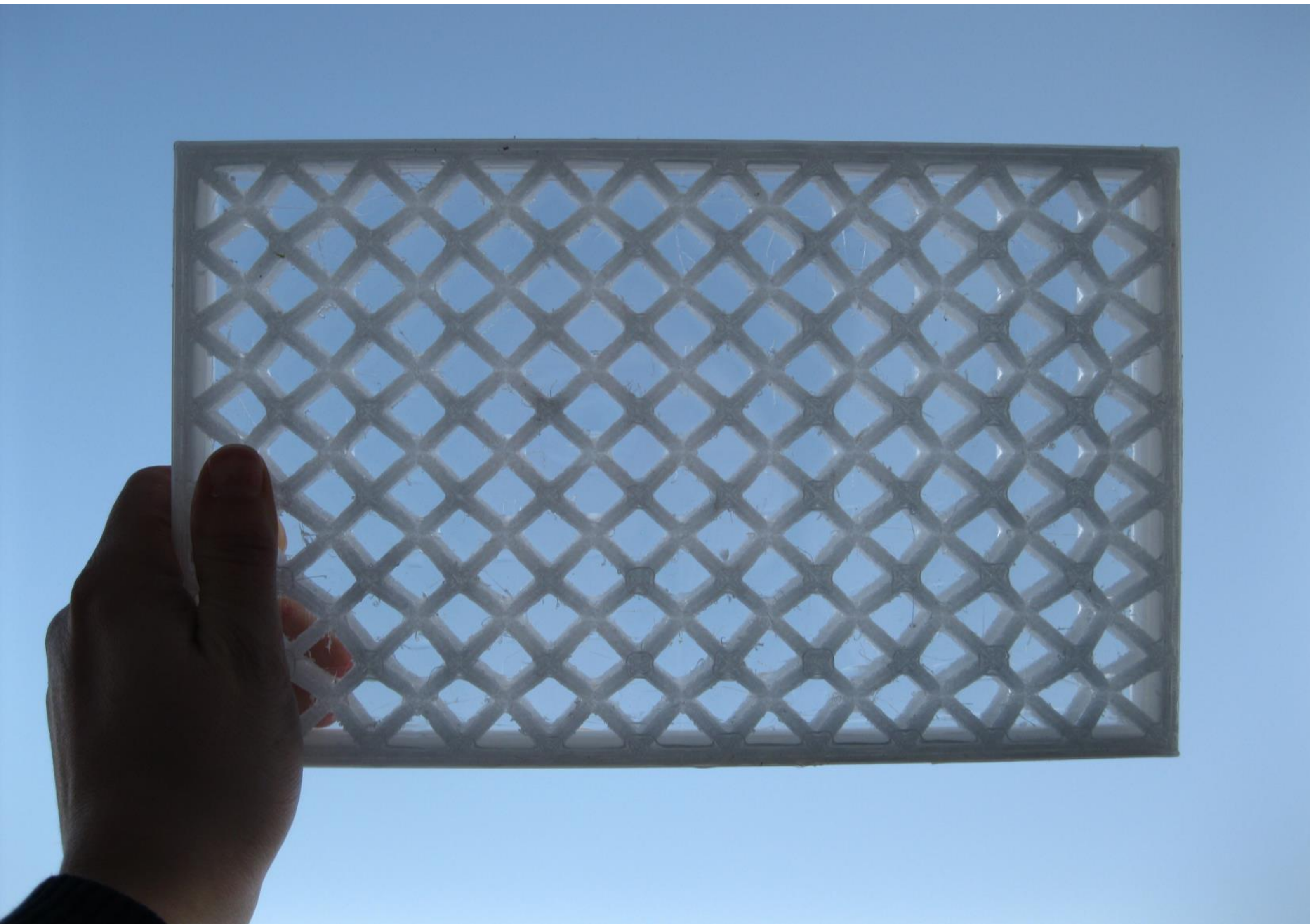
THIN GLASS COMPOSITE PANEL WITH 3D PRINTED CORE

Thermal and structural properties

- Stella Brugman -



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Master of Science (MSc) thesis
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Abstract

The research of this thesis is focussed on the thermal insulation and structural properties of a thin glass composite panel with 3D-printed polymeric core.

Aluminosilicate glass, used in this research, is only 0,5 mm thick. This aluminosilicate can be used to replace current windows and structural façade element to reduce the use of scarce, raw materials. Due to its flexibility, a lightweight, trussed polymeric core is used to stiffen the glass. The core and the glass now act as a sandwich panel. The core is produced through additive manufacturing and an UV-curing glue is used to bond the core to the glass. Three different arrangements of the sandwich panel are tested. The first panel has a trussed pattern with an angle of 51˚, now called 'standard pattern', the second panel an angle of 67˚, now called 'dense pattern', and a third panel has three glass layers and two layers of a trussed pattern with an angle of 51˚, now called 'double pattern'. The panels are tested with a heat flow test for their thermal insulation properties and a compression test to determine the failure mode of the panel, to check if the panel is structurally safe to use.

This research shows that the 'double pattern' panel almost meets the thermal insulation regulations of today. The panel will meet the regulations with some small improvements as using a gas instead of air an applying a coating. The failure mode of is delamination, this means that the panel is not safe to use as a load-bearing façade element. But the test showed that the panel can bear their self-weight, when increased to 1,245 x 3,2m.

Keywords: thin glass, PET, trussed pattern, thermal insulation, heat flow test, structural behaviour, compression test.

Table of content

List of abbreviations

Abbreviations

BENG:	Bijna Energie Neutrale Gebouwen
AM:	Additive Manufacturing
FDM:	Fused Deposit Modelling
FEM:	Finite Element Model
IGU:	Insulated Glass Unit
VIG:	Vacuum Insulated Glass

Programmes

Excel	Microsoft Office
Grasshopper	Grasshopper 3D
Rhinoceros	Robert McNeel & associates
Trisco	Physibel

File extensions

.stl:	STereoLithography file
.dat:	Data file

Nomenclature

Thermal

Symbol	Unity	Property
λ	W/m·K	Thermal conductivity (*warmtegeleidingscoëfficiënt)*
R	K·m²/W	Heat insulation
U	W/m²·K	Thermal transmittance
α	W/m²/K	Heat transfer coefficient
Δ T	K	Difference in temperature
ϕ	W/m²	Heat flux *(warmtestroom)*
ε		Grey body radiation emission coefficient
S	mV/(W/m²)	Sensor sensitivity
Sen.	mV	Sensor input
σ	W/m^2K^4	Stefan-Boltzmann constant = $5.67\ 10^{-8}\ W/m^2K^4$

Structural

Symbol	Unity	Property
E	N/mm²	Youngs' Modulus
M	N·m	Bending moment
P	N	Normal force [Newton]
t	mm	Thickness of the face
A	mm²	Area of cross section
L_0	mm	Length of specimen
ΔL	mm	displacement
Δσ	MPa	Stress
Δε	mm	Strain
ρ	kg/m³	density
ui		shape coefficient of the roof
Ce		exposure coefficient
Ct		thermal coefficient
sk		characteristic value of the snow load on the ground

INTRODUCTION

1 OUTLINE FOR RESEARCH FRAMEWORK

1.1 Introduction

Today we cannot imagine a world without glass. It is everywhere around us. The use of glass started during the time of the Roman Empire with jewels and small objects. Later, especially during the Middle ages, we started to use glass in buildings. The first windows in buildings were small, just big enough to let a little bit of light in. From around the years 700 till 1080, the size of the window glazing slowly increased, while the prize slowly decreased (Hees et al., 2018).With the start of the Industrial Revolution, the glass industry got a boost. More and more people were able to buy glass for their homes. The demand for glass became so high that, during the industrial revolution, a lot of new glass production-techniques were invented to make the sheets of glass bigger and the production faster. From this time on it became possible to apply big sheets onto/ into buildings. Nowadays it is possible to buy a regular flat sheet of glass of 3,2 x 6 meter and some companies are able to make even bigger sheets. We love glass, it is shiny and transparent.

There are different types of glass for different applications. Soda-lime glass is a type of glass which is generally used in the building industry, while Silica glass, for example, is mostly used as ovenware. Due to strict insulation regulations nowadays, a window generally consists out of two or three sheets of glass, with gas in between the panes and a coating on the glass panes. The thickness of the glass is 4 till 6 mm (Koninklijk Nederlands Normalisatie-Instituut, 2018). The Dutch Building Code (Bouwbesluit) from 2012 requires a U-value of <1,65 W/m²·K. But in the near future, the new Bijna Energie Neutrale Gebouwen (BENG) regulations asks for a U value of <0,6 W/m²·K (van der Heide, Vreeman, & Haytink, 2016). This requirement forces people to use very heavy triple or quadruple glass windows.

All these layers of glass increase the use of valuable raw materials. Energy is needed to process materials into a product. A lot of energy is needed for some materials, while others are more easily to process. When the Soda-lima glass is compared to concrete based on Portland cement in terms of energy needed for the primary production process, there is a big difference. The energy needed for the primary production process of soda-lime glass is 10,5 MJ/kg and for concrete it is 0,8 MJ/kg (CES EduPack, 2018). This is a big difference, especially in term of sustainability. To conclude, to be more sustainable in the future we have to use less material, or materials which need less energy for the primary production.

Still we are using more and more glass, we can make complete buildings out of glass (Apple). This is the reason why scientists are searching for other materials and techniques to apply in the build environment. A much lighter variant of glass is available: thin glass. Thin glass is a material which is mostly applied in electronics, such as a mobile phone. In this report thin glass is referred to as thin chemically strengthened aluminosilicate glass. The energy needed for the primary production process of aluminosilicate glass is 14 MJ/kg. This is more than the energy needed for soda-lime glass, but this glass has a thickness of 0,1 mm to 2 mm. This means that, in the end, less energy is needed for the production of a thin glass sheet. This sounds very promising and sustainable, but it is not a ready-to-use solution. The thin glass sheet is flexible due to its thinness. Flexibility brings complications in the building industry, because we are not used to flexible materials.

This flexibility can be solved by using a core. A spacer pattern can be used to turn the thin glass into a stiff, yet lightweight building material (Louter et al., 2018). 3D printing of the core can be used to test the properties of a thin glass composite panel. 3D printing has a lot of advantages, such as: almost any free form can be made and there is a wide variety of materials and colours to choose. 3D printing, or additive manufacturing, is not a very common production technique in the building industry. The printing takes time, the material needs to be chosen carefully and the 3D print needs to be bonded with the thin glass (Strauß & Knaack, 2015).

1.2 Problem statement

1.2.1 Main problem

Windows and glass façades need to be insulated. To meet the high insulation requirements, the amount of material and therefore the weight of the elements, increases. This results in a high energy demand for the production of glass and more CO_2 emission during the production.

1.2.2 Sub problem

Thin glass is a relatively new material in the built environment. The flexibility of the material is a challenge because it asks for a different approach to apply the material in a correct way (Image 1). Also, 3D printing, or additive manufacturing, is not a very common production technique in the building industry. The printing takes time, the material needs to be chosen carefully and the 3D print needs to be bonded with the thin glass. Some research is already done in the combination of the thin glass and 3D printed core and the results are very promising. There is no information yet on the thermal insulation performance as an façade and what happens when a linear load, in-plane is applied on the panel.

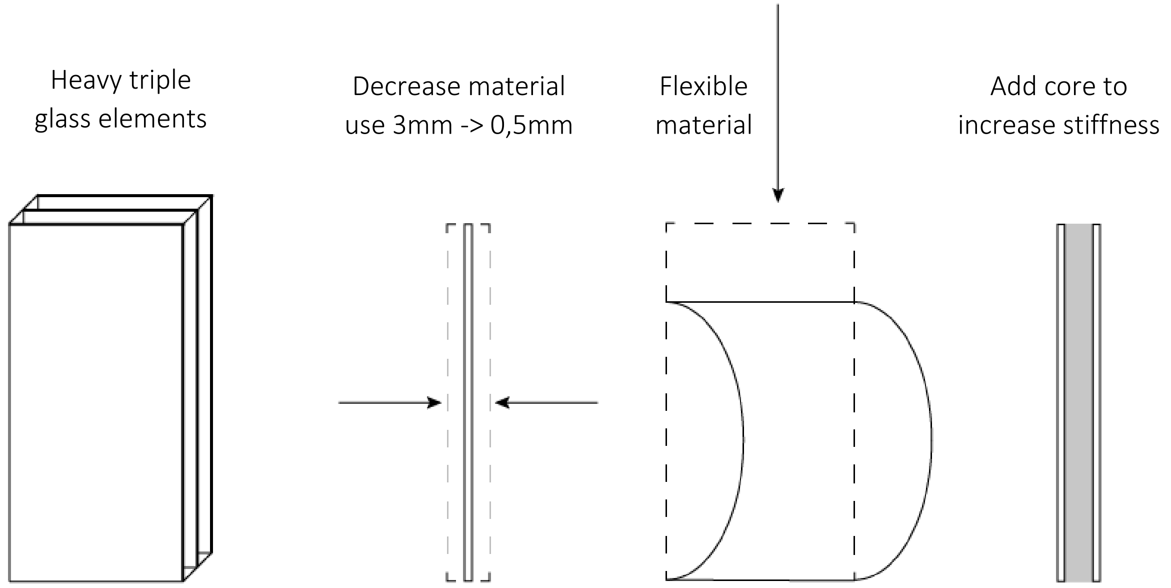


Image 1 - Diagrams of research. Own image.

1.3 Context

1.3.1 Previous researches

Thin glass composite with 3D printed spacer pattern has a potential as a lightweight alternative to replace current windows/ façades (Louter et al., 2018). Some research is already done in the field of thin glass composite with 3D spacer pattern. Akilo is the first who explored the possibilities of thin glass composite panel. He tried two patterns, one honeycomb and one trussed pattern (Image 2), and tested them for their structural properties when a wind-load is applied (Akilo, 2018). Van der Weijde dedicated her master thesis to a lightweight, yet stiff and strong glass façade panel (Image 4) (Van der Weijde, 2017). While Neeskens (Neeskens, 2018) explored the concept of 3D printed polymer core to create a structurally optimized stiff and self-supporting sandwich panel (Image 3). All these researches focussed on the application of the composite as an window.

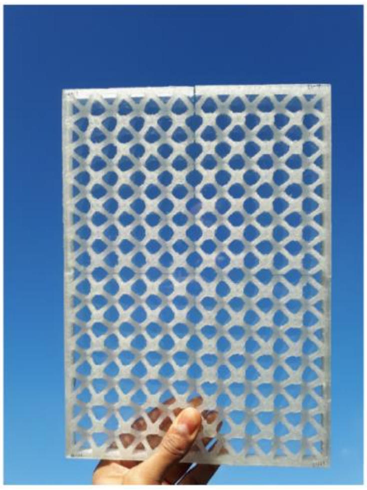


Image 2 - 11 mm core thickness. 0,7 mm thin glass (Akilo, 2018)

Image 3 - 8 mm core thickness. 1 mm thin glass (Neeskens, 2018)

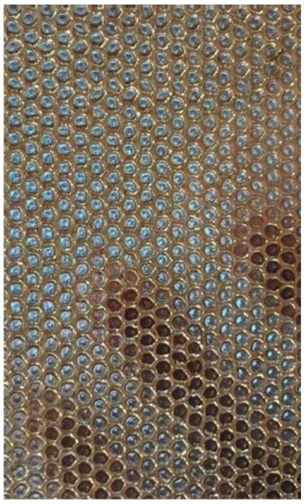


Image 4 - 10 mm core thickness. 2 mm thin glass (Weijde, 2017)

1.3.2 Design

This research will be done to gain more insight in the possibilities of the composite panel as construction material in the built environment. The purpose of the composite panel in this research, is a façade of a small, one floored building. The Glass House designed by Philip Johnson (Image 5) is a good example. The façade is going to support the roof and needs to be insulated according the standards of today, in the Netherlands.

Image 5 - The Glass House, designed by Philip Johnson. Photo: Michael Biondo

Because of the flexibility of the thin glass, a core is needed to provide enough stiffness to the glass. In this research the core is going to be a trussed pattern. A trussed pattern structurally works like a space frame. On a big scale, for example a span of 10 meters with a truss is not a problem. But it might not be the best way to stiffen the composite panel, the thin glass and the core really need to work as one structure. The structure will fail if, for example, delamination occurs. On the other hand, a big advantage of a trussed pattern, in comparison with an honeycomb pattern for example, are the few contact points is the contact area of the core and the glass layers. The structure needs to meet at least the minimal requirements of the Bouwbesluit in the Netherlands. When the future is taken into account, it would be good to have a better insulation value.

1.4 Objective

The main objective is to design a glass façade that is lightweight with the least amount of material needed. This results in a substantial lower energy demand for the production of the glass and less CO_2 emission during the production. The ambition is to design a trussed 3D-printed core in a thin glass composite panel which is lightweight, uses the least amount of materials needed, meets the current thermal insulation requirements and is structurally safe to be used as a structural façade element.

1.5 Research questions

1.5.1 Main question

To what extent can a thin glass composite panel, with a polymeric 3D-printed trussed core, be improved to meet the thermal insulation and structural regulations of today, to be used as a façade element in the building industry?

1.5.2 Sub-questions

1. What is a sandwich structure and which typologies are used to create a stiff and lightweight structure?
2. What is (thin) glass and how is it made?
3. Which production technique and material is most suitable to realize the core?
4. How can the thermal insulation value and structural properties theoretically be determined?
5. What is the actual effect of a trussed pattern in a thin glass composite panel on the thermal insulation and structural properties of the panel?

1.6 Approach and methodology

This research can be classified as an exploratory research. The research area of thin glass composite panels is further explored, still more research is needed before the panels are ready to use. This research is divided in four phases Figure 1 on page 24 shows a schematisation of the methodology

Part one: Literature study

Part one covers the sub-questions 1 till 4. These questions are going to be answered through literature research. Papers and books from writers such as Allen, Ashby, Wadly and Wurm are used to answer literature questions. The program CES is going to be used to find the properties of different materials. Production information from producers will be used to check if it matches with the information from CES.

Part two: preliminary design

Part two covers sub-question 5. The preliminary design is shown and calculated and tested in this part. The software that is going to be used to design the panel is Rhinoceros and Grasshopper, the software to perform calculations is Excel and Trisco.

- Rhinoceros + Grasshopper will be used to draw/ model the composite panel
- Excel-sheet, for the thermal analyses (Tenpierik & Cauberg, 2007)
- Validation of the excel-sheet with Trisco

There is a high probability that it is not possible to find a perfectly optimized panel. One panel will be more structurally optimized and one panel will be more thermally optimized. Therefore three panels will be tested to find a difference between the panels to understand what is the most important property to maintain and what to improve. The tests which are going to be performed are a compression test and a heat flow test.

A compression test is going to be done to determine the behaviour of the panel under a load. The panel will be tested for its ultimate limit state. The location of the failed parts will show where the panel can be improved. The most important thing is that the panel can withstand the weight of the roof structure, snow load and dynamic load. Needed materials:

- 9x panels
- Zwick Z010

A heat flow sensor test will be done to find out what the influence of the spacer pattern is on the thermal insulation properties of the panel (Antoniadis, 2011)(Zhao, Qian, Gu, Jajja, & Yang, 2016). Needed materials:

- 2x heat flux sensor HFP01
- 4x Thermocouples type T
- 2x voltmeter
- 2x Eltek Genll transmitters
- Eltek Genll Quirrel data logger
- Eltek Darca+ software
- Heater
- Laptop

The core needs to be printed before the composite panels can be made and the tests can be performed. Three designs are going to be tested for at least three times, so in total 9 cores need to be printed. Some test pieces are going to be printed to find out what the limits of 3D printing are and to get to know how the 3D printer works. The material PETG from ‘REAL filament’ is used for printing, printing tests are done with a ‘Leapfrog’ 3D-printer. The final panels/ test specimen are printed by the company MTB3D in Delft, the printer they used is ‘Creality cr10 S5’ 3D-printer and the material is PETG from MCPP.

Part three: Design proposal

Part three covers the main question and therefore conclusion. The final design is an example for the implementation of a panel in the façade. All the questions will give input for the final design. The final design is a thin glass composite panel with 3D printed spacer pattern which meets at least the minimal thermal requirements from the 'Bouwbesluit' in the Netherlands and the panel can be used as a structural façade of a one-floored building. The final design will be showed in renders of a small, one floored building, together with technical drawings and details. A final mock-up will be made, to demonstrate the real dimensions and weight of the panel. The final mock-up will not be full scale, but a smaller piece, about 700 x 350mm. Finally, the main research question will be answered and recommendations will be done for further research.

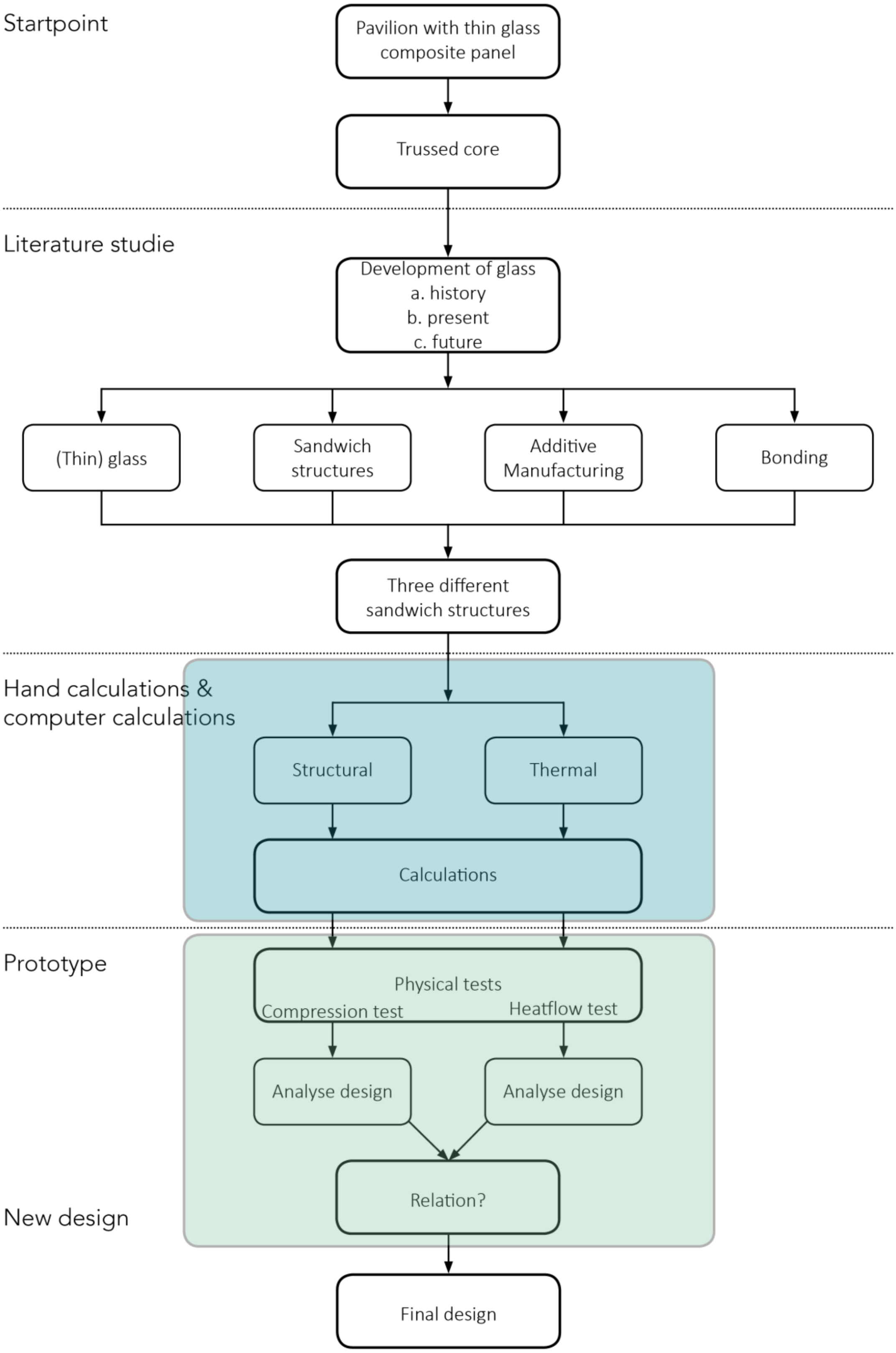


Figure 1 - Methodology scheme. Own figure.

1.7 Planning and organisation

A short planning is shown below. A detailed planning can be found in the appendix.

P1 - P2 13/11/2018 – 10/01/2019 5 weeks	Literature research on glass. - History - Current applications - Material (chemical composition) Determine the main research question + sub questions
P2 - P3 11/01/2019 – 28/03/2019 10 weeks	- Answer research questions (literature research and case study) - Make mock-up & perform tests - Document results & draw conclusions - Write report
P3 - P4 28/03/2019 – 16/05/2019 7 weeks	- Answer research questions - Optimize the 3D pattern - Continue with report
P4 - P5 16/05/2019 – 24/06/2019 4 weeks	- Finish the report and make presentation - Remake the best model/ mock-up

Research team:

Executor:	Stella Brugman
1st supervisor:	Dr. ir. C. Louter
2nd supervisor:	Dr. ir. M. Tenpierik
Consultant:	Octatube – ir. Arjen Veenstra
Advisory board:	A. Ersoy

Financial framework:

Thin glass samples from AGC	€ 0,-
3D filament	€ 200,-
Adhesive	€ 0,-

1.8 Relevance

Societal relevance

This façade creates different architecture than we are used to. It is possible to use different colours and density of the pattern. Due to the thinness of the material, the amount of energy needed for the production is less than the energy needed for the conventional glass pane. This results in a lower CO_2 emission, which is better for the environment.

Scientific relevance

Thin glass is a relatively new material in the built environment. The flexibility of the material is a challenge because it asks for a different approach to apply the material in a correct way. This research will be one of the stepping stones in the bigger picture of research on application of new materials in de built environment. This research will not only contribute in the field of material research but sustainability as well. If the result of this research is promising, it will set an example on how to decrease the material use in the building industry.

The master programme is MSc and the track is Building technology. My graduation topic fits in the chair Building Physics and the chair Structures at the faculty of architecture and the built environment because it is about thermal conductivity and the structural capacity of a façade.

2 STATE OF THE ART

The development of glass in the building industry is discussed in this chapter by mentioning and describing some state of the art buildings and glass applications. First a short research of history, after that a research about the present-day utilisation of glass and to finalize, the future perspective is going to be described.

2.1 History

In the middle ages, from 500 – 1000, people could only produce small pieces of crown glass (Image 6). The small pieces are connected to each other with lead. The production of glass evolved a lot in that time span. Well trained glassmakers could spin glass plates up to 1 meter at the end of the middle ages. This production process is called 'spinning glass' and this production method is used until glass makers started to blow the glass, like a balloon and swing it in the form of a cylinder. The glass from this production method is called cylinder glass (Image 8). The top and the bottom are cut off, and with one cut along the length of the cylinder, it was possible to lay the glass out. This way the glassblowers were able to make big, transparent flat glass panes (Sauzay, 1875). The Crystal Palace, for example, is build up with cylinder glass. The production of cylinder glass started around 1080 and, because the glass had such a high quality, it was produced until 1940 (Hees et al., 2018). During the industrial revolution a lot of new production techniques were developed. Not all techniques were successful, but some are still used this day, for example float glass and down-draw glass.

Image 6 - Crown glass. Photo: Edward Belding

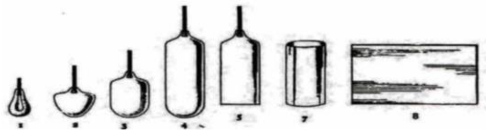


Image 8 - Making of cylinder glass. Image: A. Sauzay

The Crystal Palace (Image 7) is born out the desire to grow exotic plants in a moderate climate. The glass allows for the sunlight to go through and it captures the heat of the sunlight. Those greenhouses were the ideal place for experiments with glass and steel (Wurm, 2007). The Crystal Palace is one of the highlights of the glass and steel industry during the industrial revolution. That is because the thin steel profiles and big sheets of glass, in that time is was unique to get this much natural light inside. A lookalike of the Crystal Palace is built in the Netherlands and is named 'Pales van Volksvlijt (Image 9).

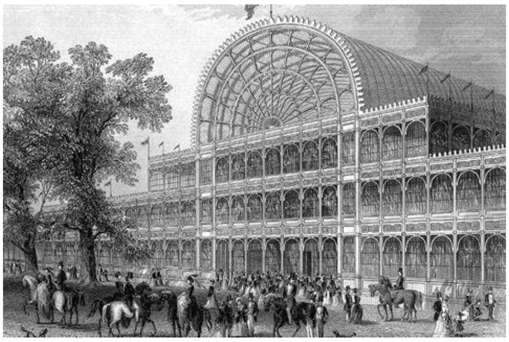


Image 7 - Crystal Palace, London 1851. Designer: Sir Joseph Paxton.

Architects became to understand the value natural light inside. To build with glass became more and more about getting outside, inside. But this time better. With the glass it is possible to control the climate inside, while you still feel like you are outside. Architects believed they could build a better living environment when they cover the space with glass.

Image 9 - Paleis van Volksvlijt in Amsteram. Photo: NOS.

