	3.3
2	Expected result	broken	14.8	4.12	-	-	3.6
	Test result	broken	38.57	6.81	-	-	5.7
2.2	Expected result	broken	7.46	5.7	-	-	1.3
	Test result	broken	22.6	10.51	-	-	2.1
3	Expected result	broken	492.8	2.9	-	-	170.0
	Test result	broken	582.63	2.05	-	-	284.7
4	Expected result	broken	492.8	2.9	-	-	170.0
	Test result	broken	434.39	2.9	-	-	261.9
5.1	Expected result	yield	-	-	672	2.8	236.3
	Test result	yield	-	-	1078	2.8	385.0
5.2	Expected result	yield	-	-	672	2.8	236.3
	Test result	yield	-	-	950	3.38	281.1

Table 7.2. Test results compared to actual results.
Source: by author.

beginning of the graph, which is before the yield point has been used.
The table shows that all samples have a larger bending stiffness than expected by the manual calculations. In the case of a laminated construction, this is possibly caused by the interlayer (SG) which adds to the mechanical performance. From graph 7.5 and table 7.2 the following conclusions can be drawn:
- As expected, the single glass sheet has the lowest bending stiffness among all test samples.
- Annealed glass is able to withstand more than 40 MPa.
- Some glass samples are stronger than others. Possibly some flaws are caused in the glass sheet during cutting process or transport.
- Adding an additional glass sheet increases the bending stiffness and flexural strength.
- When several layers of glass are used, the one on the bottom will break first due to tensile forces. Whether the stacked construction is a sandwich panel (test 3, 4, and 5) or not (test 2).
- Once the glass sheet on top is broken, in test 2, the remaining top plate has a bending stiffness which is simular to test 1.
- With laminated constructions, the interlayer adds to the flexural strength and bending stiffness.
- Chemically strengthened glass is able to withstand a much larger stress then annealed glass, which explains by chemically strengthened glass has not yet broken under a significantly larger load.
- When a stronger core would be chosen in test 5, the yield point will not be reached before the maximum bending force. If a core with a larger shear modulus would be chosen, an extremely high stiffness could be achieved with chemically strengthened glass.
- The sandwich panels have a much larger bending stiffness than the single- and stacked glass sheets.
- In test 1 and 2 the annealed glass broke into several pieces, while in test 3 and 4 the glass was held into its place by the interlayer, resulting in a safe failure scenario.

Discussion results

The sandwich samples have been made in a regular oven, without pressurizing or creating a vacuum. Therefore, the adhesion might be (mechanically) better when manufactured with an established method.

Also, the annealed glass sheets has been cut manually and transported without taking protective measurements. Both could have caused minor damages to the surface and the edges of the glass Which could cause some samples to break easier than others.

08

Case study

A fire burnt down TU Delft's entire Faculty of Architecture in 2008. Quickly a new location had to be found to accommodate all the students. The old main building of the Technical University was found to be perfect, it was completely refurbished and renovated into the new faculty building: BK City. Its capacity had to be enlarged to host all the required functions, to do so two glass volumes were added to the building. These new volumes are submissive to the original 19th century building, it is barely affected by this renovation. The original building was since than enlarged with +/- 2100m², which made it possible to fit the program.
The expansion had to take place quickly, thus Octatube, the involved design- , engineering- and manufacturing company, designed a roof construction built out of space frames. This system allowed for the required large span and a free floorplan. Because of the lightness of this system, it was possible to build fast. The grid of the space frame is 2,7 m by 2,7 m. The façade construction is based on greenhouse structure, only trusses were added in order to reach the required height of approximately 12 m (Octatube, 2017).

These volumes offer space for model making, lectures, studying and other events. However, when using these spaces, there are some disadvantages.
Because both volumes have a fully glazed façade, they heat quickly when the sun is shining. The solar gain is large, especially because both are facing south eastern direction. Meaning that the sun will heat the volumes in the morning and in the entire afternoon. To avoid excessive solar irradiation and glare, solar shading is hung on the inside of the façade. Unfortunately indoor solar shading is not beneficial for the thermal quality of a building, it accumulates even more heat (Buck, 2006). Due to the large amount of solar irradiation, the spaces can become very warm. Besides that, glare is not avoided at all time because the sun shading is mechanically controlled.

In the Orange hall (Oostserre) every now and then, events take place and expositions are shown, but most of the time it is used for student who are individually studying. The Zuid serre is mostly used for modeling, and some courses take place. In terms of use, both volumes require better thermal performance. Because, in general, more students need to be focused in the Orange hall, this is the façade that is selected for the design.

Lightness was already one of the main goals when this façade was designed, the large glass surface however, opposes this concept. With the proposed panel design the thermal performance will be improved, by integrating solar shading. Glare will be prevented, while (at least) the same thermal insulation is achieved.

photo: by Octatube

8.1 Analysis

In order to design an ultra-lightweight alternative for this facade, an analysis of the current one was inevitable. All its elements need to be investigated, the grid sizes should be determined and an approximation of the weight of the façade needs to be calculated.

Elements

By taking a closer look at the facade (figure 8.1 & 8.2), it can be discovered what the elements are of which the facade consits.

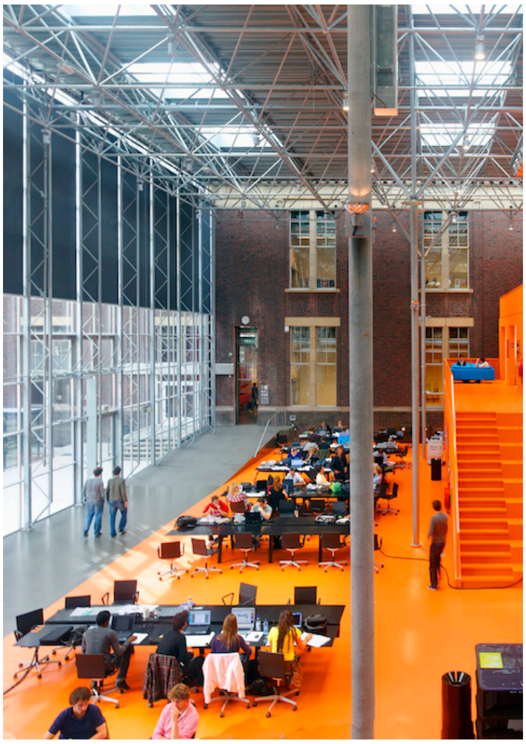


Figure 8.1 (right). Roof, facade system and sunshading.
Source: MVRDV

Figure 8.2 (right). Trusses, U-profile and windowframes.
Source: by author

The roof construction is carried by a spaceframe which is built from hollow tube profiles. The grid of this spaceframe is 2,7 x 2,7 m. It carries a steel deck concrete roof.

In the facade, there are 12 steel trusses, built from tube profiles. The sizes of these profiles are 140 x 140 (1), 30 x 30 (2) and 80 x 50(3) mm. Profile 1 spans from the bottom to the top, 13.1 m, profile 3 is 11.5 m. Profile 2 makes the triangular connection between Profiles 1 and 3. The trusses in the facade provide for the stability of the facade, it carries the wind load. They also carry the load of the curtainwall itself and, partially the load of the roof construction.

The windows of which the facade consists are insulating, double glazing units. The assumption is made that the glass consists of two sheets with different thicknesses, 4 and 6 mm, for noise reduction. The part of the glass which is not in the windowframe is 1300 x 1300 mm.

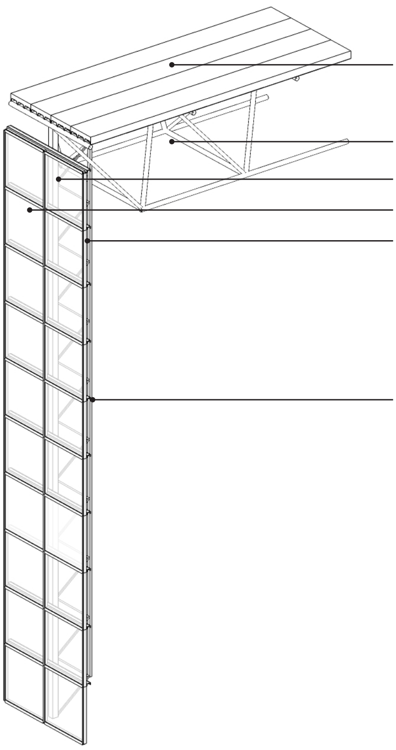


Figure 8.3: Fragement elements in facade.
Source: by author

Probably the glass sheets are 1320 x 1320 mm. The windows are held into place by an aluminum curtain wall. The profile of this system is 5 x 4.5 cm. On the top of the facade, roller blinds are hung. In total, they are 2,6 in width and 9 in lenght.

To keep the curtain wall in the correct position, a U-profile is used. Through these profiles, the windload is transferred from the window frames to the trusses.

Gridsizes

The gridsize of the facade is derived from the dimensions of the spaceframe, which is 2700 x 2700 mm. Every other 2.7 m a truss is required to carry the load of the roof. The subdivision of the curtain wall grid is derived from this grid, it is half the size thus 1.35 m.
An important note is that on each side where the facade connects to the original building, there is some remaining space. Figure 8.4 shows a fragment of the building in which this remaining space and the regular grid is shown.

Weight calculation

Now an investigation of the gridsizes and the facade elements is done, the weight of the current facade can be calculated. The weight of each element (per kg) is found by investigating factsheets of product suppliers. This weight times the size and the amount of elements in the facade gives the result. For example, the weight of a truss is calculated by:

1. Profile 140 x 140
Section thickness: 5 mm
Length profile: 13.1 m
Amount: 1
Weight: 21.3 kg/m (Bouwenmetstaal, 2016)
Weight element: 278.6 kg

2. Profile 30 x 30
Section thickness: 2 mm
Length profile: 1.07 m
Amount: 18
Weight: 2.4 kg/m (Bouwenmetstaal, 2016)
Weight element: 2.557 kg

3. Profile 80 x 50
Section thickness: 2 mm
Length profile: 11.5 m
Amount: 1
Weight: 3.96 kg/m (Bouwenmetstaal, 2016)
Weight element: 45.7 kg

Total weight: = 278.6 + (18 * 2.557) + 45.7 = 370.3 kg

Construction element		Assemble	Size	Weight element [kg]	Amount	Weight [kg]	Weight total [kg]
Glass surface	Double glass element	Glass - cavity - glass 4-12-6 mm	1.3 x 1.3 m	50.7	216	10951.2	
		Glass - cavity - glass 4-12-6 mm	1.3 x 0.4 m	15.6	18	280.8	11232
	Curtain wall frame	Horizontal	36.15 m	131.9475	11	1451.4225	
		Vertical	13.5 m	49.275	28	1379.7	2831.1225
Support construction	Truss	Tube profile 14 x 14	13.1 m	278.6	12	3343.2	
		Tube profile 3 x 3	1.07 m	2.557	216	552.312	
		Tube profile 8 x 5	11.54 m	45.7	12	548.4	4443.912
	U-profiles	UNP 90	35.35 m	374.71	9	3372.39	3372.39
	Sunshading	Thickness 0.5 mm	9 x 2.6 m	10.998	12	131.976	131.976
							22011.4005

Table 8.1. Weight calculation current facade.
Source: by author.

In table 8.1, the weight of all elements is calculated, the weight all elements in this facade is approximately 22011.4 kg. Devided by the area of the complete facade (36.2x13.5 m) gives a weight of 45.1 kg/m². The glass makes up for almost half the weight of the entire facade. This can be reduced by implementing the to-be-designed thin glass sandwich panels. The other half of the weight is the construction. This weight, could possibly be reduced aswell.

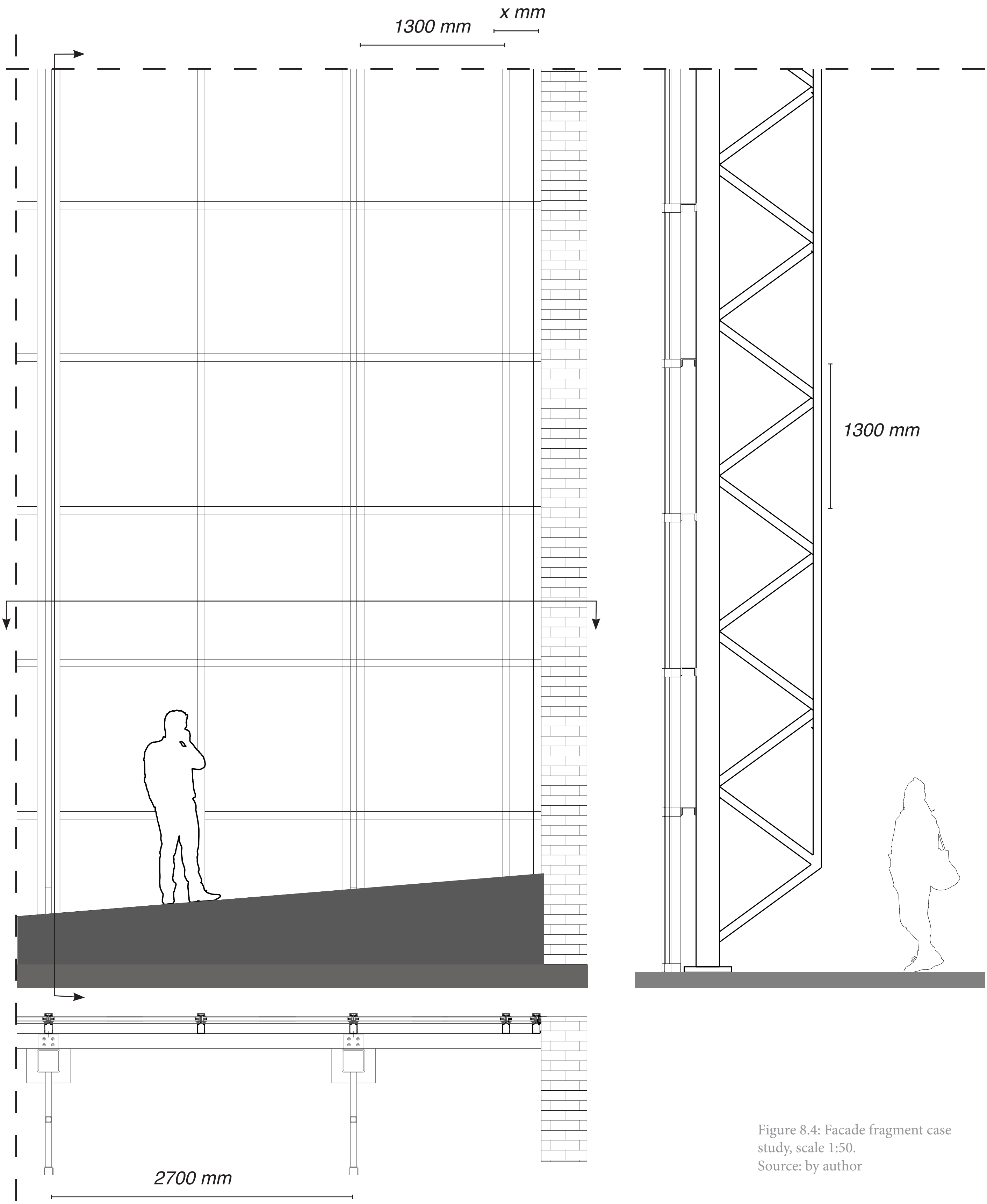


Figure 8.4: Facade fragment case study, scale 1:50.
Source: by author

Load case assumption

To select a core material and dimension it by the required mechanical properties, the loadcases that the panels are subjected to need to be determined. The panels are subjected to their own weight, and the wind load. The weight of the panel is depending on the component geometry.

The wind load differs per location, NEN-EN 1991-1-4 (2011) describes the Dutch wind areas and their corresponding maximum wind load. This is dependant on the height of the building, and the environment type (appendix 2). Regarding this case study, located in Delft, the following data should be considered in order to find suitable component geometry:

Wind area	II
Type of environment	built
Height of the building	13.5 m
Maximum wind load	0.9 kN/m2

To include safety in the calculation, both SLS (serviceability limit state) and ULS (ultimate limit state) should be considered. For the SLS a shape factor of 1.0 is normally used for wind loads. The wind load remains the same:

0.8 kN/m2 * 1.0 = 0.8 kN/m

The safety factor for dynamic wind loading is 1,3. Considering this, the ULS is:

0.8 kN/m2 * 1,3 = 1,04 kN/m

Since it is the largest load, the ULS, of 1.04 kN/m, should be considered in the calculations.

8.2 Initial design
In the initial design of the facade, not only the weight of the glass surface is reduced also the weight of the support construction is lighter. Built lightweight support constructions are often made with tension cables.

Predecent
The OZ-building, also built by Octatube, is an example of a facade which is built with steel tension cables. With the use of spiders and pressure bars, the glass facade is held into place. The spider is connected to a pressure bar, this steel tube profile transfers the pressure from the wind load to the tension cables. Additional cable are used to keep the pressure bars in their place. The surface of the wall is 16 m (width) x 52 m (lenght). The size of the complete facade is bigger than the facade in this case study, therefore the OZ-building seems like a suitable predecent.

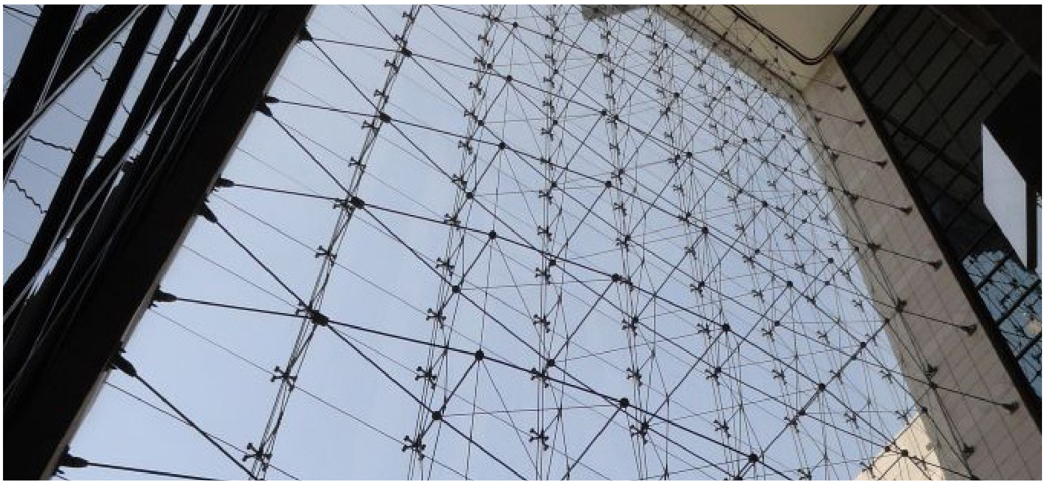


Figure 8.5. OZ building, Tel Aviv, by Octatube.
Source: Octatube.

Design
Based on the discussed precedent, a cable truss construction is projected onto the facade of the case study. In the short direction (height) two cables span in a mirrored parabolic shape while in the longer direction a cable spans in straight direction. At each intersection of the grid is a pressure bar situated which is connected to the described cables. In total, 243 pressure bars are applied. 8 steel cables span horizontally and 50 (25x2) cables span vertically. This initial design is shown in figure 8.6.

Weight calculation
The main objective of this research is to reduce weight, and material use. To check if a cable truss construction, like in the OZ building, could reduce weight a calculation is made. In this calculationthe weight of the steel tension cables, pressure bars, double glass elements and an aluminum curtain wall frame are calculated (table 8.2).

Construction element		Assemble	Size	Weight element [kg]	Amount	Weight [kg]	Weight total [kg]
Glass surface	Double glass element	Glass - cavity - glass 4-12-6 mm	1.3 x 1.3 m	50.7	216	10951.2	
		Glass - cavity - glass 4-12-6 mm	1.3 x 0.4 m	15.6	18	280.8	11232
	Curtain wall frame	Horizontal	36.15 m	131.9475	11	1451.4225	
		Vertical	13.5 m	49.275	28	1379.7	2831.1225
Support construction	Cables	Horizontal	36.15	12.6953	8	101.5624	
		Vertical fish shaped	2 x13.2 m	20.856	25	521.4	
		Pressure bars	1 m	2.5	243	607.5	1230.4624
							15293.5849

Table 8.2. Weight calculation initial design facade.
Source: by author.

In total, the weight is 15293 kg, which is 40.8 kg per square meter. This is approximately 5 kg / per square meter less than the original facade. Therefore it can be concluded that a cable truss construction could substantially reduce the weight of the facade construction. Even without taking the lightweight thin glass sandwich panels into account. Before being able to implement these sandwich panels into a weight calculation, first the materialization and dimension need to be defined.

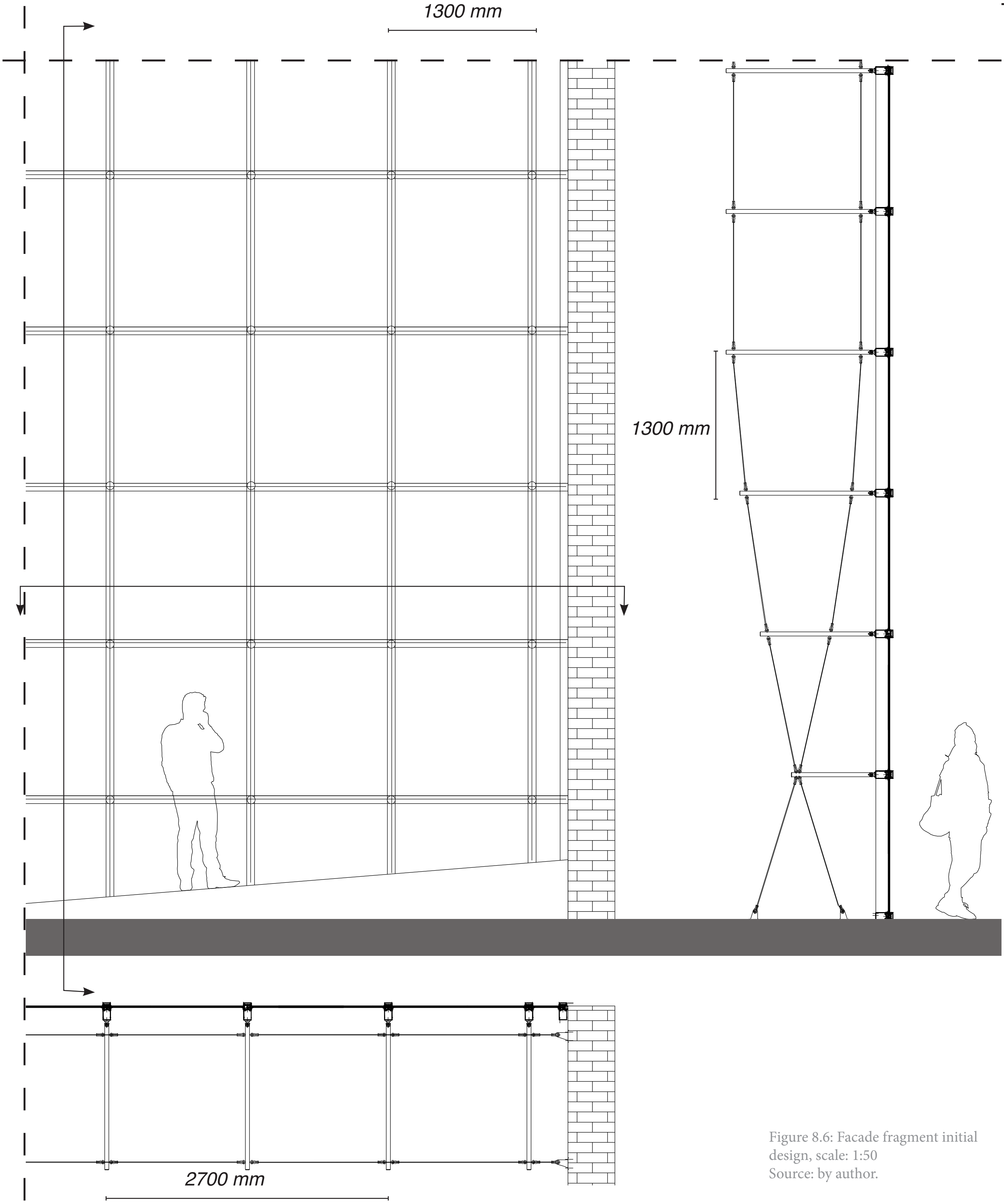


Figure 8.6: Facade fragment initial design, scale: 1:50
Source: by author.