2.2 Present

Glass is applied in every building, but with different purposes. The normal/ original application of glass is still as a window. This can be a regular size window (1 x 2m) in residential buildings. But offices often have big glass curtain walls. Some older residential buildings have windows with one glass pane, but most buildings nowadays have two layered glass panes and every new residential buildings has windows with three glass panes. This is due to the thermal insulation regulations in the Dutch Building Code of 2012 (van der Heide et al., 2016). The company Reynaers develops the newest windows and curtain walls. The development of glass is not only limited to windows and insulation. Glass can also be used as a construction material. The most important factor to take in account when using glass as construction material is safety. Safety is important because when glass brakes, it brakes completely. Therefore multiple layers of glass are laminated to each other, to maintain structural cohesion and the outer layer is a sacrificial layer.

2.2.1 Structural application

The Apple House in New York is one of the first buildings which is completely build up from glass (Image 10). Only some small parts, to connect the beams to the façade, are not glass but a metal. The first design was built in 2006 and contained 106 panels and 250 fittings. With the re-design of the cube in 2011 it was possible to reduce the amount of panels to 15 and the fittings to 40. By laminating the panels it was possible to produce much larger panels, with a size up to 18 x 3,6 meters. The details and connections are more sophisticated because the metallic inserts are entirely laminated in the glass (Eckersley O'Callaghan, 2019). The architect is Bohlin Cywinski Jackson and the structural design is done by Eckersley O'Callaghan.

Image 10 - The Apple House, New York. 2006. Photo: EOC

The Steve Jobs Theatre in California is a building with the newest structural glass application (Image 11). The dimensions of the panels are 7 x 3,2 meters. The glass panels are build-up of four layers of 12 mm thick glass. The connection between the panels is just a silicone bond of 30 mm wide. This building is an extraordinary building and the first which is build this way. The roof is kept in place via steel rods in the silicone sealant. The stability of the building is secured by the round form of the building itself with a diameter of 41 meters (Eckersley O'Callaghan, 2018). The architect is Foster + Partners and the structural design is done by Eckersley O'Callaghan.

Image 11 - Steve Job Theatre, California. 2018. Photo: Foster + Partners

The MAS museum in Antwerp gives the visitor an illusion of massive floating boxes (Image 12). In reality the boxes are not floating, they are kept in place by big, invisible trusses. But still, the boxes will move independently from each other due to life load. The curved glass panels are designed to withstand the load due to this movement. The curvature is brought in the panels to prevent the buckling phenomenon in the loaded elements. The glass is at the top and bottom connected clamps to the floors and the dimensions of the panels are 5,5 m x 3,6 m (ABT, 2019). The architect is Neutelings Riedijk and the structural design is done by ABT Antwerp.

Image 12 - MAS museum Antwerp, 2011. Photo: Dirk Verwoerd

2.2.2 Thermal glass application

A regular, old window with only one glass layer, without any coatings, has a U-value of 5,6 W/m²K (Image 14). This was the start of windows in the built environment. When the windows became bigger, and comfort and saving energy became important, a window with two glass layers was introduced. The U value of a window with two layers of glass, without any coatings is 2,6 W/m²/K. Different kind of gasses, such as argon and krypton, and coatings, such as hard and soft coatings, are introduced to improve the thermal performance of the window. The window with these improvement is called a HR+/ HR++ glass and has an U value of 1,1 W/m²K. It is even possible to buy triple or quadruple glass with U = 0.5 W/m²K or less (Image 14) (Koninklijk Nederlands Normalisatie-Instituut, 2018). Appendix 15.7show a standardized table with the effect of different gasses on the U value of a window. The use of this many layers of glass increases the weight significantly. But AGC shows that the amount of glass layers is not essential for the thermal insulation with a new product. AGC, a leading company on innovative glass applications in the building industry, made a new glass panel called ‘Fineo’ (AGC Glass, 2019a). It is a Vacuum Insulating Glass (VIG) panel of two times 3 mm glass panes with a cavity of 0,1mm (Image 15). As seen in Image 15, the panel has a lot of small, black dots. These are spaces to prevent the two glass panes to touch each other, because there is no air or gas inside the panel. This new window panes shows that the coatings and gasses have a great influence, as well as the way the spacer is used. The current u value of this panel is 0,7 W/m²/K.

Image 14 - Single layer and double layer of glass in window pane. Image:

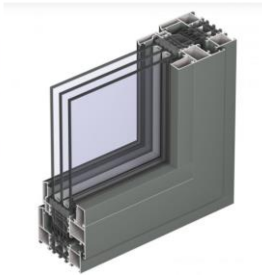


Image 14 - Triple layer of glass in window frame. Image: Reynaers.

Image 15 - VIG panel. 2 layers of 3mm glass with cavity of 0,1mm. Photo: AGC

2.2.3 Future

It is hard to predict the future, but for now it is possible to take a look at the near future. The trend in architecture is to get as much natural light inside as possible, together with a minimalistic use of materials. Thus, the use of glass in the built environment is still increasing, as well as the need for sustainable solutions in terms of material use and thermal insulation. This applies for both residential and non-residential buildings. The result is a need for high performance building materials and products need to be invented. To answer to this demand for high performance materials and products, new and innovative designs are brought on the market. An example of a new material is the thin glass screen on smart phones (Image 16). This is very thin glass which has a slightly different chemical composition and production process from normal window glass. Because the material is very thin, transparent and strong, it is very interesting to use this material. Less material means a reduction in the CO_2 emissions during the production process of the materials.

The flexibility of the material is a challenge. Several ideas are proposed to enhance this flexibility, for example image 17 and 18, or to stiffen it. Zha used an pneumatic exoskeleton to move the glass pane. The movement of the window can create extra airflow, when this pane is applied in a façade (Zha, 2018). And Simoen bend the glass to stiffen it. When the glass is bend, is cannot buckle (Simoen, 2016).

Image 16 - Thin glass screen on iPhone. Image: Apple.com.

Image 17 - Pneumatic exoskeletonwindow. Image: Congrui Zha, 2018.

Image 18 - Cold bent glass in the façade. Image: Carlym Simoen, 2016.

LITERATURE STUDY

3 SANDWICH STRUCTURES

Sandwich structures are widely used in aerospace engineering. The sandwich panels in airplanes are build up from high quality and expensive materials which are as lightweight and stiff as possible. Sandwich structures are sometimes used in the building industry, mostly in façades. The weight of the panels is, in general, no issue in the building industry. The reason to use sandwich structures is thermal insulation. This means that sandwich structures are not used in the most optimal way. In this chapter the first sub-question will be answered:

What is a sandwich structure and which typologies are used to create a stiff and lightweight structure?

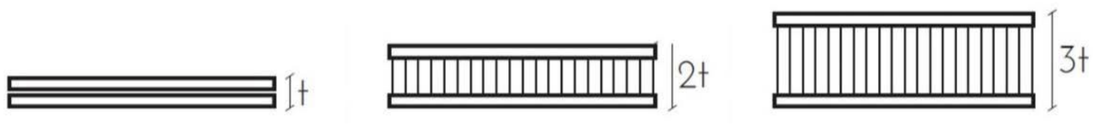
3.1 General properties of sandwich structures

A sandwich panel consist of two thin, stiff and strong sheets, which are the faces. A thick layer of low density material, mostly arranged in a pattern, which is the core can be found in between these faces. The faces and the core are bonded together to create a lightweight and stiff panel (Ashby, Shercliff, & Cebon, 2014).

Evans, Hutchinson & Fleck (2001) talk about the purpose of sandwich structures in their paper on 'The topological design of multifunctional cellular metals'. They want to add even more functionalities to the sandwich panel:

> *"The underlying concept is to design the topology of the structural alloy to carry load, conduct heat (and so on) in the most efficient manner (that is, at lowest weight): whereupon, the intervening space can be used to enable other functionalities, such has passages for flowing fluids that remove heat, spatially distributing plastic deformations that absorb energy and adding power sources."* (Evans, Hutchinson, & Fleck, 2001, page 2)

The most important factors are the weight, to carry load, heat conduction and smart use of the space in between the faces. In the context of this research, the main criteria are: lightweight, use as less materials as possible, carry load, provide thermal insulation and let daylight through. Also, Evans makes a distinction between periodic patterns and lattice pattern in his paper (Evans et al., 2001). Vitalis, Veer & Oikonomopoulou, 2018 made a very informative diagram about the load carries properties in comparison with the weight of the sandwich panel (Image 19). They show that with three times increase of thickness the weight only increases with 40%, but the stiffness increases 15 times (Vitalis, Veer, & Oikonomopoulou, 2018).



Relative Weight			
	1	1,2	1,4
Relative Bending Stiffness			
	1	5	15
Relative Strength			
	1	2,5	6,5

Image 19 - Increase thickness of core

3.2 Pattern

Wadley (2006) presents an overview of different patterns for a sandwich structure in his paper 'Multifunctional periodic cellular metals' (Image 20). These images show different core structures and their density versus compressive strength (Pingle, Fleck, Deshpande, & Wadley, 2011; Wadley, 2006) (Image 21). The pyramidical lattice structure is the most lightweight. Therefore this structure is chosen in this research as starting point.

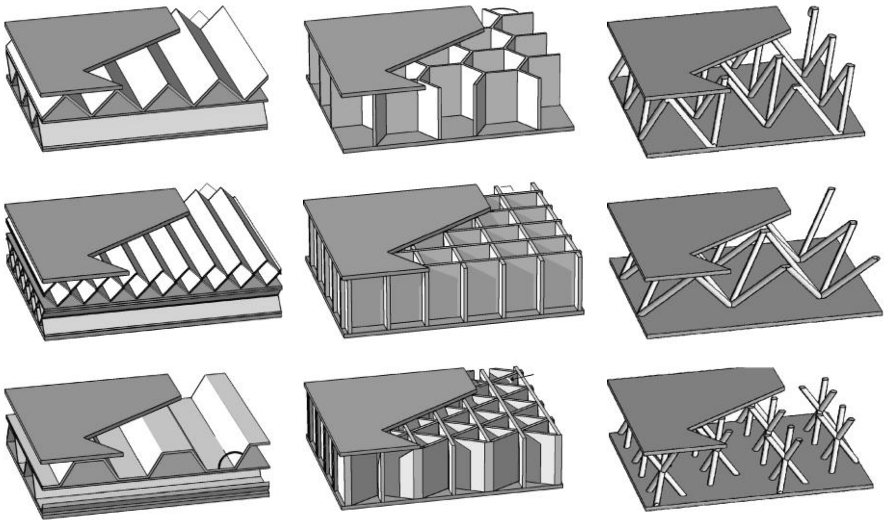


Image 20 - Different patterns in sandwich structures. Wadly, 2006.

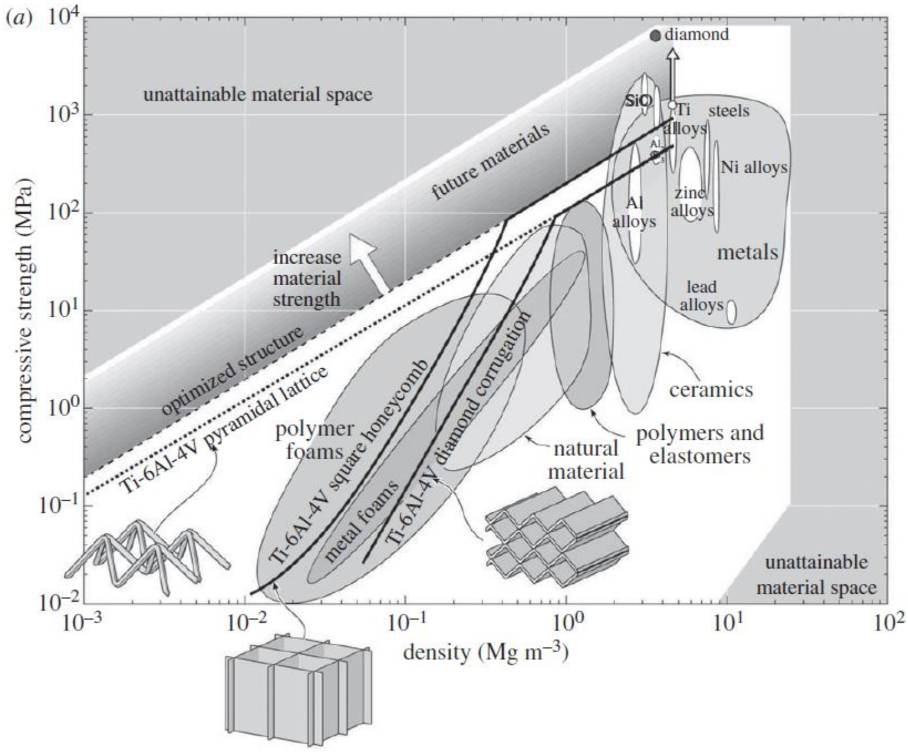


Image 21 - Compressive strength of lattice materials shown on a plot of strength versus density along with other engineering materials. Pingle, Fleck, Deshpande & Wadley, 2011.

Out-of-plane loading of the sandwich structure is discussed in most of the papers. It was really hard to find a paper about in-plane loaded structures or compression tests. Only later, when the tests were already done, a paper named 'Exploiting negative Poisson's ratio to design 3D-printed composites with enhanced mechanical properties (Li, Chen, Hu, Li, & Wang, 2018). The images from this paper show that a trussed pattern is not the best choice when loaded in-plane (Image 22 and Image 23).

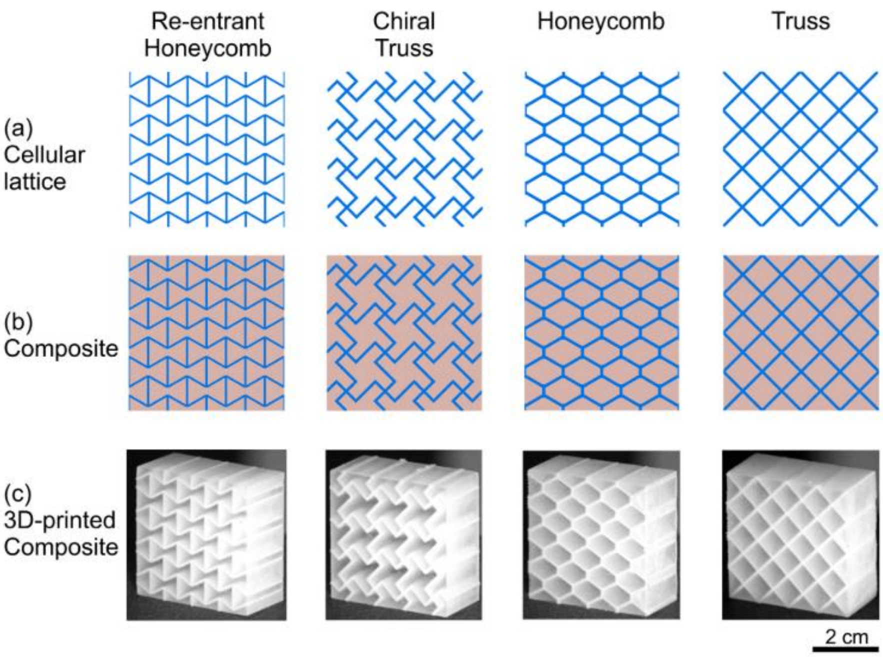


Fig. 1. Schematics of (a) lattice structures, (b) lattice reinforced composite structures and (c) 3D-printed lattice reinforced composite specimens consisting of 4 × 4 unit cells with re-entrant honeycomb, chiral truss, honeycomb, and truss structures.

Image 22 - different types of patterns. Image from Li, et al, 2018.

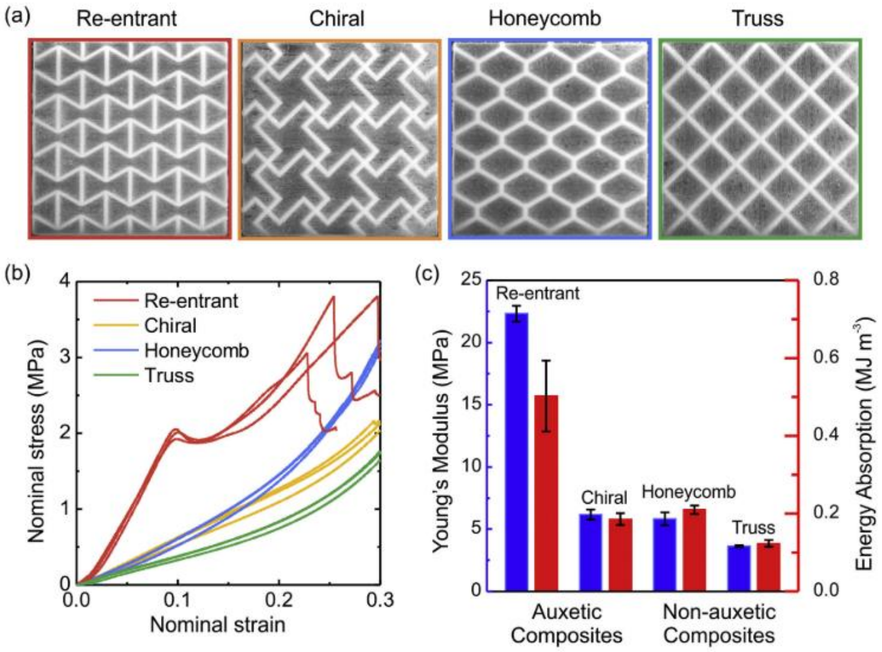


Fig. 3. Mechanical response of the 3D-printed lattice reinforced composites during uniaxial compression tests. (a) The 3D-printed composites with a re-entrant honeycomb reinforced, chiral truss reinforced, regular honeycomb reinforced, and truss reinforced designs. (b) Nominal stress and strain curves for various designs. For each design, three specimens are tested to validate the repeatability. (c) Calculated Young's modulus from the initial linear region of the nominal stress-strain curves and computed energy absorption as the work under the nominal stress-strain curve before 25% uniaxial compressive strain for each composite sample.

Image 23 - Stress-strain diagram for different compressed patterns. Image from Li, et al, 2108.

3.3 Bonding

There are two options to bond two different materials. It can be done through lamination or by using an adhesive. Both processes require specific properties of the to be processed materials. That raises the question:

What is the best way to bond the thin glass and the core to obtain structural cohesion?

3.3.1 Lamination

PolyVinyl Butyral (PVB), SentryGlass (SG), TPU & Ethylene Vinyl Acetate (EVA) are proven interlayers to laminate two sheets of glass. Lamination is done with an Autoclave. The layers which need to be bonded (glass, interlayer and core) are put on each other, in a vacuum bag. Then the materials are put in an oven and heated till 135 ˚C. The pressure and the heat makes the different layers bond and create an almost uniform structure (Louter, 2017; Wurm, 2007).

3.3.2 Adhesive bonding

An adhesive is needed to bond the 3D printed core to the thin glass. In general, there are four types of adhesives used in the glass industry to bond glass (Louter, Veer, & Belis, 2008). The four types are discussed in this chapter. After that the strength and weakness considering loading directions will be discussed. But first the general procedure to create adhesive joints will be discussed.

General procedure to create adhesive joints

1. Surface pre-treatment (cleaning & degreasing, etc.)
2. Adhesive preparations (mixing of components)
3. Application of the adhesive
4. Joining the substrates (thickness control)
5. Curing (2-component is chemical reaction, cure to air, UV-curing)

Types of adhesives

There are four types of adhesives which are mostly used in the glass and façade industry. They are: epoxy, acrylate, silicone, polyurethane (Louter, 2017). The properties of the adhesive bonds are shown in Table 1. The type of glue is going to be selected in combination with the 3D printing material. Machalická & Eliášová tested two types of adhesive to bond glass to other materials (Machalická & Eliášová, 2017). PU, one and two component and a UV-curing acrylate.

Table 1 - Summary of adhesive properties (Louter, 2017).

	Epoxy	Acrylic	Silicone	Polyurethane
Types	2-components Hybrid epoxy with increased elasticity (toughened epoxy)	1. Cyanoacrylate 2. methacrylate 3. UV-curing acrylate	1-component & 2-component	1-component & 2-component
Curing	UV-curing & cold curing & hot curing	1. air curing 3. UV-curing	1. air curing 2. chemical curing Hot curing film (TSSA)	Physical & chemical curing
General properties	High strength and stiffness	In general a high shear strength.	Low strength and stiffness (exception: TSSA)	Medium strength and stiffness Stronger than silicone and MS-polymers, less brittle than epoxies and acrylates
Thickness	<0,5mm	<0,5mm	>6mm	
Durability		Methacrylate's: good durability UV-acrylates: some durability problems	High durability, UV as well as humidity	Used to have low UV resistance (UV-blocking primers)
Colour	Transparent	Transparent	Not transparent	Not transparent
Structural application	Aircrafts, boats, metal structures…	Adhesive layers in structural double-sided tape Indoor applications like bonded door hinges etc.	Structural sealant glazing (ETAG 002)	In automotive, e.g. windshield bonding. Bonding non-transparent façade panels or external insulation.
Materials	Metal	Plastics, glass	Glass	

Bonding load

An adhesive bonding can take certain loads, and performs bad under the other loads. Adhesives are in general bad against peeling forces and cleavage. But they perform very well under a tensile force, shear force and compressive force (Ashby et al., 2014) (Image 24).

The expected load on the bonding is tensile load when delamination occurs and shear force when the panel starts to buckle.

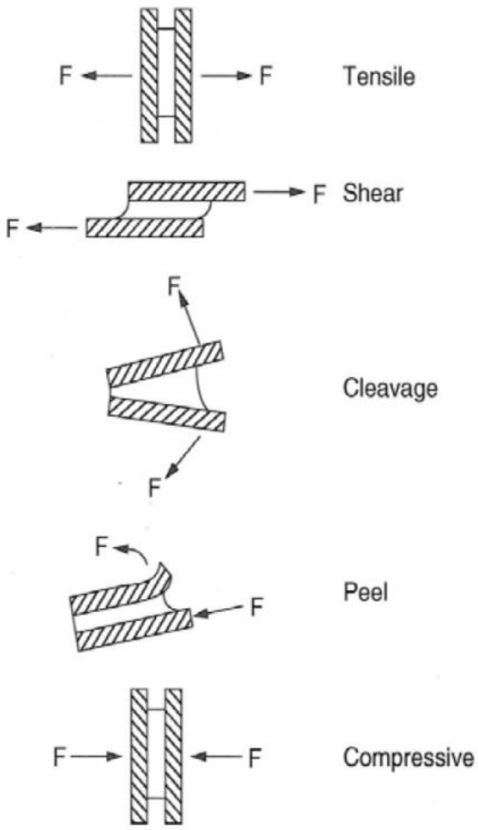


Image 24 - Different loads on adhesive bonds.

3.4 Failure modes

Ratwani (2010) has written a paper on 'Composite materials and sandwich structures – a primer'. Several failure modes of sandwich structures are described in this paper (Image 25).

General buckling of a panel might occur if the panel is not thick enough or the core is not rigid enough.

Shear crimping occurs as a consequence of general buckling. It happens when the core has a low shear modulus or when the bond has low shear strength.

Face wrinkling happens when the face sheet buckles and the core acts as an elastic foundation. The face sheet may wrinkle to the inside or outside, this depends on the relative strength of the core in compression and adhesive strength in tension.

Intracell buckling (dimpling) happens in panels with cellular cores due to thin face sheets or large core cell size.

Face sheet failure happens due to insufficient panel thickness, face sheet thickness or face sheet strength.

Transverse shear failure is caused by low core shear strength of insufficient panel thickness.

Flexural crushing of core is caused by insufficient core compressive strength or excessive panel deflection.

Local crushing of core is caused by low compressive strength of the panel (Ratwani, 2010).

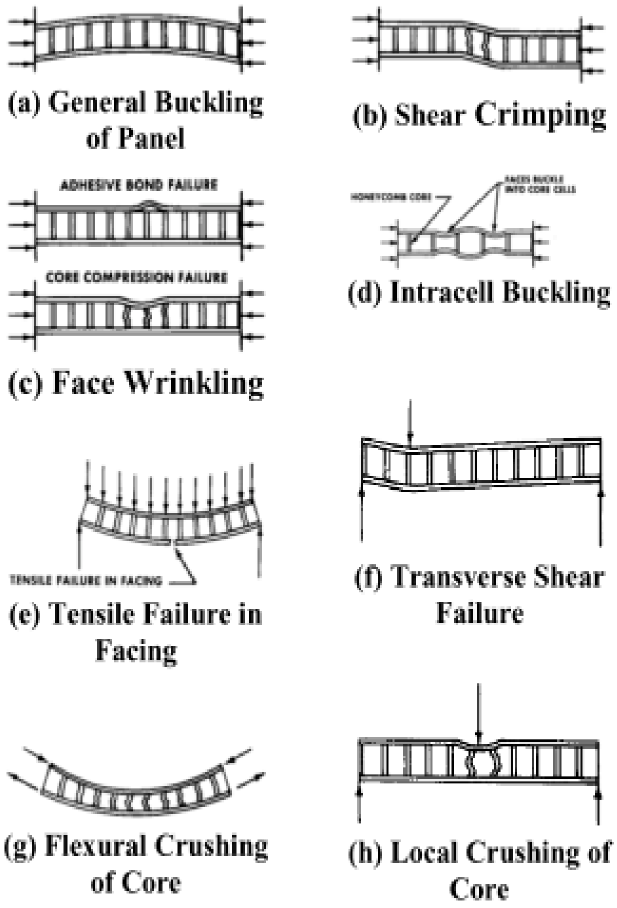


Image 25 - Failure modes in sandwich structures. Ratwani, 2010.

3.5 Conclusion

What is a sandwich structure and which typologies are used to create a stiff and lightweight structure?

The most important factors to make use of a sandwich structure are the weight and smart use of the structure. The pyramidical lattice structure is the most lightweight. Therefore this structure is chosen in this research as starting point.

Because the glass needs to be bonded to a thermoplastic, it is best to use an UV-curing acrylate.

When the panel, as described earlier in this thesis, is loaded in-plane, it is probably going to buckle (Image 26). When the panel buckles, the core needs to withstand the occurring shear forces.

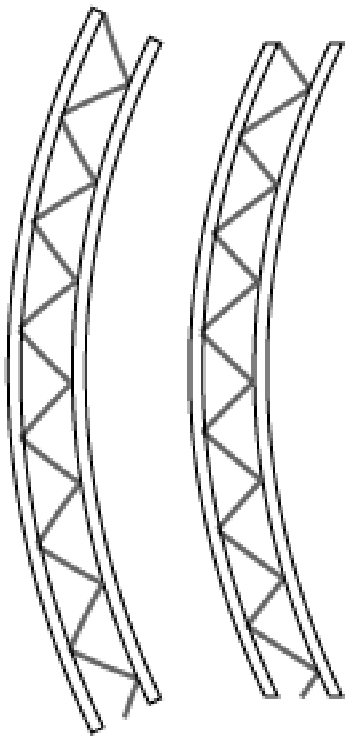


Image 26 - Buckling of a sandwich panel. Own image.

4 (THIN) GLASS

Glass in general and the difference with thin glass will be discussed in this chapter. Glass has very specific characteristics and therefore production process. The following, first sub-question is going to be answered:

What is (thin) glass and how is it made?

4.1 Chemical composition

Thousands of years ago it happened that some people made glass by accident. Sand got so hot that it started to melt, but it did not crystallize. When the mixture cooled down, it became one solid block. Glass is made of sand (silica) and other minerals which happened to be present in the mixture (Table 2). Image 27 shows the chemical bond of silica and oxygen, which is the base for glass. One part of silica is always attached to three parts of oxygen, the bond can be ordered or chaotic. Nowadays it is possible to add, or subtract different materials to play with the properties of the glass. Therefore different types of glass are made for different functions, for example ovenware glass. The glass used as ovenware has a different chemical composition than glass used in the built environment, because it has to resist higher temperatures. Glass has a density of around 2500 kg/m³, a young's modulus of 70000 N/mm² and a poisson ratio of 0,22. With a side note that all these numbers differ per glass type.

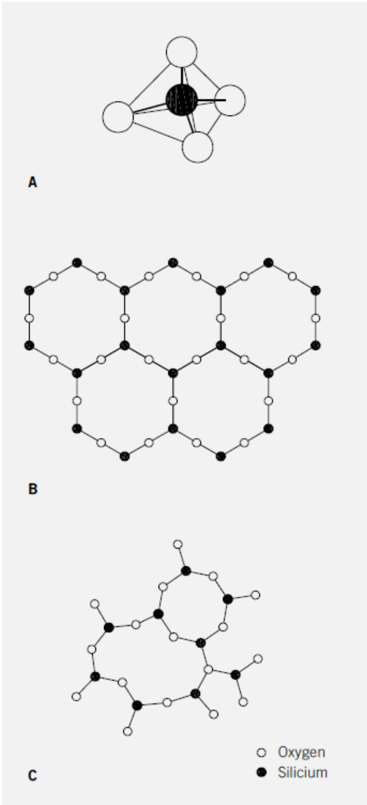


Image 27 - Chemical bond of glass. Wurm. 2007

Table 2 - General glass composition (Wurm, 2007)

Material	Formula	Composition (%)
Silica	SiO_2	69-74
Lime	CaO	5-14
Soda	Na_2O	10-16
Magnesia	MgO	0-6
Alumina	AL_2O_3	0-3

The glass types which are most used are soda-lime, borosilicate and aluminosilicate. They belong to the biggest group for most types of glasses which is the silicate group. Soda-lime is the most common type and can be found in windows and bottles. Borosilicate is the glass of ovenware. The lime is replaced by boron oxide, which has a higher melting point. Therefore, the glass has a high resistance to thermal shock, a lower expansion coefficient and is harder to work. Aluminosilicate glass contains a high level of aluminium (Ashby, 2013). Table 3 shows the composition of the three glass types.

Table 3 - Composition of different glass types (Wurm, 2007).

		Soda-lime	Borosilicate	Aluminosilicate
Material	*Formula*	*Composition (%)*	*Composition (%)*	*Composition (%)*
Silica	SiO_2	73	74	60
Soda	Na_2O	17	4	2
Boron oxide	B_2O_3	-	15	10
Lead oxide	PbO	-	5	-
Lime	CaO	5	-	8
Magnesia	MgO	4	-	-
Alumina	Al_2O_3	1	2	20

4.2 Physical properties

One of the most important characteristic of glass is brittle behaviour when loaded in tension. There is no warning before the glass breaks, it just breaks. This is in contrast with most other materials which show pre-fracture behaviour, for example through cracks or deformation (Image 28). But glass is a very good material when loaded in compression, like concrete. The Young's modulus is around 70 – 80 GPa.

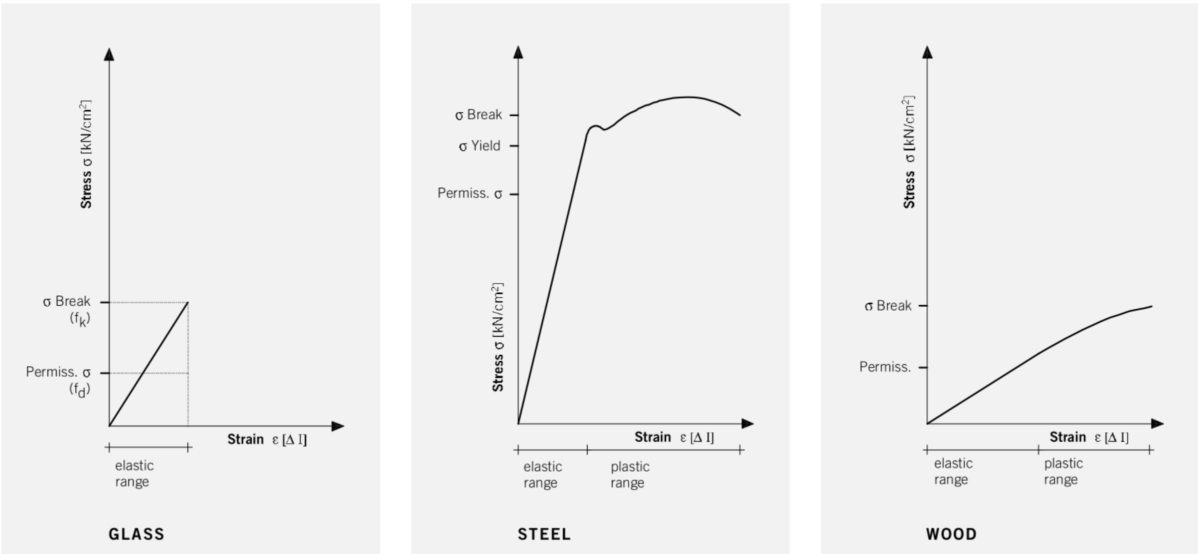


Image 28 - Stress/ strain curvature for glass, steel and wood (Wurm, 2007).

4.3 Primary production process

Glass producers have always tried to make the production process better, faster and cheaper. Over the years different kind of process have been developed. The most common production methods are discussed here.

4.3.1 *Float glass*

Float glass is a production technique which is mostly used. The image below (Image 29) show the different steps in the production technique. The production starts with the raw materials and some pieces of glass which are being recycled. These materials are mixed and heated in the furnace to make one mass of the different ingredients. The furnace has a temperature of 1600˚C. When the materials are completely heated and mixed, it flows over to a tin bath. The temperature is 1100˚C when it enters the tin bath. The glass stays on top because the tin is way heavier than the glass. This is the floating process. This is a very slow and controlled process. The glass should get the precise thickness and it has to be very smooth. At the end of the tin bath the glass is cooled down till 600˚C and almost completely solidified. The final step is to cool the glass more with air coolers to 200˚C, which compresses the outside layer. The glass is now cut into the right size and put on a truck (AGC Glass, 2019b).

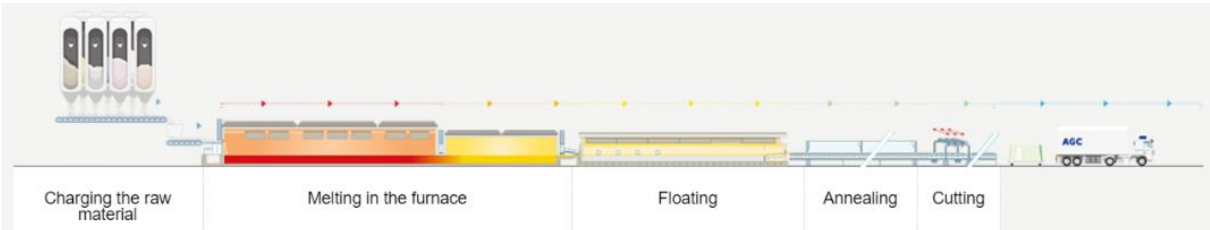


Image 29 - Production process of float glass. Image: AGC.

4.3.2 *Rolled glass*

Rolled glass almost looks the same, but instead of the tin bath, the glass goes on a bank of rolls. Rolled glass is not very common anymore because it is possible to see small deflections in the pane due to the rolls.

4.3.3 *Overflow and down-draw*

The overflow and down-draw process are similar and both processes are still used to produce thin glass.

The down-draw process was patented in 1925 by inventor A. Fowle from Libbey Owens Sheet Glass Co. The molten glass flows through the reservoir and is poured on a slab (image 22). The flow speed is controlled by a slot. the glass flows down to the tip. The opening of the tip defines the thickness of the glass. When the glass flows out, it is cooled water. The cooled glass sheet is guided down by rolls (Image 30). This method is first used to produce car shields (Eglass, 2016).

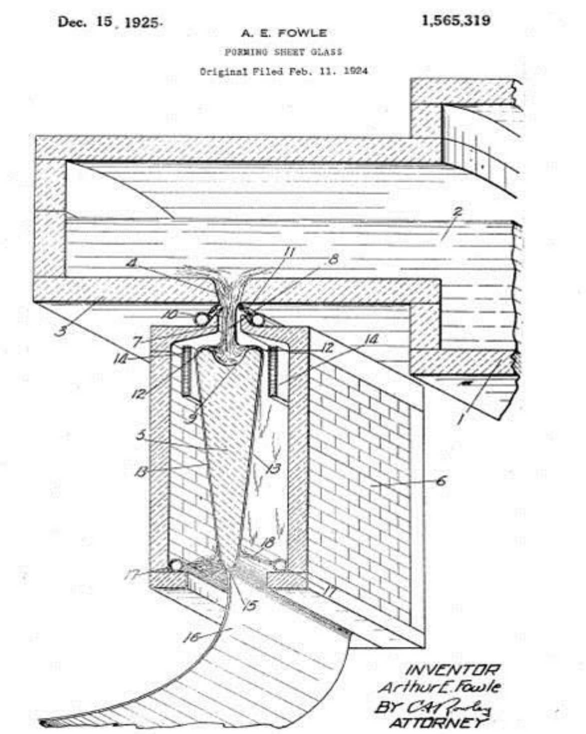


Image 30 - Down-draw process. Image: A. Fowle.

Corning re-invented the down-draw process by designing a v-shaped box called 'isopipe' (Image 31). This production process is called 'overflow' or 'fusion' process. The isopipe has the same temperature as the molten glass to ensure an uniform flow. Corning writes on their website:

> *"Molten glass flows evenly over the top edges of the isopipe, forming two thin, sheet-like streams along the outer surfaces. The two sheets meet at the V-shaped bottom point of the isopipe and fuse into a single sheet."* (Corning, 2018, page1)

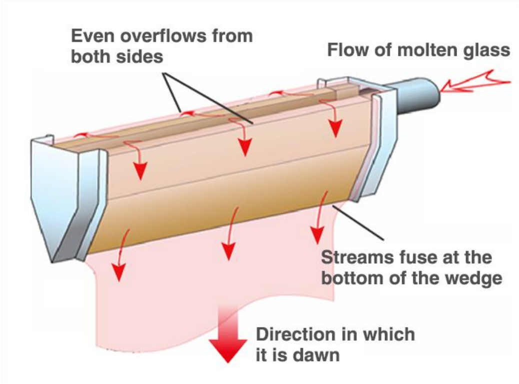


Image 31 - Overflow process. Image from www.neg.co.jp.

After the fusion the glass is guided by drawing equipment and as is goes down it is cooled in mid-air. The fusion process is precisely controlled as it impacts the thickness and quality of the glass. At the bottom of the draw (Image 32) the glass is cut and the secondary processes will take place (Corning, 2018).

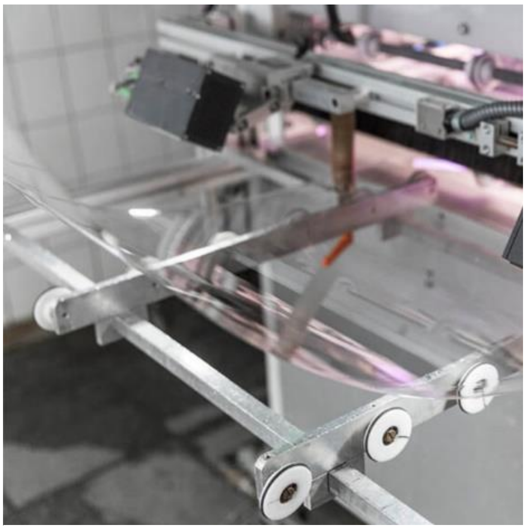


Image 32 - Down-draw of thin glass. Photo SCHOTT.

4.4 Post production processes

The glass can be strengthened, bent, cut and it is also possible to apply a coating on the glass to improve its properties. All these treatments are secondary production processes.

4.4.1 Strengthening

There are two processes to strengthen the glass. This is done with a heat treatment or a chemical treatment (O'Regan, 2014; Wurm, 2007). Those treatments can be divided in four different levels: annealing, heat-strengthening, fully-tempering and chemically strengthening. The different treatments can be identified by the break pattern of glass (Image 33), but a break pattern does not only show the treatment it got, but it also shows the weak spot.

Annealed glass breaks in large pieces. It is the glass which comes directly from production. It can break when temperature difference occur in the material. The glass must be at least 4 mm thick.

Heat strengthening glass panes are heated till 620˚C and then quenched quickly by cool air. The surface cools down faster than the inside. Tension occurs inside the panel, the surfaces gets compressed. The surface pre-compression is between $24N/mm^2$ to $52N/mm^2$. The glass must be between 4 mm and 12 mm thick. When the glass breaks, the pieces are smaller than the pieces of annealed-glass.

Fully-tempered glass is also heated till 620 ˚C, this is the same as for heat strengthened glass, there is one difference. The cooling down goes faster and the surface gets compressed more. The compression is between $80N/mm^2$ and $150N/mm^2$. The glass must be between 4 mm and 19 mm thick. When the glass brakes, it shatters in small pieces. This characteristic is favourable when the glass is applied as a roof. The small pieces do not cause that much damage if it falls on your head.

Left: annealed glass *Middle: heat-strengthened* *Right: fully-tempered*

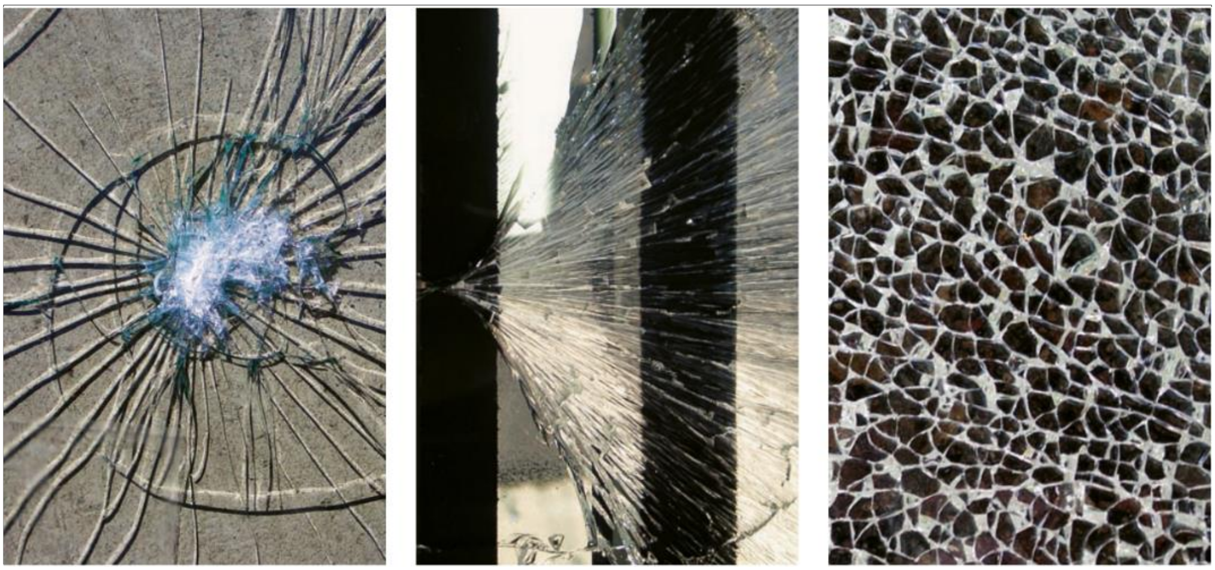


Image 33 - Break pattern of glass. Wurm, 2017.

Chemical strengthened glass panes are dipped in a electrolysis bath which contains potassium ions. Sodium ions on the surface of the glass are exchanged for potassium ions, which are 30% bigger. Two advantages of this process over heat strengthening are: less deformation during the process and thinner sheets of glass can be toughened. Two disadvantages are: a much thinner compressive surface and it is more expensive than thermal strengthening (Image 34).

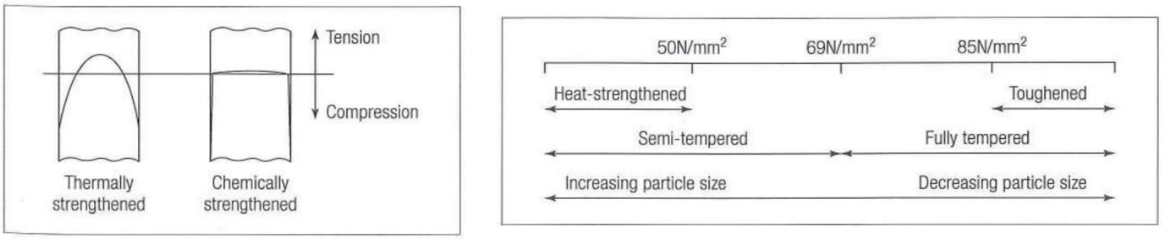


Image 34 - Effect of strengthening the glass. Wurm, 2007.

4.4.2 Edge processing

Glass production is a continues process. The standard dimensions of a glass plate are 6 x 3,2 m. When a smaller plate is ordered, it needs to be cut out the big plate. This can be done in two ways, one way is cutting with a sharp knife and the other way is by using a waterjet. Cutting the glass means that the surface is scratched. Scratching the surface means distortion of the compressive layer and therefore the glass is weakened. This means that that all the edges of a glass sheet need to be handled carefully, it is not possible to apply a load directly on the edge (Veer, 2007; Wurm, 2007). The edges of a sheet are usually ground to smoothen the surface and thus provide a better strength. The angle of the edge is 45˚, in the belief that this improves the strength (Image 35). But some edges are finished by sanding or polishing.

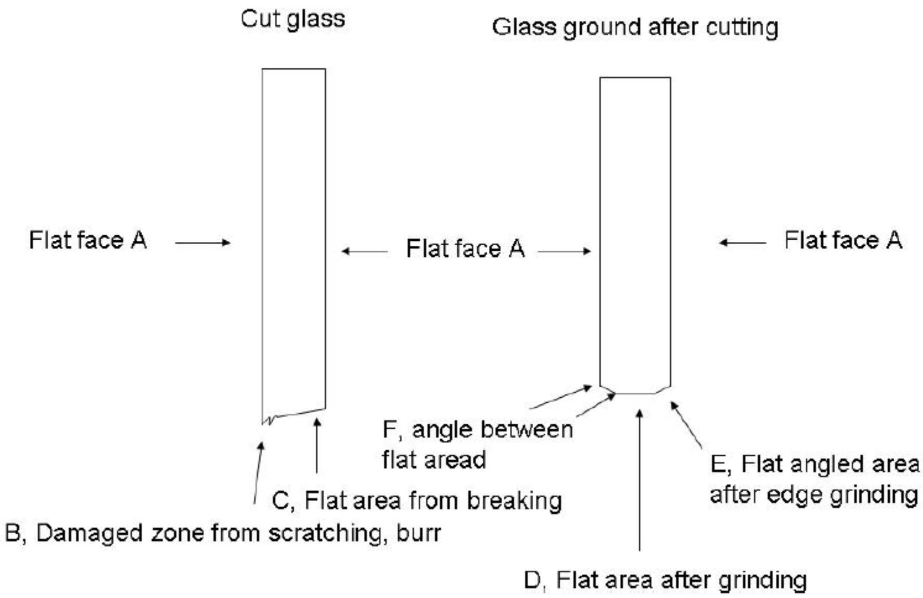


Image 35 - Edge finish. Veer, 2007.

4.4.3 Curved glass

Glass can be bent in one of two different ways: hot bent and cold bent (O'Regan, 2014; Wurm, 2007). It depends on the situation and desired curvature to use one of the two options.

Hot bending of glass is done by placing a glass pane above a mould. The glass is then heated between 600˚C and 750˚C, so the glass turns semi- fluid. The semi-fluid sheet takes the form of the mould, thereafter the glass is cooled. The glass is now permanently bent.

Cold bending of glass is done in a temperature range of 20˚C to 70˚C. When glass is cold bent it needs a supporting structure to stay bent, because when the structure is taken away, the glass will go back to its former appearance. Image 36 shows the combined stresses in a glass sheet when the glass is tempered and cold bend.

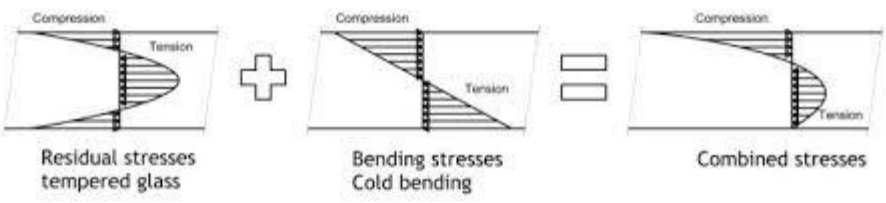


Image 36 - Cold bending stresses in glass. retrieved from Ivo Vrouwe.

4.4.4 Coating

Coatings are put on the glass to control the solar transmittance. There are two ways a coating can be applied on a sheet of glass. They are called on-line and off-line coatings. On-line coating: The coating is put on the glass while it is still a fluid, this is a pyrolytic coating. Off-line coating: The coating is put on the glass sheet when it is already cooled-down, this is a sputtered coating (Bokel, 2017).

4.4.5 Lamination

Lamination of two, or more, glass panes is done with an interlayer. The interlayer is a polymer and there are different types of interlayers, such as PolyVinyl Butyral (PVB), SentryGlass (SG), TPU & Ethylene Vinyl Acetate (EVA) (Louter, 2017; Wurm, 2007). Lamination is done with an 'autoclave'. An autoclave is an compression chamber and an oven in once. The layers which need to be bonded (glass, interlayer, glass) are put on each other and in a vacuum bag. Than the materials are put in an oven and heated till 135 ˚C. This makes the interlayer melt and therefore bond with the glass. Lamination gives the glass new structural properties (Image 37).

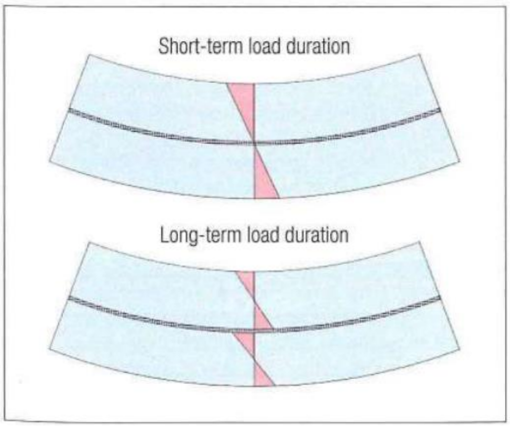


Image 37 - Bending stress in laminated glass. Wurm, 2007.

Safety

When the glass is used as a load bearing structure, it needs a sacrificial layer. when someone hits the glass, accidently or not, the sacrificial layer is there to protect the integrity of the main structure. The sacrificial layer may break and the structure is safe.

4.5 Thin glass - characteristics

Due to its thinness it is only possible to chemically strengthen it, and due to the overflow production process it is not yet possible to apply an on-line coating. Some experiments are done to apply a off-line coating, but this is not a standard production process yet. Also, the edge of the material is very sensitive. This has to be taken in account when designing the edge connection. The biggest advantage of thin glass is it's thinness, flexibility and scratch resistance. Therefore it is now widely used as mobile phone screen and microchips. Different types of thin glass are produced, only small differences in chemical composition. The thin glass used in this research is Falcon glass from AGC. The properties of the glass are stated below, in Table 4 and Table 5 .

Table 4 - Properties of thin glass from AGC.

Properties	Parameters	1,6mm	0,5mm
Mechanical properties	Density	2,48 g/cm³	
	Young's Modulus	71 - 73 GPa	
	Poisson's Ratio	0,22	
	Shear modulus	30 GPa	
Chemical strengthening properties	Depth of layer	>40 μm	
	Compressive stress	>500 MPa	
Thermal properties	T_g	~555˚	
	Coefficient of thermal expansion	$90 \cdot 10^{-6}$	
	Thermal conductivity	0,95 W/(m	

Table 5 - Size of the glass, AGC.

Thickness (mm)	Standard tolerance	Sheet size (mm)
0,5	+/- 0,05 mm	1245 x 3210
0,7		1350 x 3210
1,1		1480 x 3210
2,1		1600 x 3210

Image 38 - Thin glass. Photo: SCHOTT, 2015

4.6 Conclusion

What is (thin) glass and how is it made?

In general, glass is a brittle material, very week in tension but very strong in compression. Glass has different chemical compositions and because of that different characteristics. This is shown in the composition of soda-lime glass and aluminosilicate glass, the silica sand is replaced by alumina (4.1).This gives the aluminosilicate glass a higher melting point.

There are several different production processes for the production of a glass sheet, the most common one is 'float glass'. Thin glass is a glass sheet with a thickness of 0,5 – 1,6mm (AGC Glass, 2017) and is produced through the overflow process. Due to its thinness it can only be chemically strengthened. Strengthening is a process to create tension in the surface area (Wurm, 2007). The edges of a sheet are very sensitive due to this strengthening.

It is not possible yet to apply a coating on thin glass. Experiments are done to apply a off-line, soft coating at this moment.

5 ADDITIVE MANUFACTURING

Several production techniques for the core are discussed in this chapter. It starts with a rapid prototype technique which is used to produce the panels during this research. After that other techniques for mass production are discussed. The following, third sub-question will be answered:

Which production technique and material is most suitable to realize the core?

5.1 FDM

In this chapter, 3D printers, filament, required files and printing technique will be discussed. Fused Deposit Modelling (FDM) is an Additive Manufacturing (AM) process. A 3D-printer is an AM process and mostly used for rapid prototyping because it is possible to print a lot of different products without a lot of preparation, only a 3D-printer and a laptop is needed. But the printing takes a lot of time, in comparison with other production processes. This 3D-printing is therefore not suitable for mass production (3D HUBS, 2019b).

5.1.1 3D-printer

A 3D printer is a machine which can turn a 3D model, in a computer, into an 3D object. A material, in the shape of a wire, on a roll, is heated by a nozzle. The nozzle can move in three directions, the X, Y and Z direction (Redwood, Schöffer, & Garret, 2017). In this way, layer by layer, an object is printed. Everyone can buy or make a printer themselves. With a little knowledge it is possible for everyone to print. But to produce a high quality of print, a lot of knowledge is needed.

The size of the print is determined by the size of the machine. The print is placed on a bed, which usually moves up and down. A standard printer is an Ultimaker (Image 39). For example the Ultimaker 3 has a bed size of 215 x 215 mm and can print a height of 200mm. The bed is heated, which ensure a good bond of the printed material to the bed. This is important because the already printed material should not move separately from the bed. When the print is not well connected to the bed and the print moves, the layers of material cannot be put on each other. The result is a distorted print (3D ninja, 2019).

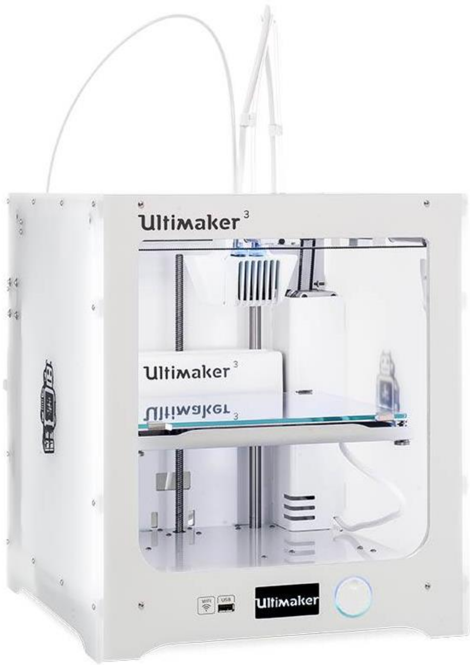


Image 39 - Ultimaker 3. From 3dninja.nl

5.1.2 Print technique

The printer deposits layers of flued material on top of each other (Image 40). A slope of 45˚ can be printed without cooling the filament directly when it is printed. Supports are needed for wider slopes. It is possible to print straight horizontally when the print is quickly cooled. A solid print will be constructed with an outer layer and an infill. The outer layer is visible and defines the form, while the infill provides stability to the structure. The infill is usually 20% and build-up from rectangles. But it could be any shape, such as honeycombs or triangles (Redwood et al., 2017).

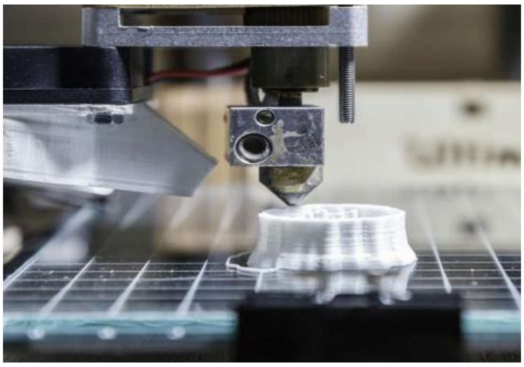


Image 40 - FDM/ 3D printing. Image: Industry week.

5.1.3 Model

Before the geometry in Rhinoceros can be printed, it need to be checked if all the lines are joined. Because when there is a small gap between two surfaces, the 3D printer will not place any material there. 3D-printing from Grasshopper: the model needs to be watertight. This means the objects need to be solids. This can be done by the command 'ShowEdge'. There is an option to choose for 'show naked edges'. This one must be chosen, because it shows all edges which are not connected with anything. If there are naked edges and overlapping elements, it is useful to use the command 'BooleanUnion'.

The software of a 3D printer only accepts a specific file, this is a STereoLithography file format (.stl file) or standard Tessellation Language (Murr, 2015). Before the model in the .stl file can be printed, the geometry needs to be checked in a programme called 'slicer'. The slicer cuts the model in layers based on the layer height of the printer and gives a print time based on the layer height and the print speed. It is important to put all the printer settings in this programme correct. The programme translates the model to a file the printer can read.

5.1.4 Print material

There are several different materials which can be used as a printing material. The most common materials are (thermoplastic) polymers, with different properties. The most commonly used print material is PLA, ABS and PET. Other, less used materials, are nylon, TPU, PC, corkfill and woodfill (3D Matter, 2019; Redwood et al., 2017). PLA, ABS, PET, Corckfill and Woodfill are discussed below, the other materials can be found in the appendix.

PLA

PLA (polylactic acid) is a very rigid material, biodegradable and odourless when it is heated. The printed model can be sanded and painted with acrylics. It also has a good UV resistance, but low humidity resistance and it is not good with glue in general. The Lambda value is 0,13 W/mK (Make it from, 2018; Sd3D.com, 2015). Image 41 shows the general characteristic in a web-diagram. Also Ashby made a list of the material properties (Ashby, 2013):

General properties		
Density	1,210	- 1,250 kg/m3
Price	2.4	- 3 USD/kg
Mechanical properties		
Young's modulus	3.45	- 3.83 GPa
Yield strength (elastic limit)	48	- 60 MPa
Tensile strength	48	- 60 MPa
Compressive strength	48	- 60 MPa
Elongation	5	- 7 %
Hardness—Vickers	14	- 18 HV
Fatigue strength at 107 cycles	14	- 18 MPa
Fracture toughness	0.7	- 1.1 MPa · $m^{1/2}$
Thermal properties		
Melting point	160	- 177 ˚C
Glass temperature	56	- 58 ˚C
Maximum service temperature	70	- 80 ˚C
Thermal conductor or insulator?	Good insulator	
Thermal conductivity	0.12	- 0.13 W/m · K
Specific heat capacity	1,180	- 1,210 J/kg · K
Thermal expansion coefficient	126	- 145 µstrain/ ˚C

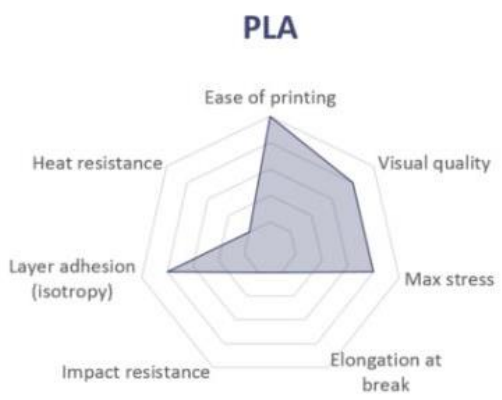


Image 41 - PLA printing characteristics. Redwood, 2017.