09

Panel configuration

In order to design a lightweight, thermally insulating thin glass sandwich panel, the suited materials need to be selected. A generic sandwich panel consists of two face sheets and a core in-between, to create a connection between these elements a bond with a proper fillet should is required. The face sheets will be chemically strengthened aluminosilicate glass. The thickness of the glass however follows from mechanical calculations.
A suitable core material has to be found and its required thickness should be determined. These dimensions will be found by doing calculations, the thermal insulation-, safety and stiffness demands have to be met.

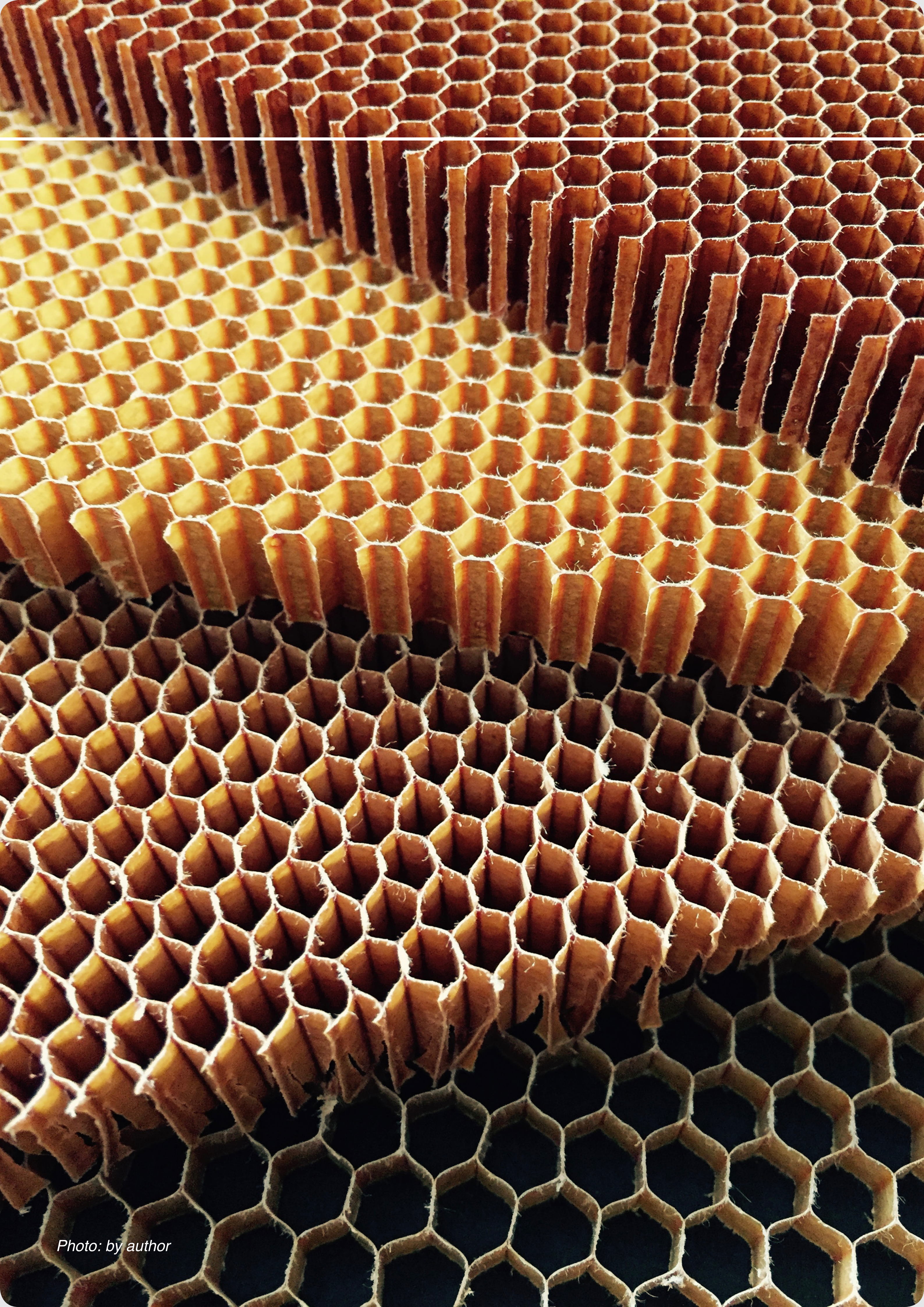


Photo: by author

9.1 Core material

Hexcel (1999) describes attributes that may help to determine the most appropriate honeycomb type. Among these, the following are most relevant considering the design criteria of this project:

1. Strength
2. Thermal properties
3. Density
4. Facings
– Material
– Bonding (process / adhesive / conditions)
– Thickness

More attributes can be considered, like cost vs. performance, the piece size, strenght (fatigue, flatwise tensile), cell wall thickness, moisture, color, environmental chemicals, processing and operating temperature range, flammability/fire retardance, electrical conductivity, wall surface smoothness, abrasion resistance, cushioning, machinability/formability.

To select a suitable core material that complies with the formulated design criteria, CES Edupack is used. From all the honeycomb types in the material database CES (160 in total), the one that is best applicable in the facade panel should be found. Since the face material of the sandwich panel is glass, the core will be subjected to UV-radiation. Therefore a limit filter is applied in CES, only honeycombs that have good (years) or excellent (tens of years) resistance to UV-light pass after applying this filter. Another material property that should be filtered is the transparency, an opaque or translucent material is more desirable in this project because than the core is able to block a certain amount of the sunlight from entering through the facade.
In summary, the applied filters in CES are:

1.	Form: honeycomb	160 materials passed
2.	Appearance: opaque/translucent	155 materials passed
3.	UV-resistance: good/excellent	148 materials passed

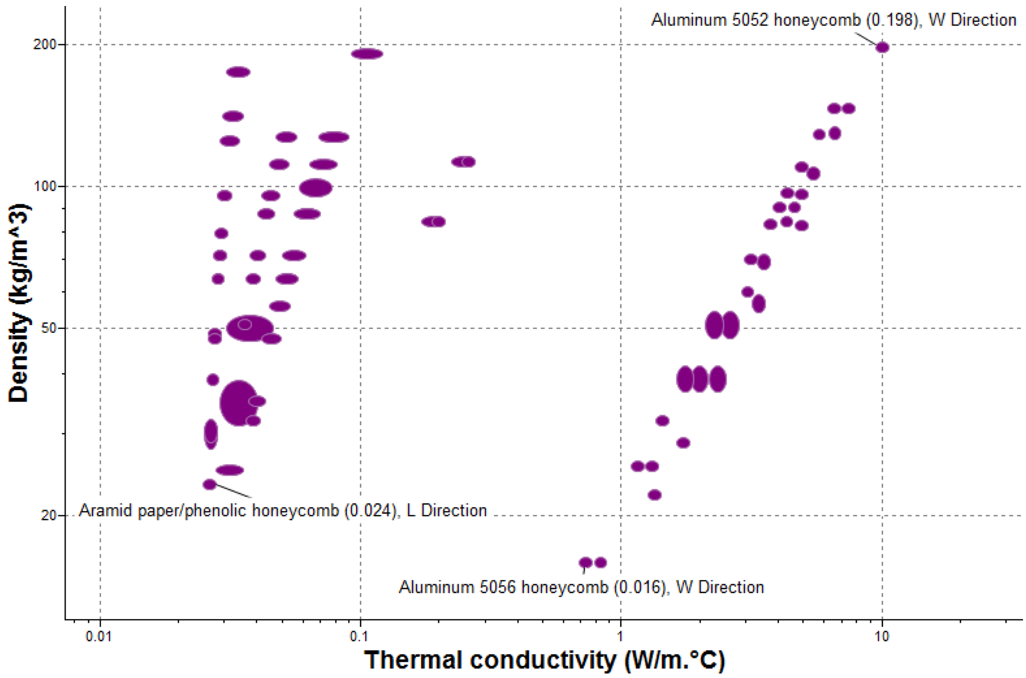
The materials passing these limit filters are aluminum, glass/phenolic, impregnated paper, aramid (para- and paper) and stainless steel. What should be noted is that the price and the density of these materials is strongly related to the cell size. Subsequently, the cell size has a lot of influence on the strenght of the core. In terms of mechanical performance, the compressive-, impact- and shear strength should be considered. In the calculations, a core should be selected and checked for its performance and optimized for it. Only than, a core with sufficient strength can be found.

The thermal conductivity of a honeycomb core is determined by the material itself, and the cell size of the core. A larger density results in a directly proportional larger amount of material conducting heat, this is clearly illustrated in graph 9.1. It shows, for example, aluminum 5056 honeycomb (0.016) has a relatively low density thus a low thermal conductivity while aluminum 5052 (0.198) has a high density and thermal conductivity.
In general, metals have a large thermal conductivity which is undesireable in this facade panel. The lowest thermal conductivity is achieved with aramid paper honeycomb, its thermal conductivity is 0.0249 W/mK.

The lowest density among the available honeycomb cores (Hexcel, 1998) is 29 kg/m3, this can be achieved with both aluminum and aramid paper.
The facing material is determined by the outline of this research, chemically strenghtened aluminosilicate glass. Glass can, in theory, be attached to all of these materials when a suitable adhesive is applied. The only criteria is that the bonding material is transparent. The specific bonding method still needs to be defined.

Conclusion

According to applied filter in CES, the aramid core performs best, in terms of thermal performance while also offering a relatively low density. Therefore, further exploration will be done with this core type to find out if its mechanical and thermal performance is according to the requirements.



Graph 9.1: Plotted density and thermal conductivity.
Source: CES Edupack.

9.2 Heat transfer sandwich panel

In general, heat transfer contains conduction, convection and radiation. However, in chapter 5 it is stated that convection is neglectable for honeycomb sandwich panels. K.Kantha Rao and K. Jayathirtha Rao (2014) also found that the insulation value of the panel improves with a larger core depth and discovered that the effect of radiation is much smaller than that of conduction. However, their tests have not been done with glass face sheets, because of this material, radiation might be more important than stated in this paper. The required heat resistance for the sandwich panel can be calculated by the required u-value of 1.4 W/m2K:

Urequired = 1/ Rtotal = 1.4 W/m2K
with
Rtotal = 1 / (αcond + αrad)
Thus
Urequired = αcond + αrad = 1.4 W/m2K

In the following calculation, the heat transfer coefficient of both conduction and radiation will be found in order to meet the required insulation value of 1.4 W/m2K. Unlike with radiation, the conduction heat transfer coefficient has many variables that need to be found. Therefore, the radiation heat transfer coefficient will first be calculated.

Radiation

As mentioned before, uncoated glass has an emission coefficient of ε = 0.84, the emission coefficient of the core can be estimated with the coefficient of paper which is ε = 0.93. The resultant of these materials, is:

1/ εres = 1/ε1 + 1/ε2 – 1
1/ εres = 1/0.84 + 1/0.93 – 1
εres = 0.79

αres = 6 εres
= 6 * 0.1 = 4.7 W/m2K

This value is larger than 1.4 (4.7 + αrad ≥ 1.4 W/m2K) which means the required u-value of 1.4 W/m2K will never be achieved with uncoated glass. Thus coated glass should be applied in the sandwich panel in order to achieve the required u-value. The calculation sheet is attached in appendix 3.

With low-e coating, an emission coefficient of $\varepsilon = 0.02$ can be achieved for the glass:

$1/ \varepsilon_{res} = 1/\varepsilon_1 + 1/\varepsilon_2 - 1$
$1/ \varepsilon_{res} = 1/0.02 + 1/0.93 - 1$
$\varepsilon_{res} = 0.02$

$\alpha_{res} = 6\ \varepsilon_{res}$
$= 6 * 0.1 = 0.12$ W/m2K

This value is sufficient ($4.7 + \alpha_{rad} \geq 1.4$ W/m2K)

Conduction

Knowing the radiation heat transfer coefficient, the required conductive heat transfer coefficient can be determined:
$U_{required} = \alpha_{cond} + \alpha_{rad} = 1.4$ W/m2K
$\alpha_{cond,required} = 1.4 - 0.12 = 1.28$ W/m2K

To calculate the conductive heat transfer coefficient of the sandwich panel, the following formula will be used used:
$R_{required} = 1/ \alpha_{cond,required}$
$= 1/1.28 = 0.78$ W/m2K

These heat resistances (r) can be found by the thickness- and thermal conductivity of the layer. The thermal conductivity (λ) is a material property and the thickness (d) is defined in the design of the panel.

$r = d / \lambda$ [m2K/W]
with
d = thickness layer [m]
λ = thermal conductivity [W/mK]

The resistance of heat transfer though the adhesive film is:
$r_{adhesive} = 0.01 - 0.03$ m2K/W

The resistance of the heat transfer from indoor to outdoor are standard values depending on the climate, in the Netherlands these are the values (NEN1720, 2011):
r_e = 0.04 m2K/W
r_i = 0.13 m2K/W

The resistance of the glass face sheets, and the core can be found by these formulas:
$r_{glass} = d_{glass}/\lambda_{glass}$
$r_{core} = d_{core} /\lambda_{core}$

For the glass face sheets, we know:
d_{glass} = 0.55 mm = 0.00055 m
λ_{glass} = 1 W/mK

To find out what core type complies with the required insulation value (U), r_{core} remains unknown.

Results:

Thermal resistance: $R_{Required}$

$R_{Required} = 1/\alpha_{cond}$ $= 1 / 1.25$
$= 0.79$ W/m2K

Resistance glass: r_{glass}

$r_{glass} = d_{glass}/\lambda_{glass}$ $= 0.00055 / 1 = 0.00055$ m2K/W

Thermal resistance, core: r_{core}

$r_{core} = R - (re + 2(r_{glass} + r_{adhesive}) + ri)$ $r_{core} = 0.79 - (0.13 + 2(0.00055 + 0.03) + 0.04)$
$= 0.57$ m2K/W

Thickness core: d_{core}

$d_{core} = r_{core} * \lambda_{core}$ $= 0.57 * 0.0249$
$= 0.0119$ m
$= 11.95$ mm

Conclusion
The selected core for the sandwich panel is aramid (paper). In CES Edupack (2014), the material properties of this core type can be found. The thermal conductivity (λ) varies from 0.0249 to 0.0372 W/mK depending on the cell size. With a cell size of 3.2 mm, required insulation can be achieved with a thickness of 11.95 mm (appendix 4). For the main suppliers of honeycomb cores, 12 mm is a common production size.

Discussion
This sandwich configuration is possible to achieve a U-value of 1.4 W/m2K. However, the lower the u-value the better. Possibly, the U-value could be decreased by increasing the thickness, or by adding an additional sandwich panel and create a cavity inbetween them.

Also, with other configurations it could be possible to achieve the U-value of 1.4 W/2K. In this configuration, the lowest possible densities have been choosen in order to design a ultra lightweight facade panel. When, for example a plastic core would be chosen (possibly for aestetic reasons), the thicknesses of the glass and the core will change and the cell size could also be different in order to achieve the required U-value.

9.3 Mechanical performance
In order to check the mechanical performance of an aluminosilicate glass - aramid honeycomb sandwich panel, calculations are required. The necessity of the stiffening method, that is derived from theoretical research, should be proven. The main goal of these calculations are to find a configuration in the panel assembly that is safe and stiff enough to not deflect more than is allowed by the NEN-2608 building code. In order to do mechanical calculations, possible variables of the geometry need to be determined. Many could influence the results of the mechanical performance of the panel. The effect of different variables is investigated with the main focus on the lightness of the overall construction.

- Force (type, direction, magnitude)
- Thickness glass sheets
- Thickness honeycomb
- Honeycomb type (material, cell sizes etc.)
- Geometry (Panel size, boundary conditions)

Since the main objective of this thesis is to reduce the weight of an façade, the aramid honeycomb core with the lowest density is selected to start with.

Force
In the Dutch regulations there exists a document which explains the wind forces. The location of the panel influences the magnitude of the wind load and the direction. In the calculations, the wind load will be considered as an evenly distributed load with an average rate. In the Netherlands, most buildings in urban areas, with a medium height of 15 - 20 m , are subjected to a maximum wind load of 1.04 kN/m. This maximum value is therefore used in this research. The direction of the load is perpendicular to the panel surface. Besides this load, also the panels' self-weight should be considered.

Geometry
Based on the information from the previous paragraphs, some general choices were made regarding the input for the studies presented in this paragraph.

Because an insulating glass panel requires an edge profile on all sides, it could be said that the all edges are simply supported. The assumption is that without the honeycomb structure, the panels will not be stiff enough to comply with the criteria.

The materials in the sandwich panel are selected by the lowest available density. For the aluminosilicate glass sheets a thickness of 0.55 mm was choosen. For the honeycomb structure this means a density of 29 kg/m3. The selected core is produced by Hexcel, HRH10 Nomex (Aramid) 29-3.

Poisson's ratios for different types of honeycomb have been determined to vary between 0.1 and 0.5. Where the Poisson's ratio for Flex-Core cell configuration is 0.1 than Poisson's ratio for hexagonal cell configuration is approximately 0.49.

A constant panel dimension was used: 1300 x 1300 x 0.55 mm. This is the panel size which is derived from the grid sizes in the design.

Criteria
Reducing the weight of the facade panel is the main focus of this thesis. Therefore the materials with the lowest weight are selected for the initial calculations. The minimum required insulation value determines the thickness of the core. Its minimum thickness is 10 mm. According to NEN 2608, the maximum deflection that is allowed for insulated glass panels can be calculated with the formula:

Umax=L/200

With

L = span, edge(mm)

Umax= maximum deflection, edge panel (mm)

The requirement on the deflection of an insulated glass panel is determined by the required connection between the sheets of glass that must remain intact. If the seal of the pane deflects too much, the cavity is no longer hermetically sealed. Then, in the worst case, the thermal insulation properties are decreased, and only the glass sheet on the loaded side of the panel will be load-carrying (NEN 2608, 2014).

Depending on the applied seal, spacer, back cover and cavity width a greater deflection may be allowed. This, however will not be taken into account within the following calculations.

Also, the maximum deflection of the center of the panel should be calculated in order to check if the design is safe. The maximum allowed deformation in the center is to be calculated with the maximum diameter length of the panel.

Udia;max = ldia /65 < 50

with

udia;max = maximum deflection of the center of the panel (mm)

ldia = biggest diagonal of the panel (mm)

Idia can be calculated by the Pythagoras theorem.

with

l1= l2 = 1300 mm

Udia;max = $\sqrt{(l1^2+l2^2)} = \sqrt{(1300^2+1300^2)}$ = 1838 /65 = 28.28 mm

		Panel size case study: 1300 x 1300 mm	
Allowed deflection side	[mm]	6.50	according to NEN 2608
Allowed deflection center	[mm]	28.28	according to NEN 2608
Allowed marginal stress aluminosilicate glass	[MPa]	260	Material property chemically strengthened aluminosilicate glass
Allowed shear stress honeycomb core	[MPa]	17	Material property selected honeycomb core

Table 9.1: Allowed values for deflection, and stressed (marginal and shear).
Source: by author

9.4 Calculation method

The method to calculate a sandwich panel is described by Hexcel compostites (2000). First it is very important to know how a sandwich panel works mechanically, how it deflects, what it's failure modes are and what steps should be followed when calculating the panel.

How a sandwich panel works

To imagine how a sandwichpanel works, you could consider a cantilever beam with a load applied at the free end. The applied load creates a bending moment which is a maximum at the fixed end, and a shear force along the length of the beam.
In a sandwich panel these forces create tension in the upper skin and compression in the lower skin. The core spaces the facing skins and transfers shear between them to make the composite panel work as a homogeneous structure. When a panel is subjected to bending forces, this compression, shear and tension are also found. In general terms, the shear forces normal to the panel will be carried by the honeycomb core. Bending moments and in-plane forces on the panel will be carried as membrane forces in the facing skins.

The deflection of a sandwich panel includes bending and shear components. The bending deflection is dependent on the relative tensile and compressive moduli of the skin materials. The shear deflection is dependent on the shear modulus of the core. You could say that:

Total Deflection = Bending Deflection + Shear Deflection.

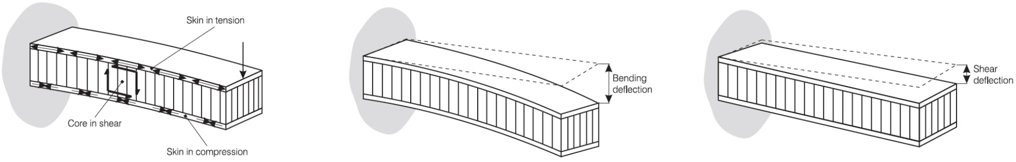


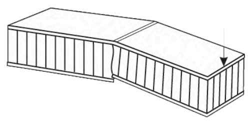
Figure 9.1: Total deflection sandwich panel.
Source: Hexcell

However, for many practical cases, where the span of the panel is large compared to its thickness, the shear deflection will be negligible.

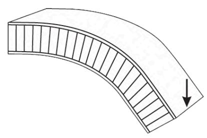
Failure modes

All potential failure modes should be considered in a structural analysis. A summary of the key failure modes is shown below:

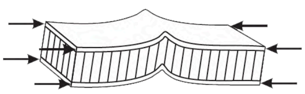
1. Strength.
The skin and core materials should be able to withstand the tensile, compressive and shear stresses induced by the design load. The skin to core adhesive must be capable of transferring the shear stresses between skin and core.



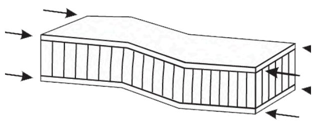
2. Stiffness.
The sandwich panel should have sufficient bending and shear stiffness to prevent excessive deflection.



3. Panel buckling.
The core thickness and shear modulus must be adequate to prevent the panel from buckling under end compression loads.



4. Shear crimping.
The core thickness and shear modulus must be adequate to prevent the core from prematurely failing in shear under end compression loads.



5. Skin wrinkling.
The compressive modulus of the facing skin and the core compression strength must both be high enough to prevent a skin wrinkling failure.

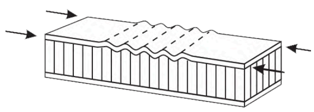
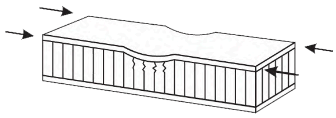


Figure 9.2: Failure modes: strength, stiffness, panel buckling, shear crimping and skin wrinkling.
Source: Hexcell

6. Intra cell buckling.
For a given skin material, the core cell size must be small enough to prevent intra cell buckling.



7. Local compression.
The core compressive strength must be adequate to resist local loads on the panel surface.

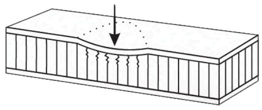


Figure 9.3: Failure modes: intra cell buckling and local compression. Source: Hexcell

For a facade panel, which is subjected to forces perpendicular to the surface, the most important failure modes to consider are strength, stiffness and local compression.

Calculation method

To calculate the strength, stiffness and local compression the following steps should be taken:

1. Define loading conditions. Care should be taken to consider all possible loading conditions. The loading condition that the panel is subjected to might be a point load, uniform distributed load or end load.
2. Define boundary conditions. This is determined by the type and extent of the panel supports. Fully built in support conditions should only be considered when the supporting structure has adequate stiffness to resist deflection under the applied loads. e.g. Cantilever, simply supported.
3. Define physical constraints. This should include an assessment of the requirements including: deflection limit, thickness limit, weight limit and factor of safety. The main focus of the preliminary materials selection is based on lightness.
4. Preliminary calculations. Make an assumption about skin material, skin thickness and panel thickness. Ignore the core material at this stage and then calculate the deflection (ignoring shear deflection), the facing skin stress and the core shear stress.
5. Optimize design. Modify skin thickness, skin material and panel thickness to achieve acceptable performance. Select suitable core to withstand the shear stress.
6. Detailed calculations. Calculate stiffness, the deflection (including shear deflection when necessary), facing skin stress, core shear stress and local compression loads on the core.

9.5 Calculation

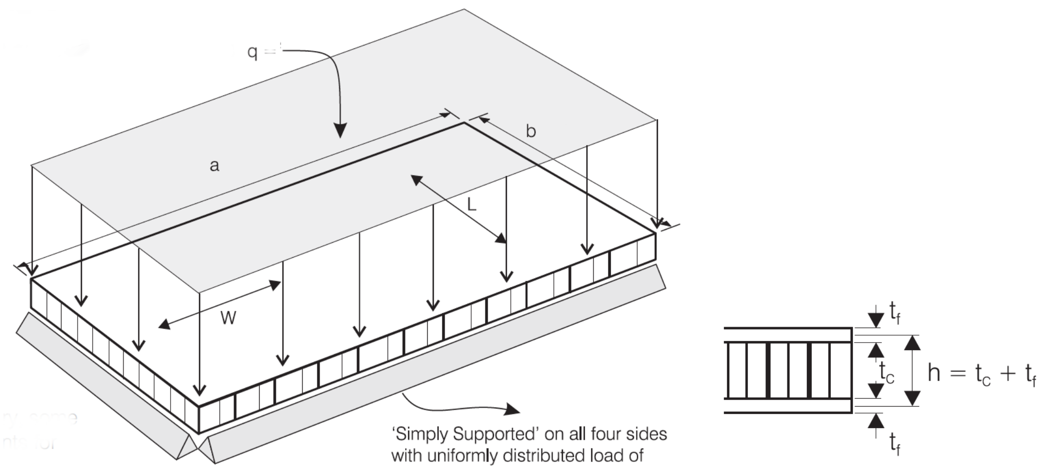


Figure 9.4: Input for mechanical analysis.
Source: Hexcell

Conditions

Loading conditions	Uniform distributed load	1.03 kN/m = 1.03 / 1.3 = 0.79 kN/m2
Boundary conditions		
	simply supported	on all four sides
Physical constraints		According to NEN 2608:
	deflection limit, side	span / 200 1300 / 200 = 6.5 mm
	deflection limit, center	According to NEN 2608: ldiameter / 65 1839.5 / 65 = 28.3 mm
	thickness limit	none
	weight limit	as little as possible

Geometry

Skin material	Aluminosilicate glass	
Skin thickness	The thinnest Leoflex type available	0.55 mm
Core material	Aramid	core with lowest density, HRH10 Nomex (Aramid) 29-3
Core thickness	The minimum thickness that is required for acceptable insulation value	12 mm

Preliminary results

Deflection

$\delta = 2\ K1\ \ q\ b^4\ \lambda\ /\ Ef\ tf\ h^2$

$K1 = 0.005$

$\delta = 2 \times 0.005 \times 790 \times 1.3^4 \times 0.95 / 74000000000 \times 0.00055 \times 0.01255^2$

$\delta = 3.33$ mm

The calculated deflection is considerably less than the maximum allowed deflection, which is 28.3 mm in the center of the panel, thus giving a factor of safety of 11.

Facing Stress

$\sigma f = K2\ q\ b^2\ /\ ht$

$K2 = 0.05$

$\sigma f = 0.05 \times 790 \times 1.3^2 / 0.01255 \times 0.00055$

$\sigma f = 7.44$ Mpa

The calculated stress is much less than the skin material typical yield strength of 260 MPa. This means that the skin material could be dimensioned even thinner.

Core shear

$\tau c = K3\ q\ b\ /\ h$

$K3 = 0.35$

$\tau c = 0.35 \times 790 \times 1.3 / 0.01255$ [Pa]

$\tau c = 0.03$ Mpa

So calculated core shear is considerably less than the core material shear value in W direction of 0.35 MPa, thus giving a factor of safety of 10.

Local Compression

$\sigma c = P/A = q \times A\ /\ A$

$\sigma c = 790 \times (1.3 \times 1.3) / (1.3 \times 1.3)$ [Pa]

$\sigma c = 0.00079$ Mpa

Local compression would not be an issue, being very small in comparison to typical core compression strength of 0.9 MPa.

Further exploration
By doing manual calculations, it seems like the dimensions of the sandwich panel and its layers are more than sufficient for the case study. For a more accurate analysis of a structure, a technique such as Finite Element Method (FEM) might be used.

9.6 Computational calculations
FEM is a computer based method of simulating/analyzing the behavior of structures and components under a variety of conditions. FEM subdivides a large structure into smaller, simpler, parts, called finite elements. It is an advanced engineering tool that can be used to replace experimental testing and augment design decisions. In this chapter, it is used to optimize the geometry of the panel.

General information
To do this analysis, first the geometry of the panel, that is to be tested, is modelled in either ANSYS Geometry or Rhinoceros 5.0. Attempts to model the individual cells of the honeycomb should be avoided for engineering analyses (Hexweb, 200). A laminated plate can be calculated, in that case, this way, it would be possible to obtain reasonable results.
Than this geometry should be imported in the FEM-analysis program ANSYS 17.2. In the first study, results from FE models are to be compared with manual calculations in order to check if the results are in the right order of magnitude, this validates the FE results (Zenkert, 1993).

Input
In ANSYS, first the geometry should be imported. Than this material properties should be inputted, before it can be assigned to the geometry. For a, layered, sandwich construction the material of both glass and the core should be inputted in the program. When defining the properties of a honeycomb core the following points should be taken into consideration (Zenkert, 1993):

EX » EY » 0
mxy » mxz » myz » 0
Gxy » 0
Gxz = GL = shear modulus in ribbon (L) direction
Gyz = GW = shear modulus in transverse (W) direction
EZ = EC = compressive modulus of core material

These are the inputted material properties:

Core	Density	29	kg/m3
	Youngs modulus x direction	1	MPa
	Youngs modulus y direction	1	MPa
	Youngs modulus z direction	60	MPa
	Poisson ratio XY	0.49	-
	Poisson ratio YZ	0	-
	Poisson ratio XZ	0	-
	Shear modulus XY	0	MPa
	Shear modulus YZ	17	MPa
	Shear modulus XZ	25	MPa
	Tensile x direction	0	MPa
	Tensile y direction	0	MPa
	Tensile z direction	5.31	MPa
	Compressive x direction	0	MPa
	Compressive y direction	0	MPa
	Compressive z direction	-0.9	MPa
	Shear strength XY	0	MPa
	Shear strength YZ	0.5	MPa
	Shear strength XZ	0.35	MPa
Glass	Density	2.48	g/cm3
	Young's modulus	74000	MPa
	Poisson's ratio	0.23	-

In ANSYS Mechanical the thickness of each layer can be assigned. Like in the manual calculations, the thickness of the face sheets is 0.55 mm and the thickness of the core is 12 mm, which follows from the heat transfer analysis.

After running the analysis, the desired output can be selected. Like in the manual calculation the deflection, facing stress and core shear are important to calculate. In ANSYS, these terms mentioned differently. The deflection is called, total deformation, in ANSYS. The facing stress is the normal stress and the core shear is called shear stress core.

Results preliminary panel design

The total deformation is shown in figure 9.5. It shows the direction of the deflection as well as the magnitude. The maximum deflection, in the center of the panel is 3.45 mm.

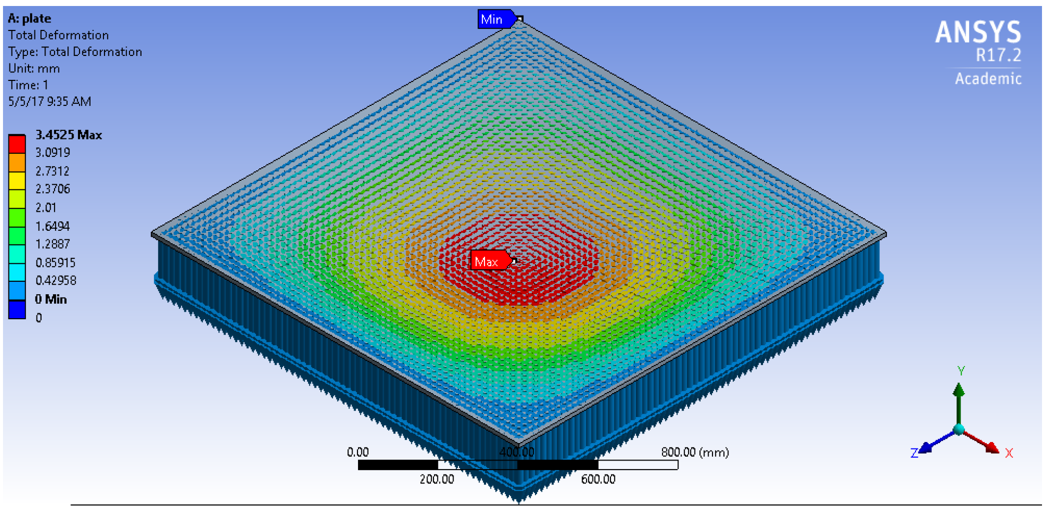


Figure 9.5. Result ANSYS calculation: deformation.
Source: by author.

From the theoretical research, it can be concluded that the bending stress is also largest at the center of the panel. The due to bending, the top of the panel shows compressive stress and tensile stress on the bottom. The maximum tensile stress is located in the bottom sheet, at the bottom of the sandwich panel, it is 10.26 MPa. This is shown in figure 9.6.

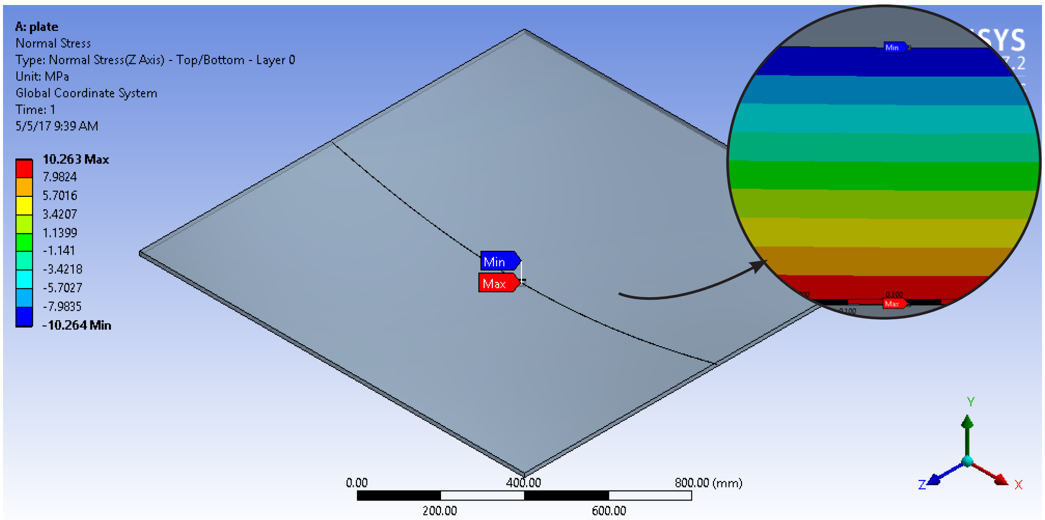


Figure 9.6: Result ANSYS calculation: normal stress.
Source: by author.

In a sandwich panel, the core is subjected to the largest shear stresses. This layer was therefore selected in this analysis. Shear caused by bending forces, is largest at the edges of the panel. The largest shear force is 0.047 MPa. This is shown in figure 9.7.

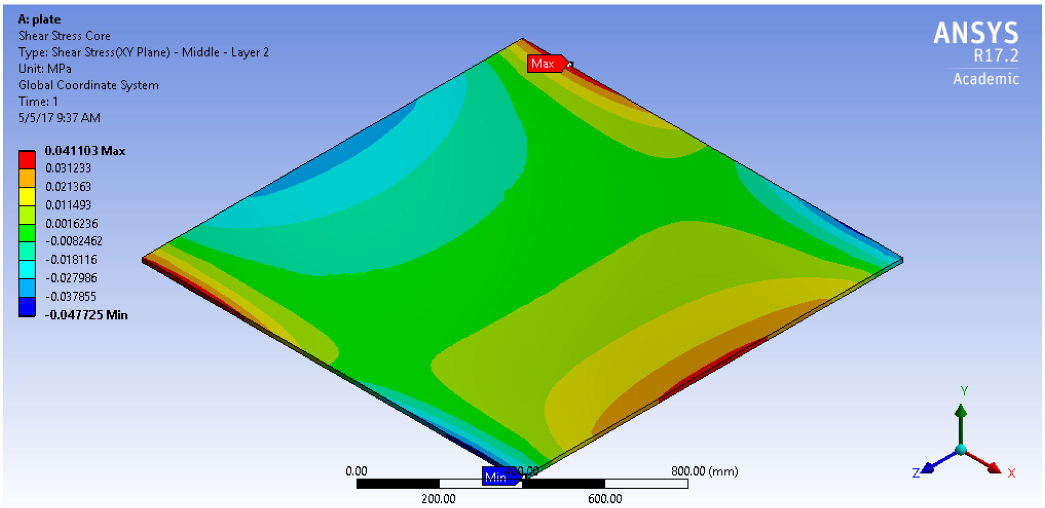


Figure 9.7: Result ANSYS calculation: shear stress.
Source: by author.

As mentioned earlier, these results need to be compared to the manual calculations to validate if the FE-results are trustworthy. If so, the results should be in the same order of magnitude. The results are compared in table 9.2.

	Allowed values		Computational calculation	Manual calculation
Deflection center	28.3	mm	3.45	3.33
Normal stress	260	MPa	10.26	7.44
Shear stress	0.35	MPa	0.04	0.03
Weight	-	kg		5.2

Table 9.2: Comparison results manual- and computational calculation.
Source: by author.

It can be concluded that the FE-analysis is a reliable method, all results are in the same order of magnitude. The computational results are a bit higher, possibly this can be explained by the weight. In the computational results, the weight of the geometry is automatically added as a load.

When comparing the results to the allowed values, it clearly shows that the geometry is over-dimensioned. The allowed deflection is almost 10 times larger than the calculated deflection.

Optimization

Since the calculated panel is largely over-dimensioned, optimization should be done. Especially because, in this project, lightness is an important design criteria. The less the total weight, the better.

The thickness of the core cannot be changed because it is required for thermal insulation, so only the glass thickness can be adjusted. This is convenient because the glass is the heaviest part of the construction. In ANSYS, several glass thicknesses are tested the results are shown in table 9.3.

Demands			Glass thickness 0.025 mm	Glass thickness 0.06 mm
Deflection center	28.3	mm	83.9	26.6
Normal stress	260	MPa	257	80.9
Shear stress	0.35	MPa	0.25	0.14
Weight	-	kg	0.7557	1.09

Table 9.3. Results optimization by computational calculations.
Source: by author.

Breakage of the glass wil occur at a normal stress of 260 MPa. With a wind load of 0.79 kN/m2 and the panel's own weight, this amount of stress will be reached with a glass thickness of 0.025 mm. With this thickness, the weight of the panel will only be 0.8 kg, but the occuring deflection exceeds the allowed amount. This means that the glass thickness should be increased.
With a glass thickness of 0.06 mm, the sandwich panel would weigh 1.09 kg. The allowed deflection is not exceeded and the amount of both normal- and shear stress is acceptable. For the stresses, a safety factor of 3 for normal stress, and 2,5 for shear stress is included. This means that the glass will not easily break, and the core will remain intact and attached to the face sheets.

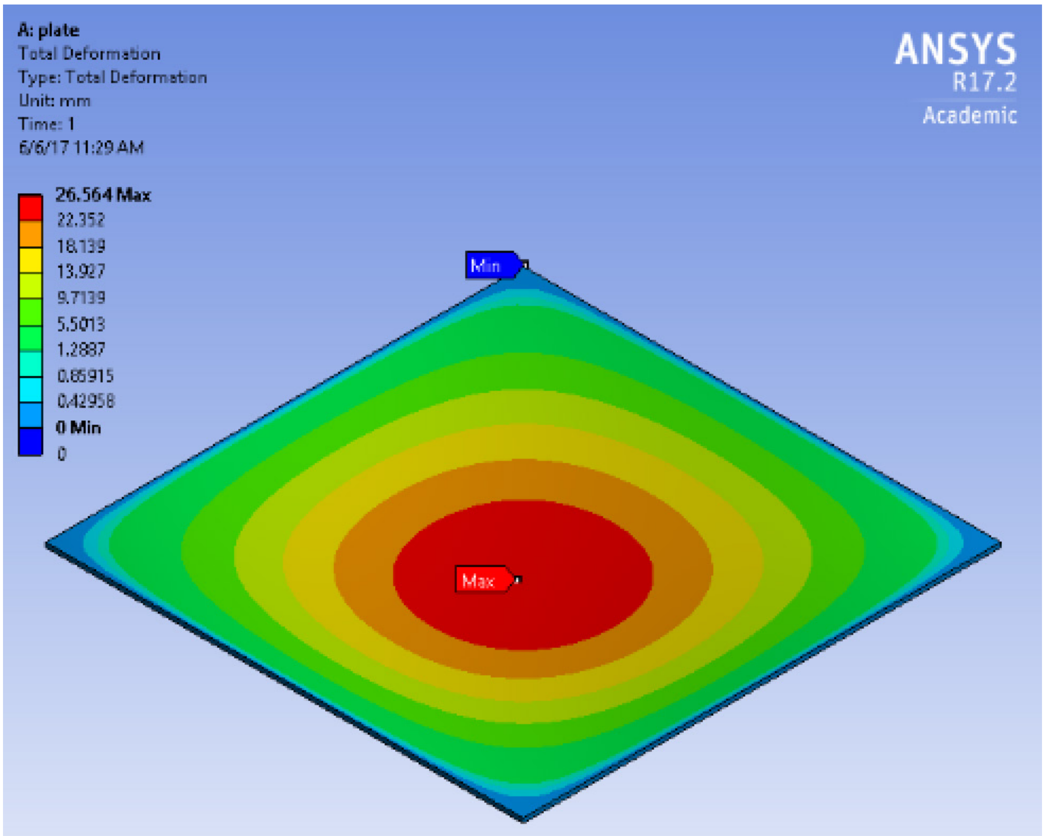


Figure 9.8. Result ANSYS calculation: deformation.
Source: by author.

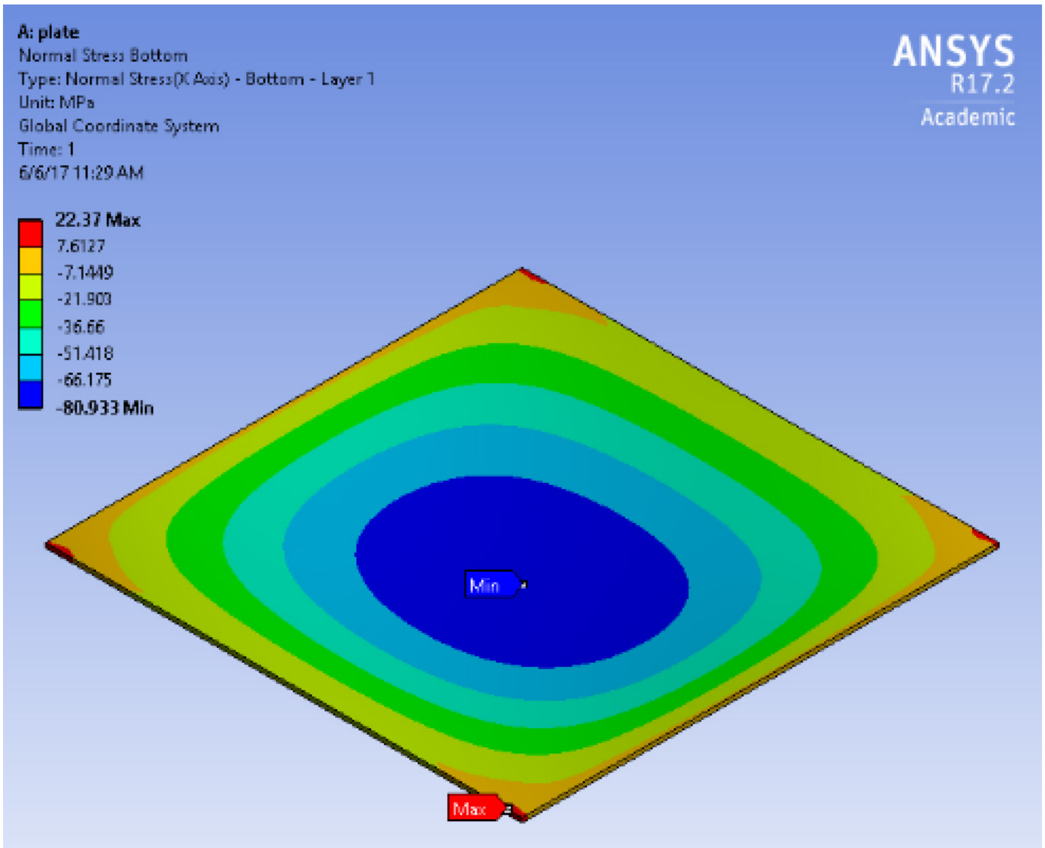


Figure 9.9: Result ANSYS calculation: normal stress.
Source: by author.