ABS

ABS (acrylonitrile butadiene styrene) is also a rigid material, but not biodegradable. The material is UV sensitive, has an odour when heated and potentially high fume emissions. Acetone can be used for a glossy finish, it is possible to sand a printed product and pieces can be glued with acrylic glues, with epoxies & acetone glue. The material also has a good abrasion resistance. The lambda value is 0,173 W/mK (Make it from, 2018; Sd3D.com, 2015). Image 42 shows the general characteristic in a web-diagram. Also Ashby made a list of the material properties (Ashby, 2013):

General properties

Density	1,010	- 1,210 kg/m^3
Price	2.4	- 2.6 USD/kg

Mechanical properties

Young's modulus	1.1	- 2.9 GPa
Yield strength (elastic limit)	18.5	- 51 MPa
Tensile strength	27.6	- 55.2 MPa
Elongation	1.5	- 100 %
Hardness—Vickers	5.6	- 15.3 HV
Fatigue strength at 107 cycles	11	- 22.1 MPa
Fracture toughness	1.19	- 4.29 MPa · m$^{1/2}$

Thermal properties

Glass temperature	88	- 128 ˚C
Maximum service temperature	62	- 77 ˚C
Thermal conductor or insulator? Good insulator		
Thermal conductivity	0.188	- 0.335 W/m · K
Specific heat capacity	1,390	- 1,920 J/kg · K
Thermal expansion coefficient	84.6	- 234 µstrain/˚C

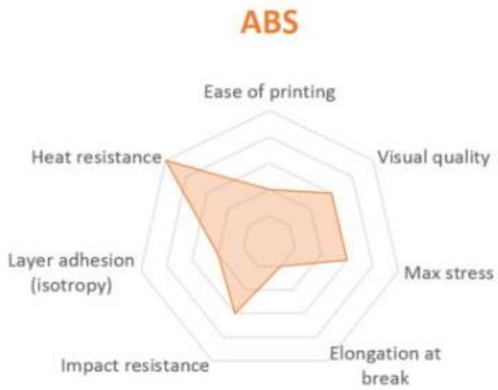


Image 42 - ABS printing characteristics. Redwood, 2017.

PET (recycled)

PET (polyethylene terephthalate) is a fairly rigid material, it is safe to use in combination with food, has a high humidity resistance and high chemical resistance. It is possible to recycle the material, it has good abrasion resistance, the product can be post-processed with sanding, be painted with acrylic paint, it can be glued with acrylic glue (cyanoacrylate). The lambda value is 0,29 W/mK(Make it from, 2018; Sd3D.com, 2015). Image 43 shows the general characteristic in a web-diagram. Also Ashby made a list of the material properties (Ashby, 2013):

General properties

Density	1,290	- 1,400 kg/m^3
Price	1.65	- 1.8 USD/kg

Mechanical properties

Young's modulus	2.76	- 4.14 GPa
Yield strength (elastic limit)	56.5	- 62.3 MPa
Tensile strength	48.3	- 72.4 MPa
Compressive strength	62.2	- 68.5 MPa
Elongation	30	- 300 %
Hardness—Vickers	17	- 18.7 HV
Fatigue strength at 107 cycles	19.3	- 29 MPa
Fracture toughness	4.5	- 5.5 MPa · m$^{1/2}$

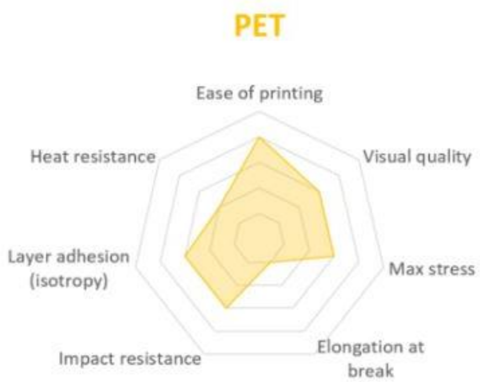


Image 43 - PET printing characteristics. Redwood, 2017.

Thermal properties

Melting point	255	- 265 ˚C
Glass temperature	67.9	- 79.9 ˚C
Maximum service temperature	66.9	- 86.9 ˚C
Thermal conductor or insulator?	Good insulator	
Thermal conductivity	0.138	- 0.151 W/m · K
Specific heat capacity	1,420	- 1,470 J/kg · K
Thermal expansion coefficient	115	- 119 μstrain/ ˚C

PVA

PVA (PolyVinylAlcohol) is a support material. It is a special material which dissolves in water, so it is very easy to remove it from the product.

5.1.5 Other materials based on PLA

Woodfill

The paper 'Effect of wood content in FDM filament on properties of 3D printed parts', written by Kariz, Sernek, Obućina & kuzman 2018, showed that the addition of wood to PLA gives a completely different material. The wood particles make the filament more porous due to uneven distribution of the wood particles during printing. The samples in this research had visible clusters of wood particles. These clusters contributed to lower mechanical properties of the 3D printed parts (Image 44). The tensile strength of the specimens decreased from 55 MPa for pure PLA to 30 MPa for 50% PLA/ wood content (Kariz, Sernek, Obućina, & Kuzman, 2018).

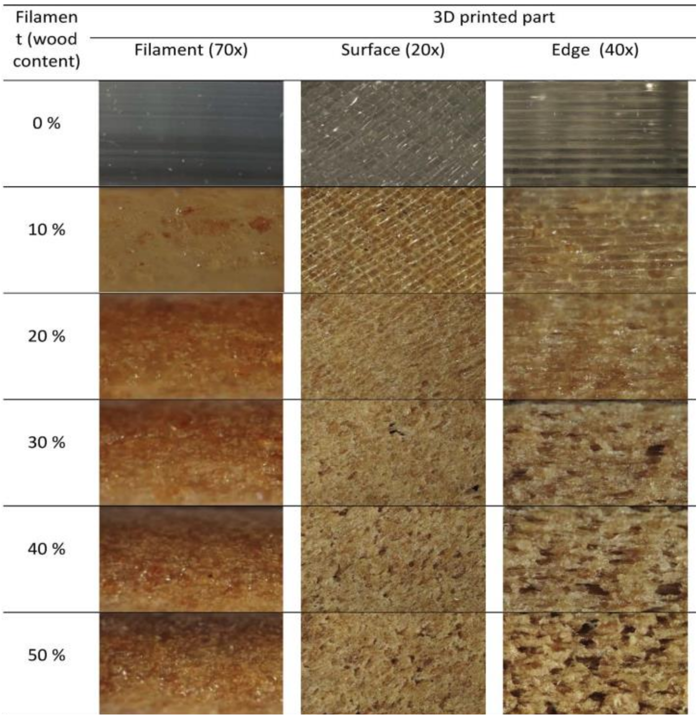


Image 44 – PLA-wood filament. Kariz, Sernek, Obucina & Kuzman, 2018.

Another research to the effect of wood combined with PLA on the properties of the 3D printing material shows almost the same findings. The tensile strength of PLA – wood filament is decreased in relation to pure PLA (Table 6) (Martikka, Kärki, & Wu, 2018).

General properties (ColorFabb, 2019b)

PLA	70%
Wood	30%

Thermal properties

Softwood	λ = 0,14 W/mK (Weersink, Zeegers, Erdtsieck, Van der Linden, & Keizer, 2006)
PLA	λ = 0,13 W/mK (Ashby, 2013)
Woodfill	λ = 0,13 W/mK

Corkfill
Not much is known about the material corkfill. There is no research done for the mechanical properties. The following properties are found after a short research on internet:

General properties (ColorFabb, 2019a)
PLA 70%
Wood 30%

Thermal properties
Cork λ = 0,046 W/mK (Weersink et al., 2006)
PLA λ = 0,13 W/mK (Ashby, 2013)
Corkfill λ = 0,1 W/mK

5.1.6 Conclusion
Table 6 shows the properties of all the possible 3D-print materials in an overview.

Table 6 - Properties of the 3D print materials (Granta Design, 2018).

Material	Young's Modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Shear strength (GPa)
PLA	3,3 – 3,6	55 – 72	47 – 70	1,2 – 1,29
ABS	2 – 2,9	29,6 – 44,1	30 – 50	0,319 – 1,03
PET	2,8 – 3	50 – 55	55 – 60	0,994 – 1,49
Nylon		28,6 – 31,5	29,3 – 30,8	
TPU		28,6 – 31,5	29,3 – 30,8	
PC	2,32 – 2,44	59,1 – 65,2	62,7 – 72,4	
Woodfill	Wood: 10 – 12	32,5 – 39,8	47 – 70	6,5 – 7,9
Corkfill	Cork: 0,025 – 0,05	1,1 – 2,2	47 – 70	0,55 – 1,1

Material	Glass temperature (˚C)	Thermal expansion coefficient (µstrain/˚C)	Thermal conductivity [W/mK]	Poisson's ratio
PLA	52 - 60	126 - 145	0,13	0,38 – 0,4
ABS	88 - 120	126 - 145	0,173	0,38 – 0,4
PET	60 – 84	115 - 119	0,29	0,381 – 0,396
Nylon				
TPU				
PC	142 - 158	120 - 125	0,189 – 0,205	0,391 – 0,407
Woodfill	77 – 102	2 – 11	0,13	0,35 – 0,4
Corkfill	77 – 102	120 - 180	0,13	0,08 – 0,4

5.2 Other manufacturing processes

3D-printing is perfect for rapid prototyping but not suitable for mass production. This sub-chapter discusses different production process which are suitable for mass production. To stay within the scope of this research, only production process which can process PET are chosen. The physical tests will prove if other materials are more sufficient.

5.2.1 *Input in CES*

CES EduPack, 2018 is a perfect program to research suitable production processes. Input in CES (Granta Design, 2018):

Step 1.
ProcessUniverse: Shaping processes: Solid 3-D, Hollow 3-D, Primary shaping process
Tree: Thermoplastics
Result:

- Ballistic particle (obsolete)
- Fused deposition
- Injection molding
- Jetting
- Mast projection stereolithography
- Polymer casting
- Reaction injection molding
- Selective laser sintering, polymers
- Solid ground curing (obsolete)
- Transfer molding

There are too may results to analyse. Therefore the batch size is changed to find a process which is suitable for a big batch size.

Step 2.
Change batch size: minimum 5000
Result:

- Injection molding (thermoplastics)
- Reaction injection molding
- Transfer molding

Three results are a good amount to analyse. These results are discussed on the next page

5.2.2 *Best fitting processes for plastics*

Injection molding (thermoplastics)

CES EduPack, 2018 gives the following information about injection molding (thermoplastics):

> *"Most thermoplastics, with low melting point, can be injection molded. The polymer is injected under high pressure into a cold steel mold. The polymer solidifies under pressure and the molding is then ejected. Various types of injection molding machines exist, but the most common in use today is the reciprocating screw machine (Image 45) Capital and tooling costs are very high."*

Mass range: 0,01 – 25 kg.
Range of section thickness: 0,4 – 6,3 mm

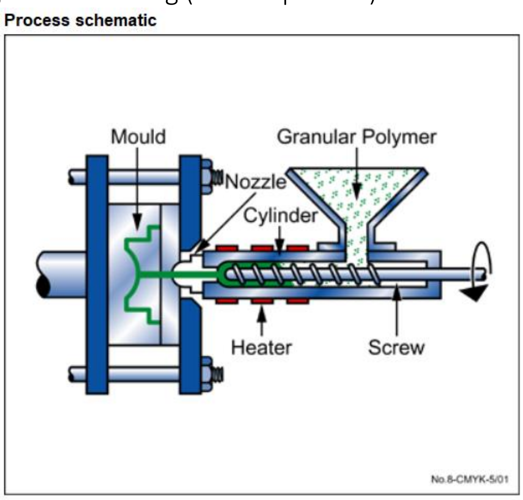


Image 45 - Scheme of injection molding. Image from CES EduPack 2018.

Reaction injection molding

CES EduPack, 2018 gives the following information about reaction injection molding:

> *"Mainly used for thermosetting polyurethane structural foam. Also used for other thermosets: epoxies, polyester, silicones, phenolics and for nylon 6. Reaction Injection Molding (RIM) is a low pressure (0,2 – 1,0 MPa) molding process used for the in-situ polymerization of parts. The process uses temperature-controlled preheated low viscosity chemicals (e.g. polyol + isocyanate for PUR). These are fed under high pressure to the mixing head, from which they are injected into the mold where polymerization occurs (Image 46). The process is general used for large parts and may be used for complex shapes. The process is most commonly used with thermosetting polyurethane (PUR) and polydicyclopentadiene (PDCPD)."*

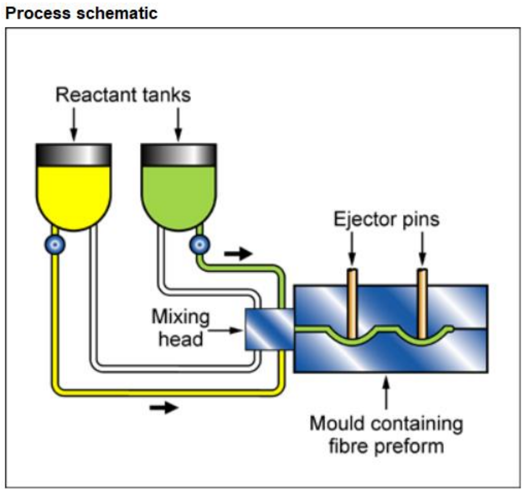


Image 46 - Scheme of reaction injection molding. Image from CES EduPack 2018.

Mass range:	0,5 – 300 kg
Range of section thickness:	2 – 150 mm

Transfer molding

CES EduPack, 2018 gives the following information about transfer molding:

> *"Used with most thermosets and rubbers and thermoset-based composites (chopped fibre and particulate filled). Transfer molding is a molding process combining features of both compression and injection molding for molding thermosetting polymers and composites (Image 47). The uncured polymer is placed in the plunger cavity where it is compressed and injected into the heated mold where the molding is cured."*

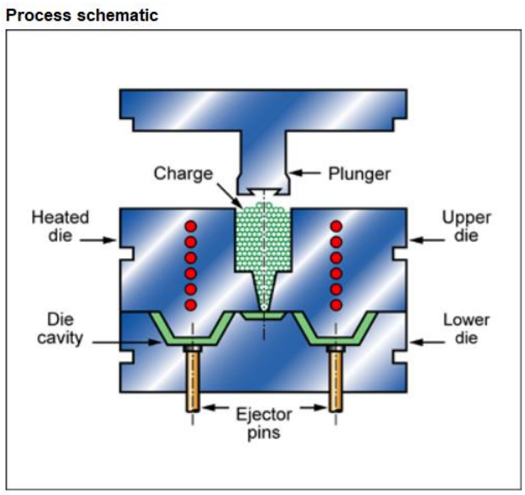


Image 47 - Scheme of transfer molding. Image from CES EduPack 2018.

Mass range:	0,2 – 20 kg
Range of section thickness:	1,5 – 13 mm

5.3 Conclusion

Which production technique and material is most suitable to realize the core?

3D printing is an AM process for rapid prototyping. This production process is used to produce the core of the sandwich structure. The big advantage of 3D printing is that almost any freeform can be printed, relative easily and cheap. But 3D printing also has various limitations, such as: the production speed, the layered production/ material deposits, material use and the limited the size of the product. For this research it is a good process to quickly produce the cores. But for future mass production, another production process is recommended. The material that is going to be used for 3D printing is PET. PET has good yield and tensile strength, in comparison with the other materials. Even though the lambda value (λ = 0,29 W/mK) is a bit worse, it is a good starting point for the calculations. Other important factors are that the material can easily be glued, acrylic glue is not a problem and it is recyclable. Injection molding is most suitable for future mass production. The mold can produce almost any freeform and can be re-used multiple times. The physical tests will prove if other materials are more sufficient.

6 THERMAL AND STRUCTURAL PROPERTIES OF THE PANEL

This chapter discusses the theory of thermal insulation and structural properties of the sandwich panel. First the thermal insulation will be discussed and after that the structural properties. The following, fourth sub-question will be answered:

How can the thermal insulation value and structural properties theoretically be determined?

6.1 Thermal insulation

This subchapter starts with an overview of normal windows and important characteristics of window insulation.

6.1.1 Insulated Glass Unit

An Insulated Glass Unit (IGU) is generally build-up with two glass panes, a spacer around the edge of the panes, a coating on one glass pane and a gas inside the panel. The glass has a thickness of 3 – 6 mm.

Spacer

A spacer is needed when two glass sheets are used in a window. A spacer should be very stiff and strong because it provides stability for the whole window, but the main function is to keep the two glass panes apart. The difficulty of a spacer is the potential as thermal bridge. So it is important to insulate it very well (Image 48). Another function of the spacer is absorption of moisture in the cavity. The spacer is filled with a material which can absorb this moisture to prevent condensation. The materials which can absorb the moisture are; polypropylene and styrene acrylonitrile resin (Technoform, 2019). Thermal expansion of the air/ gas in the cavity makes the glass curved (Buddenberg, Hof, & Oechsner, 2016). Therefore it is important to choose a material for the space which is a bit flexible, so it will not break immediately (Image 49).

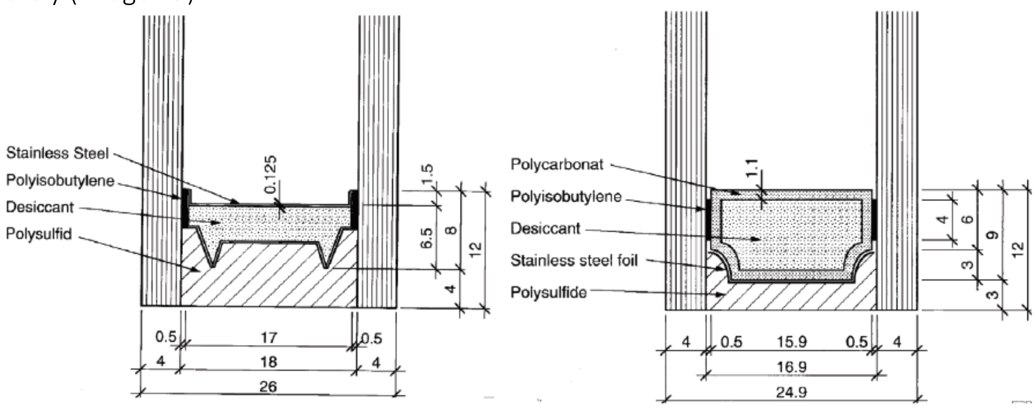


Image 48 - Example of spacers. Lecture notes Building Physics, R. Bokel.

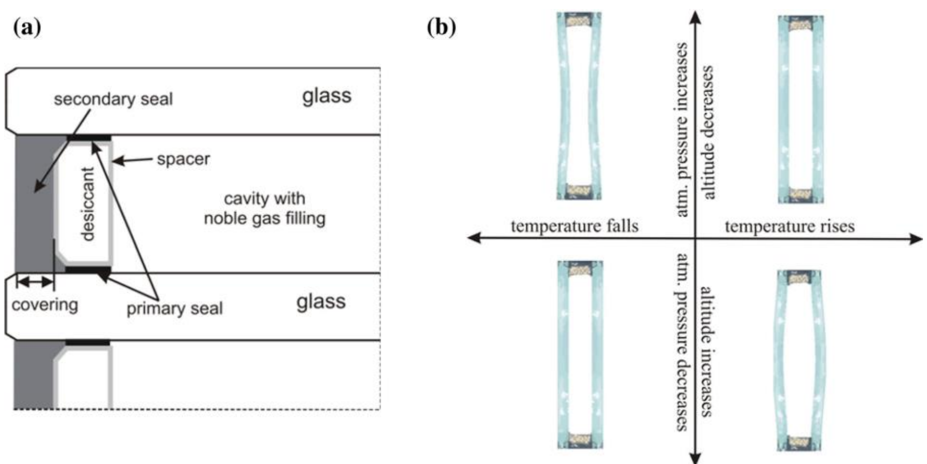


Image 49 - Thermal expansion in IGU. Image: S. Buddenberg, P. Hof, M. Oeschner.

Coating

A coating is a very thin layer which can be placed on the glass to reduce emissivity. There are two types of Low-E coatings: sputtered (off-line) and pyrolytic (on-line) (Bokel, 2017). And a low-E coating is subdivided in:

- High transmittance Low-E
- Moderate transmission Low-E
- Low transmittance Low-E

Coatings are applied on the glass in two different ways. An on-line and off-line coating. Sputtering is a technique to apply a thin layer on a surface at low temperature. A sputtered coating is always build up from multiple layers and the last layer is always a metal. A sputtered coating must be protected from humidity and contact, therefore they are also called 'soft-coatings'. This is why the coatings always need to be applied at the cavity side. The emittance is typically between Ɛ = 0,20 and Ɛ = 0,02. A pyrolytic coating is applied when the glass is still hot, this means that the coating is 'baked' in the glass and therefore it is called a hard coating. The coating is a metal oxide which is sprayed on the glass. Pyrolytic coatings are very durable and can be exposed to air and cleaned by normal cleaning products. The emittance is not as good as the sputtered coating, the emittance is typically between Ɛ = 0,20 and Ɛ = 0,10.

Companies are still working on producing better technologies for coating. RavenWindow, 2019, developed a coating which can switch its functionality (Image 50). When the temperature exceeds a certain value, the coating shifts to a tinted state, so it blocks the sun. During colder months, the coating remains clear, so the sun can heat up the space behind the window (RavenWindow, 2019).

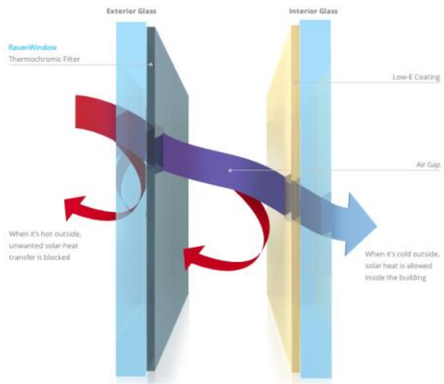


Image 50 - Technology from RavenWindow to block the sun on hot days. Image from RavenWindow.

When there is no background information on a window, it is still possible to make a rough estimation about the thermal insulation. Different kind of glass layers can be counted and the presence of a coating can be checked. The only thing that cannot be seen is which type of gas sits in between the glass panes. It is possible to check if the window has a coatings, with a small light from a lighter (Image 51). If one of the reflections, of the lighter, is more clear than the others and has another colour, it shows that a low-e coating is applied. The location of the reflection shows where the coating is applied, in this on the inside of the outside glass pane.

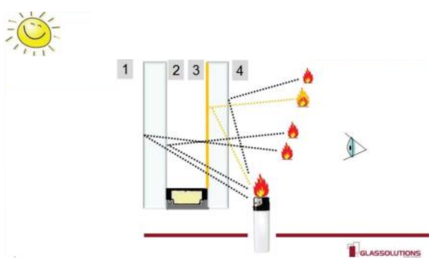


Image 51 - Check reflection with lighter.

Gas

The insulation of a window is not only defined by the glass layers, the width of the cavity and foils, but also by the gas in the cavity. Gasses which can be used to fill the cavity are Argon, Krypton, SF_6 and Xenon (Koninklijk Nederlands Normalisatie-Instituut, 2018). Those insulated panels are called Insulated Glass Unit (IGU). Instead of using a gas it is possible to vacuum the space. Panels which are made vacuum are called Vacuum Insulated Glass (VIG).

Heat transfer

Heat is transferred in three different ways, this all needs to be taken in account when performing calculations of a structure. The three modes of heat transfer are: radiation, convection and conduction(Bokel, 2017; Weersink et al., 2006) (Image 52).

Radiation (straling) is the heat that is felt from, for example, a fire. This heat transfer goes through the air as well as through vacuum.
*Convection (*convectie) is heat that transfers by the movement of air. For example the movement of air above a candle.
Conduction (geleiding) is heat that goes through a material or gasses. Stone, for example, can feel cold, because it transfers heat very good.

Image 53 shows a graph about radiation, convection and conduction in relation to the cavity width. Radiation is always constant, at any cavity width. Convection van be eliminated from the calculation when staying below 15 mm cavity width. Conduction is playing a big part in the heat transfer when staying below the 15 mm, because the materials affect each other. If a material is put in the cavity and touches the two surfaces, it conducts heat is well.

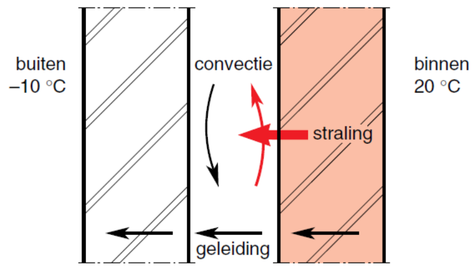


Image 52 - Radiation, convection and conduction. Image from Weersink et al, 2006.

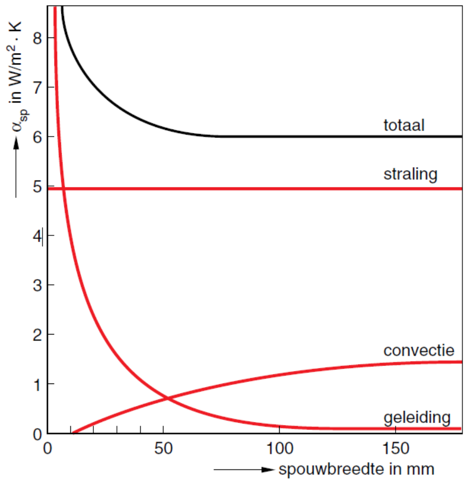


Image 53 - Graph about radiation, convection and conduction in relation to the cavity width. Image from Weersink et al, 2006.

6.1.2 Thermal insulation

To calculate the total thermal insulation, all the heat resistances need to be add up. This includes the heat resistance (conduction) from the materials, glass and PET, the heat transmission coefficient and the radiation (Tenpierik & Cauberg, 2007). Image 54 shows a scheme of the different resistances which need to be added up (Pinterić, 2017). In case of this research, the core material (in the cavity) also needs to be added. This requires a more complicated formula, because the geometry is complicated.

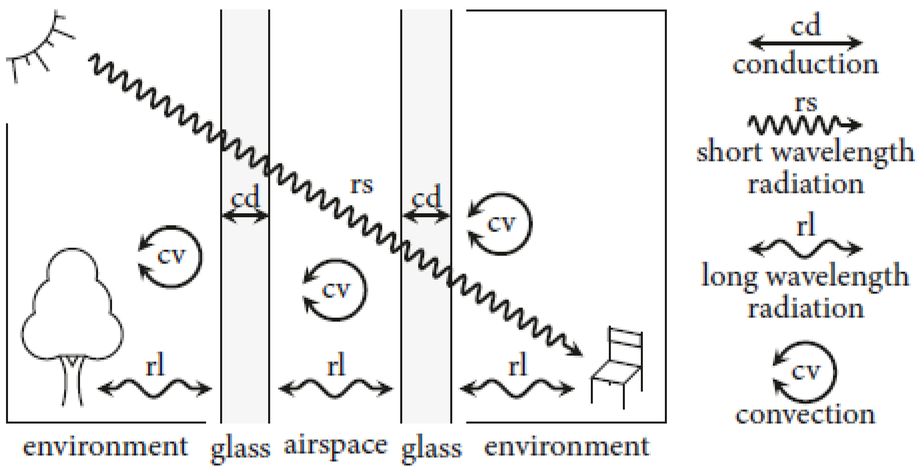


Image 54 - Scheme of heat transfer through a double glazed window. Pinterić, 2017.

Thermal resistance

Overall calculation of the thermal insulation, the R value is the value of thermal resistance and is calculated by dividing the thickness of the material by the thermal conductivity of the material (λ).

$$R = \lambda \cdot t \qquad (1)$$

With:
R = thermal resistance [m²K/W]
λ = lambda [W/m/K]
t = thickness [m]

U value

When the U value is calculated as the inverse of the R value, the inside and outside convection needs to be added in this formula. The values of the inside and outside convection are determined by the temperature, see Table 7 (Koninklijk Nederlands Normalisatie-Instituut, 2018).

$$U = 1/(R + 1/\alpha_{Inside} + 1/\alpha_{Outside}) \qquad (2)$$

With:
U = thermal transmittance [W/m²/K]
α_{Inside} = heat transmission coefficient inside layer [W/m²/K]
$\alpha_{Outside}$ = heat transmission coefficient outside layer [W/m²/K]

Table 7 - Heat transmission coefficient.

α (W/m²/K) Heat transmission coefficient		
α_{Inside}	293K	7,8 W/m²/K
$\alpha_{Outside}$	263K	25 W/m²/K

Complete formula to calculate U value

When all these different components are put in one formula, it will look like this:

$$U = \frac{1}{R} = \frac{1}{\frac{1}{\alpha_i} + \frac{\lambda_g}{t} + \frac{\lambda_{cav}}{t} + \frac{\lambda_g}{t} + \frac{1}{\alpha_o}} \qquad (3)$$

The λ_{cav} is a combination of different factors, which are the radiation, conduction, convection and the infill of the cavity, air and PET, combined.