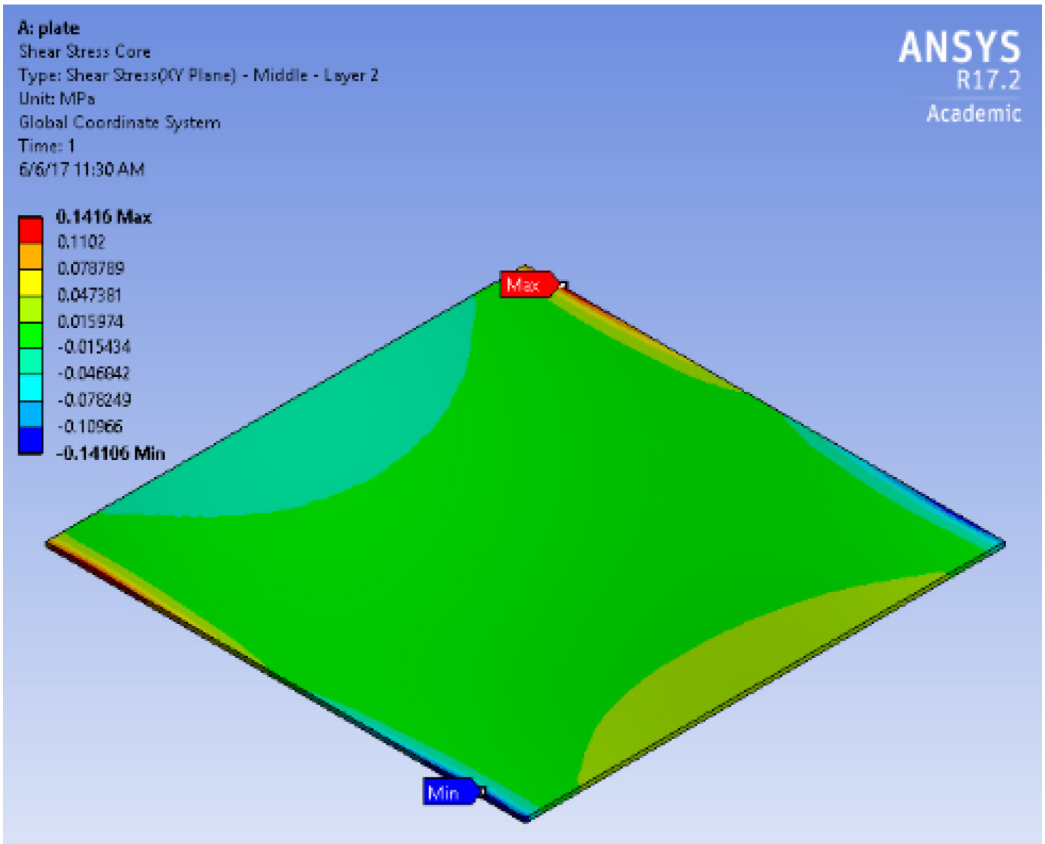


Figure 9.10: Result ANSYS calculation: shear stress.
Source: by author.

Panel design

After selecting the core material, calculating its thickness and optimizing the glass thickness, the configuration of the panel is completed.

The selected core is aramid, with a cell size of 3.2 mm and a thickness of 12 mm. Combined with chemically strenghtened aluminosilicate glass face sheets of 0.06 mm thick, an ultra lightweight panel can be made which is according to the design criteria. This panel configuration (figure 9.11) is optimized for the specific windload, a 4 sided support and the size of the selected case study.

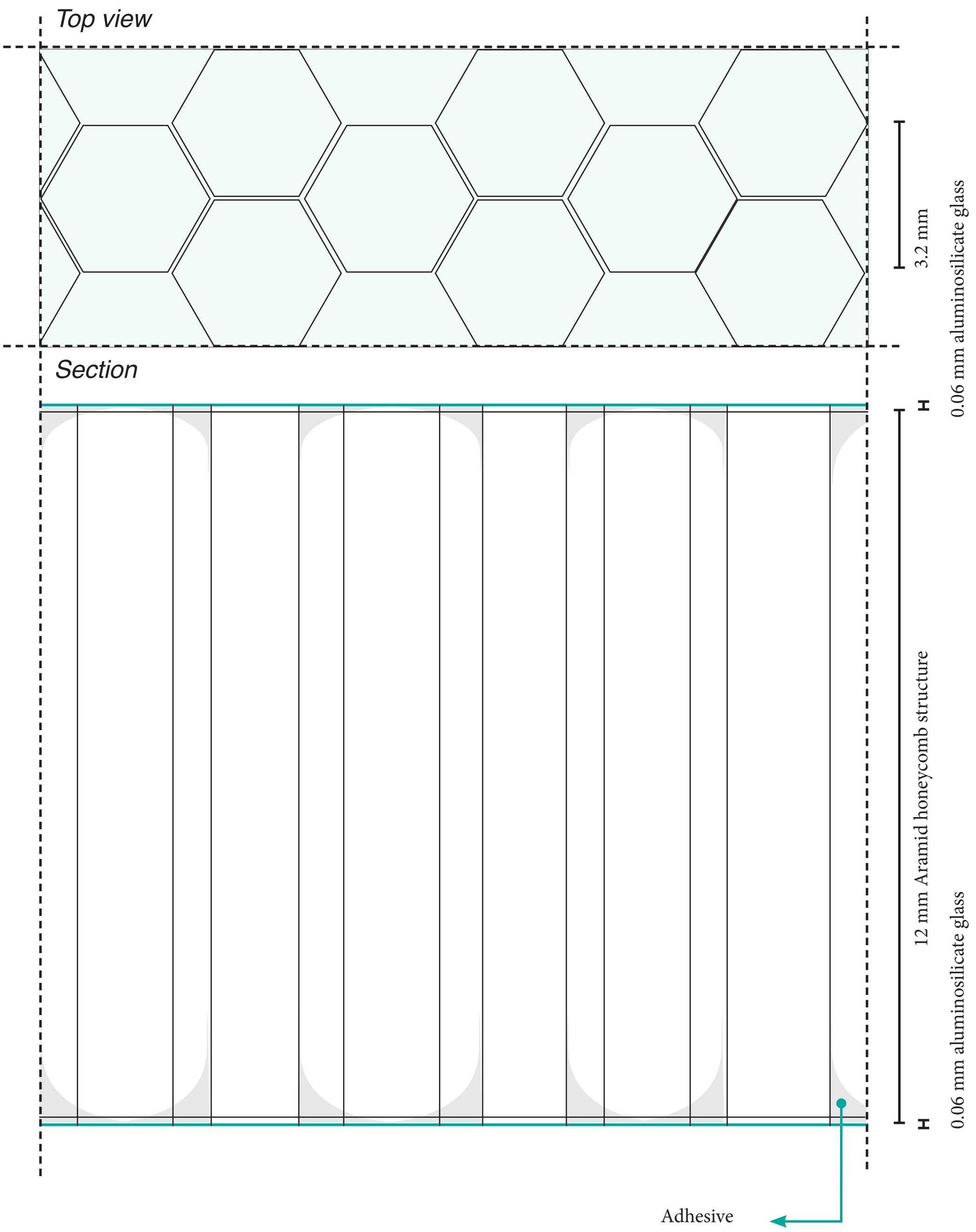


Figure 9.11: Top view and section of the final panel design.
Source: by author.

9.7 Possible configurations

In the previous paragraph, the panel was supported on all edges. But the panel could also be applied in other curtain wall configurations. Besides the regular aluminum curtain wall system, also cable truss and cable net constructions can be used. The supports are different with each facade construction, figure 9.12 shows the possibilities and their corresponding deflection

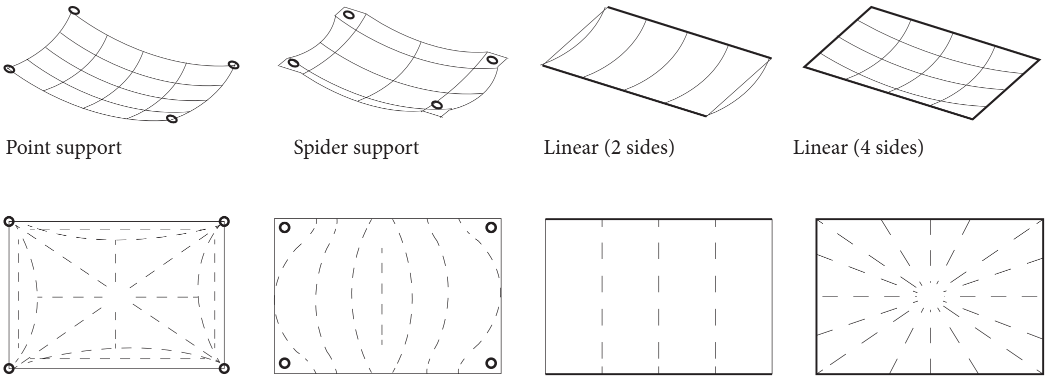


Figure 9.12: Possible configurations and their deflection behaviour and stress distribution.
Source: C. Schittich.

behavior. It shows that the spider-, and point supports deflect much more than the linear supports. They would require a larger glass thickness in order to comply with the NEN 2608 regulation. As the linear, 4 sides support is already studied in the previous paragraph, point- , spider- and 2 sided linear supports will be evaluated.

Point support

The analysis started with the 4 point supported panel (1.3 x 1.3 m) configuration of 0.06 mm glass thickness. After running an analysis in ANSYS, it showed that the allowed stresses as well as the deflection were exceeded in this configuration (table 9.13).

Point support	Allowed					
Thickness top sheet		mm	0.06	0.1	0.1	0.55
Thickness core		mm	12	12	15	12
Thickness bottom sheet		mm	0.06	0.1	0.1	0.55
Normal stress	260	MPa	277	172	143	38.4
Shear stress	0.35	MPa	2.2	2.2	1.8	2.2
Deflection center	28.3	mm	179	109	70.9	19.6
Weight	-	kg	1.09	1.43	1.57	6.2
Conclusion:			not sufficient	not sufficient	not sufficient, a different core type must be chosen	sufficient when core HRH10 80(5.0) is selected

Figure 9.13: Optimization of 4 point supported thin glass sandwich panel.
Source: ANSYS

With a thickness of 0.06 mm for both top- and bottom sheet (analysis 1), the normal stress, shear stress and the deflection exceed the allowed amount. This means that both ULS (ultimate limit state) and SLS (servicibility limit state) are exceeded. The panel will deflect too much, the core due to the large shear stress and the glass will fail.

When a glass thickness of 0.1 mm is used (analysis 2), the glass will not break, the ULS is no longer exceeded. However, the SLS and the allowed amount of shear stress is. This means the core will fail.

To check if increasing the core thickness decreases the shear stress, a panel is analysed with a core thickness of 15 mm and face sheets of 0.1 mm (analysis 3). From 2.2 MPa, the shear stress decreased to 1.8 MPa. However, this is still far from succient (0.35 MPa). Therefore another core should be selected.

The aramid honeycomb core that can withstand 2.2 MPa, was choosen for the final analysis (4): HRH 10 80(5.0) with a thickness of 12 mm. Also the face sheets should be thickner in order to have an acceptable amount of deflection. A thickness of 0.55 on both top and bottom is choosen. The results are acceptable for ULS, SLS and shear, the panel weighs 6.2 kg. The results of this ANSYS analysis is shown in figure 9.13, 9.14 and 9.15.

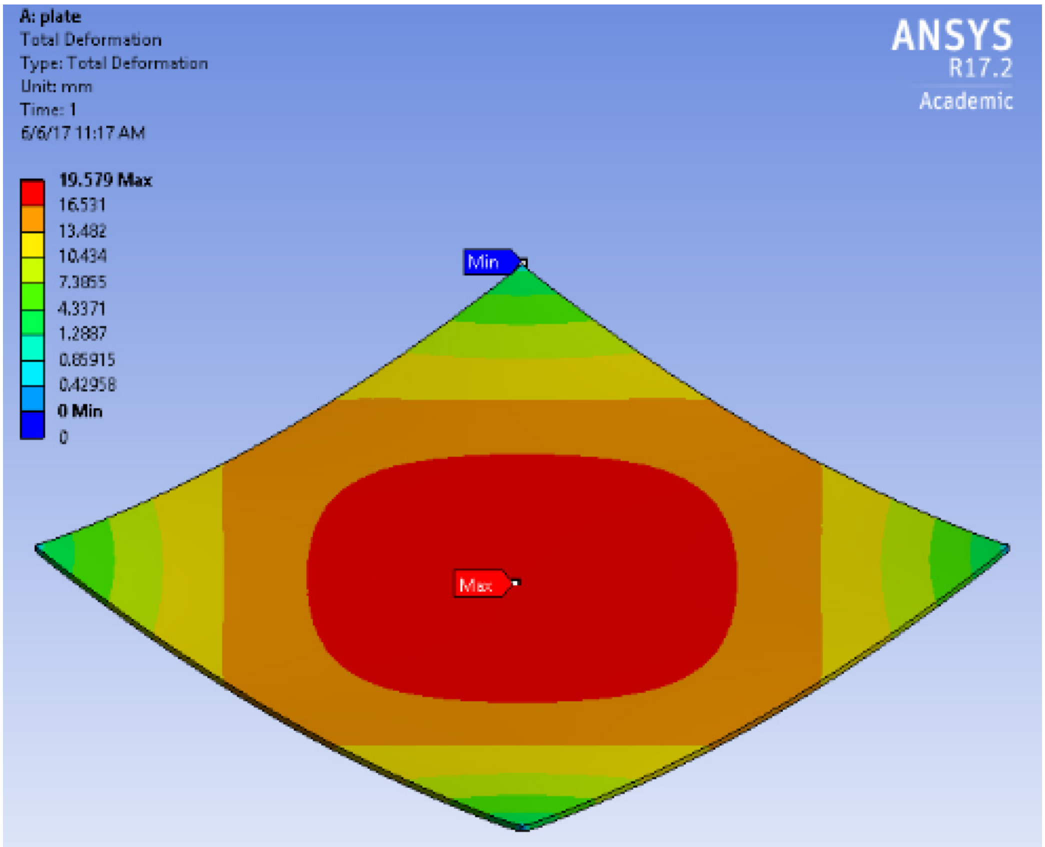
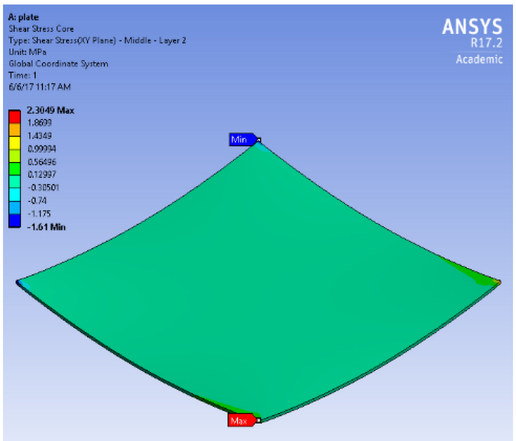


Figure 9.13. Result ANSYS calculation point support: deflection.
Source: Own image.



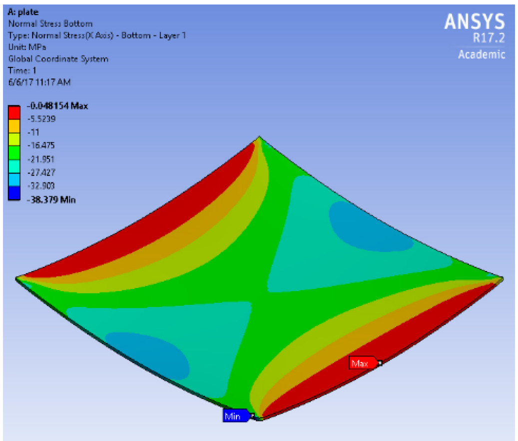


Figure 9.14 (right): Result ANSYS calculation point support: normal stress.
Source: by author.

Figure 9.15 (left): Result ANSYS calculation point support: shear stress.
Source: by author.

Spider support

For the configuration in which spiders support the facade panel, again the 0.06 mm panel configuration was the starting point of this optimization. The ULS, SLS and the allowed shear stress are exceeded.

Spider	Allowed				
Thickness top sheet		mm	0.06	0.55	0.55
Thickness core		mm	12	12	12
Thickness bottom sheet		mm	0.06	0.55	0.55
Normal stress	260	MPa	507	23.7	25.9
Shear stress	0.35	MPa	3.7	0.9	1.16
Deflection center	28.3	mm	99.1	13.2	12.4
Weight	-	kg	1.09	5.19	5.58
Conclusion:			not sufficient	not sufficient, a different core type must be chosen	sufficient when core HRH10 48(3.0) is selected

Table 9.5. Optimization of a spider supported thin glass sandwich panel.
Source: ANSYS

The first optimization is done with an increased glass thickness of 0.55 mm (table 9.5). This results in an acceptable SLS and ULS. However the allowed shear stress is exceeded therefore another aramid core should be selected. The HRH10 48(3.0) can withstand a shear force of 1.3 MPa(Hexcell, 2000) In the final analysis, this core is used. With a weight of 5.58, it is sufficient for the deflection, shear- and normal stress.

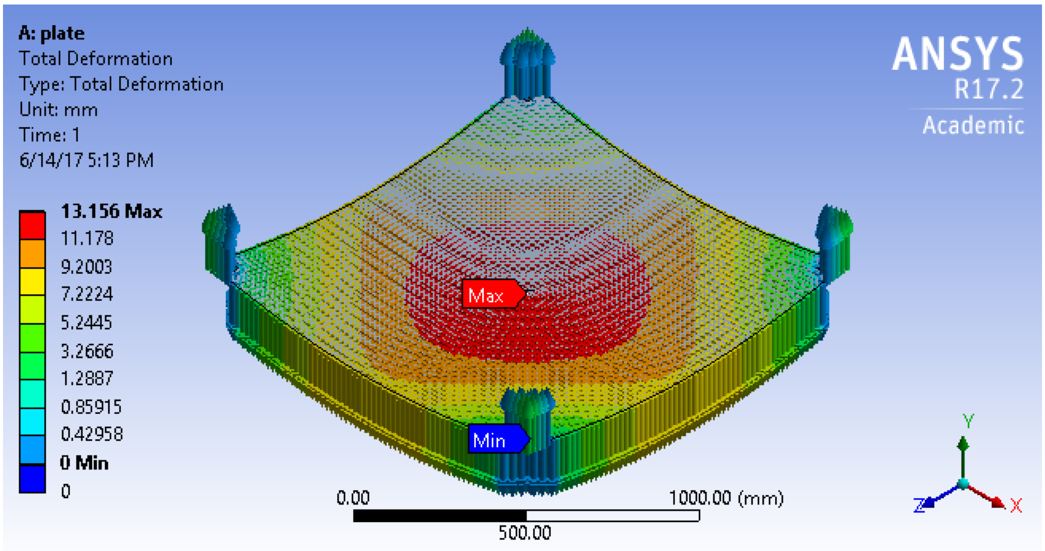
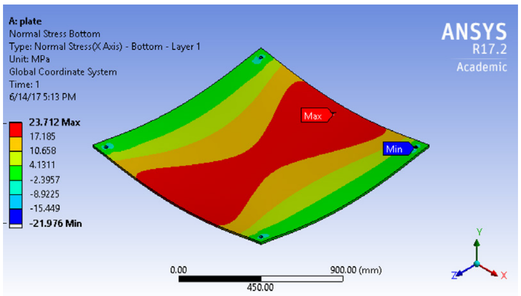


Figure 9.16: Result ANSYS calculation spider support: deflection.
Source: by author.



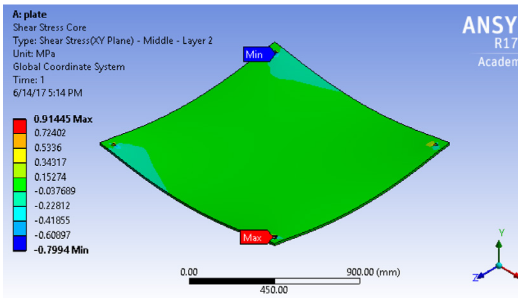


Figure 9.17 (left): Result ANSYS calculation spider support: normal stress.
Source: by author.

Figure 9.18 (right): Result ANSYS calculation spider support: shear stress.
Source: by author.

Linear support (2 sides)

Another analysis is done for the panel supported on only two of its edges (table 9.6).

Linear (2 supports)	Allowed				
Thickness top sheet		mm	0.06	0.1	0.1
Thickness core		mm	12	12	12
Thickness bottom sheet		mm	0.06	0.1	0.55
Normal stress	260	MPa	220.8	21.7	38.6
Shear stress	0.35	MPa	0.16	0.14	0.08
Deflection center	28.3	mm	88.9	57	21.1
Weight	-	kg	1.09	1.43	3.31
Conclusion:			not sufficient	not sufficient	sufficient

Table 9.6. Optimization of 2 edges supported thin glass sandwich panel.
Source: ANSYS

First the initial 0.06 mm configuration is tested. It resulted in too much deflection, the normal- and shear stress however were sufficient. Therefore, a thickness of 0.1 mm was analyzed. Its deflection exceeded the ULS, so a thickness of 0.55 was used for the bottom sheet in the final calculation. This configuration was sufficient, it weighs 3.31 kg.

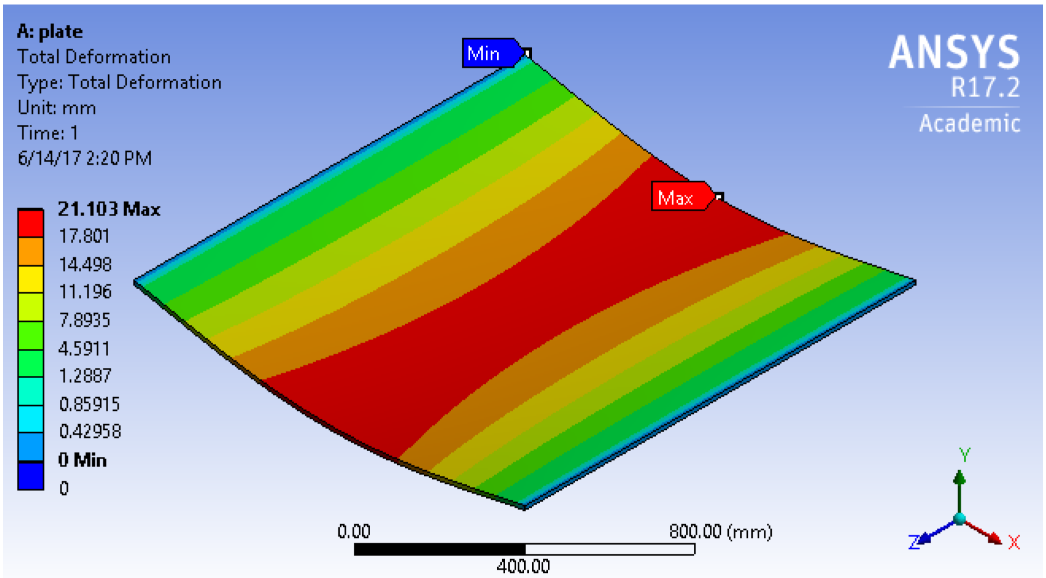
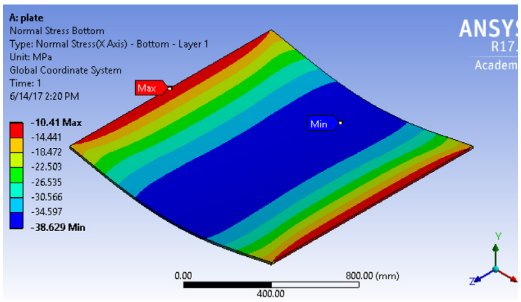


Figure 9.19: Result ANSYS calculation spider support: deflection.
Source: by author.



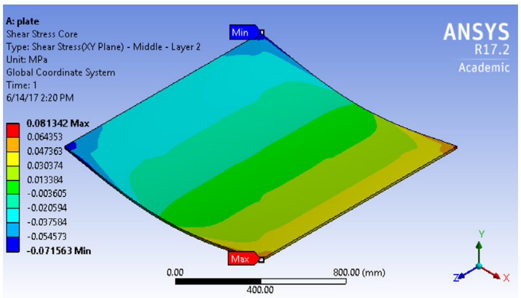


Figure 9.20 (left): Result ANSYS calculation two edge support: normal stress.
Source: by author.

Figure 9.21 (right): Result ANSYS calculation two edge support: shear stress.
Source: by author.

9.10 Panel detailing
The variety in panel configurations are derived from several possible facade designs namely: an aluminum curtain wall system supporting all edges, a system which supports only two edges, a cable truss construction with spider supports and a cable net constructions that supports each corner of the panel. All result in different detailing.

The detailing of the facade panel is based on two aspects. First, the established connection options of honeycomb sandwich panels according to Plascore (2008). And secondly, the input from the theoretical glass research. Finally the lightness concept should be considered when detailing.

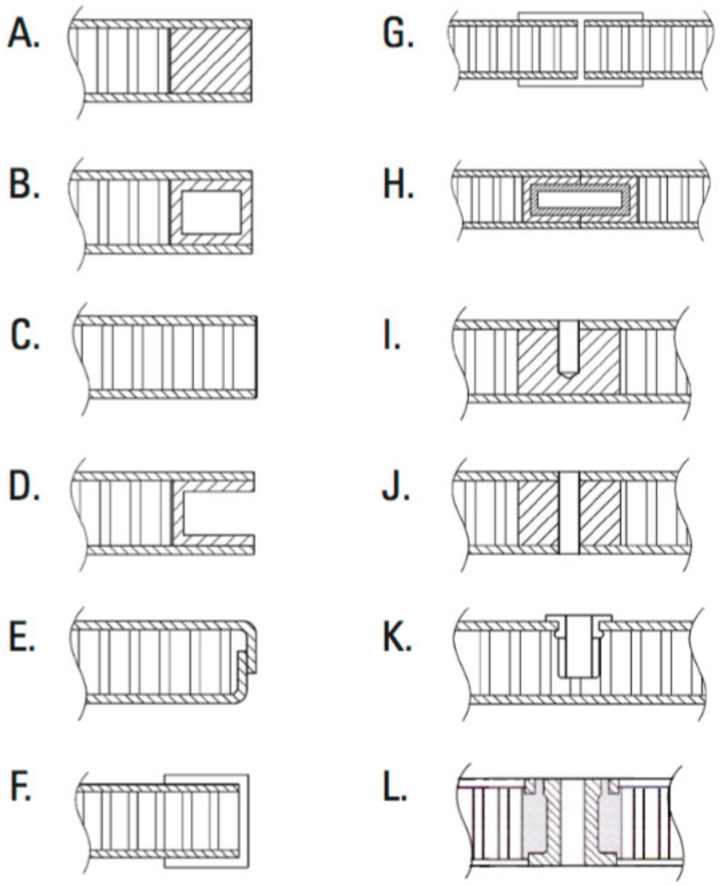


Figure 9.22: Panel edge and insert design concepts.
Source: Plascore

Honeycomb edge connections
In figure 9.22, many different panel edge- and insert design concepts are shown. Some of the edges can be co-fabricated, others are post-fabricated edge closeouts. Connections inbetween panels can be made by blind fastening, thru fastening or other panel considerations.
- The co-fabricated edge closeouts are: Solid (A), tube (B), channel (D), formed (E)
- The post-fabricated edge closeouts are: Solid (A), tube (B), channel (D & F), formed (E).
- Blind fastening: Potted insert (I & L), Rivnut (K)
- Thru Fastening: (J)
- Other panel considerations are: External (G), Internal (H), Internal honeycomb section

Theoretical requirements
In the theoretical glass research, it is concluded that the edges of the glass are the most vulnerable to damage. If an edge becomes damaged, the entire sheet can easily scatter. Hence, they should be protected especially during transport.
Another aspact that should be taken into account is heat transfer, the connecting piece cannot be creating a thermal bridge between the inner- and outer climate.
The selected core material is aramid-paper. This paper is coated with a phenolic resin, which provides heat resistance and moisture protection. It should, however, be avoided to create condensation within the panel. Especially the edges must be protected from moisture, often at the

cut resin is not applied which could cause moisture to go into the rest of the core by the cappilary effect of paper. Besides from effect of moisture, the edges of the core are most vulnerable to external forces. From the edge, forces/impact could damage to the core and thus the strength of the panel. For all details, water- and airtightness should be achieved, and of course the architectural concept, lightness, should be considered.

Linear support (4 sides)

This panel combines two 0.06 mm glass sheets and a 12 mm aramid core. Because the aluminum frame surrounds the panel in this configuration, the water- and air tightness, as well as the glass protection can be integrated in the aluminum frame. As an example, a standard aluminum frame (from the company Reynaers) has been used as a base for the design. It is a frame which can be assembled on site by a 'clicking' mechanism. Their original profile design is attached (appendix 5). The profile has been slightly adjusted to meet the requirements, figure 9.24.

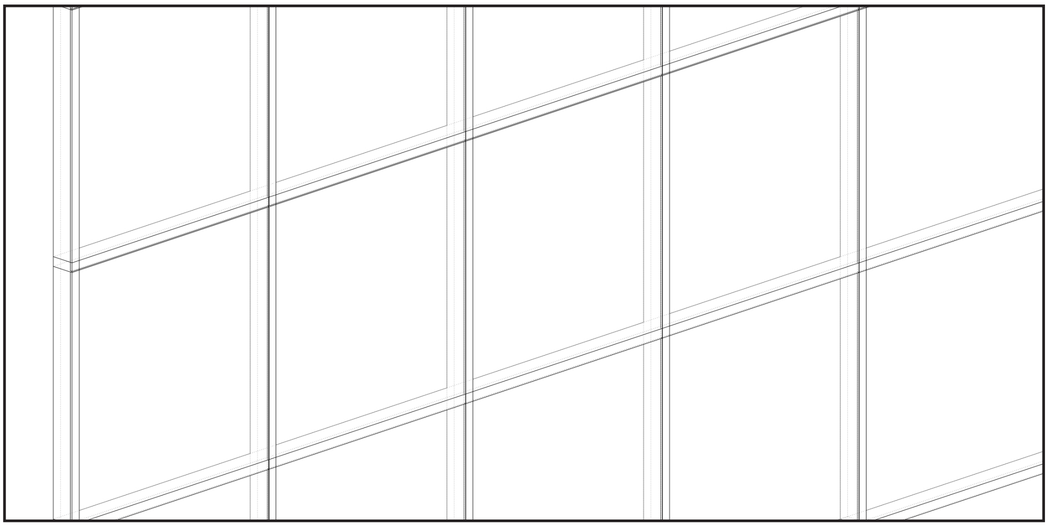


Figure 9.23: Facade concept linear support (4 sides).
Source: by author.

A big advantage of this structural glazing type is how the panels are completely surrounded by the aluminum frame on all sides, also when not assembled, this protects the glass edges during transport (figure 9.25). When all elements have arrived on site, the elements can be clicked together by the rubber inserts.

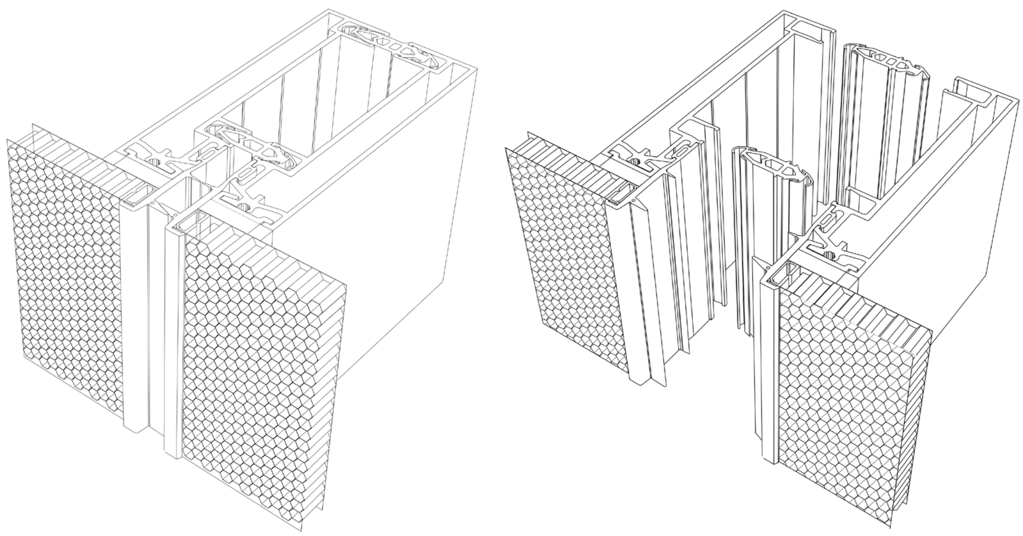


Figure 9.24: Isometric view aluminum structural glazing detail.
Source: by author.

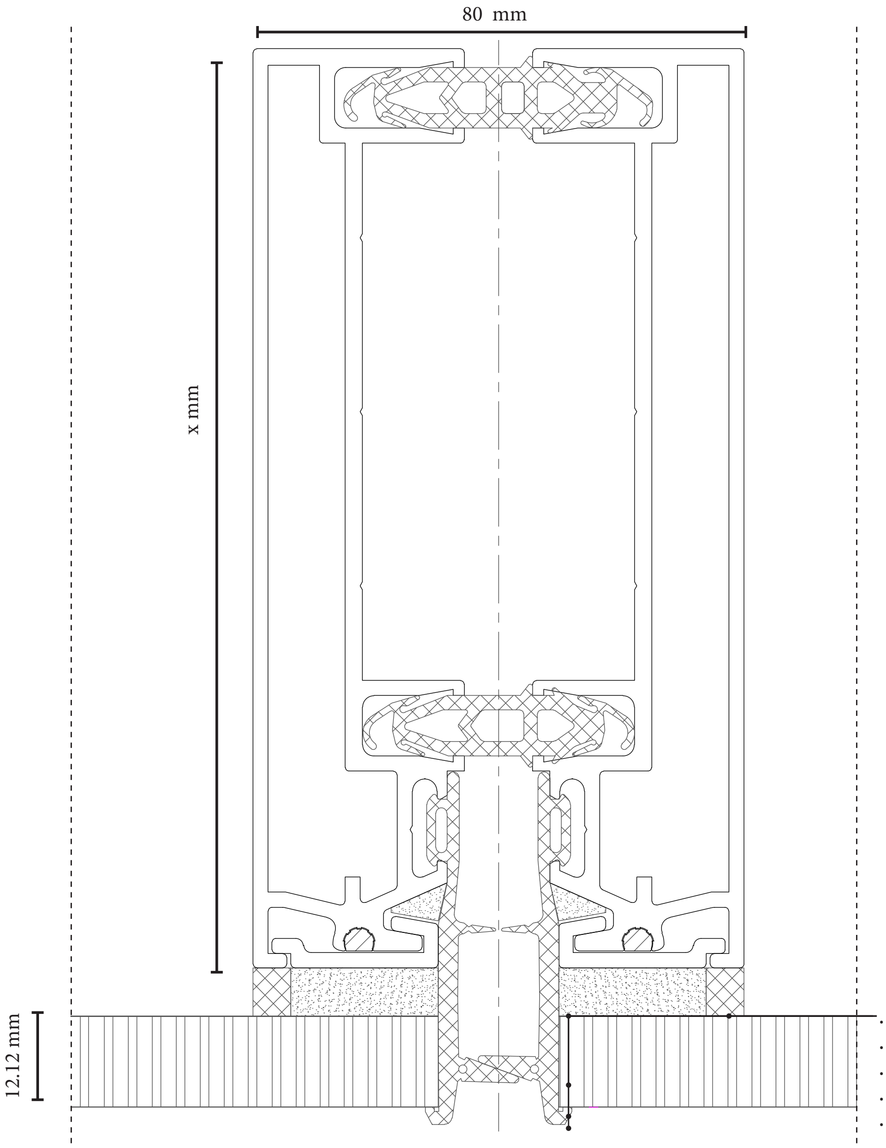


Figure 9.25: 1:1 detail linear support (4 sides)
Source: by author.

Linear support (2 sides)

In comparison to the 4 sides supported panel, this panel consists of a 0.1 and a 0.55 mm glass sheet with a 12 mm core. Since this type of detail does not have an aluminum frame around all its edges, the edge protection should be provided by the an edge insert that has to be designed. In this detail, also thermal breakage, should be taken into account. Therefore an edge has been designed that consists of an aluminum insert inbetween the glass sheets and additional aluminum profiles which click into it, these have to be bonded by a silicon adhesive. This will provide edge protection. Inbetween the secondary profiles, a thermal breakage is applied (figure 9.27).

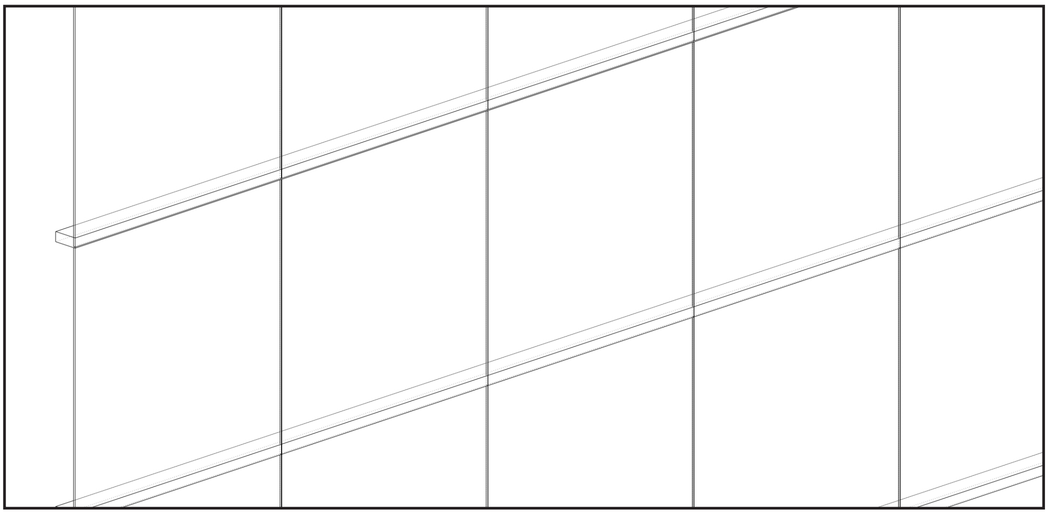


Figure 9.26: Facade concept linear support (2 sides).
Source: by author.

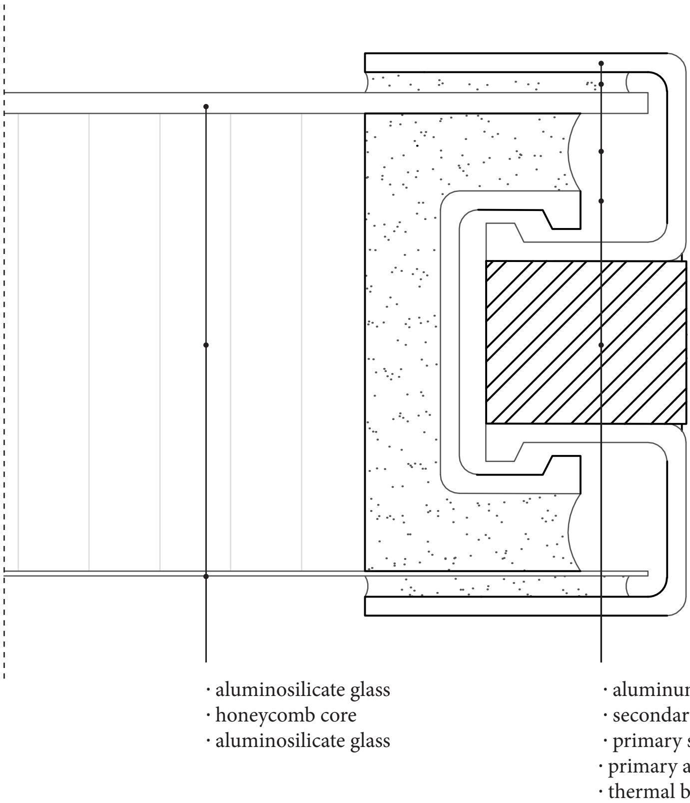


Figure 9.27: Detail 5:1 of edge protection for thin glass sheets.
Source: by author.

The 2 sided linear support results in two different details, one supported and one unsupported. The difference with the linear supported (on all 4 edges) is the previously explained edge.

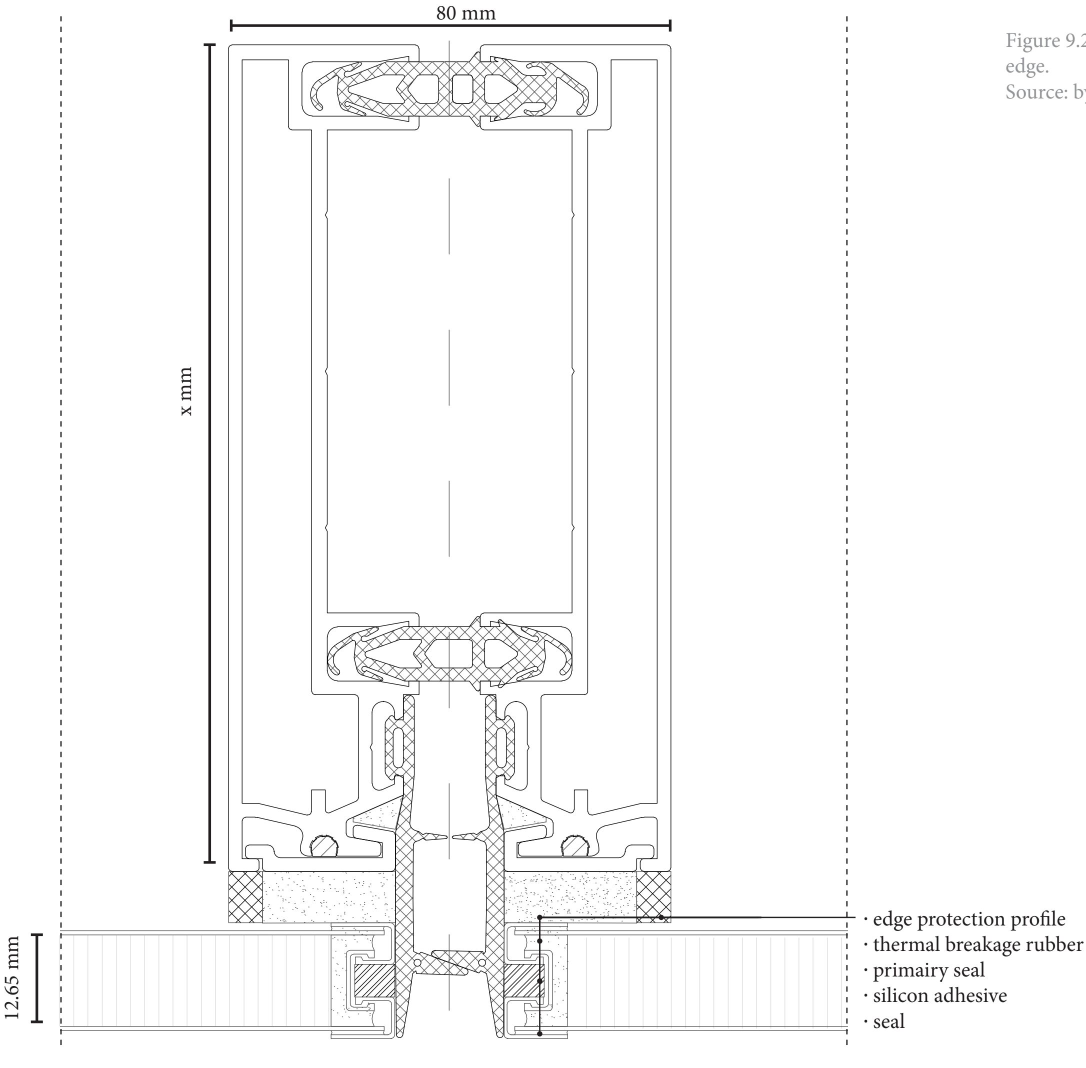


Figure 9.28: 1:1 detail of supported edge.
Source: by author.

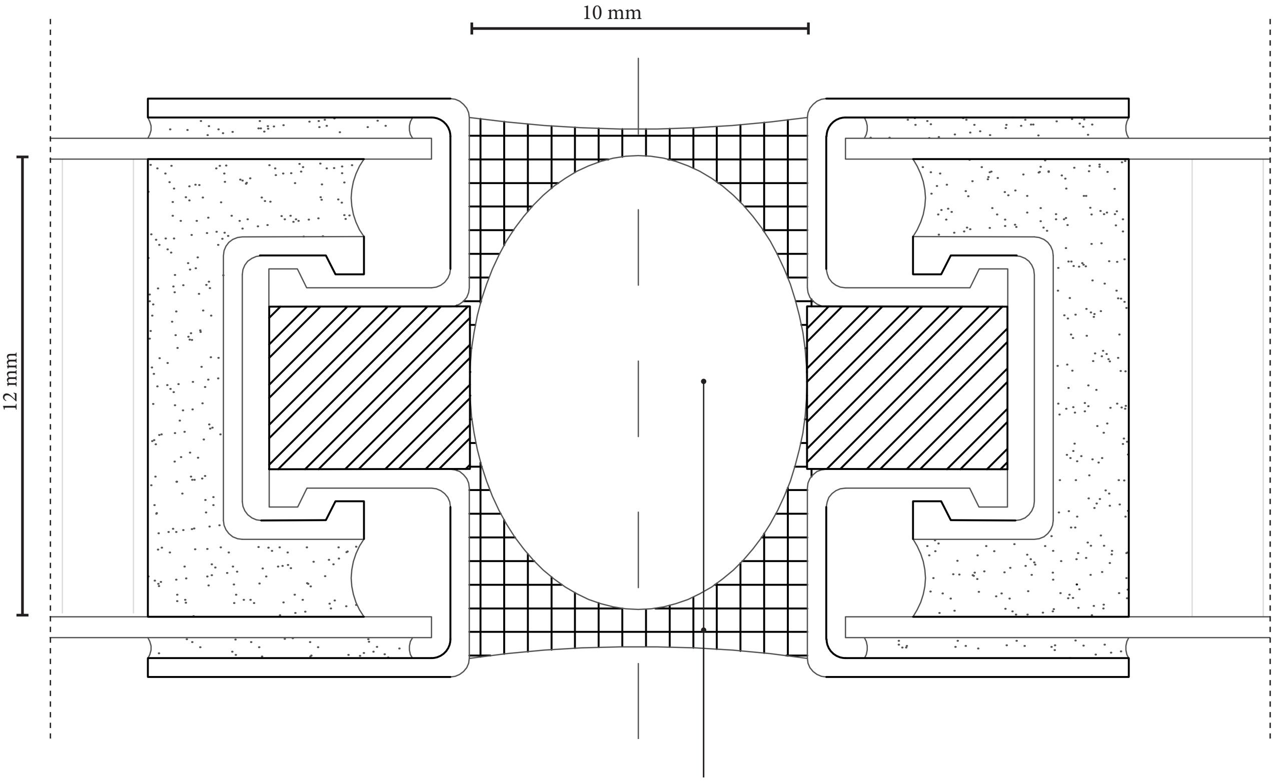


Figure 9.29: Detail 5:1 of unsupported edge.
Source: by author.