Radiation

The radiation needs to be calculated as formula 6, the convection applies only on the two air layers at the surface of the panel, not in the cavity and the conduction of the used materials. A panel without a coating has an emission constant of 0,9. When a coating is applied, an emission constant of 0,2 or lower can be obtained.

$$\alpha_{rad} = \varepsilon_{res}\sigma T^4 \qquad (4)$$

With:
α_{rad} = radiation heat flow density per wavelength [W/m²]
ε_{res}= emission constant of the surface [-]
σ = Stefan-Boltzmann constant (5.67 10^{-8} W/m²K⁴)
T = surface temperature [K]

And

$$\varepsilon_{res} = 1/(1/\varepsilon + 1/\varepsilon - 1) \qquad (5)$$

With:
ε_{res} = total emission constant of the surface [-]

ε = emission constant of one surface [-]
ε = emission constant of second surface [-]

Conduction and convection

The cavity thickness determines if conduction or convection is dominant.

$\alpha_{cond\ \&\ conv} = \lambda_{air}/$ thickness $= \lambda_{PET}/$ thickness

Core

There are several different formulas which can be used to calculate the effect of the spacer on the total U value of the panel. The formulas are characterised by the following type of formulas:

- Optimistic versus pessimistic calculation (Weersink, Zeegers, Erdtsieck, Van der Linden, & Keizer, 2005)
- Thermal bridge effect (Tenpierik & Cauberg, 2007)

The '*optimistic*' calculation makes use of a ratio between air and PET in the cavity. While the '*pessimistic*' calculation only takes into account the contact surface area of the PET on the glass. These calculations are very rough calculations, the geometry of the spacer pattern is not included. While the '*thermal bridge effect*' calculation of Tenpierik & Cauberg, 2007 takes into account the geometry of the pattern. The formula includes the edge effect, that is the first part. The second part is the effect of one glass pane and the third part includes the effect of the second pane. The only thing that is missing in this formula, because the formula is designed for VIG panel, is the air in the cavity (Tenpierik & Cauberg, 2007).

$$\psi_{\text{vip,edge}} = \frac{1}{1 + (\lambda_c/\alpha_1 d_p) + (\lambda_c/\alpha_2 d_p)} \times \left[\frac{\alpha_1 (N_2^2 - B)}{\frac{\varphi d_p \lambda_f}{\lambda_f'} (N_1^2 N_2^2 - B^2) - \lambda_1 \sqrt{N_1^2 N_2^2 - B^2} \left(\frac{2B}{\sqrt{D}} + 1 \right) - \lambda_2 \sqrt{N_1^2 N_2^2 - B^2} \left(1 - \frac{2B}{\sqrt{D}} \right)} \right] \quad (6)$$

1 2 3

Image 55 - 'thermal bridge effect' formula from Tenpierik & Cauberg, 2007.

Edge of the panel

Normal U calculation for the overall U value, including the edge, can be calculated with the following formula (Bokel, 2017):

$$U_\omega = \frac{\Sigma A_g \cdot u_g + \Sigma A_f u_f + \Sigma l_g \cdot \psi_g}{\Sigma A_g + \Sigma A_f} \quad (7)$$

With
A_g = glass area [m²]
U_g = U value over glass [W/m²/K]
A_f = Frame area [m²]
u_f = U value over frame [W/m²/K]
lg = length of the glass edge [m]
ψg =linear heat transfer of the glass edge [W/mK]

6.1.3 Conclusion

How can the thermal insulation value theoretically be determined?

A high thermal insulation value can be achieved by choosing the right spacer, coating, gas and cavity width. All these factors are important to calculate the thermal insulation value. A cavity smaller than 15 mm is dominated by conduction, convection is discarded. This means that the trussed pattern is expected to have a big influence on the thermal insulation properties of the panel. Optimistic and pessimistic calculation combined represent a simplified representation of reality. Excel-sheet for the VIG panels is converted to a panel with air in the cavity. Trisco computer program, gives the most accurate representation of reality. All the U values are really close to each other, which means that the values are validated. With the calculations it is proven that the truss indeed has an influence, but not as big as expected. The difference with a normal, air filled, double glass window is 0,2 $W/m^2 \cdot K$.

6.2 Structural properties

This subchapter is about determination of the loads on the panel, considering the small, one-floored building.

6.2.1 Loads

The structural loads, working on the façade element, can be divided in two load-cases. A permanent load, which is de self-weight of the façade panel and the weight of the roof structure, and a variable load, which is the snow load, wind load and life load. The structure has to withstand all these loads with ease. A safety factor of 1,5 is therefore used, to make sure that the structure will not be overloaded and collapse.

Permanent load

The permanent load is the self-weight of the sandwich panel and the weight of the roof. The self-weight can be calculated by multiplying the density by the thickness of the materials. A standard value will be used for the weight of the roof, this can be estimated as 4,9 kN/m² (Arends, 2017).

Formula for the self-weight of the sandwich panel:

$$G = \rho \cdot t \tag{8}$$

ρ = density of aluminosilicate glass, 2430 kg/m³
t = thickness of face, 0,5 mm
ρ = density of PET, 1380 kg/m³
t = thickness of core, 10,0 mm * infill percentage

By inserting the values in the equation, it gives the following self-weight of the glass:
G = 2430*2*0,0005+1380*0,01*0,26 = 6 kN/m²

Variable load

The snow load is based on the Dutch Norm NEN-EN 1991-1-3+C1/NB (Koninklijk Nederlands Normalisatie-Instituut, 2011a). This is a distributed permanent load onto the roof and therefore panel. The snow load can be determined by the following equation:

$$q = u_i \cdot c_e \cdot c_t \cdot s_k \tag{9}$$

ui = shape coefficient of the roof = 1,0
Ce = exposure coefficient = 1,0
Ct = thermal coefficient = 1,0
sk = characteristic value of the snow load on the ground = 0,7 kN/m²

Inserting the properties into equation 2, gives the following distributed snow load:
Q = 1 * 1 * 1 * 0,7 = 0,7 kN/m²

A standard value will be used for the life load, which is 1,0 kN/m² (Arends, 2017). And based on the NEN-EN 1991-1-4 +A1+C2:2011 norm the wind load is set to 0,8 kN/m². This is based on the location of the building and extreme wind load as a function of height (Koninklijk Nederlands Normalisatie-Instituut, 2011b).

6.2.2 Structural behaviour

The way the loads are applied in the case study, suggests a compression test, because the panel will be loaded in compression. Some research considering a compression test on sandwich panels is already done, but in all cases the research is conducted with other materials. For example Image 56, where a compression test is done with an aluminium sandwich panel with honeycomb core (Sun, Huo, Chen, & Li, 2017). Different failure mode were found, namely face wrinkling, core shear and delamination. The sandwich panel in this research is most likely going to react the same way. Although, face wrinkling is not very presumable, it is expected that the glass will break. It is very likely that the panel is going to buckle, that the core fails due to shear and that delamination will occur (Image 57andImage 58).

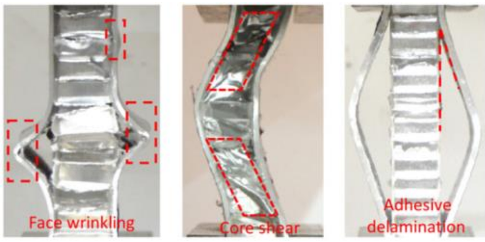


Image 56 - Failure modes aluminium sandwich panels with honeycomb core. Image by sun, Huo, Chen & Li, 2017.

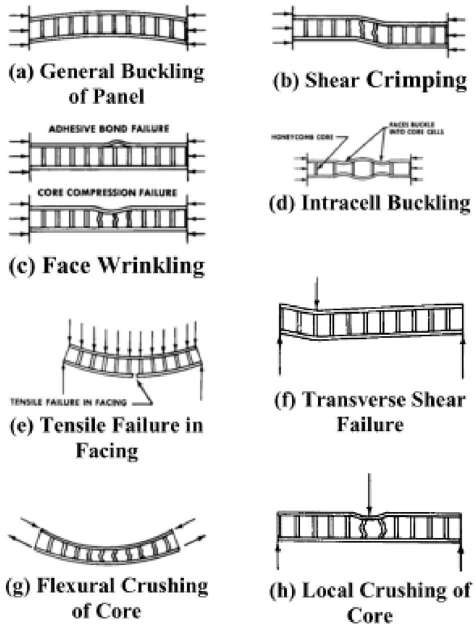


Image 57 - Failure modes in sandwich structures. Ratwani, 2010.

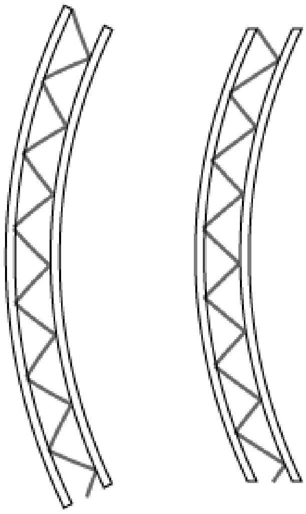


Image 58 - Deformation, buckling, of the sandwich panel. Own image.

Buckling and shear stress

The critical load is the load for the column to start buckling. Thus the critical load has to be bigger than all the loads (permanent and variable loads) combined for the panel. The formula below shows that the buckling length, thus the connection of the panel, has a big influence on the critical buckling load of the panel (Image 59). A smaller effective length results in a bigger critical load, which is positive. Euler critical load of slender columns:

$$P_{cr} = \frac{\pi^2 \cdot E \cdot I}{L^2} \quad (10)$$

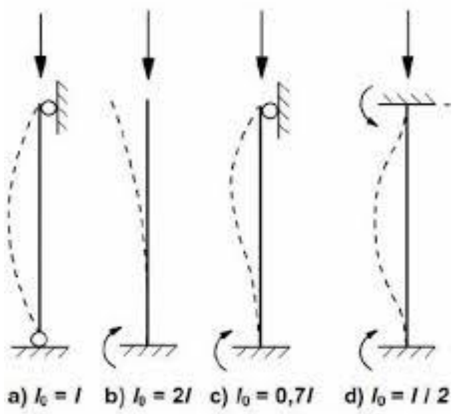


Image 59 - Effective length of column.

Where

E = Young's Modulus [N/mm²]

I = Second moment of area [mm^4]

L = effective length of the column [mm]

The I (second moment of area) can be calculated as in formula 18 when the cross section is a rectangle. If the cross section not a rectangle, the I can be calculated by first finding the centroid of the composed areas. This formula shows that the thickness of the section has a big effect, because the thickness must be multiplied to the power 3. Second moment area formula:

$$I = \frac{1}{12} b t^3 \tag{11}$$

With:
b = width of the section [mm]
t = the thickness of the section [mm]

Euler sandwich beam (Mamalis, Manolakos, Ioannidis, & Papapostolou, 2005). Mamalis, Manolakos, Ioannidis and Papostolou used the following formula in their paper 'On the crushing response of composite sandwich panels subjected to edgewise compression: Experimental'. This formula already include the young's modulus of the materials and the different elements, two faces and core, in the sandwich panel:

$$EI_{eq} = \frac{E_f \cdot b \cdot tf^3}{2} + \frac{E_f \cdot b \cdot tf^3}{6} + \frac{E_c \cdot b \cdot tc^3}{12} \tag{12}$$

Where
E_f = Young's modulus of the face
E_c = Young's modulus of the core
b = width of the material
tf = thickness of face
tc = thickness of core

Bažant and Beghini used the following formula's in their paper 'Sandwich buckling formulas and applicability of standard computational algorithm for finite strain'. The top formula is used to calculate the bending stiffness of the panel (EI) and the bottom formula is used to calculate the shear stiffness of the pane (GA) (Bažant & Beghini, 2004):

$$\overline{EI} = b\left[E_s \frac{t^3}{6} + \frac{1}{2} \cdot E_s t (t+h)^2 + E_c \frac{h^3}{12}\right] \tag{20}$$

$$\overline{GA} = \frac{1}{2b}\left\{\frac{E_s^2}{4\overline{EI}^2 G_s}\left[a^4 t - \frac{2}{3}a^2(a^3 - d^3) + \frac{1}{5}(a^5 - d^5)\right] + \frac{E_s^2}{\overline{EI}^2 G_c}\left[t^2 c^2 d + \frac{2}{15}\frac{E_c^2}{E_s^2} d^5 + \frac{2}{3}\frac{E_c}{E_s} t c d^3\right]\right\}^{-1} \tag{13}$$

where
a = t+h/2
c = (t+h)/2
d = h/2
Es = the Young modulus of the skin
Ec = Young's modulus of the core
Gs = the shear modulus of the skin
Gc = the shear modulus of the core

All these formulas are general formulas to calculate the second moment area of the panel. But the geometry of the core cannot be calculated by multiplying the width times the thickness. The geometry is far more complex to calculate. Allen, 1969, explains in his book 'Analyses and design of structural sandwich panels' how the second moment area of a core can be calculated(Allen, 1969). But since this is a difficult calculation and there is not enough time to dive into this theory, it is decided to not calculate this.

6.2.3 Conclusion

How can the structural properties theoretically be determined?

The permanent load is:
Weight of roof = 4,9 kN/m²
Self-weight panel= 0,326 kN/m²

The variable load is:
Snow load = 0,7 kN/m²
Life load = 1,0 kN/m²
Wind load = 0,8 kN/m²

The safety factor is 1,5.

Possible failure modes are delamination, core shear, buckling and tension in the glass faces. The critical buckling load has to be bigger than all the loads above together. The thickness of the panel and the buckling length has a big influence on the critical buckling force of the panel. Since the calculation for the second moment area of the panel a difficult calculation is and there is not enough time to dive into this theory, it is decided to not calculate this.

6.3 Overall conclusion

How can the thermal insulation value and structural properties theoretically be determined?

Thermal

By performing different calculations (optimistic, pessimistic, Excel, Trisco) and taking into account all the different factors which can influence the thermal insulation properties. The calculations show a small decrease of 0,2 $W/m^2 \cdot K$ in comparison with air filled, double glass windows.

Structural

The panel has to withstand at least all the permanent and variable loads, as shown above. The possible failure modes of a panel are expected to be delamination, core shear, buckling and tension in the glass faces.

PRELIMINARY DESIGN

7 PROTOTYPE

Before answering the sub-question 5, the production of the prototype sandwich panels will be discussed in this chapter. The production starts with 3D-printing of the core. The 3D-printing process is elaborated here, as well as the need for a tensile glue test. The glue test is done to research what the structural properties will be is two (or more) core pieces are glued to each other. After that the core needs to be bonded with the thin glass. When the core is bonded to the glass faces, the panel is ready to be tested.

7.1 3D-printing the core

At first the goal was to keep the beams of the truss as thin as possible. Thus the beams in the initial pattern design were only 1 mm thick. Unfortunately, it is not possible to print 1 mm beams with a 3D printer. It could be possible to produce a panel with 1mm beams with a robot arm because a robot arm can extrude the filament, go around the corner and continue with extruding to finish the model. Due to a lack of knowledge in the field of robot arms and time, it was decided to stick with the 3D-printing for this research. The diameter of the beams was increased to 3mm to make the core printable. Although this is still very small with a 1mm nozzle and resulted in a poor quality panel (Image 60). Therefore the diameter is increased to 4mm (Image 60). With this diameter it was easier to print a core from acceptable quality.

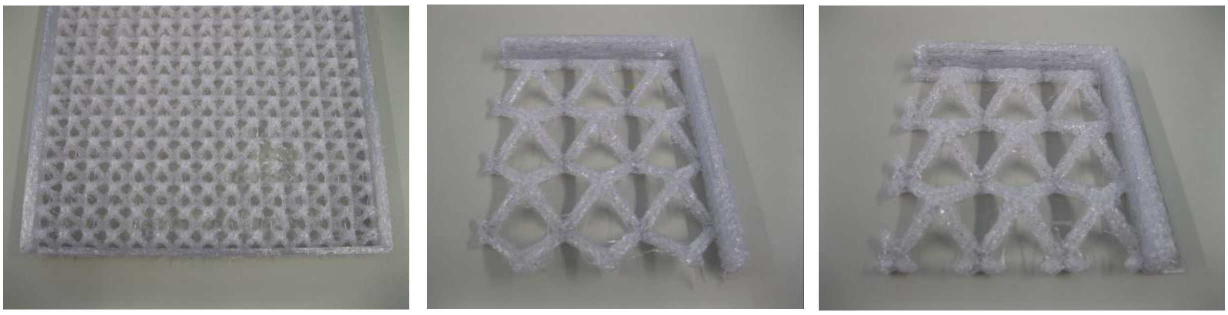


Image 60 - Test prints with 3 mm beams Right image; test print with 4mm beams. . Own image.

The print temperature is also a variable which influences the print quality. The best temperature to print PET is 230 ˚C. The maximum print speed was kept at 20 mm/s. The fan speed was adjusted for the first few layers of the print: layer 1 = 0%, layer 2 = 35%, layer 3 = 50%, layer 4 = 75%. The print speed could be increased a little when the first few layers are already printed when it was clear that the print was sticking to the print bed.

Unfortunately it was not possible to print the panel as a whole. The print is split in two, at the location where the contact points are at the bed (Image 61). This means that the two pieces need to be put together. This can be done in several ways, one way is to glue and the other way is to weld the parts. At the faculty of Industrial Design and Engineering, Don van Eeden recommended two types of glue, a fast drying glue and a two-component glue. The parts can also be weld together, this is done by melting the material with heat, or chemically melt with dichloromethane. The tests with the glue are described in the next sub-chapter 7.2.

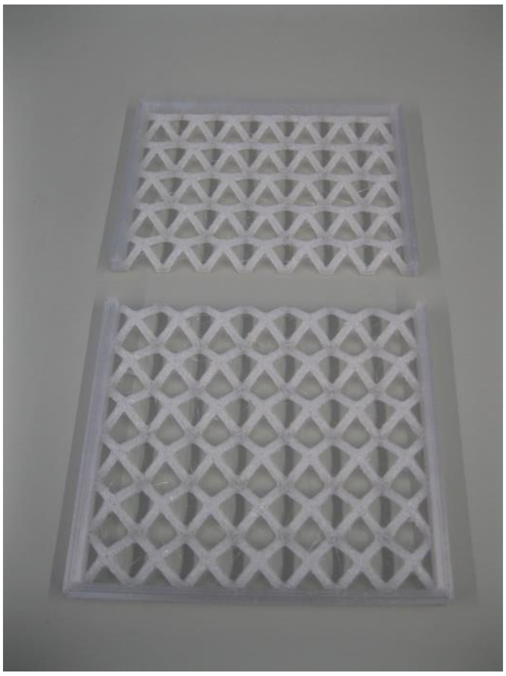


Image 61 - The core completely printed. Own image.

Just when the printing seem to go fine, some other problems occurred. The prints somehow did not want to stick to the bed anymore, so warping occurred. Therefore a piece of material came in front of the sensor which causes the printhead to calibrate at a wrong location. The whole print shifted, the result is shown in Image 62. Because it was not possible to solve this error, the decision was made to order the panels at a professional 3D-printing company, named MTB3D in Delft.

Image 62 - Distorted print. Own image.

7.2 Bonding test and tensile test

Due to the difficulty of printing the panels as one piece, the need for bonding the parts arose. People from the faculty of Industrial Design and Engineering have more experience with bonding of plastics and they advised to test three different types of glue and two different ways of welding. Welding is done with heat or with a plastic dissolver, gluing is done with special types of glue for plastics. First a geometric test is done to understand how the bond needs to be applied and how to prepare the specimen correct. Several small pieces of the final geometry are printed in such way that the most important parts, which need to be bonded, are tested. The bonds are being judged on:

Ease to use:	- thickness fluid
	- time to dry
	- how to apply
Preparation of the surface:	- Neat and smooth or 'fills the gaps'
Visibility of the bond	- transparent/ non-transparent

7.2.1 Bonding test

Welding is done with heat, dichloromethane) and kunststoffkleber both dissolve the material. When the dissolvers dry, the bond is welded. Gluing is done with Loctite 495 and a two-component glue from Griffon (Image 63).

Image 63 - Different types of bonding materials. From left to right: Dichloromethane, Kunststoffkleber, Loctite 495, Two-component Griffon. Own image.

Dichloromethane (weld):

In theory this is the perfect way to bond two pieces in terms of structural properties. It is easy to work with the fluid, just lay the two pieces down next to each other and drip the fluid on the joints. But in practice it is not so easy, because the pieces need to be prepared perfectly. The surfaces need to be perfectly smooth, which is very difficult to accomplish with such small parts. Because the fluid is very thin, it is hard to put enough in between the joints. It takes at least 12 hours for the fluid to dry.

Kunststoffkleber (weld):

This fluid is a bit thicker than the dichloromethane which makes it easier to apply on the surface. It is still very important to carefully prepare the pieces, the surfaces need to be smooth. It also takes at least 12 hours for the fluid to dry.

Heating (weld):
The two pieces which need to be connected are heated so the material gets soft. Then the soft parts need to be put against each other very quickly. If this is not done fast enough, the surfaces cool down and harden. Another disadvantage is that when one part of the surface is bonded, it is hard to reach the rest of the surfaces to heat. In conclusion, this bonding method is not easy to use, you have to be very quick to put the two parts together because the materials cools down very fast (Image 64).

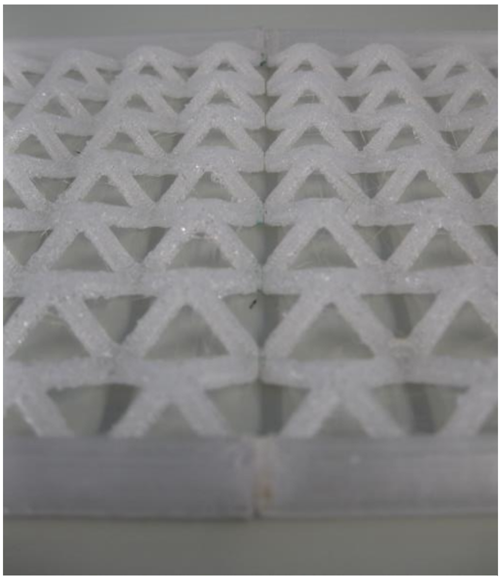


Image 64 - Bonded through heating. Own image.

Loctite (glue):
Loctite is a fast drying acrylic glue. The glue is a bit thick and fills the gaps, this makes it easy to apply the glue at the right place. The two pieces need to be put together in one flow because the glue dries quickly. There is time to adjust a little bit, but the pieces should not be moved when they are put together. The pieces need to be prepared (sanded), but small flaws in the surface are acceptable.

Two-component Griffon (glue):
Before the glue can be used, the two-components need to be mixed. When the two components are mixed, the fluid becomes very thick. This makes it easy to apply and it fills up gaps. Thus the pieces need to be prepared (sanded), but small flaws in the surface are acceptable. Glue is a little bit visible, but still transparent. Does not dry fast, so there is time to adjust the joints.

7.2.2 Conclusion

Ease to use:	- thickness fluid
	- time to dry
	- how to apply
Preparation of the surface:	- Neat and smooth or ‘fills the gaps’
Visibility of the bond	- transparent/ non-transparent

Considering the criteria as above, the Kunststoffkleber, Loctite and two-component Griffon are chosen to use for the tensile test. Because these glues were easy to use, allowed for small flaws on the surface which needed to be glued and they are all transparent, or at least translucent.

7.2.3 Tensile test

A tensile test was done to gain insight in the behaviour of the material under tensile stress. The test is a 'displacement controlled test', this means that the displacement/ force is controlled. The stress- strain diagram will be compared with the diagrams of other materials (Image 65), this will give insight in the properties of the material and the effect of the bond (CROW Polymerdatabase, 2015) (Schodek & Bechtold, 2014). Plastics also differ in stress-strain properties amongst each other (Image 66).

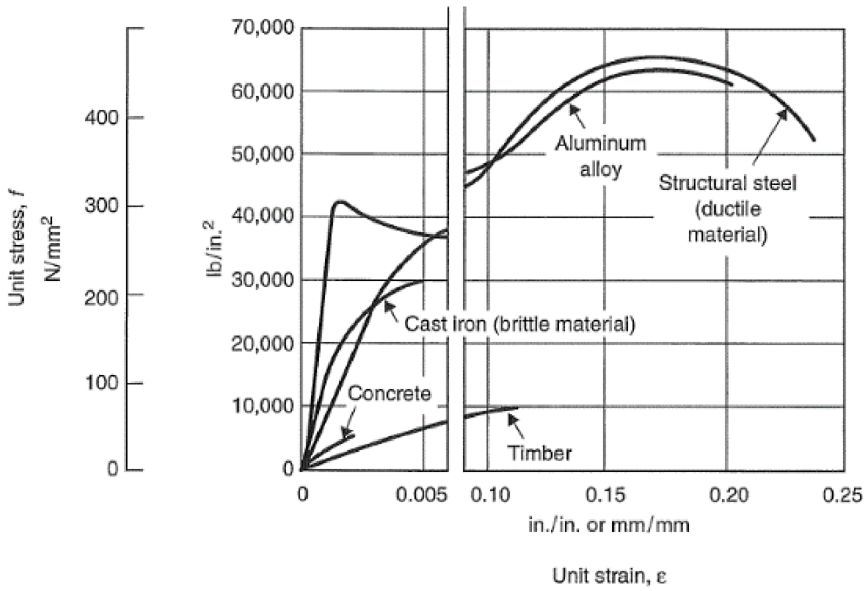


Image 65 - Typical stress-strain diagrams for different materials. Schodek & Bechtold, 2014.

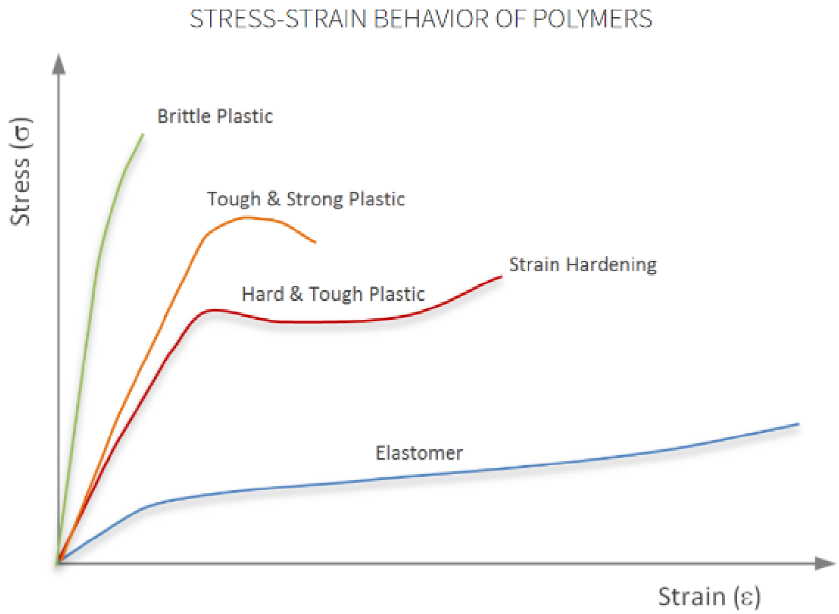


Image 66 - Stress-strain diagram of plastics. Image from CROW Polymerdatabase.

Table 8 - Symbols

Symbol	Unity	Property	Symbol	Unity	Property
E	N/mm²	Youngs' Modulus	L_0	mm	Length of specimen
M	N·m	Bending moment	ΔL	mm	displacement
P	N	Load [Newton]	Δσ	MPa	Stress
t	mm	Thickness of the face	Δε	mm	Strain
A	mm²	Area of cross section			

Equipment and procedure

The samples are experimentally researched on their tensile properties by applying a tension load. The samples are dog-bone structures to localize the point of failure to the centre of the samples during testing (Image 67). The samples are clamped at the edges and the length of the samples are measured to determine the initial length, before the test is done. The Zwick Z010 is used to perform the tests (Image 67). The temperature was around 20˚C and the testing speed was 2 mm/min.

Image 67 - Tension/ compression testing machine. Own image.

From the load, load / displacement, δ curves are recorded directly during the test. This leads to the following tension characteristics of the test specimens which are calculated and recorded:

- Peak load, P_{max}
- Displacement, ΔL
- Strain, ε_e, due to the displacement
- Stress, σ_e, due to the applied load

The formulas are as followed:

Strain:

$$\varepsilon_e = \Delta L / L_0 \quad (14)$$

With:
ΔL = displacement [mm]
L_0 = Initial length of specimen [mm]

Stress:

$$\sigma_e = P/A \quad (15)$$

With:
A = area cross section [mm²]
P = applied load [N]

Young's modulus

$$E = \Delta\sigma_e / \Delta\varepsilon_e \quad (16)$$

Test materials

The test specimens used for the tension test are dog-bone structures with the overall dimensions as in Image 69. The specimens are made of 3D printed PET. Two samples are whole dog-bones, but two types of PET. Three samples are half dog-bones and three types of glue. The *PET1* has a thickness of 4mm with a density of 1,38*10^{-3} kg/cm³, a Youngs modulus of 2,8 - 3 GPa and a shear modulus of 0,994 - 1,49 GPa (123-3D, 2019). The *PET2* has a thickness of 4mm with a density of 1,27*10^{-3} kg/cm³, a Youngs modulus of 2,8 - 3 GPa and a shear modulus of 0,994 - 1,49 GPa (MCPP, 2019). The first dog-bone is from PET1, which is used as a refence specimen because the half dog-bones are made from PET1. The second dog-bone is from PET2, the material which is used for all the panels. The third dog-bone is from PET1 and glued with KLEBER. The fourth dog-bone is from PET1 and glued with a two-component glue from GRIFFON. The fifth dog-bone is from PET1 and glued with LOCTITE (Table 9). Image 68 shows the production process of the dog-bones produced with PET1, and Image 70shows an overview of all the dog-bones.