Spider support

This sandwich has a glass thickness of 0.55 mm on both sides of the sandwich panel, again the core is 12 mm. Since this type of detail is completely frameless, the edge protection should, again, be provided by an edge insert which also takes thermal breakage into account. In figure 9.31, a 1:1 scale detail is showed which is built with the same panel-to-panel connection as showed in figure 9.29. Inbetween the glass and the spider, a seal should be applied on the surface and around its edges in order to not harm the glass. This detail is inspired by a standard spider detail (appendix 6).

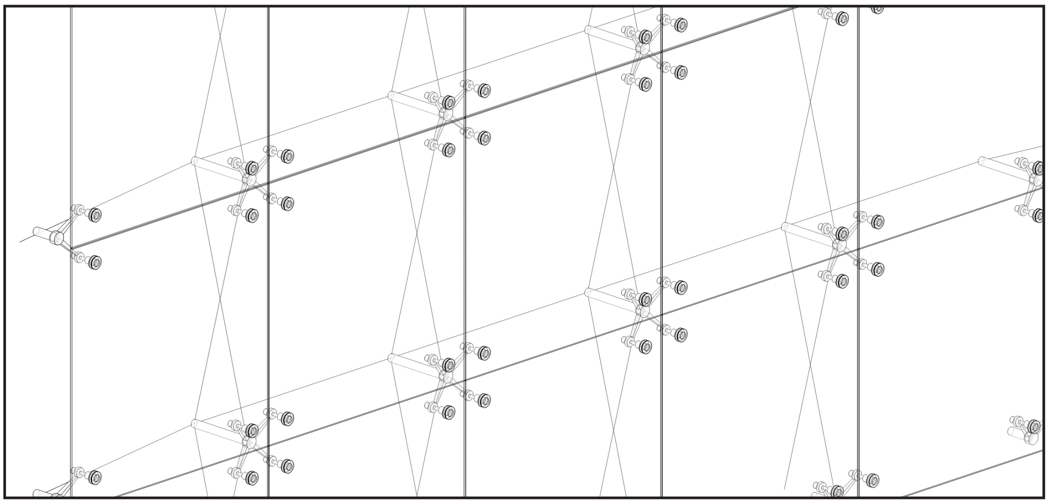


Figure 9.30: Cable truss facade, spider support.
Source: by author.

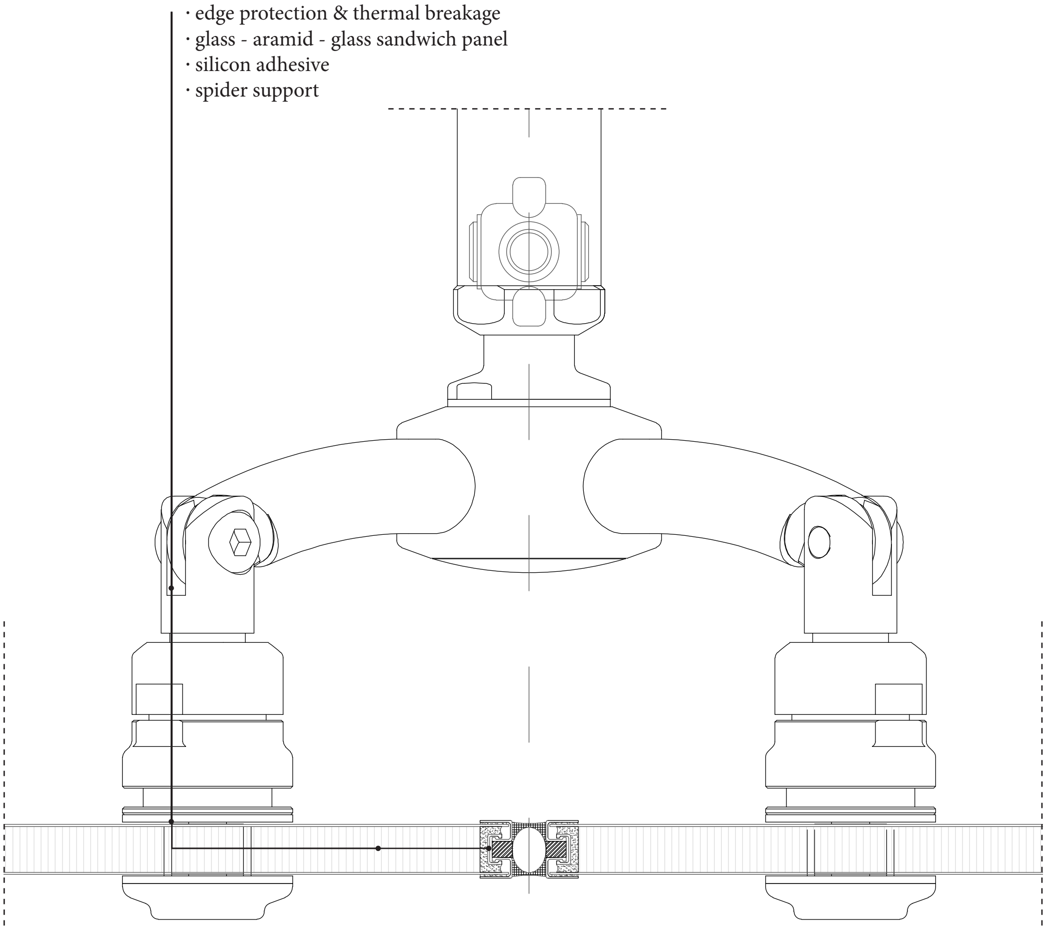


Figure 9.31. 1:2 detail spider support.
Source: by author.

Point support

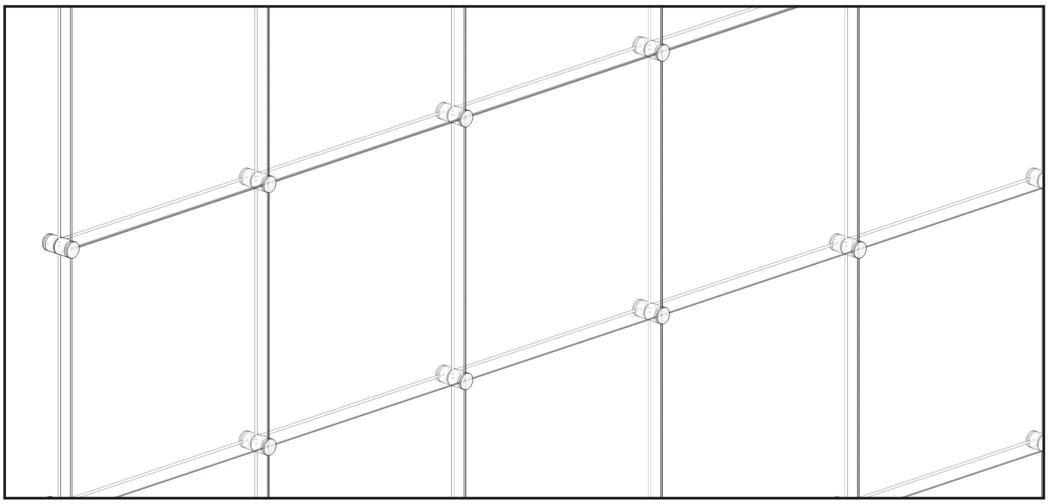


Figure 9.32. Facade concept linear support (2 sides).
Source: by author.

The panel configuration of this connection is the same as with the spider support. Also, the panel to panel connection is the same. The connections, are however a bit different (figure 9.33). This detail is derived from the facade construction of the Markthal, Rotterdam (appendix 7).

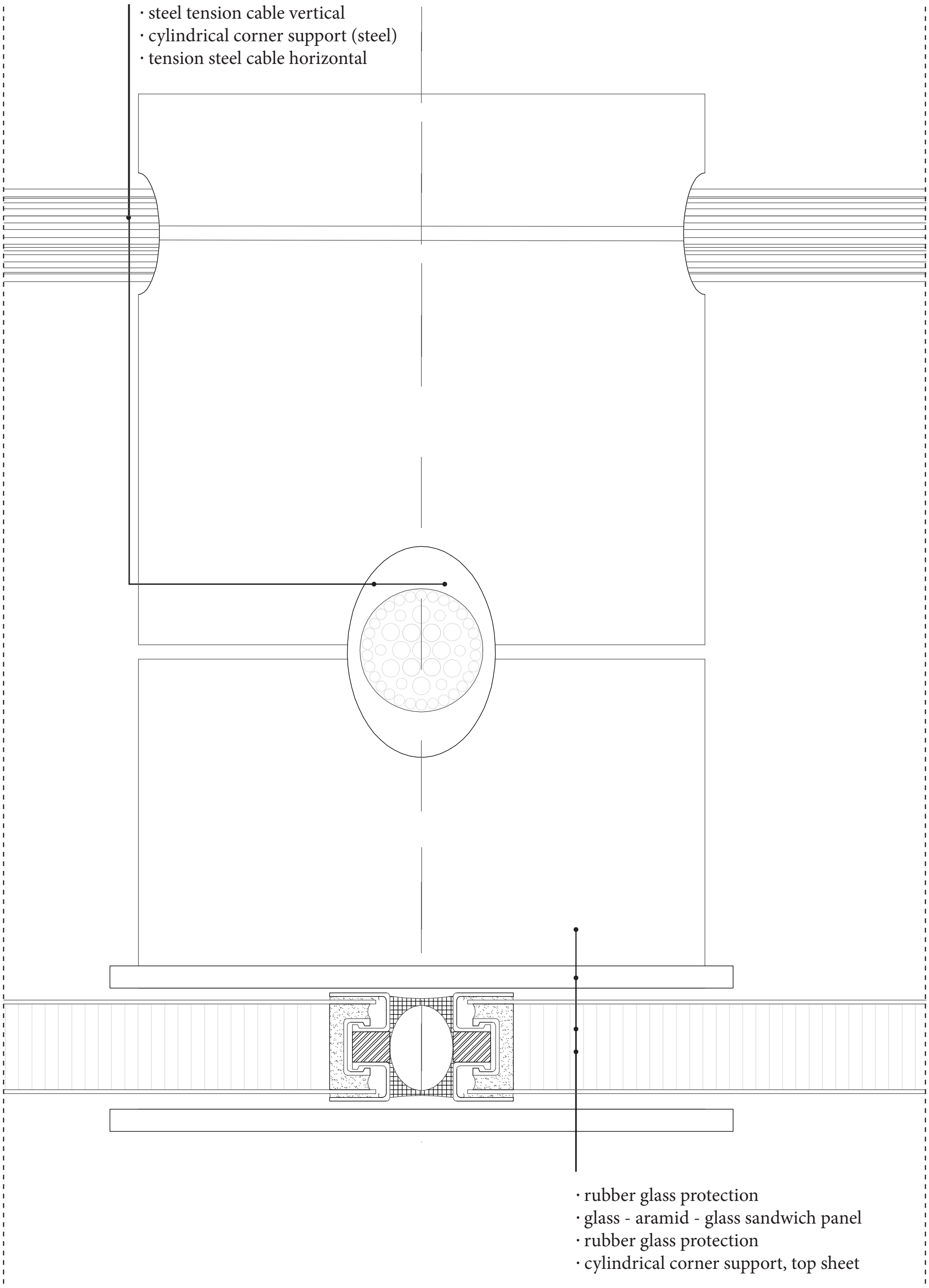


Figure 9.33: 1:1 detail linear support (4 sides)
Source: by author.

10

Facade design

In the initial design stage (chapter 8), it is discovered that a cable truss construction would save quite some weight, compared to the weight of the façade of the case study even without taking the thin glass facade panels into consideration.
By exploring several possible lightweight façade constructions a suitable façade solution should be chosen for the façade of the selected case study. Cable truss and cable net constructions will be analyzed, and their advantages and disadvantages will be evaluated in comparison to the current façade construction of the case study.

Photo: by author

10.1 Precedents

A lightweight facade construction is found in the aforementioned OZ building in Tel Aviv, there a cable truss construction is applied. In the Markthal (Rotterdam) and Hotel Kempinski (Munich), another facade construction is applied, a cable net construction.
To discover if one of these facade construction systems is applicable for the facade of the case study, an elaborated analysis needs to be done.

Cable net construction

An example of a cable net construction is the Markthal, Rotterdam. In this facade, panels are supported on its four edge points. According to Octatube (2017), the enginering company of the Markthal façade, the façade consists of 26 vertical and 22 horizontal cables, which form a suspended net, similar to a tennis racket. They state that one of the technical challenges for the structural facades of the Market Hall, was to deal with the large pre-stress forces that have to be transferred to the concrete arch. The cables are pre-stressed to a maximum of 300 kN each, of which 50 kN is in fact surplus capacity to deal with the consequences of creep in the concrete. The cables are pre-stressed between 60 mm thick steel boxes embedded and cast in the concrete walls.

Figure 10.1: Tension cable net facade, Markthal.
Source: octatube.nl

Directly after pre-stressing the cables, a large tension is created in the surrounding concrete arch, this is clearly shown in figure 10.2.

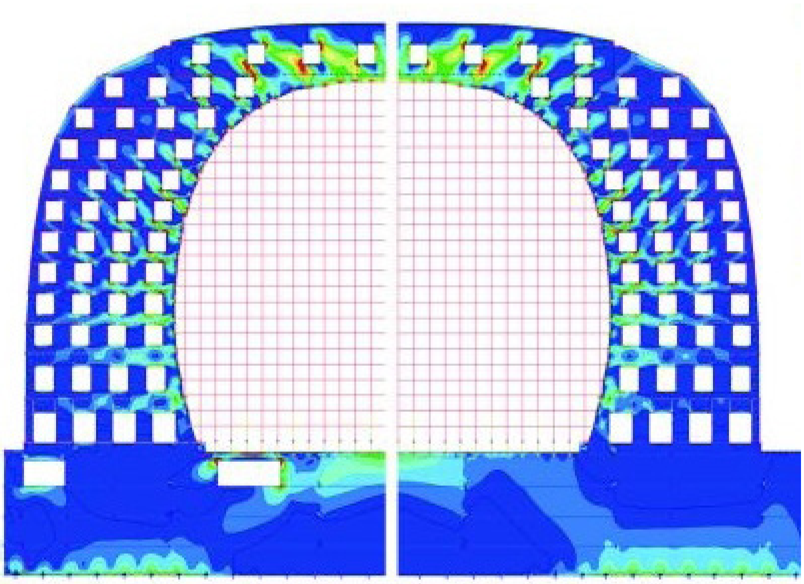


Figure 10.2: Stress distribution of caused by pre-stressing cable net facade, Markthal.
Source: masesoft.com

Two things should be noted about this facade type. First thing is that the facade allows for quite a bit of deflection, thus no stability is achieved. And, while it is not visible at first sight, the steel boxes and the concrete arch add a lot of weight to the façade construction.

Figure 10.3: Hotel Kempinski, Munich
Source: octatube.nl

In Kempinski Hotel a similar construction method is applied. The lightweight atrium facade is constructed by the surrounding construction which is capable to absorb large tension forces. In the case of Kempinski hotel, the surrounding buildings absorb the tensile stresses.

Cable truss construction

Cable trusses rely on the introduction of pre-stressed forces into the tensile elements of the truss to provide stability, therefore, no deflection occurs. Depending on the span and loading conditions, the required pre-stress forces can be quite high, and must be resisted by adjacent building structure. Often cable trusses are located at each vertical line of the glazing grid to resist lateral loads on the glass wall.
In the OZ-building the solid surrounding walls fulfill the inevitable task of absorbing the tensile forces (figure 10.4).

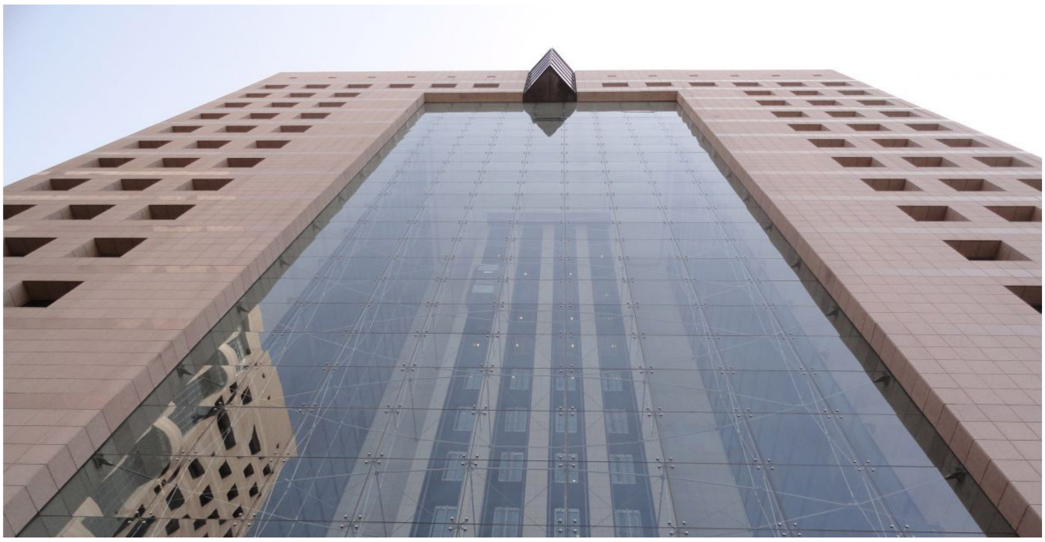


Figure 10.4: Tension cable truss facade, OZ-building
Source: octatube.nl

It can be concluded that a cable truss and a cable net construction both require a strong (and often heavy) surrounding construction which is capable of absorbing large tensile stresses.

Possible configuration

For a cable truss construction many configurations are, in theory, possible. Various configurations are discussed in this paragraph in order to find out if it would be possible to apply these configurations in the facade of the case study. It is important to keep in mind that the choosen glass facade is located inbetween two original 19th century walls which are monumental and therefore protected.

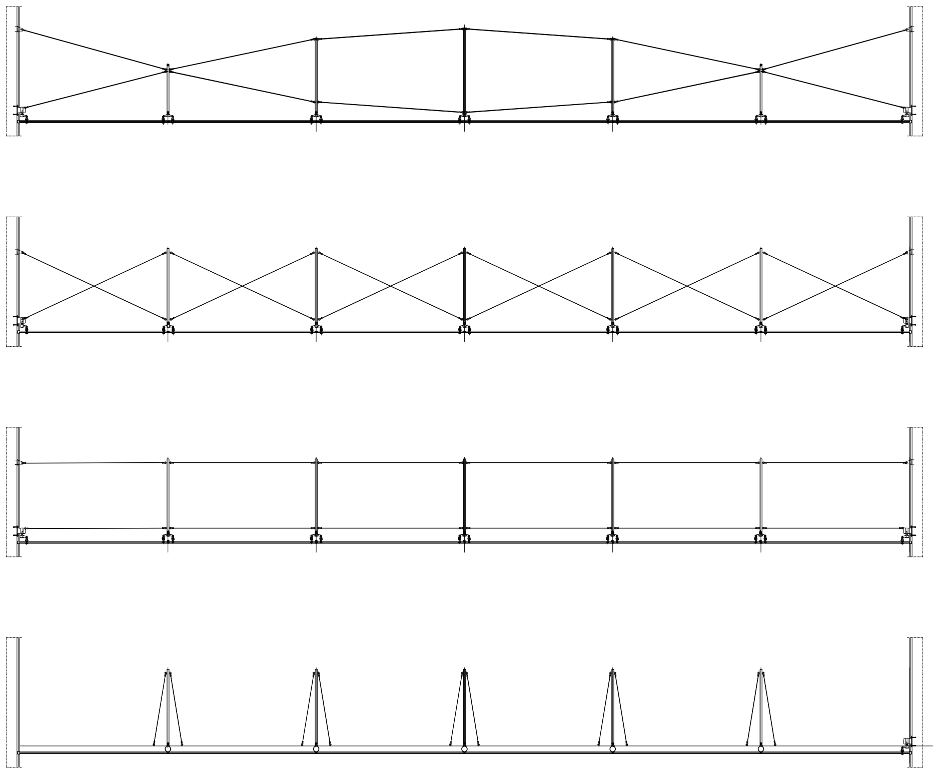


Figure 10.5: Possible horizontal configurations cable truss construction from top to bottom: a, b c and d. Scale 1:200
Source: by author.

In figure 10.5 some horizontal sections (A, B, C and D) are shown of possible configurations found in precedents.

In section A, two parabolic cables span inbetween two walls. This parabolic shape provides for the stability of the facade. Combined with pressure bars and spiders the glass is held into place. In section b, the stability is also provided by the horizontally tensioned cables. Again, combined with pressure bars and spiders the glass is held into place. Unlike with section a and b, he stability is not provided by horizontally tensioned cables in section c. In this case, the horizontal cables are required to prevent flipping pressure bars. The final horizontal section, d, does not hold the glass sheets into place by spiders. Linear aluminum profiles are used, which are connected to pressure bars. They are prevented from flipping over by cables. Onto all intersections pressure bars are placed. Stability needs to be provided by the vertical cables.

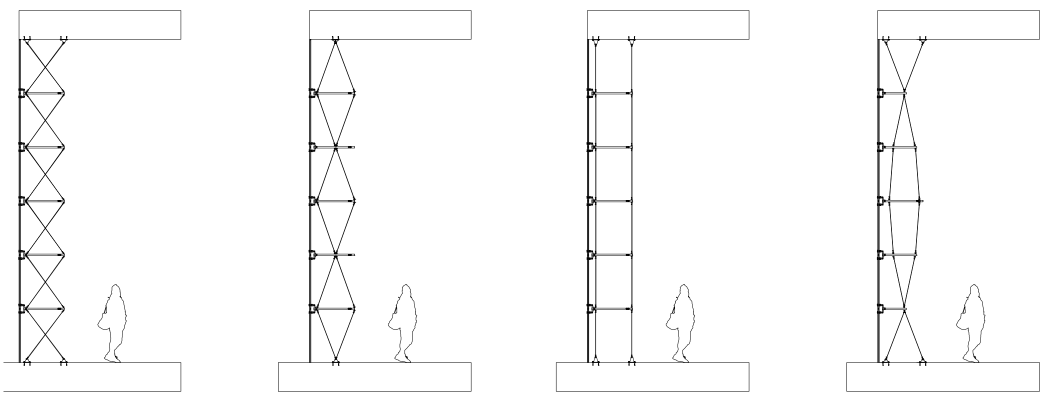


Figure 10.6: Possible vertical configurations cable truss construction. From left to right: 1, 2, 3 and 4.
Source: by author.