Table 9 - Dog-bone specimen.

Specimen	H (mm)	W1 (mm)	W2 (mm)
PET2.1	10,50	4,00	4,00
PET2.2	10,50	4,00	4,00
PET2.3	10,40	4,00	4,00
PET1.1	10,70	4,15	0,41
PET1.2	10,15	4,15	4,25
PET1.3	10,70	4,05	0,41
Kunstst.1	10,20	4,20	4,10
Loctite1	10,25	4,00	4,10
Loctite2	10,30	4,00	4,10
Loctde3	10,50	4,10	4,10
Griffon1	10,70	4,65	4,15
Griffon2	10,15	4,75	4,15
Griffon3	10,25	4,40	4,15

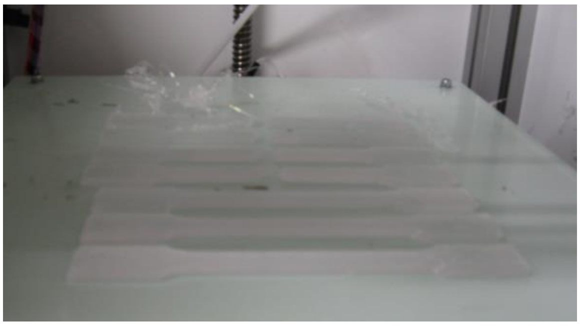


Image 68 - Production of the dog-bones. Own image.

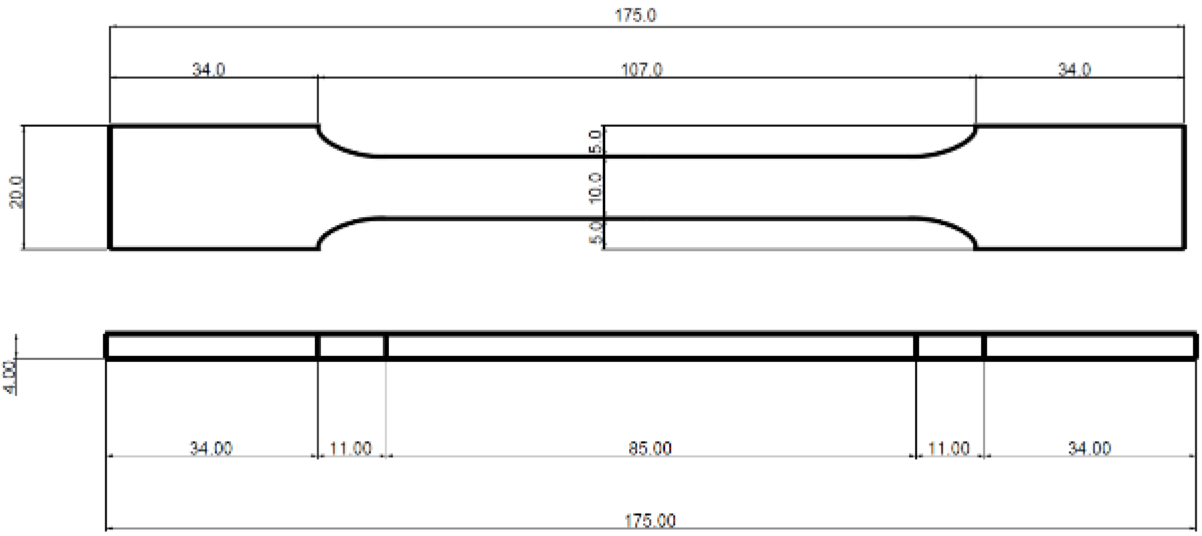


Image 69 - Dimensions of the dog-bones. Own image.

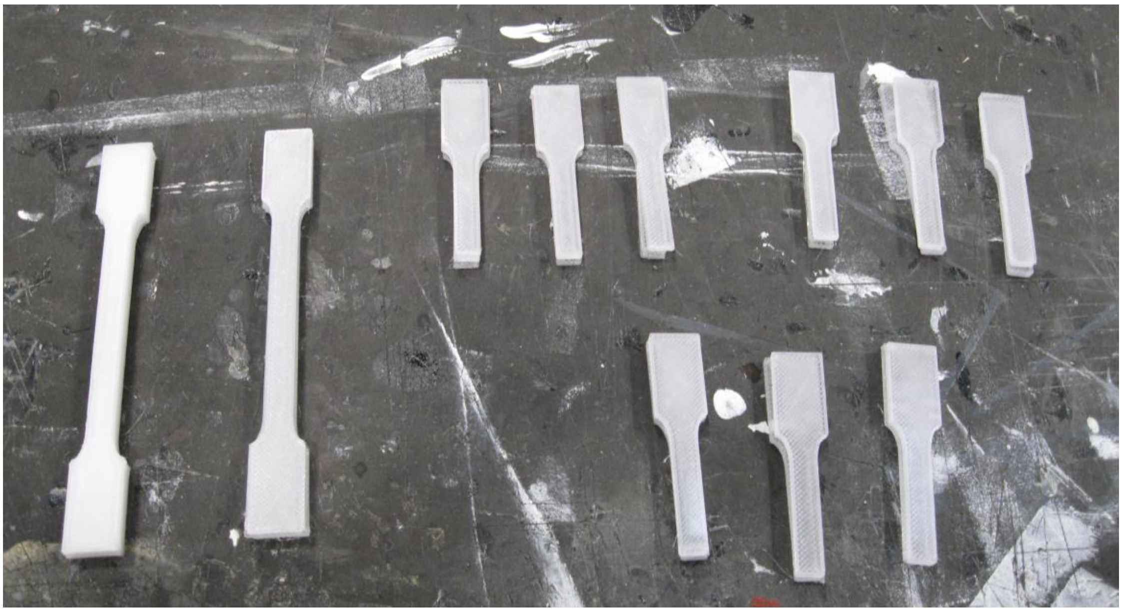


Image 70 - Overview of the dog-bones. Own image.

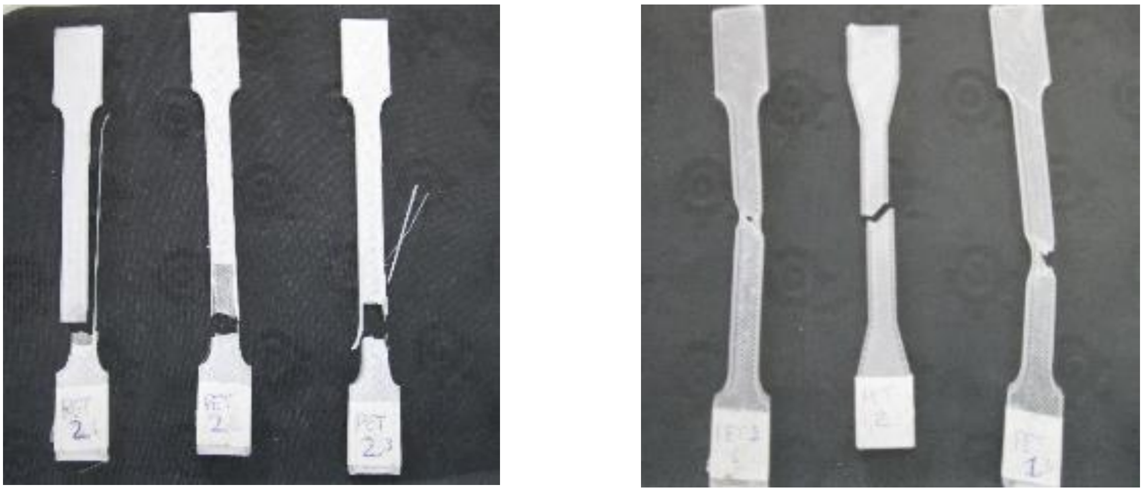


Image 71 - Complete dog-bones broken. Left PET2, right PET1. Own image.

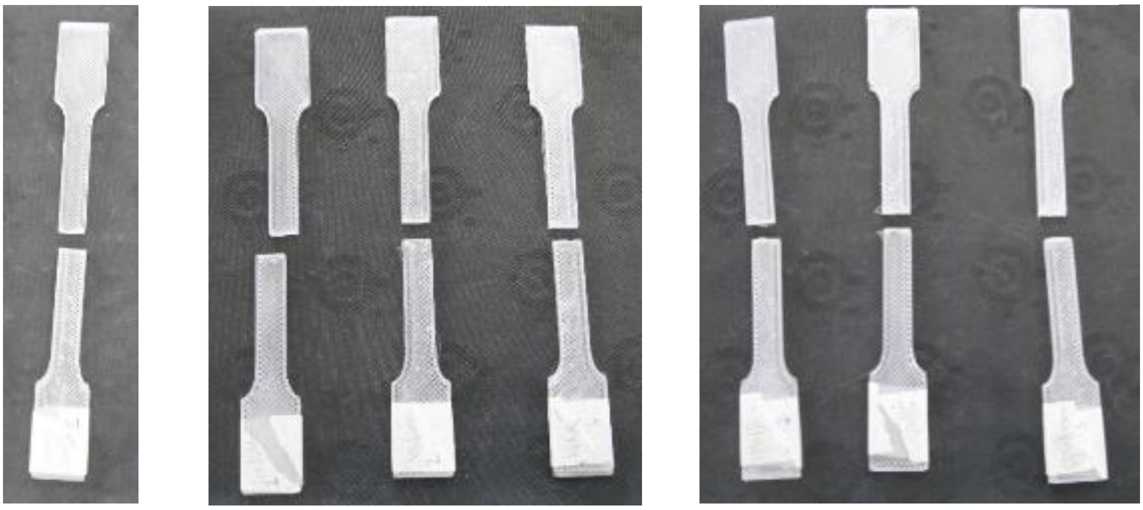


Image 72 - Glued dog-bones broken. From left to right: Kunststoffkleber, Loctite and two-component Griffon. Own image.

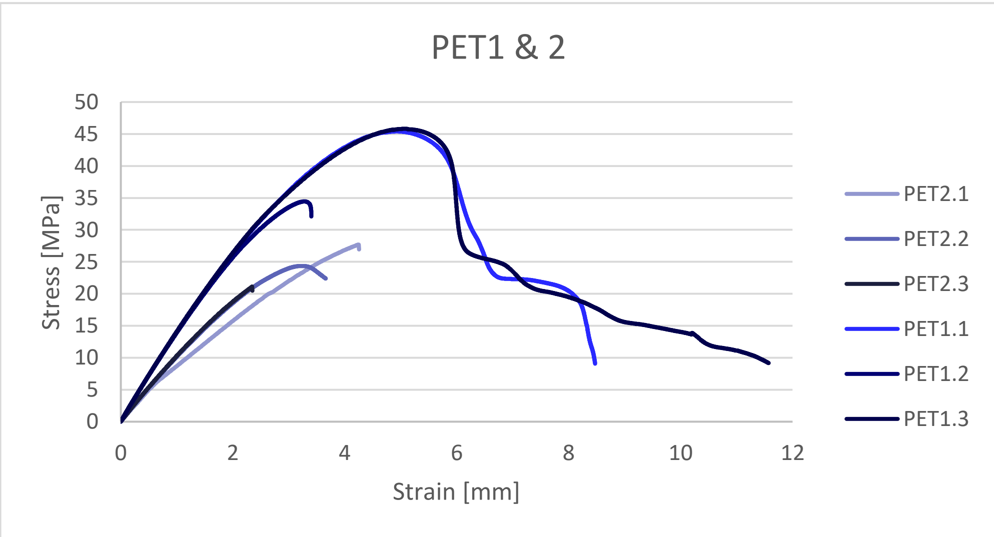
Results

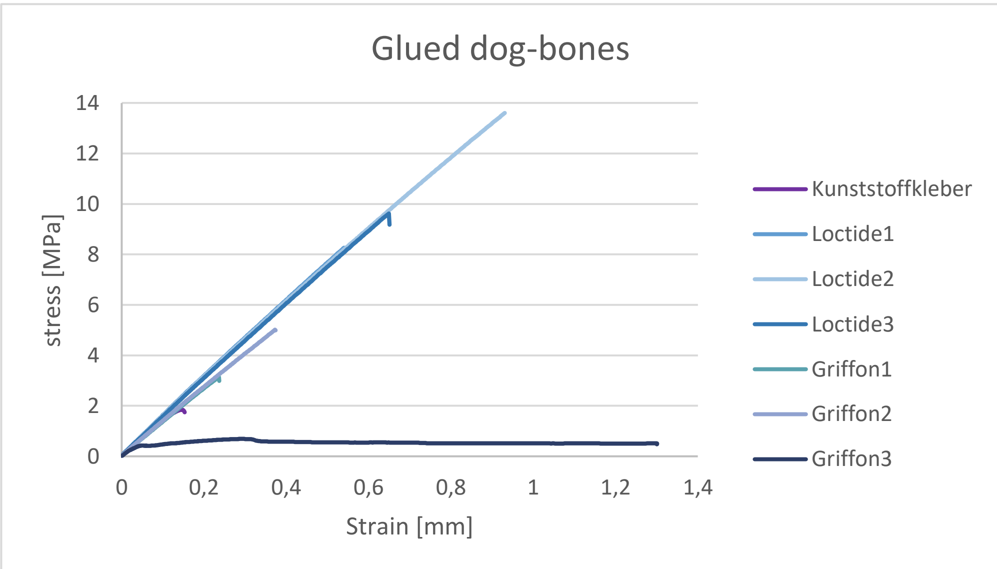
The specimen from PET2 are made by the company which also produces the panels. PET 2 is not as transparent as the PET1, the colour is much whiter and the layers of PET2 are detached and splintered, this is brittle behaviour. This could be explained by a lower printing temperature. The layers did not stick very well to each other (Image 71).

The PET1 specimen seem much denser and there seems to be much more cohesion between the layers. The curve from specimen 1.1 and 1.3 show plastic behaviour, this is called 'necking'. PET1.2 is different from the other PET1 specimen because it is printed in another batch. The initial PET1.2 broke during the preparation of the machine (Image 71).

Two kunststoffkleber specimens already detached when they were taken of the glue-board, therefore only one specimen could be tested in the machine. The bond could only take 80 N, the stress was less than two MPa. The reason for this could be that the surfaces where not well enough prepared and the pieces not well enough pushed together (Image 72).

All three the Loctite samples gave the same curve, which implies valid results. The Loctite also gave the best results, but the maximum stress is still significant less than the whole dog-bones. The Loctite and Griffon specimen show the same curve, but the Loctite could take double the stress. Considering the odd curve of the Griffon3 sample, the glue was still intact and only the glue yielded.





7.3 Bond the core and the glass

The glue used for this research is DELO photobond 4494 (Image 74). This is an acrylic, one component, transparent, UV-curing glue. Before applying the glue, the surface must be cleaned with isopropanol. When using isopropanol it is very important to ventilate the room. The isopropanol cleans the surface from any kind of grease, but it is very important to clean the surface in one direction. Then the glue can be applied on the surface. First on the pattern, than, after a couple of seconds, the glass is put on the pattern. The next step is to cure the glue with a Delolux 80 UV lamp. This needs to be done in 40 seconds, two times. Image 73 and Image 74 show me at work with the glue (DELO, 2015).

Properties of DELO photobond 4494

T_g	100 °C
Shrinkage	9 %
Viscosity	20000 mPas
Compression shear strength	15 MPa
Tensile strength	18 (MPa)
Elongation at tear	160 %
Young's modulus	400 MPa

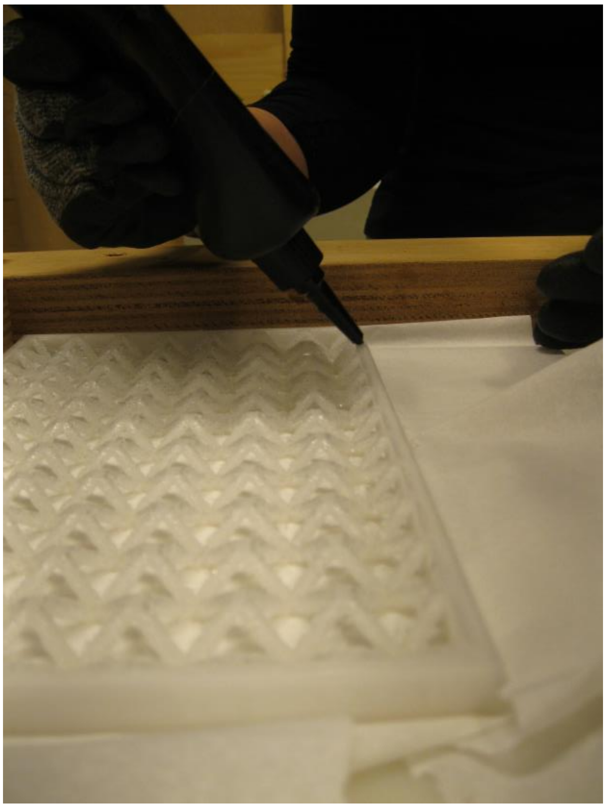


Image 74 – Applying glue on the panel. Own image.

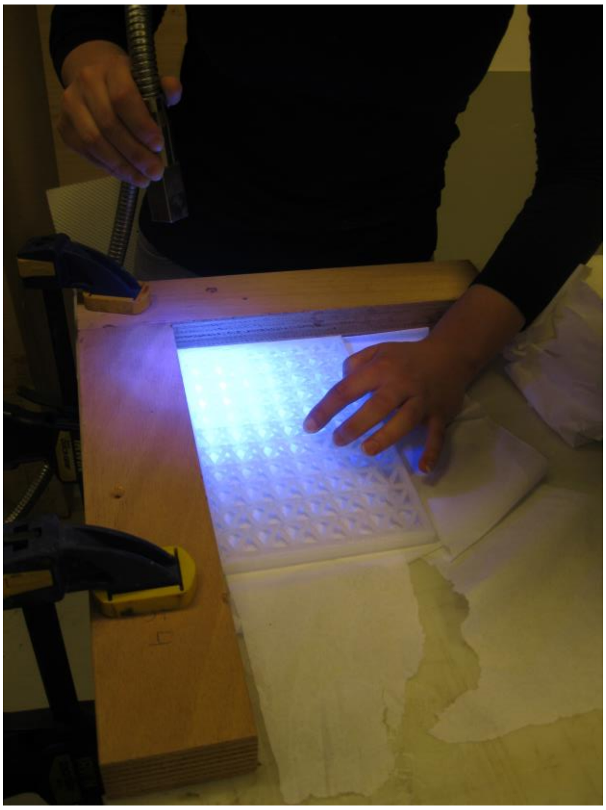


Image 73 – UV-curing the panel. Own image.

7.4 Conclusion

Unfortunately it was not possible to print the panel as a whole. The print is split in two, at the location where the contact points are at the bed (Image 64). This means that the two pieces need to be put together. This can be done in several ways, one way is to glue and the other way is to weld the parts. At the faculty of Industrial Design and Engineering, Don van Eeden recommended two types of glue, a fast drying glue and a two-component glue. The parts can also be weld together, this is done by melting the material with heat, or chemically melt with dichloromethane. Because it was not possible to solve the 3D-printing errors, the decision was made to order the panels at a professional 3D-printing company, named MTB3D in Delft.

Considering the criteria as above, the Kunststoffkleber, Loctite and two-component Griffon are chosen to use for the tensile test. Because these glues were easy to use, allowed for small flaws on the surface which needed to be glued and they are all transparent, or at least translucent.

In general it is best to prevent the use of glue, because it can take approximately half the stress of a normal/ complete dog-bone. But if there is no other option than to use the glue, it is best to use the Loctite because it is easy in use and gave the best results.

8 THE COMPOSITE PANEL

This chapter will discuss the thermal and structural properties of the thin glass composite panel as a whole. Subchapter 8.1 will first discuss the thermal insulation value of normal windows of today and points for attention when designing such panel. After that, the results of the calculation are going to be explained. Subchapter 8.2 has the same layout as subchapter 8.1, but this time for the structural properties. A summary of all the findings will be given to conclude this whole chapter. The fifth and last sub-question will be answered:

What is the actual effect of a trussed pattern in a thin glass composite panel on the thermal insulation and structural properties of the panel?

But before diving in the techniques, an overview of the thin glass composite panel is given. A trussed pattern is chosen because it has the best ratio of material use versus stiffness. And it is to be expected that the heat flow is less due to small contact area (points) instead of the line contact of a honeycomb pattern. Three different types/ core arrangements will be tested. The first is a trussed pattern under an angle of 41˚ (Image 75). The second core is a trussed pattern under an angle of 67˚. And the third panel has a two core patterns with an angle of 41˚ and consists of three glass layers. Due to the low melting temperature of PET, it is only possible to bond it to the glass with an UV-curing acrylic glue. The size of the thin glass for the tests is 250 x 150 mm. This is the available size which can be used for the tests.

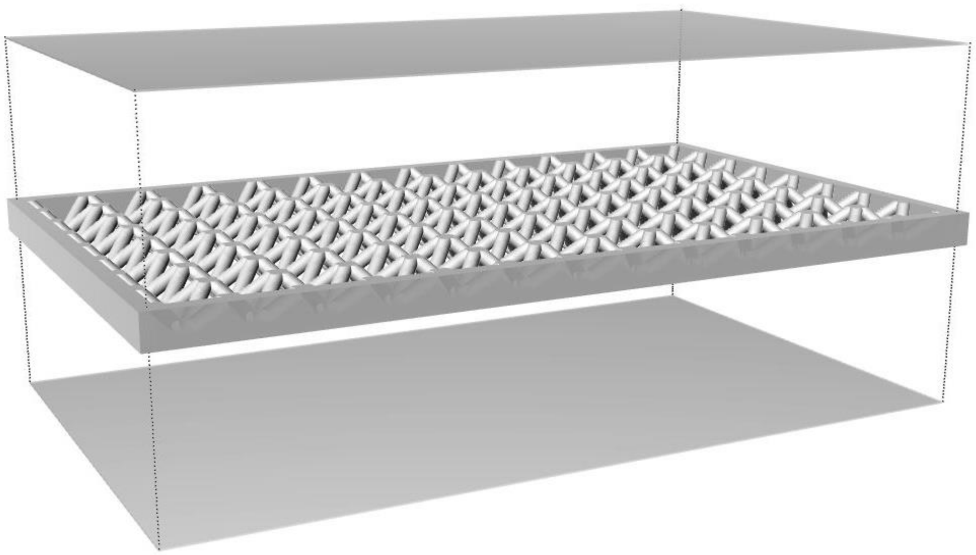


Image 75 - 3D exploded view of the panel. Own image.

8.1 Thermal insulation

This subchapter starts with hand calculations considering the sandwich panel. After that a program is used for validation of the hand calculations. The physical test is discussed to conclude this sub-chapter. The following question will be answered:

What is the actual effect of a trussed pattern in a thin glass composite panel on the thermal insulation properties of the panel?

8.1.1 Hand calculations

Hand calculations are done to estimate if the results from the tests are valid. Two different hand calculations are done. The first is a very rough estimation of the panel in reality, therefore there is an optimistic and a pessimistic calculation. The optimistic calculation only accounts for the volume of the materials used. The pessimistic calculation includes the area of the thermal bridge. Image 76 shows the different parameters of the panel.

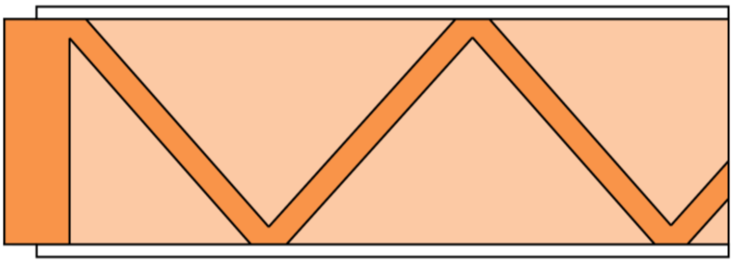


Image 76 - Schematic section of panel. Own image.

The following values are used to calculate the U value of the panel:
λ_{air} = 0,025 (Koninklijk Nederlands Normalisatie-Instituut, 2008)
αi & αo = 7,8 to replicate the test situation.

Table 10 - different parameters and their values

Symbol	Value	Unit		Symbol	Value	Unit
λ_{air}	0,025	W/(m·K)		ε	0,9	
λ_{glass}	0,95	W/(m·K)		ε	0,9	
λ_{PET}	0,29	W/(m·K)		ε res	0,818182	
				σ	5,67E-08	W/m²/K
t_{cavity}	0,01	m		α rad	5,21E+00	W/m²/K
t_{glass}	0,005	m		α conv. + cond.	2,5	W/m²/K
				αi & αo	7,8	W/m²/K
R_{glass}	0,001053	m²K/W		R cavity	0,1297	m²K/W
				λ cavity	0,07713	W/m/K

α Heat transmission coefficient (W/m²/K)		
α Inside	293K	7,8 W/m²/K
α Outside	263K	25 W/m²/K

Optimistic

First, as a reference, a the R value of 10 mm PET and 10 mm air and 1 mm glass is determined. After that, combinations are made with the (100%) PET + glass and (100%) air + glass. Than the real percentage of the PET in the cavity (26%) and the air (74%) are combined to find the optimistic U value of the three different panels (Table 11) (Weersink et al., 2005).

Table 11 - overview optimistic calculation.

	Lambda [W/(mK)]	t [mm]	R [m²K/W]	1/R	Perc. [%]	U value [W/m²K]	Perc. [%]	U value [W/m²K]	Perc. [%]
PET	0,290	0,010	0,034	6,080					
AIR cavity	0,077	0,010	0,130	3,851					
Glass	0,950	0,001	0,001	7,631					
PET + glass		0,011		3,372	100	0,877	26	0,978	29
Air + glass		0,011	0,131	2,553	100	1,889	74	1,812	71
U value						2,77		2,79	
Double layer PET + Glass				3,011	100	0,753	26		
Double layer AIR + Glass				1,914	100	1,435	74		
U value						2,19			

Pessimistic

The contact area of the spacers on the glass is needed for the pessimistic calculation (Weersink et al., 2005). The contact area of one spacer could be derived from the Grasshopper model and is multiplied with the total amount of spacers which contact the surface (Table 12).

$$u = \frac{1}{\frac{A}{\frac{A_1}{R_{C;1}}+\frac{A_2}{R_{C;2}}}+0{,}26} \qquad (17)$$

A = Total surface area of the panel [m²]
A_1 = surface area of the PET contact area [m²]
A_2 = surface area of faces minus the PET contact area [m²]
$R_{c;1}$ = heat resistance (R) of the PET [m²K/W]
$R_{c;2}$ = heat resistance (R) of the glass [m²K/W]
0,26 = the inverse heat transmission coefficient inside and outside (1/7,8 + 1/7,8 W/m²/K)

Table 12 - overview pessimistic calculation.

	Lambda [W/(mK)]	t [mm]	R [m²K/W]	Area [m²]	U value [W/m²K]
PET	0,290	0,010	0,034		
AIR cavity	0,077	0,010	0,130		
Glass	0,950	0,001	0,001		
Area panel, total				0,0375	
Area PET, rand				0,002025	
Area 1 spacer				3,11E-05	
Are spacers (77)				0,002395	
U value standard					2,82
Area 1 spacer				3,08E-05	
Area spacers (104)				0,0032032	
U Dense					2,85
U double					2,22

Thermal bridge effect

The thermal bridge effect in calculated with the following formula which is explained in chapter Thermal insulation. (Tenpierik & Cauberg, 2007):

$$\psi_{\mathrm{vip,edge}} = \frac{1}{1+(\lambda_c/\alpha_1 d_p)+(\lambda_c/\alpha_2 d_p)} \times \left[\frac{\alpha_1 (N_2^2 - B)}{\frac{\varphi d_p \lambda_f}{\lambda_f'}(N_1^2 N_2^2 - B^2) - \lambda_1 \sqrt{N_1^2 N_2^2 - B^2}\left(\frac{2B}{\sqrt{D}}+1\right) - \lambda_2 \sqrt{N_1^2 N_2^2 - B^2}\left(1-\frac{2B}{\sqrt{D}}\right)} \right] \quad (18)$$

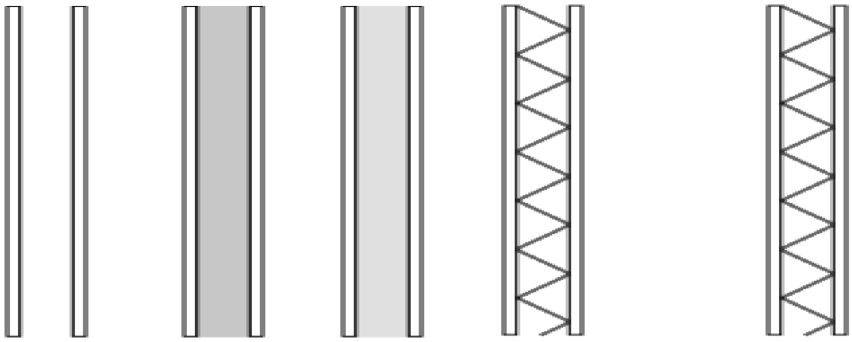


Image 77 - Visualisation thermal calculations. Own image.

Panel type	2x 0,5 mm glass Air filled	2x 0,5 mm glass PET filled	Optimistic 74% PET 26% air	'Standard truss 41°' Pessimistic 2x 0,5 mm glass PET filled	'Standard truss 41°' Thermal bridge eff. 2x 0,5 mm glass PET filled
U [W/m²/K]	2,6	3,4	2,77	2,82	2,662

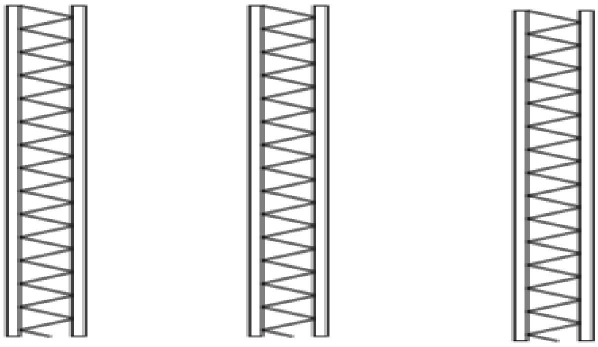


Image 78 - Visualisation thermal calculations. Own image.

Panel type	'Dense truss 67°' optimistic 71% PET 29% air	'Dense truss 67°' pessimistic	'Dense truss 67°' Thermal bridge eff.
U [W/m²/K]	2,79	2,85	2,670

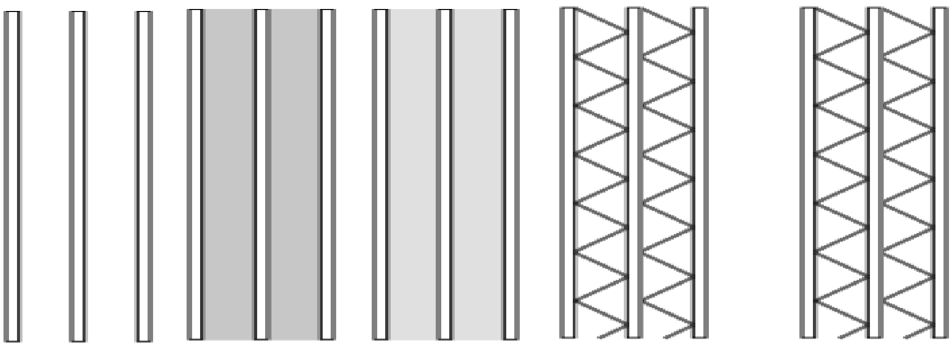


Image 79 - Visualisation thermal calculations. Own image.

Panel type	3x 0,5 mm glass Air filled	3x 0,5 mm glass PET filled	Optimistic 75% air 25% PET	'Double layer 41°' Pessimistic	'Double layer 41°' Thermal bridge eff.
U [W/m²/K]	1,9	3,0	2,19	2,22	2,035

8.1.2 Trisco

Trisco is a program developed by Physibel. Trisco is a validated 3D program to check the heat flow in a structure. A small part of the sandwich panel is put in the program, the effect of the glue is neglected. The effective U value is calculated with the heat flow value provided by Trisco. The effective U values come really close to the values from the hand calculations, but still there are small differences. Table 13 shows the input data for Trisco. For αi & αo is chosen to use 7,8 W/m²/K because this replicates the values from the physical tests.

Table 13 - Input Trisco.

Material	Lambda [W/(mK)]	αi & αo [W/m²/K]	Temp. [°C]	Area [m²]
Glass	0,95			
PET	0,29			
Cavity	0,077			
αi		7,8	50	
αo		7,8	20	
Surface area				0,0064

The output is the temperature difference from inside to outside and the heat flow [W] through the structure. With this information it is possible to calculate the effect of the of the contact point and therefore the effective u value. The following formulas are used:

$$Q_{empty} = A*\Delta t / U_{empty} \qquad (19)$$

With:
Q_{empty}= heat flow through a panel with empty cavity (only air) [W]
A = Surface are of the panel used for calculation [m²]
Δt = difference in temperature over the panel [°C] or [K]
U_{empty} = U value of a panel with empty cavity (only air) [W/m²/K]

$$chi = (Q - Q_{empty}) / dT \qquad (20)$$

With:
Chi = heat flow per temperature of the spacer pattern [W/K]
Q = heat flow going through the panel [W]
Q_{empty} = heat flow through a panel with empty cavity (only air) [W]
Δt = difference in temperature over the panel [°C]

$$U_{eff} = U_{empty} + chi / A \qquad (21)$$

With:
U_{eff} = the effective U value of the panel [W/m²/K]
Q_{empty} = heat flow through a panel with empty cavity (only air) [W]
Chi = heat flow per temperature of the spacer pattern [W/K]
A = Surface are of the panel used for calculation [m²]

Standard truss

Image 80 shows the geometry as it is in Trisco as well as the temperature distribution through the geometry. The effect of the spacer is not visible in the 'standard truss'.

Unit	Value
Q [W]	0,1258
A [m²]	0,0064
Δt	30
U_{empty}[W/m²/K]	2,560
Q_{empty} [W]	0,07501
Chi [W/K]	0,00169
U_{eff} [W/m²/K]	2,824

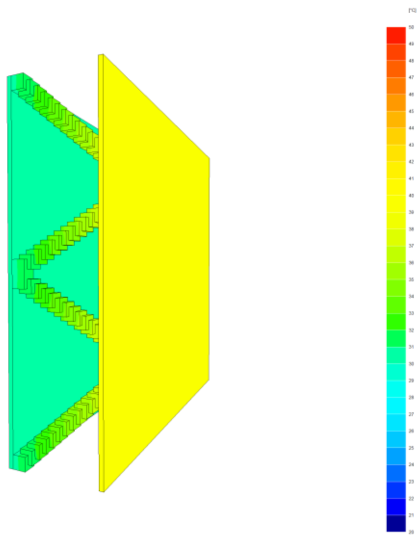


Image 80 - Trisco temperature range, standard truss. Own image.

Dense truss

Image 81 also shows the geometry as it is in Trisco as well as the temperature distribution through the panel. Here the effect of the spacer pattern is visible. This can be explained by the density of the grid. The spacers / contact area influence each other and therefore intensify the effect. The effect is increased heat flow through the spacer pattern.

Unit	Value
Q [W]	0,1789
A [m²]	0,0064
Δt	30
U_{empty}[W/m²/K]	2,560
Q_{empty} [W]	0,07501
Chi [W/K]	0,00350
U_{eff} [W/m²/K]	3,099

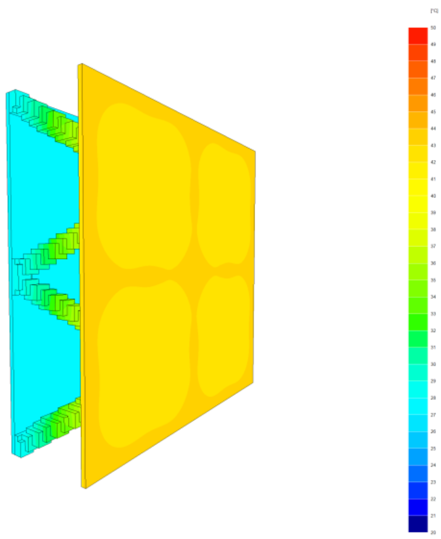


Image 81 - Trisco temperature range, dense truss. Own image.

Double truss

Image 82 again shows the geometry in Trisco and the temperature distribution. The effect of the spacer is also visible here, but the impact is different. More PET is used, which increases the heat flow, but the effective heat flow is decreased because the PET is divided over two layers.

Unit	Value
Q [W]	0,0954
A [m²]	0,0064
Δt	30
U_{empty}[W/m²/K]	1,919167
Q_{empty} [W]	0,100043
Chi [W/K]	-0,00015
U_{eff} [W/m²/K]	1,895

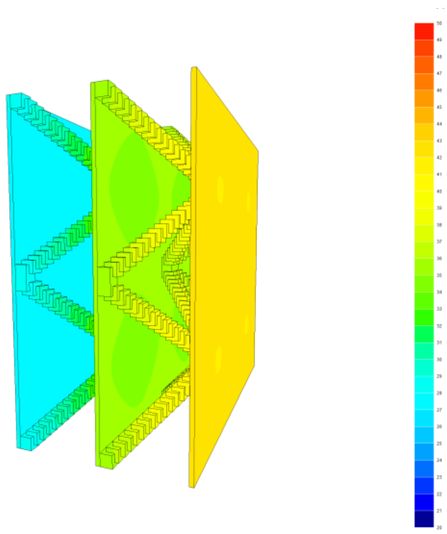
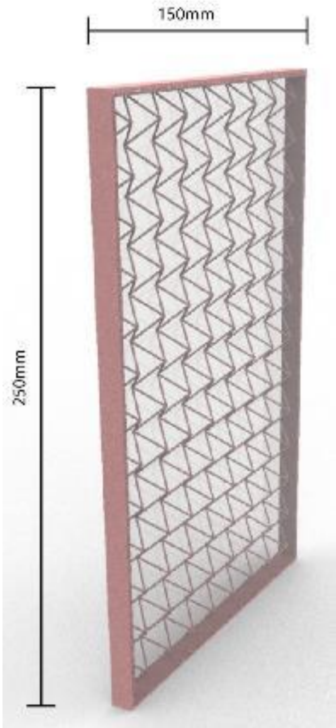


Image 82 - Trisco temperature range, double layer. Own image.

8.1.3 Physical test

A heat flow sensor test will be done to find out what the influence of the spacer pattern is on the thermal insulation properties of the panel. The general dimension of the panel are shown in Image 83.



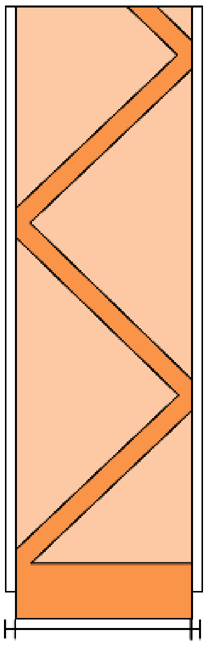


Image 83 - Schematic layout of test specimen. Own image.

Equipment and procedure

The panels are experimentally investigated on their thermal insulation properties by creating a temperature difference over the panel. The dimensions of the specimen are 250 x 150 x 11mm. A styrofoam box (Image 84), with a cut out for the panel, is heated with a lamp till +/- 48 ˚C. The temperature is measured at four locations: inside the box, the surface of the panel inside the box, the surface of the panel outside the box and the room temperature surrounding the box. Heat flux, i.e. heat flow rate intensity is a flow of energy of unit per area of unit. The output of a heat flux sensor is mV, which means the output needs to be converted to heat flux values [W/(m²·K)]. Table 14 shows the specifications of the heat flux sensors from Hukseflux. The test for one panel will take about one hour because the temperature to be steady. Only one of each pattern needs to be tested, so that will be 3 panels in total. Needed equipment (Image 85):

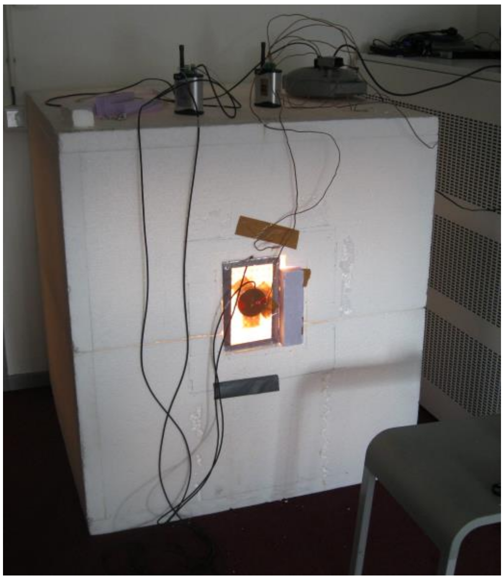


Image 84 - Test set-up. Own image.

- 2x heat flux sensor HFP01
- 4x thermocouples type T
- 1x voltmeter
- 2x Eltek Genll transmitters
- Eltek Genll Quirrel data logger
- Eltek Darca+ software
- Heated box
- Laptop

Table 14 - Specifications heat flux sensor (Hukseflux Thermal Sensors B.V., 2016).

Measurand	heat flux
Measurement range	-2000 to +2000 W/m^2
Sensitivity (nominal)	60 x 10^{-6} $V/(W/m^2)$
Sensing area	8 x 10^{-4} m^2
Guard width to thickness ratio	5 m/m (as required by ISO 9869 D.3.1)
Sensor thermal resistance	71 x 10^{-4} $K/(W/m^2)$
Sensor thickness	5.4 x 10^{-3} m
Uncertainty of calibration	± 3 % (k = 2)
Rated operating temperature range	-30 to +70 °C
Cable diameter	4 x 10^{-3} m

Inaccuracy test results

Image 85 - Photo of the complete test set-up. Own image.

- Heat is leaking through small gaps between the panels and the box. This can create an airflow which can affect the measurement.
- It is hard to put the two heat flux sensors at the exact same spot as the other one. This creates a small difference in the heat flow.
- Radiation from the light (daylight and lamplight) can affect the heat flux sensor output.
- It is difficult to place the temperature sensor exactly on the surface of the panel. This can give a deviation in the measured temperature.
- When someone is performing the test, it is necessary to wait for the box to completely warm up. It could be the case that the measurements are done a bit too early. This can give a small deviation in the temperature results.

Hukseflux writes in their manual about inaccuracy considering test results:

> *"Under ideal conditions, measurements of heat flux in building physics may attain uncertainties in the ± 6 % range. Contributions to the uncertainty budget: calibration, temperature dependence from -10 to + 30 °C, thermal conductivity of the surrounding environment from 0.5 to 1.5 W/(m·K), representativeness of the measurement location. ISO 9869 chapter 9 shows examples of uncertainty evaluation, for thermal resistance measurement. This uncertainty budget also includes contributions from the temperature measurements and dynamic effects. It arrives at typical uncertainties of the order of ± 20 % of on-site measurements of thermal resistances. Corrections may be applied according to chapter 8 of ISO 9869. These corrections include corrections for the thermal resistance and corrections for the finite dimension of the sensor. ISO also calls the latter the operational error, we use the term deflection error." (Hukseflux Thermal Sensors B.V., 2016)*

Test location

One set of heat flux sensors is placed where a printed beam is connected to the glass and one set is placed in between connection areas. The red dot shows the exact area where measurement will take place (Image 86). The diameter is 32 x 10^{-3} m. The measurements per panel start with the left location. Thus, the left image is 1 and the right measurement is 2. These two locations are chosen because it is expected that there will be a difference in result. It is expected that 1 (left) will give a better result than 2 (right).

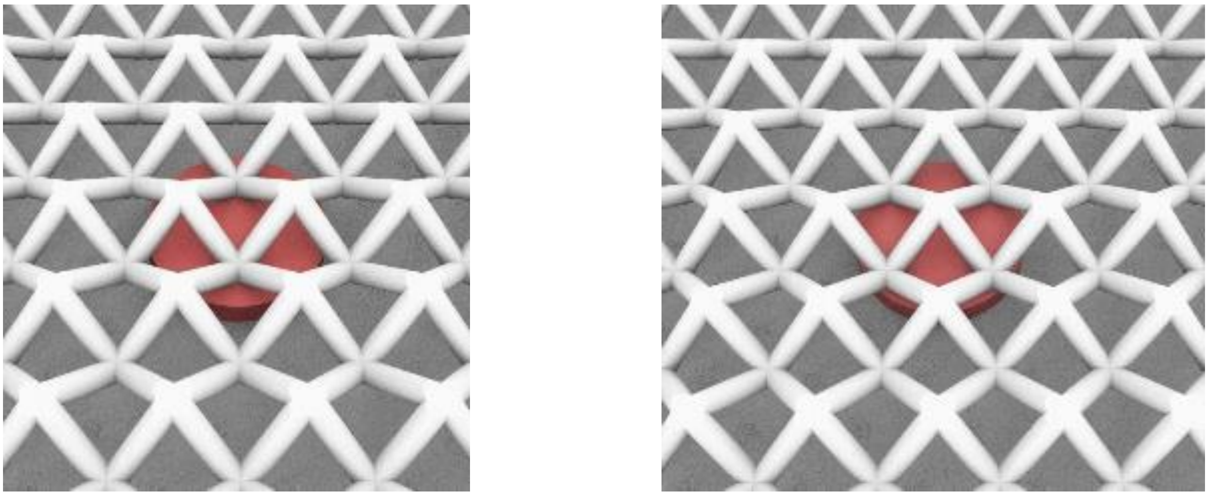


Image 86 - Location of heat flux sensor. Own image.

Test materials

The test specimens used for the thermal test are three composite sandwich panels with the overall dimensions of 150 x 250 mm . The specimens are made of thin glass facings and a 3D printed PET 3D-space-frame and there are three types of panels. The first panels has a 3D-space-frame with an angle of 41 degrees and the diameter of the beams is 4mm, which is used as a refence panel for the other panels. The second panel has a 3D-space-frame with an angle of 67 degrees, this results in more contact points between the two faces. The third panel consists of three thin glass layers and two cores (Image 87). An aluminium tape is used to prevent hot air form flowing out of the panel (Image 87).

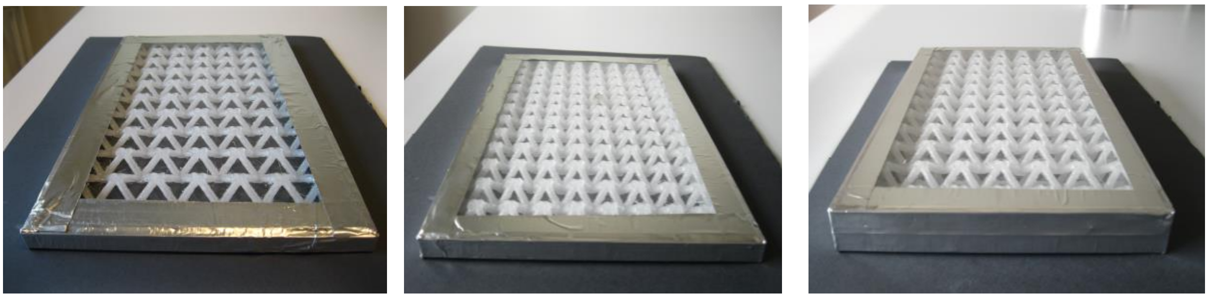


Image 87 - Taped panels for the thermal test. From left to right: Standard pattern, dense pattern and double pattern. Own image.

The following formulas are used to convert the outcome of the sensors to an U value:

$$\varphi = \frac{\text{Sen.}}{\text{S}} \tag{22}$$

$$\text{R} = \frac{\Delta\text{T}}{\varphi} \tag{23}$$

$$\lambda = \frac{\text{d}}{\lambda} \tag{24}$$

$$\lambda = \frac{d}{\text{R}} = \frac{\text{d} * \varphi}{\Delta\text{T}} \tag{25}$$

With:

Table 15 - Explanation of symbols.

Symbol	Unity	Property
λ	W/m·K	Thermal conductivity *(warmtegeleidingscoëfficiënt)*
R	K·m²/W	Heat insulation *(warmteweerstand)*
U	W/m²·K	Thermal transmittance
Δ T	K	Difference in temperature
ϕ	W/m²	Heat flux *(warmtestroom)*
α	W/m²/K	Conduction
ε		Grey body radiation emission coefficient
S	mV/(W/m²)	Sensor sensitivity
Sen.	mV	Sensor input

Results

Table 16 shows the test results per panel. The results show that there is no big difference between the two test locations. This means that the PET has an influence over the whole panel with these patterns. The contact area of the PET would have more influence if the grid of the pattern would be wider. Furthermore it is notable that the difference in U value between the standard and the dense pattern is not that significant, the difference in transparency is more contrasting. This means that the results in U value of small differences in the amount of PET used as a core is negligible. The effect of adding an extra layer of PET and air is way more effective. But the improvement of 0,5 is not in line with the improvement from the hand calculations, 0,6. So, the PET has a bigger effect here, even though the path of the heat flow is lower. This result is in line with the earlier notion, that the contact points are too close to each other, they influence each other.

The difference in U value between the calculation and the test is more outstanding than the difference between the test locations (Table 17). This could be explained by the simplification of reality in the hand calculations.

Table 16 - Test results per panel.

Panel	Average Heat flux	Delta T [°C]	Average lambda [W/m/K]	R average [m²K/W]	U average [W/m²/K]
Standard 1	86,598	14,10	0,0614	0,163	2,37
Standard 2	86,934	14,20	0,0612	0,163	2,36
Dense 1	91,527	14,50	0,0631	0,158	2,39
Dense 2	87,605	13,90	0,0630	0,159	2,39
Double 1	67,821	18,10	0,0375	0,267	1,90
Double 2	67,024	18,10	0,0370	0,270	1,89

Table 17 - Calculation and test results.

	Standard [W/m²/K]	Dense [W/m²/K]	Double [W/m²/K]
Optimistic	2,77	2,79	2,19
Pessimistic	2,82	2,85	2,22
Thermal bridge eff.	2,66	2,67	2,04
Trisco	2,82	3,10	1,90
Test 1	2,37	2,39	1,90
Test 2	2,36	2,39	1,89

8.1.4 Conclusion

What is the actual effect of a trussed pattern in a thin glass composite panel on the thermal insulation properties of the panel?

More PET contact points, standard versus dense pattern, is not equal to worse thermal conduction. This only applies when the difference in amount of PET is bigger. The effect of the contact points, with these patterns, is very small because the points are too close to each other. The effect of a contact point will be increased when the grid size is increased. This is also shown in the double panel, the increase of the insulation value is not in line with the expected insulation value in the hand calculations. The results of the tests are better than the 'percentage hand calculation', this could be explained by the simplification of reality in the hand calculations.

8.2 Structural properties

This subchapter starts the structural behaviour of a sandwich panel is discussed in relation with the thin glass composite panel design used for this research. The following question will be answered:

What is the actual effect of a trussed pattern in a thin glass composite panel on the structural properties of the panel?

8.2.1 Physical test

After the thermal tests, a compression test is done to determine the behaviour of the panel under a load. The panels will be tested for their ultimate limit state. The location of the failed parts will show where the panel can be improved. The aim for this test is to research the effect of the spacers on the structural properties of the panel. Image 88 shows the general dimensions of the panel and the location of the applied load.

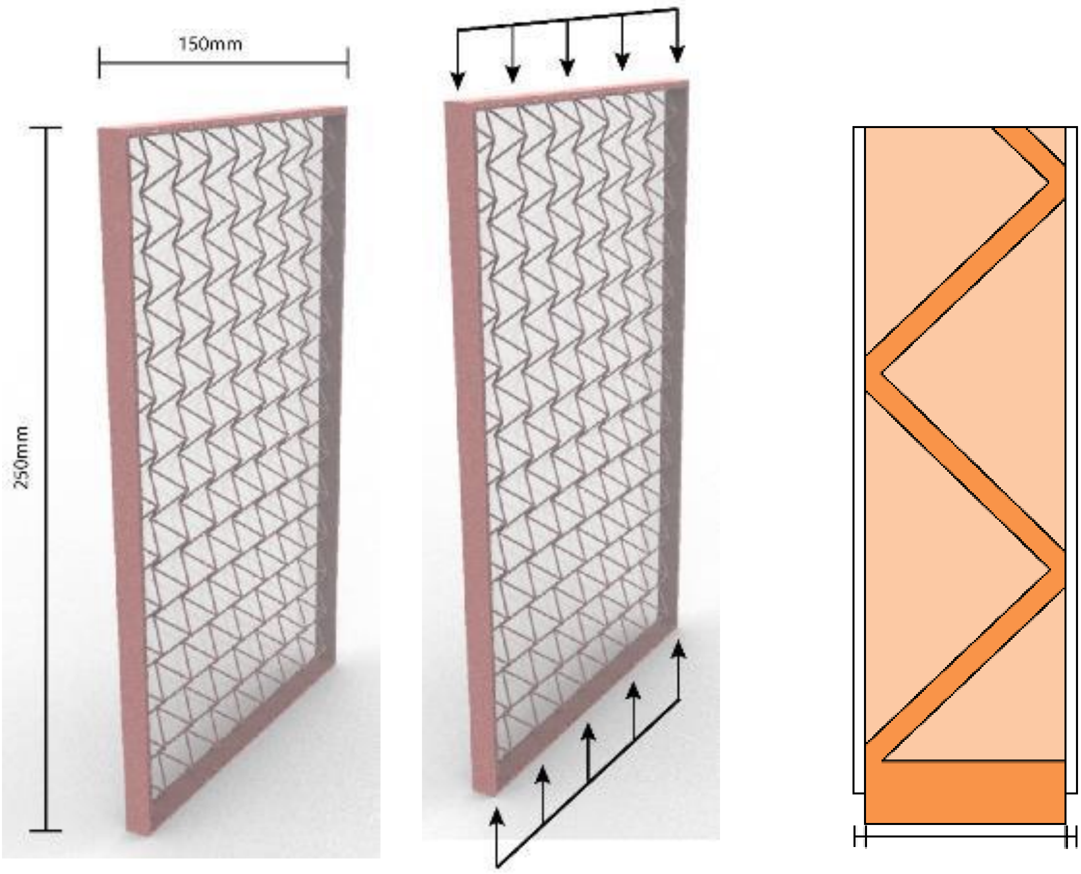


Image 88 - Schematic layout of test specimen. Own image.

Table 18 - Explanation of symbols.

Symbol	Unity	Property	Symbol	Unity	Property
δ	mm	Deformation	c	mm	Thickness of core
P_{max}	N	Peak load	t	mm	Thickness of the face
L	mm	Length of the specimen			

Equipment and procedure

The panels are experimentally investigated on their compressive properties and crushing behaviour by applying an in-plane compressive load in the edgewise direction along the length of the panels (Image 1). Dimension of the specimen. The edges put on a piece of wood to prevent compression on the edge of the glass, the core is compressed. The tests are interrupted when the glass starts to break or when one glass layer is broken in such way it cannot take any load. The testing conditions are: temp. 20˚C and compression speed 1mm/ min.

From the load, load/ displacement, δ curves that were recorded directly during the testing works the following compressive and crushing characteristics of the test specimens were calculated and recorded:

- Peak load, P_{max}
- Deformation, δ = Pmax/(b x d)(mm)

Image 89 - Tension/ compression testing machine. Own image.

Test materials

The test specimens used for the compressive test are composite sandwich panels with the overall dimensions of Image 88 and Image 90. The specimens are made of thin glass facings and a 3D printed PET 3D-space-frame and there are three types of panels. The material of the faces is thin glass with a thickness of 0,5mm with a density of 2,48 kg/cm³, a Youngs modulus of 71 - 73 GPa and a shear modulus of 71 - 73 GPa. The material of the core is PET with a density of $1{,}38*10^{-3}$ kg/cm³, a Youngs modulus of 2,8 - 3 GPa and a shear modulus of 0,994 - 1,49 GPa. Table 19 shows the properties in an overview.

The first panel has a 3D-space-frame with an angle of 41˚, which is used as a refence panel for the other panels. The second panel has a 3D-space-frame with an angle of 67˚, this results in more contact points between the two faces. The final panel consists of three thin glass layers and two 41˚ cores (Image 90). Table 20 shows the amount of materials in an overview.

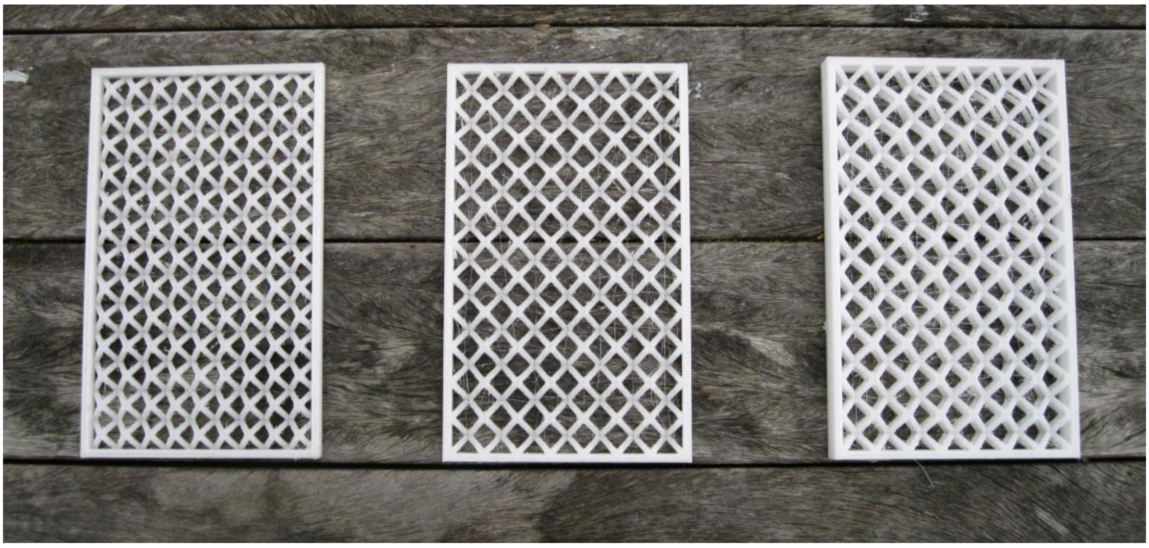


Image 90 - Overview of test specimen. Own image.

Table 19 - Material properties.

Material	Size	Density (kg/m³)	Youngs modulus (GPa)	Shear modulus (GPa)
Thin glass	150 x 250 x 0,5 mm	2,48 $*10^3$	71 - 73	71 - 73
PET	~ 50 gr	1,38$*10^3$	2,8 - 3	0,994 - 1,49

Table 20 - Amount of materials used.