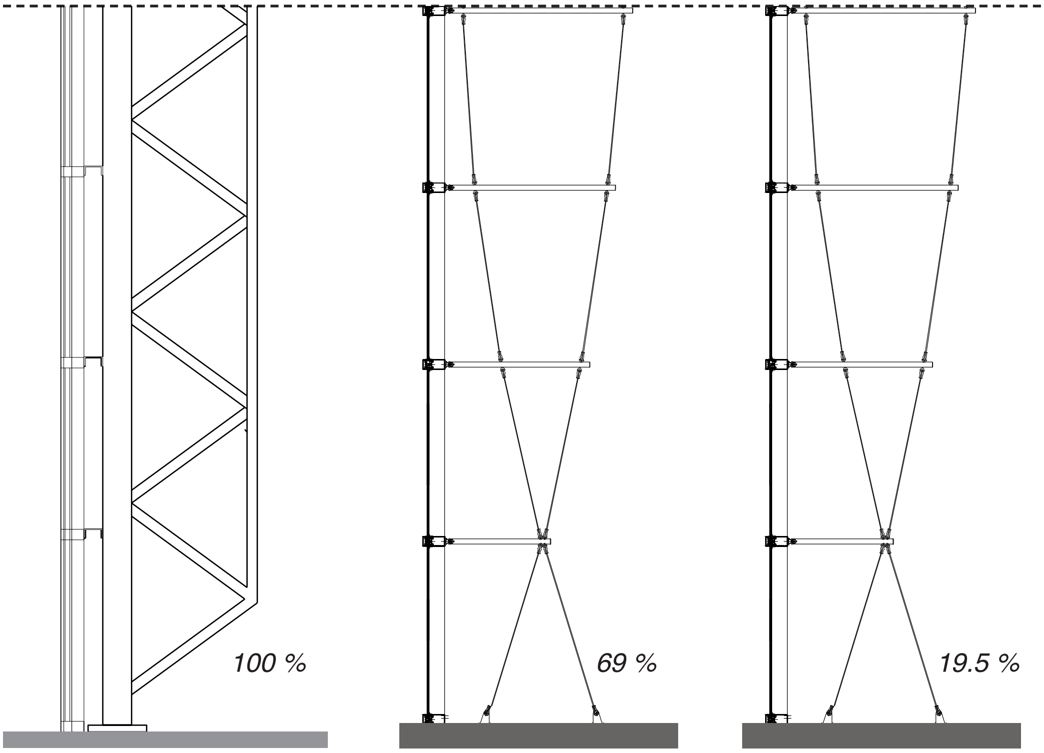
In vetical section 1, 2 and 4 the stability is provided by the vertical components. They can be combined with horizontal section C. Horizontal sections A, B and D can be combined with vertical section 3.

10.2 Facade design

When projecting these possible configurations onto the case study, some options can be excluded for the final design. In order to choose a suitable configuration for the facade, the weight is taken into account. The weight of the facade should be as low as possible, according to the architectural concept.

Evaluating the initial design

In the chapter 8, case study, an initial design was opposed. It consisted of a cable truss construction. By doing so, the weight of the facade could be reduced with 30 percent, even without using the thin glass facade panels if these would be taken into account a reduction of 80% of the weight could be achieved (figure 10.7).



Current facade
22011.4 kg
= 46.58 kg/m^2

Inital design, regular glass
15293.6 kg
= 32.3 kg/m^2

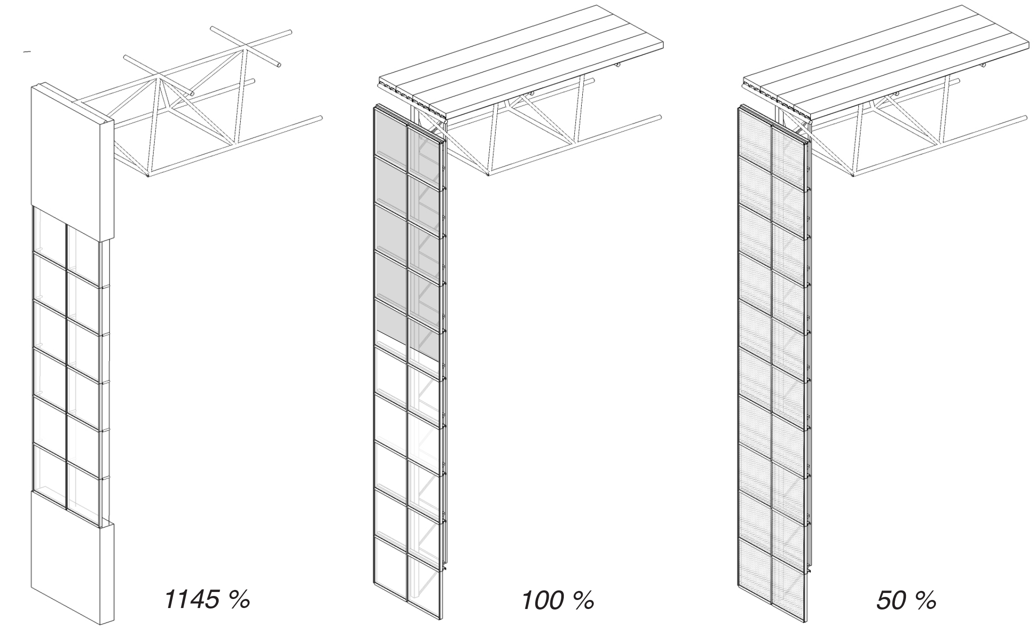
Inital design, thin glass panel
4304.1 kg
= 11.5 kg/m^2

Figure 10.7: Possible facade configurations and their weight.
Source: by author

An important note is that the weight of the roof is carried by the trusses, meaning that they cannot be removed, if they were, they should be replaced with an element that can carry this load.

Another problem with the cable facade typologies is the fact that the cables create a lot of tensile forces. In the OZ-building, the Markthal and Hotel Kempinski the adjacent building structure is capable of resisting these forces. In the case study however, the surrounding facades are a monumental building built out of bricks. The roof construction is also not able to withstand these forces, it is simply not built for resisting tensile forces. This means it would deflect or maybe even break by introducing these forces, this is of course unwanted. Therefore an extra structure should be added, that is able to withstand these loads. This would result in heavier facade, aestetically and physically (figure 10.8).

Figure 10.8: Added structure with loadbearing properties and tensile forces
Source: by author.



Initial design, additional construction
22011.4 kg
= 527 kg/m2

Current facade
22011.4 kg
= 46.58 kg/m2

Facade design
11020 kg
= 23.3 kg/m2

Figure 10.9: Possible facade configurations and their calculated weight.
Source: by author.

When calculating the weight of this added concrete construction (figure 10.9), the total weight of the facade increases enourmously. If the thin glass facade panels would be implemented instead of the current double glazing units, a weight reduction of 50 % can be achieved. This option is therefore more favourable, hence the current facade needs to be further analyzed and optimized.

Optimizing current facade construction

When looking at the weight calculation of the current facade (appendix x), it clearly shows that the steel trusses are the heaviest part of the facade construction, followed by the aluminum curtain wall frame. The trusses however, are necessary for carrying the load of the roof, this is clearly shown in figure 10.10. It might be possible to re-design these trusses, in such a way that the element becomes lighter. This could, for example be done by using round tube profiles instead of rectangular ones. Besides that, the way the aluminum curtain wall is attached to the trusses could be re-designed. Currently, a steel u-profile is used along the full horizontal length of the facade. The aluminum curtain wall elements could also be changed, but than the panel configuration changes along with it, and in the previous paragraph we also discovered that a different support construction results in a lot of additional mechanical research.

However, within the timespan of this project, it is not possible to mechanically analyze and optimize all these elements. Also, because it is not within the scope of this thesis hence the panels are inserted in the current facade construction in the final design. The only actual change, is the removal of solar shading, since it is integrated in the designed thin glass sandwich panels. The sections and details of the new facade construction is shown in figure 10.11 to 10.13.

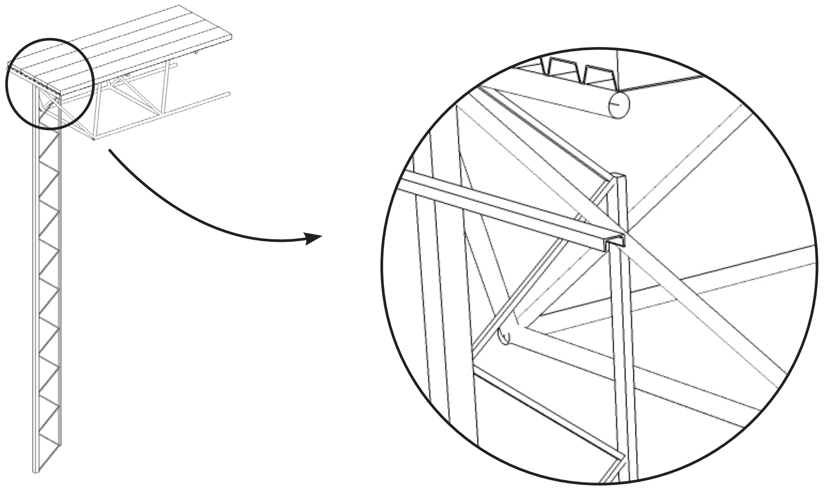


Figure 10.10: Elements current facade construction.
Source: by author.

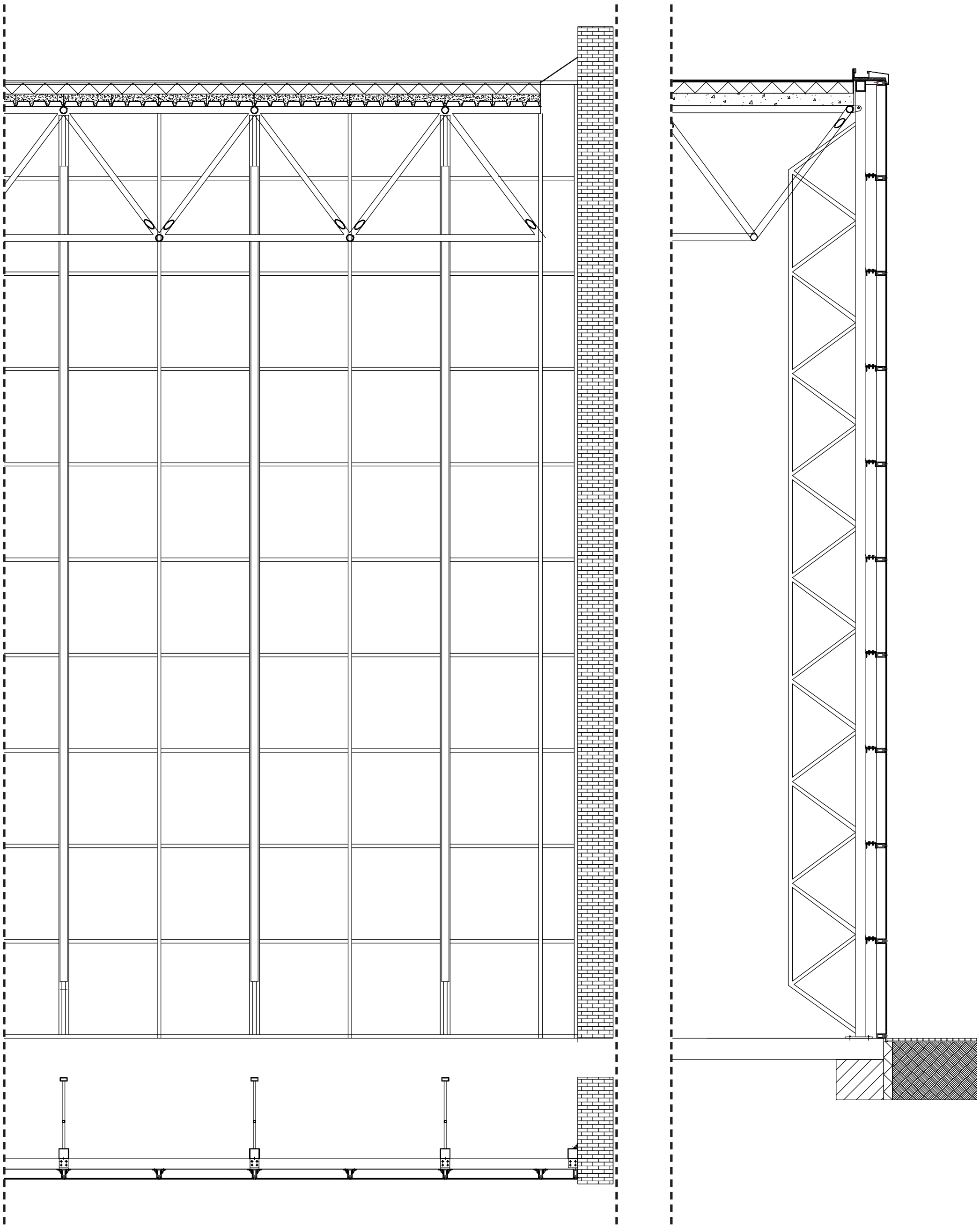


Figure 10.11: Final design, acade fragment, horizontal and vertical section. Scale: 1:100
Source: by author.

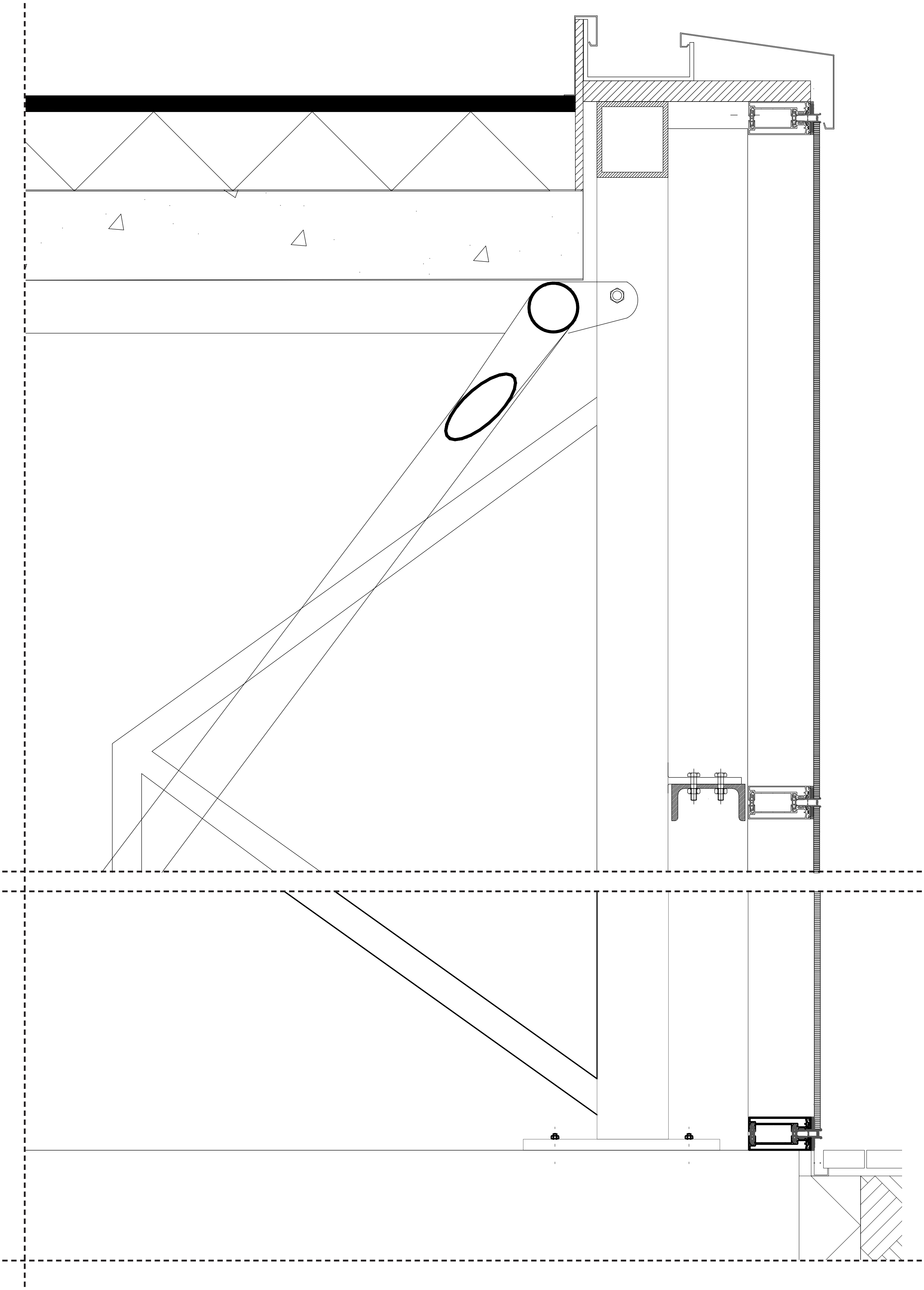


Figure 10.12: Final design, vertical section top and bottom. Scale: 1:5
Source: by author.

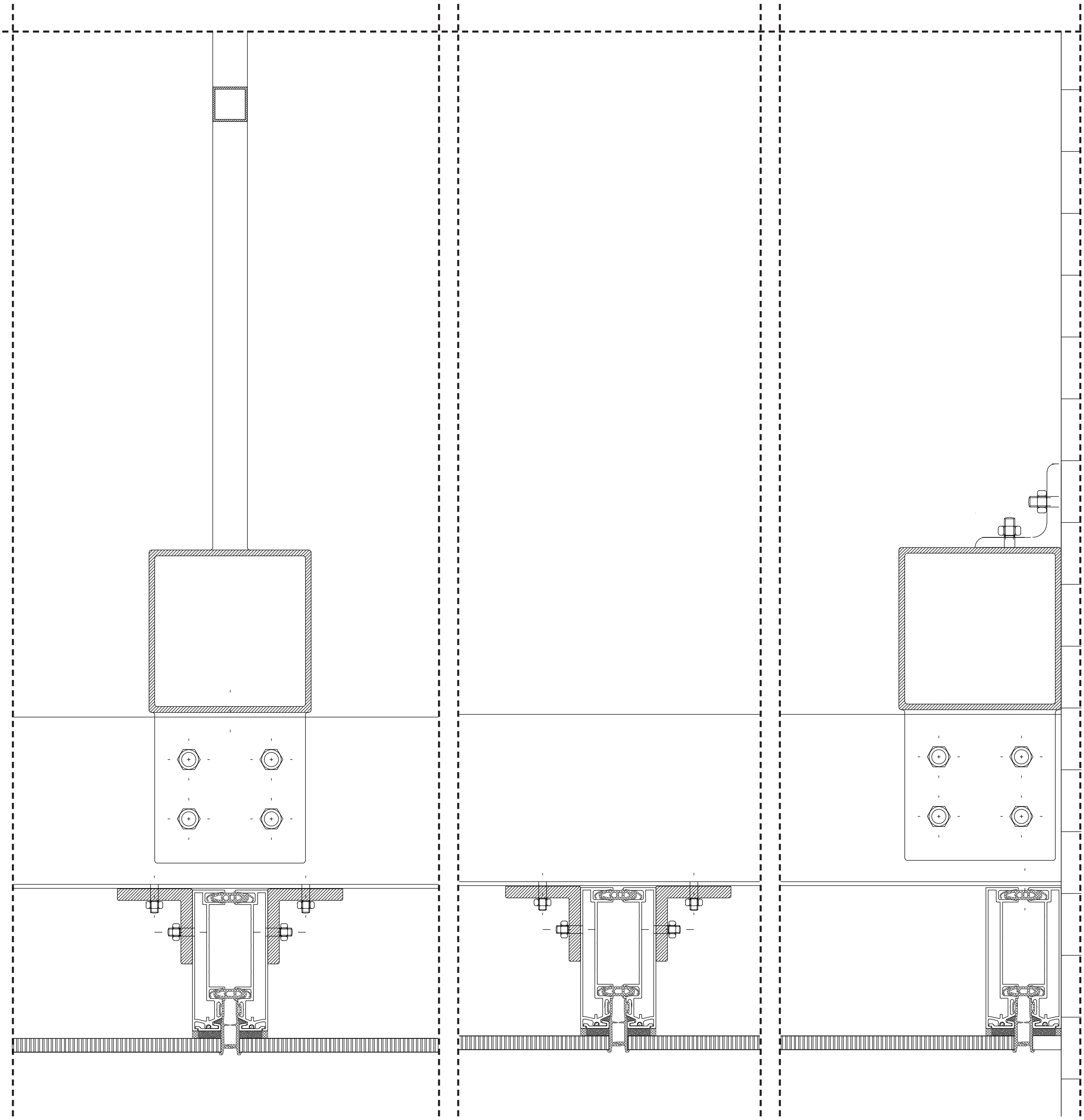


Figure 10.13: Final design, horizontal section top and bottom. Scale: 1:5
Source: by author.

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Figures

Tables

Graphs

Attachments

Appendix 1: Leoflex material properties

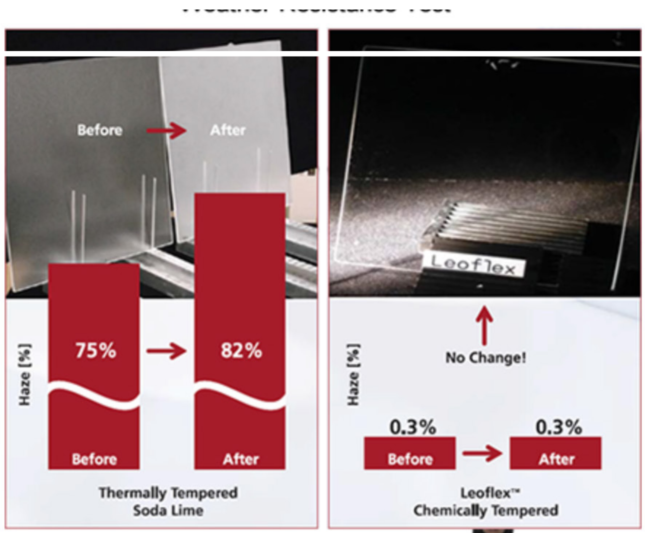
lime glass

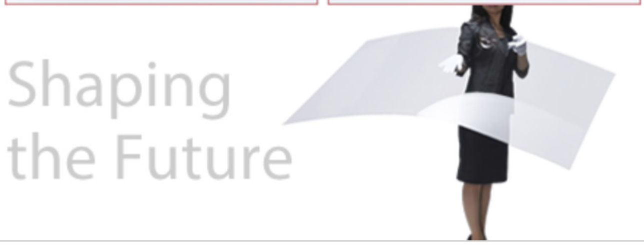
- ✓ Lightweight
- ✓ Bendable
- ✓ High scratch resistance
- ✓ Outstanding weather resistance
- ✓ High optical clarity
- ✓ High strength compared to soda lime glass

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.





Leoflex™ Properties

	Property	Measurement	Leoflex™	Soda Lime
Mechanical	Density	g/cm^3	**2.48**	2.50
	Young's Modulus	GPa	**74**	73
	Shear Modulus	GPa	**30**	30
	Poisson's Ration		**0.23**	0.21
	Vickers Hardness	Before CT	**595**	533
	Vickers Hardness	After CT	**673**	580
Thermal	CTE	$[10^{-7}]$(50~200°C)	**98**	85
	Tg	°C	**604**	550
	Softening Point	°C	**831**	733
	Annealing Point	°C	**606**	554
	Strain Point	°C	**556**	511
Optical	Refraction Index	Nd	**1.51**	1.52
	Photoelastic Constant	nm/cm Mpa	**28.3**	25.6
Electrical	Volume Resistivity	log (Ω·cm)	**8.4**	8.5

Available Sizes & Thickness:

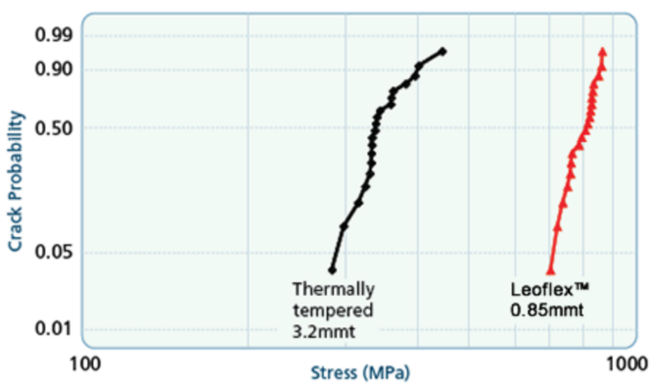
Thickness:

From 0.5mm to 2.0mm

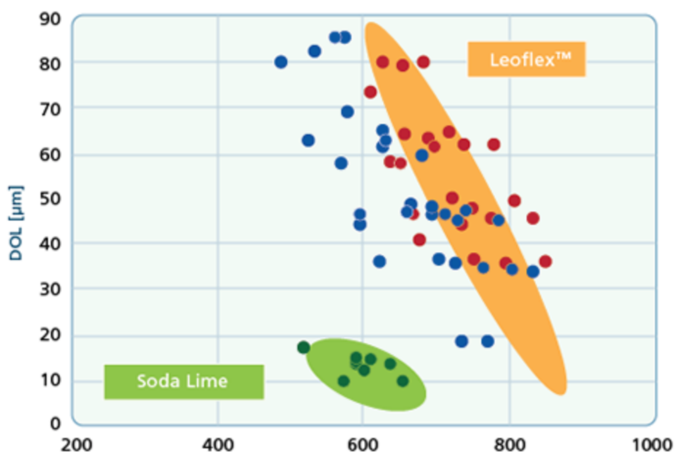
Sizes:

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

Toughness Ring-on-Ring Test



Chemical Tempering Performance



Appendix 2: Wind load NEN-EN 1991

Hoogte boven maaiveld	Gebied I			Gebied II			Gebied III	
	Kust	Onbebouwd	Bebouwd	Kust	Onbebouwd	bebouwd	Onbebouwd	bebouwd
8	1,51	0,94	0,73	1,26	0,79	0,62	0,65	0,51
10	1,58	1,02	0,81	1,32	0,85	0,68	0,70	0,56
15	1,71	1,16	0,96	1,43	0,98	0,80	0,80	0,66
20	1,80	1,27	1,07	1,51	1,07	0,90	0,88	0,74
25	1,88	1,36	1,16	1,57	1,14	0,97	0,94	0,80
30	1,94	1,43	1,23	1,63	1,20	1,03	0,99	0,85
35	2,00	1,50	1,30	1,67	1,25	1,09	1,03	0,89
40	2,04	1,55	1,35	1,71	1,30	1,13	1,07	0,93
45	2,09	1,60	1,40	1,75	1,34	1,17	1,11	0,97
50	2,12	1,65	1,45	1,78	1,38	1,21	1,14	1,00
55	2,16	1,69	1,49	1,81	1,42	1,25	1,17	1,03
60	2,19	1,73	1,53	1,83	1,45	1,28	1,19	1,05
65	2,22	1,76	1,57	1,86	1,48	1,31	1,22	1,08
70	2,25	1,80	1,60	1,88	1,50	1,34	1,24	1,10
75	2,27	1,83	1,63	1,90	1,53	1,37	1,26	1,13
80	2,30	1,86	1,66	1,92	1,55	1,39	1,28	1,15
85	2,32	1,88	1,69	1,94	1,58	1,42	1,30	1,17
90	2,34	1,91	1,72	1,96	1,60	1,44	1,32	1,18
95	2,36	1,93	1,74	1,98	1,62	1,46	1,33	1,20
100	2,38	1,96	1,77	1,99	1,64	1,48	1,35	1,22
110	2,42	2,00	1,81	2,03	1,68	1,52	1,38	1,25
120	2,45	2,04	1,85	2,05	1,71	1,55	1,41	1,28
130	2,48	2,08	1,89	2,08	1,74	1,59	1,44	1,31
140	2,51	2,12	1,93	2,10	1,77	1,62	1,46	1,33
150	2,54	2,15	1,96	2,13	1,80	1,65	1,48	1,35
160	2,56	2,18	2,00	2,15	1,83	1,67	1,50	1,38
170	2,59	2,21	2,03	2,17	1,85	1,70	1,52	1,40
180	2,61	2,24	2,06	2,19	1,88	1,72	1,54	1,42
190	2,63	2,27	2,08	2,20	1,90	1,75	1,56	1,44
200	2,65	2,29	2,11	2,22	1,92	1,92	1,58	1,46
225	2,70	2,35	2,35	2,26	1,97	1,97	1,62	1,62
250	2,74	2,40	2,40	2,30	2,01	2,01	1,66	1,66
275	2,78	2,45	2,45	2,33	2,05	2,05	1,69	1,69
300	2,82	2,5	2,5	2,36	2,09	2,09	1,72	1,72

Appendix 3: Calculation insulation value uncoated panel

Input			Comments
$U_{required}$	[W/m2K]	1.4	according to: NEN
λ_{glass}	[W/mk]	1.000	Material property: λ_{glass}
d_{glass}	[m]	0.001	Thin glass sheet
λ_{air}	[W/mk]	0.025	Material property
$\lambda_{honeycomb}$	[W/mk]	0.025	Material property

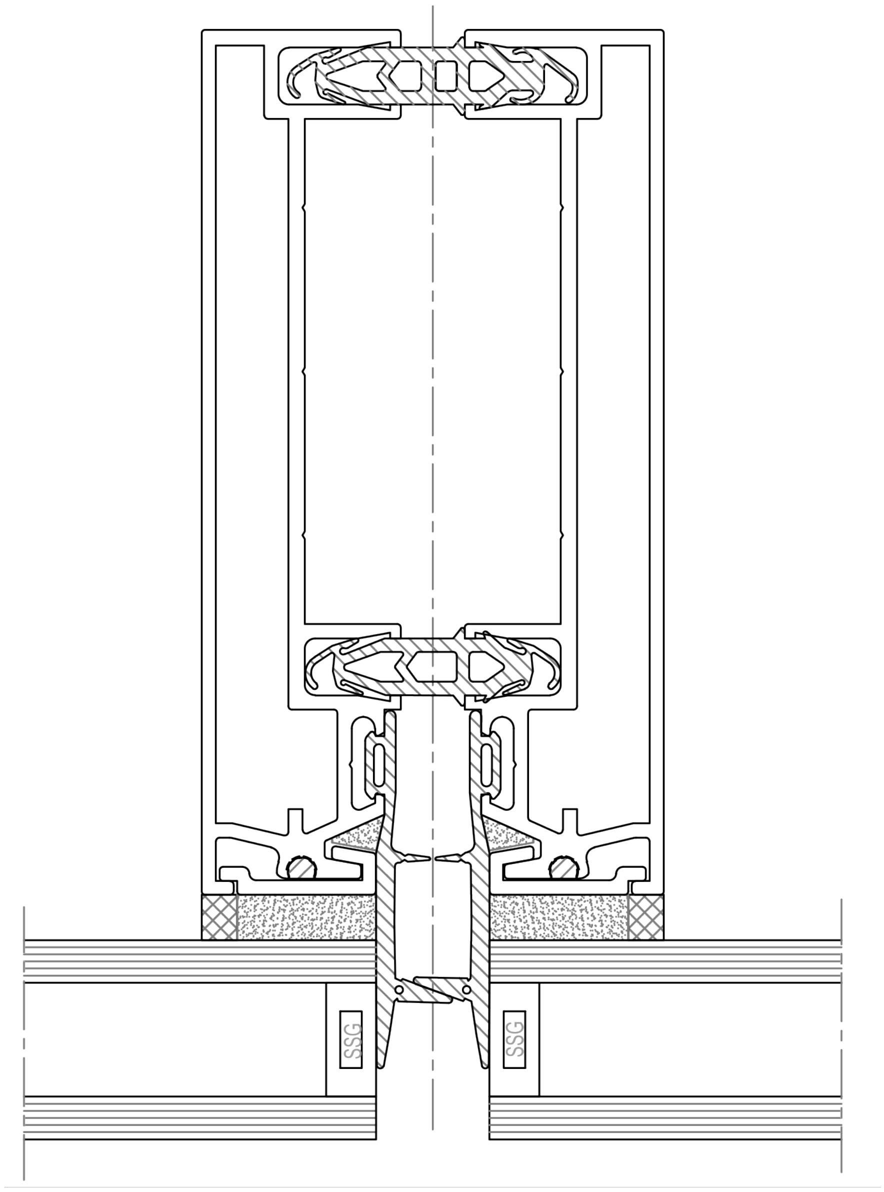
Calculation			Comments
ε_{glass}	[-]	0.830	Material property
ε_{paper}	[-]	0.930	Material property
$\varepsilon_{res, uncoated}$	[-]	0.781	$1/\varepsilon_{res} = 1/\varepsilon_{glass} + 1/\varepsilon_{glass} + 1/\varepsilon_{paper} - 1$
α_{rad}	[W/m2K]	4.687	$\alpha_{rad} = 6 * \varepsilon_{res}$
$\alpha_{conduction, required}$	[W/m2K]	-3.287	$\alpha_{conduction, required} = 1.4 - \alpha_{rad}$
$R_{core, required}$	[m2K/W]	-0.304	$R_{core, required} = 1 / \alpha_{conduction, required}$
r_e	[m2K/W]	0.040	standard value, Netherlands
r_i	[m2K/W]	0.130	standard value, Netherlands
r_{glass}	[m2K/W]	0.001	$r_{glass} = d_{glass}/\lambda_{glass}$
$r_{adhesive}$	[m2K/W]	0.030	Material property
R_{core}	[m2K/W]	-0.535	$r_e + r_i + r_{cavity} + 2^* r_{glass}$
d_{core}	[m]	-0.013	$d_{core} = R_{core} \cdot \lambda_{honeycomb}$
	[mm]	-13.329	**IMPOSSIBLE**

Appendix 4: Calculation insulation value coated panel

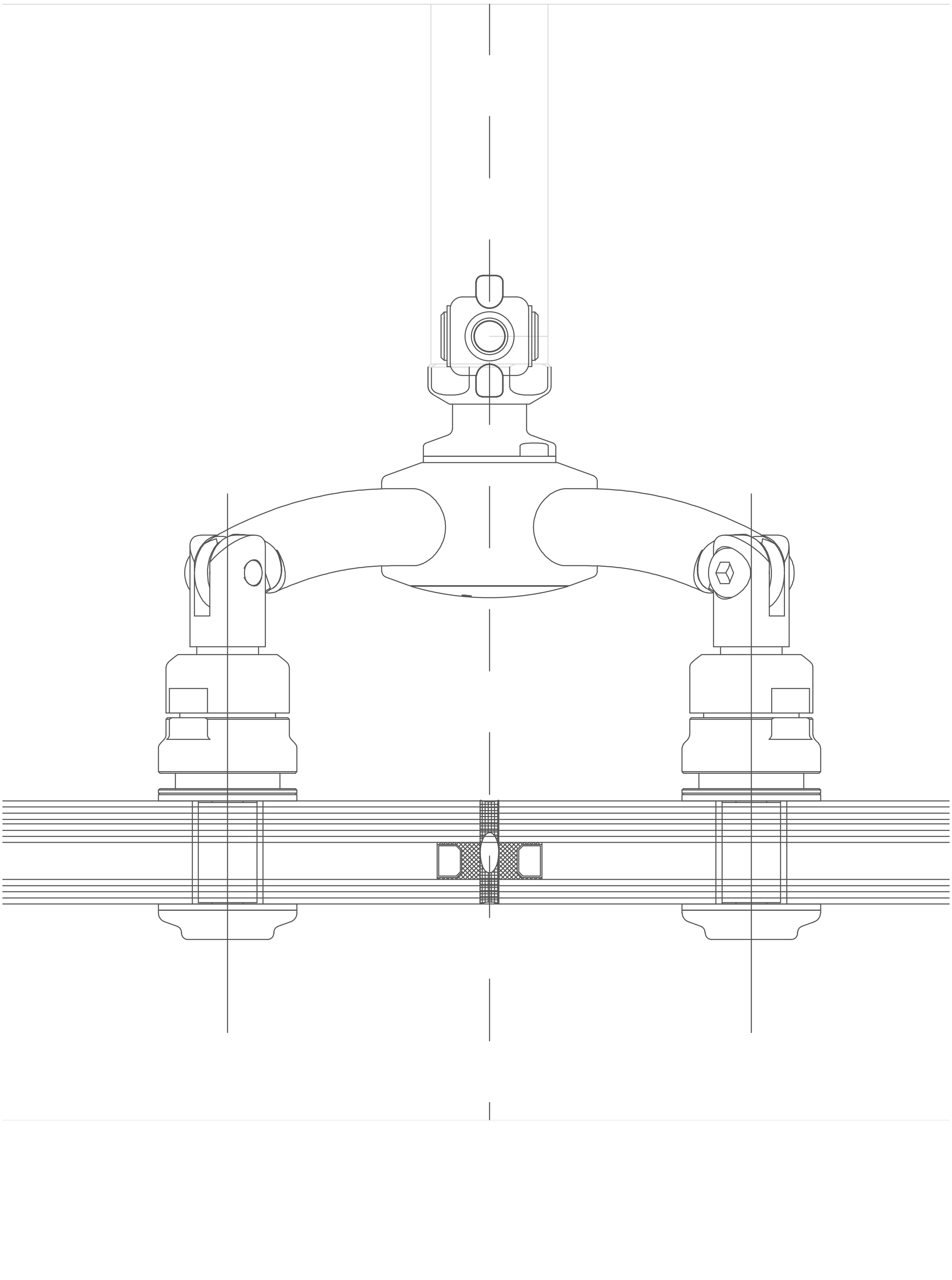
Input			Comments
$U_{required}$	[W/m2K]	1.4	according to: NEN
λ_{glass}	[W/mk]	1.000	Material property: λ_{glass}
d_{glass}	[m]	0.001	Thin glass sheet
λ_{air}	[W/mk]	0.025	Material property
$\lambda_{honeycomb}$	[W/mk]	0.025	Material property

Calculation			Comments
ε_{glass}	[-]	0.020	Material property
ε_{paper}	[-]	0.930	Material property
$\varepsilon_{res, uncoated}$	[-]	0.020	$1/\varepsilon_{res} = 1/\varepsilon_{glass} + 1/\varepsilon_{glass} + 1/\varepsilon_{paper} - 1$
α_{rad}	[W/m2K]	0.120	$\alpha_{rad} = 6 * \varepsilon_{res}$
$\alpha_{conduction, required}$	[W/m2K]	1.280	$\alpha_{conduction, required} = 1.4 - \alpha_{rad}$
$R_{core, required}$	[m2K/W]	0.781	$R_{core, required} = 1 / \alpha_{conduction, required}$
r_e	[m2K/W]	0.040	standard value, Netherlands
r_i	[m2K/W]	0.130	standard value, Netherlands
r_{glass}	[m2K/W]	0.001	$r_{glass} = d_{glass}/\lambda_{glass}$
$r_{adhesive}$	[m2K/W]	0.030	Material property
R_{core}	[m2K/W]	0.550	$r_e + r_i + r_{cavity} + 2^* r_{glass}$
d_{core}	[m]	0.012	$d_{core} = R_{core} \cdot \lambda_{honeycomb}$
	[mm]	11.696	**thus 12 mm**

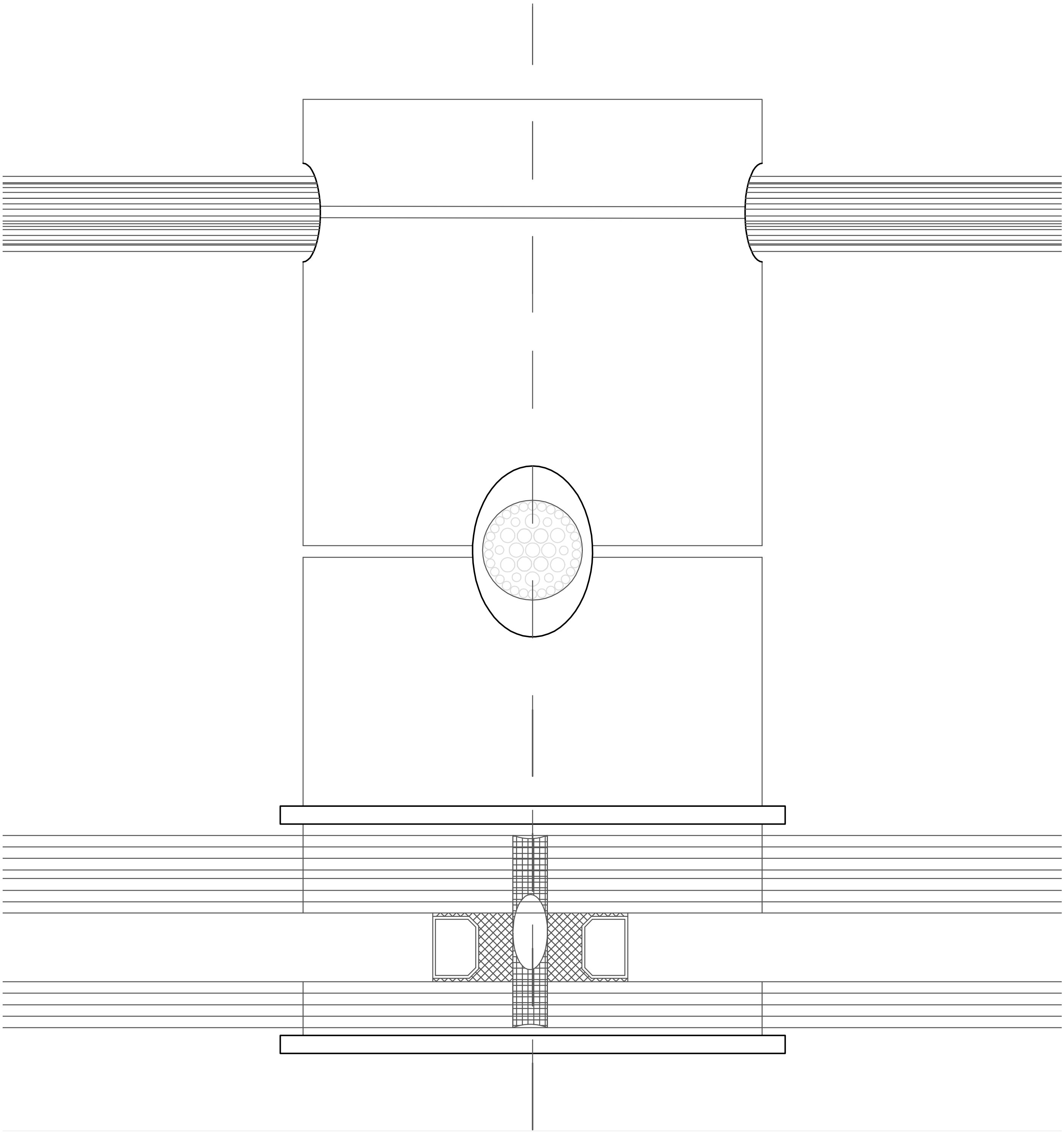
Appendix 5: Detail SG system



Appendix 6: Detail glass spider



Appendix 7: Detail corner support



Appendix 6: Calculation sheet weight

Current facade construction

Construction element		Assemble	Size	Weight element [kg]	Amount	Weight [kg]	Weight total [kg]	[kg/m2]
Glass surface	**Double glass element**	Glass - cavity - glass 4-12-6 mm	1.3 x 1.3 m	50.7	216	10951.2		
		Glass - cavity - glass 4-12-6 mm	1.3 x 0.4 m	15.6	18	280.8	**11232.00**	
	Curtain wall frame	Horizontal	36.15 m	131.9475	11	1451.4225		
		Vertical	13.5 m	49.275	28	1379.7	**2831.12**	
Support construction	**Truss**	Tube profile 14 x 14	13.1 m	278.6	12	3343.2		
		Tube profile 3 x 3	1.07 m	2.557	216	552.312	2221.96	
		Tube profile 8 x 5	11.54 m	45.7	12	548.4	**4443.91**	
	U-profiles	UNP 90	35.35 m	374.71	9	3372.39	**3372.39**	
	Sunshading	Thickness 0.5 mm	9 x 2.6 m	10.998	12	131.976	**131.98**	
							22011.40	**58.79**

Initial design, cable truss

Construction element		Assemble	Size	Weight element [kg]	Amount	Weight [kg]	Weight total [kg]	[kg/m2]
Glass surface	Double glass element	Glass - cavity - glass 4-12-6 mm	1.3 x 1.3 m	50.7	216	10951.2		
		Glass - cavity - glass 4-12-6 mm	1.3 x 0.4 m	15.6	18	280.8	**11232.00**	
	Curtain wall frame	Horizontal	36.15 m	131.9475	11	1451.4225		
		Vertical	13.5 m	49.275	28	1379.7	**2831.12**	
Support construction	Cables	Horizontal	36.15	12.6953	8	101.5624		
		Vertical fish shaped	2 x13.2 m	20.856	25	521.4		
		Pressure bars	1 m	2.5	243	607.5	**1230.46**	
							15293.58	**40.85**

Initial design, cable truss with thin glass panel

Construction element		Assemble	Size	Weight element [kg]	Amount	Weight [kg]	Weight total [kg]	[kg/m2]
Glass surface	Double glass element	Glass - core - glass	1.3 x 1.3 m	1.09	216	235.44		
		Glass - core - glass	1.3 x 0.4 m	0.34	18	6.04	**241.48**	
	Curtain wall frame	Horizontal	36.15 m	131.9475	11	1451.4225		
		Vertical	13.5 m	49.275	28	1379.7	**2831.12**	
Support construction	Cables	Horizontal	36.15	12.6953	8	101.5624		
		Vertical fish shaped	2 x13.2 m	20.856	25	521.4		
		Pressure bars	1 m	2.5	243	607.5	**1230.46**	
							4303.06	**11.49**

Additional concrete construction

Construction element		Assemble	Size	Weight element [kg]	Amount	Weight [kg]	Weight total [kg]	[kg/m2]
Glass surface	Double glass element	Glass - cavity - glass 4-12-6 mm	1.3 x 1.3 m	1.09	95	103.55		
	Curtain wall frame	Horizontal	24.7 m	90.155	6	540.93		
		Vertical	6.5 m	23.725	20	474.5	**1015.43**	
Support construction	Cables	Horizontal	24.7	**12.6953**	6	76.1718		
		Vertical fish shaped	2 x13.2 m	10.27	20	205.4		
		Pressure bars	1 m	2.5	72	180	**461.5718**	
	Concrete	Wall 40 cm	1.3 x 1.3 m	1554.8	126	195904.8	**195904.8**	
							197381.80	**527.19**

Final design

Construction element		Assemble	Size	Weight element [kg]	Amount	Weight [kg]	Weight total [kg]	[kg/m2]
Glass surface	**Double glass element**	Glass sandwich panel	1.3 x 1.3 m	1.09	216	235.44		
		Glass sandwich panel	1.3 x 0.4 m	0.34	18	6.04	**241.48**	
	Curtain wall frame	Horizontal	36.15 m	131.9475	11	1451.4225		
		Vertical	13.5 m	49.275	28	1379.7	**2831.12**	
Support construction	**Truss**	Tube profile 14 x 14	13.1 m	278.6	12	3343.2		
		Tube profile 3 x 3	1.07 m	2.557	216	552.312	2221.96	
		Tube profile 8 x 5	11.54 m	45.7	12	548.4	**4443.91**	
	U-profiles	UNP 90	35.35 m	374.71	9	3372.39	**3372.39**	
							10888.90	**23.05**