Type of panel	Amount of panels to test	Amount of cores	Amount of faces
Basic: truss 45˚	3	3	6
Variant 1: truss 67˚	3	3	6
Variant 2: truss 45˚, double layer	3	6	9
Total	9	12	21

Expectation

The panel will buckle over the whole length and therefore the glass, on the outside of the curve will break in the middle. Depending on the shear stress in the core, the panel will buckle like the left, or the right. If the core is strong enough to take all the shear stresses, the panel will deform like the left panel in Image 91. Of the core is weak in shear stresses, it will fail like the right panel in Image 91. Another possible failure mode is delamination, but how this will happen cannot be predicted.

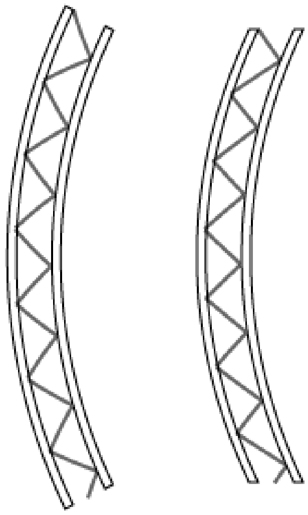
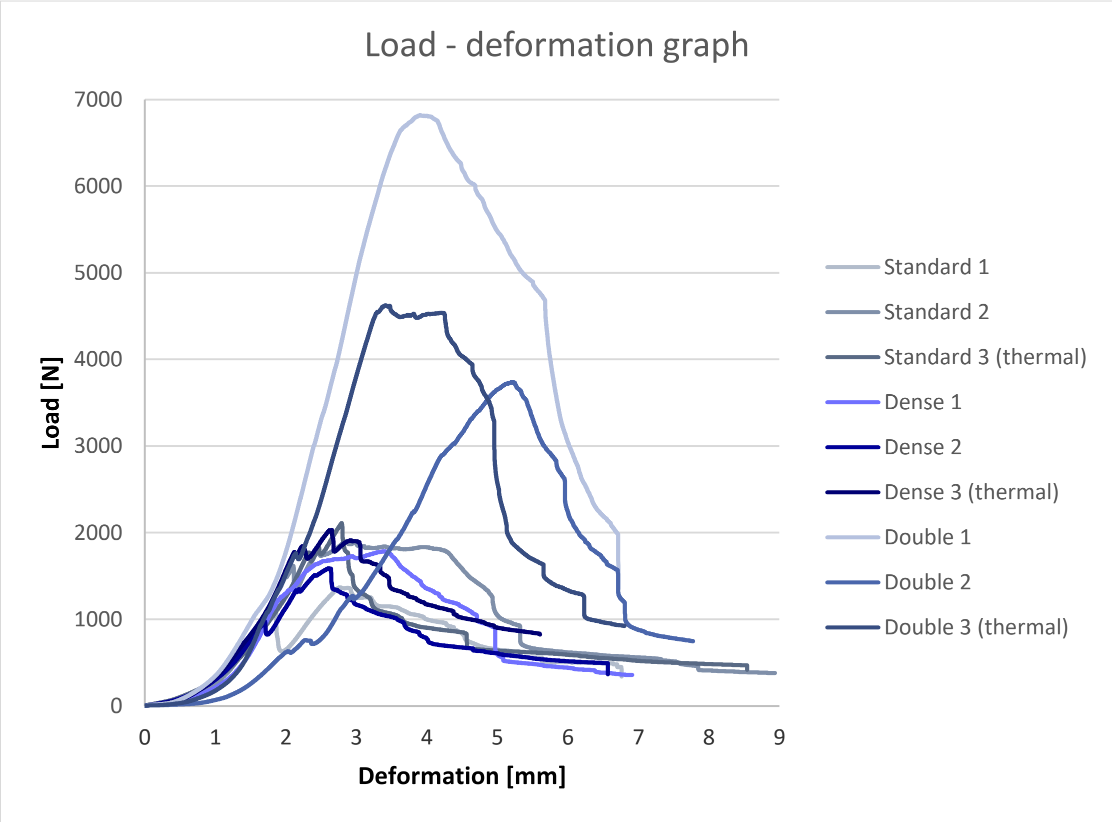


Image 91 - Deformation, buckling, of the sandwich panel. Own image.

Results

The results of all the specimen are shown in the graph below. Every panel is tested for their ultimate limit state, which means every panel suffered tensile fracture of the facing. The graph shows a scattering of curves, especially the curve of the 'Double' specimen. This makes the behaviour of the panel unpredictable. There is also a small difference in curves between the panels which are used for the thermal tests and the ones who are not used for that test. But the same thing for every panel happened, which is as followed: 1. Delamination, 2. Bending of the panel, 3. Tension fracture of the facings. The results of the different panels are discussed more in-depth on the next pages.



Standard pattern, 145 gr. PET

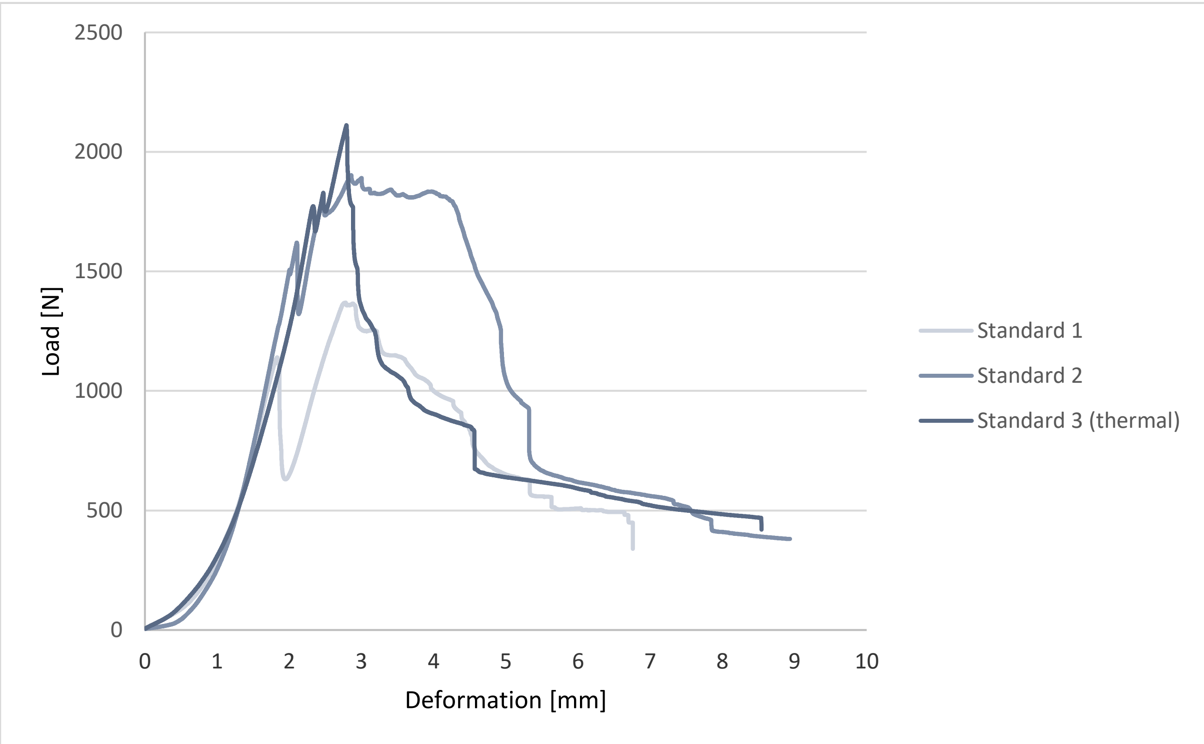
Standard 1 | Standard 2 | Standard 3 (thermal)



Image 92 - Maximum deformation. Own image.

	Crack distance from edge (mm)	Delamination
1	39	Broken + unbroken
2	39	Broken + unbroken
3	119	Broken + unbroken

Only nr. three buckled over the complete length of the panel. Nr. 1 & 2 acted as they had fixed ends. Therefore they buckled near the edge, at the weakest part of the core.



Dense pattern, 160 gr. PET

Dense 1

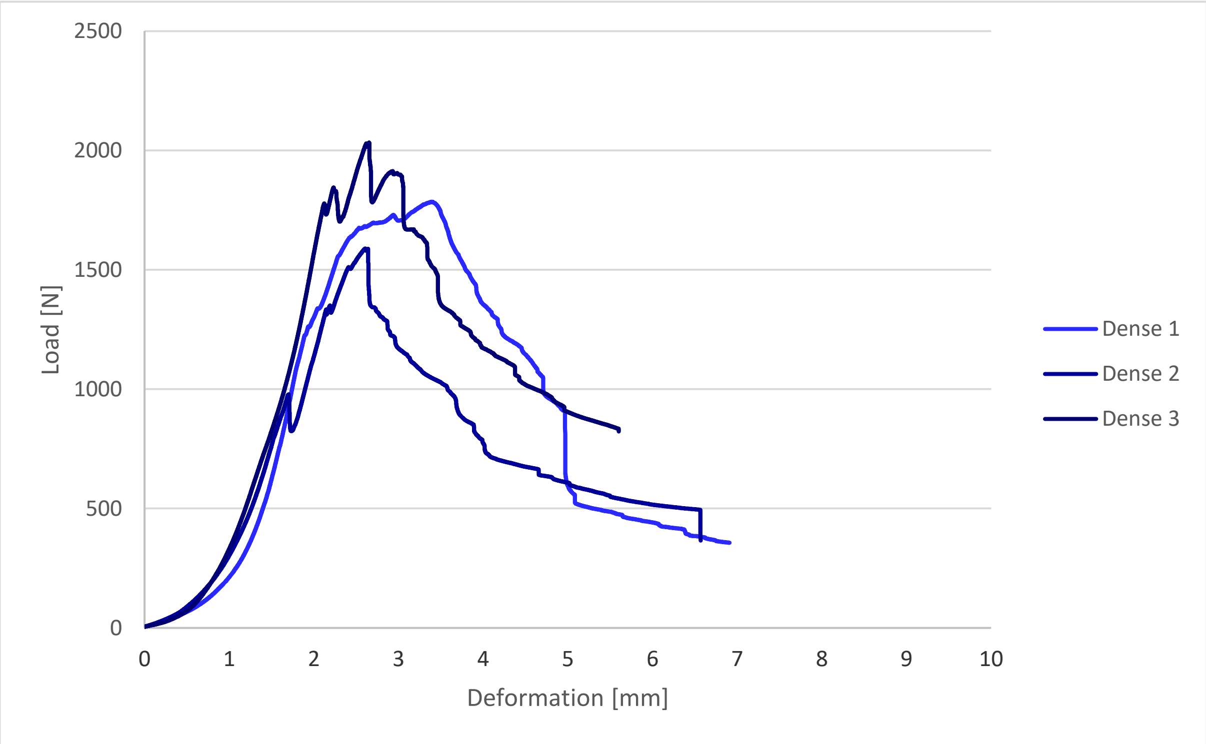
Dense 2

Dense 3 (thermal)

Image 93 - Maximum deformation. Own image.

	Crack distance from edge (mm)	Delamination
1	27	Unbroken
2	51	Broken + unbroken
3	49	Unbroken

Less delamination of the glass sheets can explain the smaller deformation of the panel. More surface area for the glue provides more stiffness.



Double layer, 190 gr. PET

Double 1

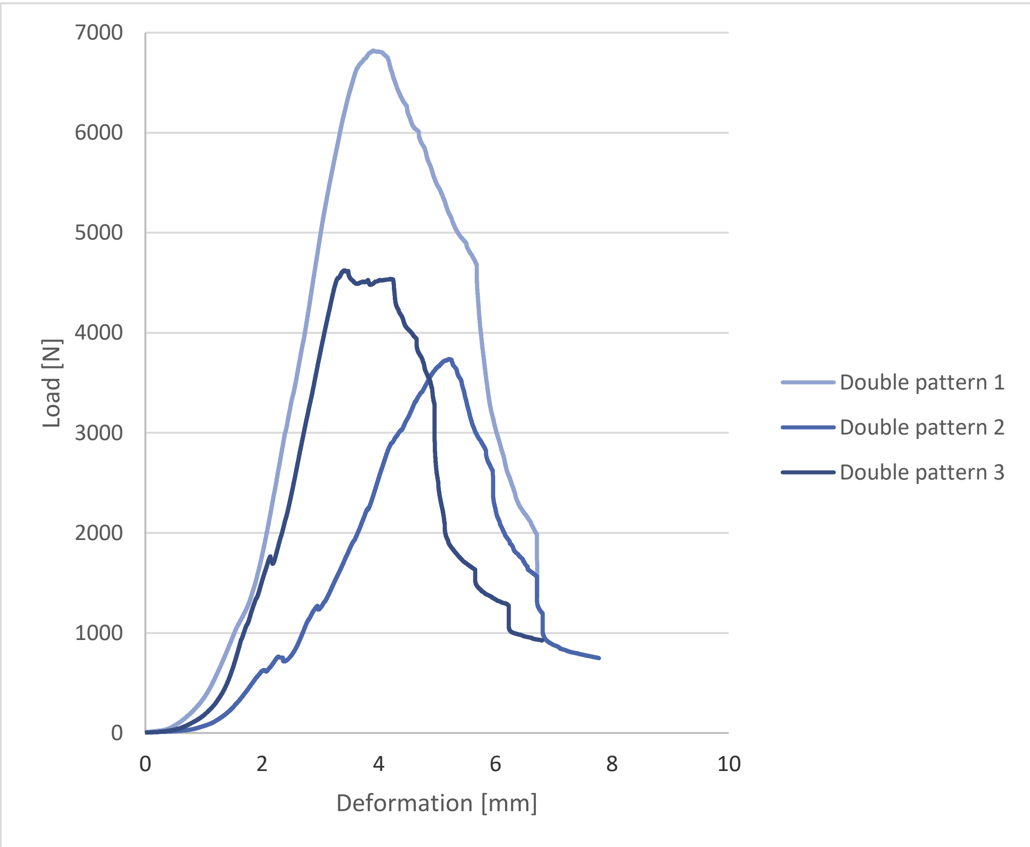
Double 2

Double 3 (thermal)

Image 94 - Maximum deformation. Own image.

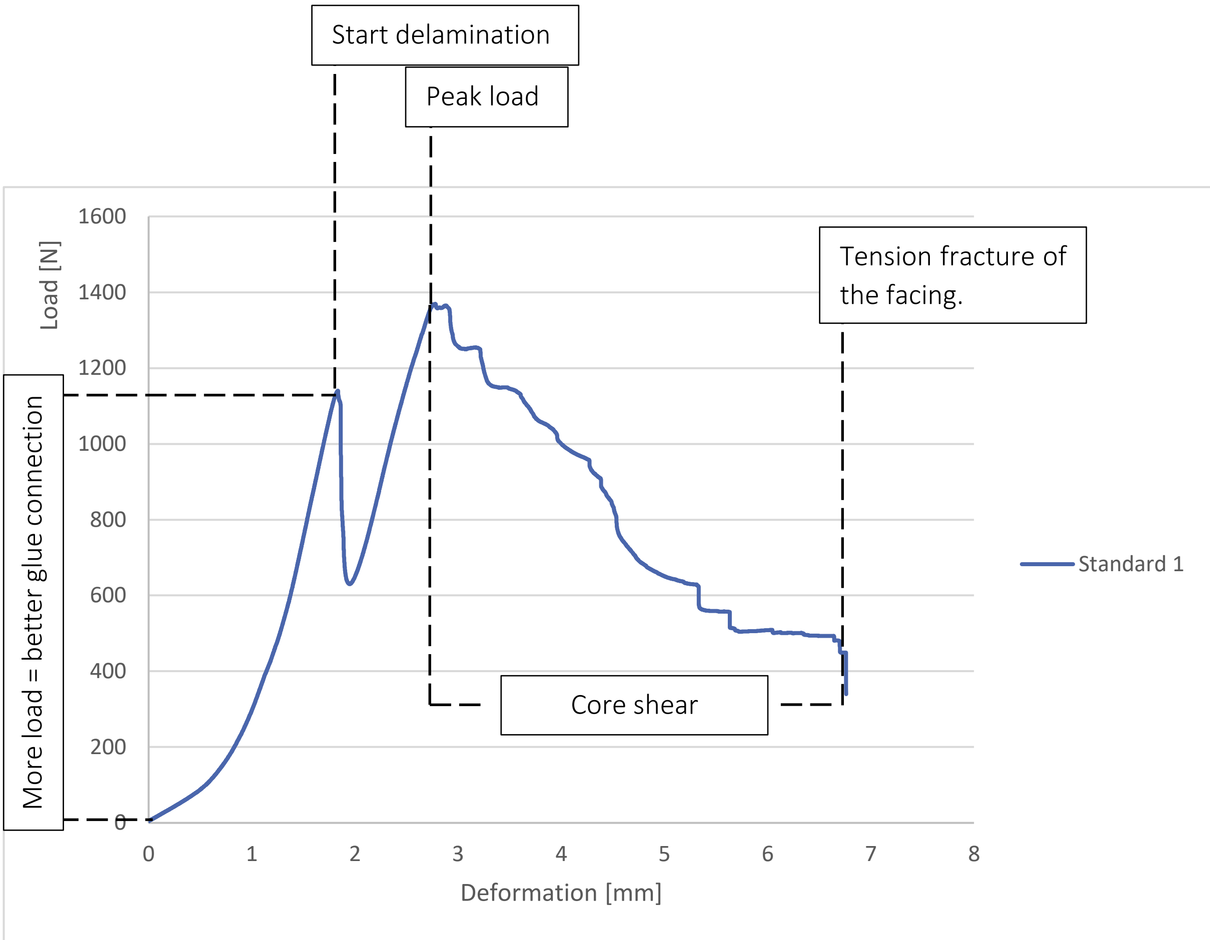
Crack distance to edge Front (7 whole points) - back (6 whole and two half points)

	Front (mm)	Middle (mm)	Back (mm)	Delamination
1 All cracks start at same side	17 and 17	+/- 20	12,5 & 22 same side	Middle
2	-	+/- 40 (other side)	37	Unbroken + middle
3	29	+/- 30 mm same side as front	42mm (other side)	Broken



8.2.2 Conclusion

What is the actual effect of a trussed pattern in a thin glass composite panel on the structural properties of the panel?



The first dip in the curve announces the start of delamination. Delamination probably goes on till the panel breaks. The amount of load the panel can take before the lamination starts equals to a glue connection of good quality. The failure mode is dominated by delamination because that it the first thing that occurs during the compression test. After that the panel fails due to shear in the core. The difference in deformation can be explained by the quality and the surface area of the glue. The better the glue quality and the more surface area, the least deformation. But more surface area is not equal to a higher strength.

To conclude, the panel is not safe to use as a load-bearing structure, because the failure mode is dominated by delamination. But the panels can take their self-weight. For example the standard pattern self-weight is: G = 24,3*2*0,0005+13,0*0,01*0,26 = 0,058 kN/m^2, 0,058*1,48*3,2 = 0,245 kN. The worst panel can take almost double that weight before it starts delaminating. Thus the compression tests proved that the panels can carry their self-weight, when the size of the panels is increased to 2,5 x 3,2m.

8.3 Overall Conclusion

What is the actual effect of a trussed pattern in a thin glass composite panel on the thermal insulation and structural properties of the panel?

Thermal insulation

More PET contact points, standard versus dense pattern, is not equal to worse thermal conduction. This only applies when the difference in amount of PET is bigger. The effect of the contact points solely, with these patterns, is very small because the points are too close to each other. The effect of a single contact point will be increased when the grid size is increased. This is also shown in the double panel, the increase of the insulation value is not in line with the expected insulation value in the hand calculations. The results of the tests are better than the 'percentage hand calculation', this could be explained by the simplification of reality in the hand calculations.

Structural properties

The first dip in the curve announces the start of delamination. Delamination probably goes on till the panel breaks. The amount of load the panel can take before the lamination starts equals to a glue connection of good quality. The failure mode is dominated by delamination because that it the first thing that occurs during the compression test. After that the panel fails due to shear in the core. The difference in deformation can be explained by the quality and the surface area of the glue. The better the glue quality and the more surface area, the least deformation. But more surface area is not equal to a higher strength. To conclude, the panel is not safe to use as a load-bearing structure, because the failure mode is dominated by delamination. But the panels can take their self-weight. For example the standard pattern self-weight is: G = 24,3*2*0,0005+13,0*0,01*0,26 = 0,058 kN/m², 0,058*1,48*3,2 = 0,245 kN. The worst panel can take almost double that weight before it starts delaminating. Thus the compression tests proved that the panels can carry their self-weight, when the size of the panels is increased to 2,5 x 3,2m.

DESIGN PROPOSAL

9 PANEL IMPROVEMENTS

This chapter discusses the main question. First a look back at the starting point of this research, the Glass House. Then the possible improvements are given and to conclude the most realistic improvements are used for a design proposal. The main question is:

To what extent can a thin glass composite panel, with a polymeric 3D-printed trussed core, be improved to meet the thermal insulation and structural regulations of today, to be used as a façade element in the building industry?

9.1 Initial design context

This research started with a scope to redesign the façade of the Glass House (Image 95).

Image 95 - The Glass House, designed by Philip Johnson. Photo: Michael Biondo.

The façade needs to perform good under all circumstances. It needs to keep the weather out, the heat (or cool air in summer) in and the building standing (Image 96). Façade criteria:

- Permanent load (dead load: self-weight, weight of roof
- Variable load (wind load, snow load)
- Insulation
- Air tight
- Water tight

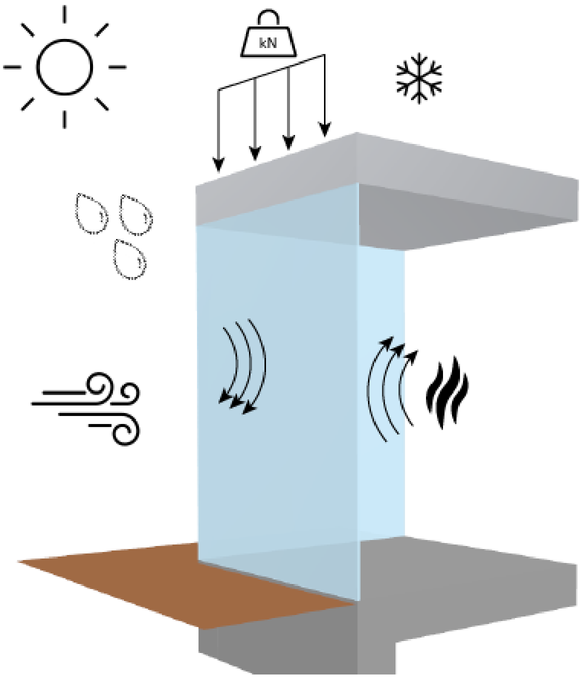


Image 96 - Schematic visualisation of the function of the façade. Own image.

The main goal of this research was to come up with a lightweight panel. Lightweight structures are generally used for houseboats, caravans, skyscrapers or renovation projects. The chosen case study, is in this case not suitable. It is not possible to design a panel which will meet the structural and thermal criteria. But it is possible to design a range of panels with a specific functionality. A range from for, example, small panels with maximum transparency and high insulation properties to bigger panels with sun shading and moderate insulation properties till big, translucent panels with good structural properties, and everything in between.

9.2 Thermal insulation panel

This sub-chapter first discusses the improvements considering the thermal insulation of the panel and after that the panel edge in relation to traditional panel edges. An overview of realistic improvements is given to conclude this sub-chapter.

9.2.1 Panel improvements

The improvements considering the thermal part of the panel are discussed in this sub-chapter. Every improvement is shown, in blue, in a section of the panel. Some things are tried which did not have success in improving the panel, such as decrease of the cavity width. These things are not further elaborated. The improvements are build-up on each other, so the new u values are a result of all the previous improvements together. The starting point is a reference panel of double glass which is air filled and then the standard truss panel which is used in this research. Improvements to increase the thermal insulation value:

- Decrease radiation
- Decrease lambda value for cavity
- Decrease lambda value for core material
- Decrease the amount of core material
- Add more layers
- Decrease sunlight coming in in summer

Reference panel

The starting point is an air filled double glass pane (Image 97), the U value is 2,58 W/m²/K. When the spacer is added, the u value becomes 2,613. The calculation of 'thermal bridge effect' is used here. The U values for the thin glass panel will be compared with traditional double glazing. The traditional double glazing, now 'normal', will undergo the same improvements as the thin glass panel.

Improvement	Thin glass	Normal
	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,583

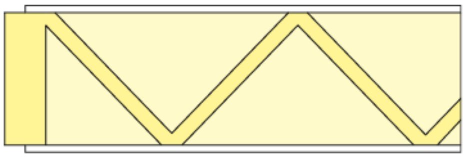


Image 97 - Section of the panel. Own image.

Decrease radiation

Radiation is reduced be a coating on the glass. It is possible to apply two coatings on the two surfaces of the glass, facing the cavity (Image 98). The biggest reduction of radiation is already achieved by one coating. The second coating will reduce the radiation a bit further, but the effect is not so big. In the case of this research, a soft coating needs to be applied. But this will give complications with the glue. Better coatings are already available, these are the hard coating. They are applied on a normal panel on both glass panes in the cavity. Therefore the U value will be lower in reality, but to compare the to panes on the same level, the same improvements are applied.

Improvement	Thin glass	Normal
	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,583
Decrease radiation (ε = 0,2)	2,066	1,907

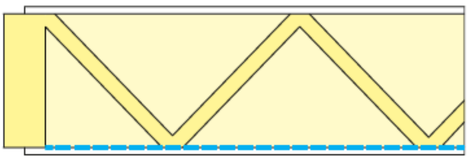


Image 98 - Section of the panel and location of the coating. Own image.

Decrease lambda value cavity

Krypton could be used to decrease the lambda value of the cavity instead of air. The lambda value of krypton is 0,009 W/m/K (Image 99). New calculations need to be done considering the alpha cond. + conv. in the cavity in order to change this lambda value (Jóhannesson, 2006). Appendix 15.10 shows the calculation considering Krypton. Conduction is still dominant, thus the alpha is now 1,3 W/m²/K.

Improvement	Thin glass	Normal
	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,583
Decrease radiation (ε = 0,2)	2,066	1,907
Krypton (λ = 0,009 W/m/K)	1,749	1,538

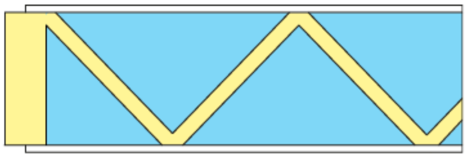


Image 99 - Section of the panel and location of the gas. Own image.

Decrease lambda of core material

The PET can be changed to another material with a better lambda value, this could be the Woodfill which is earlier presented in this research (Image 100). Using woodfill brings other difficulties. More research needs to be done considering the right type of glue for this material and the behaviour of the woodfill and glue in combination with moisture.

Improvement	Thin glass	Normal
	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,583
Decrease radiation (ε = 0,2)	2,066	1,907
Krypton (λ = 0,009 W/m/K)	1,749	1,538
Woodfill (λ = 0,13 W/m/K)	1,690	

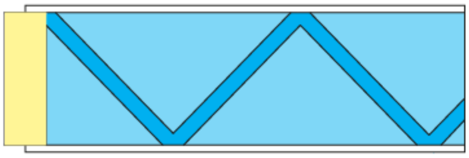


Image 100 - Section of the panel with different core material. Own image.

Decrease the amount of core material

The amount of core material can be decreased by stretching the grit (Image 101). This way, less material is used which can transport the heat from one side to the other. But this method seems to be not very effective.

Improvement	Thin glass	Normal
	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,583
Decrease radiation (ε = 0,2)	2,066	1,907
Krypton (λ = 0,009 W/m/K)	1,749	1,538
Woodfill (λ = 0,13 W/m/K)	1,690	
Wider grit (10%)	1,635	

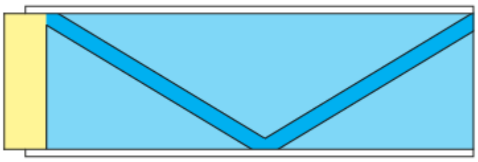


Image 101 - Section of the panel when a wider grit is applied. Own image.

Add more layers

Adding layers has a high contribution in the decrease of the U value (Image 102). But adding layers also means adding thickness. A cavity of 10 mm is not very thick, the thickness is doubled by adding one layer. Thus, adding layers increases the thickness and material use of the panel, but has a significant effect on the thermal insulation value of the panel.

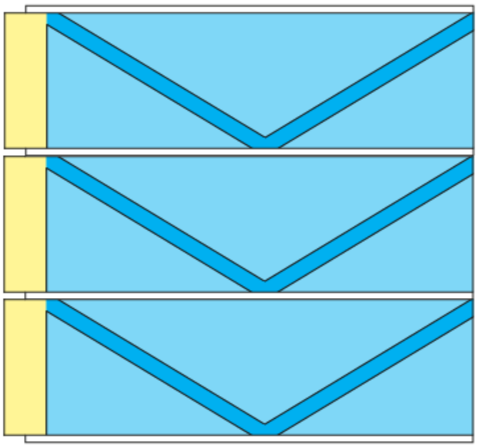


Image 102 - Section of the panel, with two added layers. Own image.

Improvement	Thin glass	Normal
	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,583
Decrease radiation (ε = 0,2)	2,066	1,907
Krypton (λ = 0,009 W/m/K)	1,749	1,538
Woodfill (λ = 0,13 W/m/K)	1,690	
Wider grit (10%)	1,635	
Add one layer	1,038	0,961
Add two layers	0,761	0,699

Sun shading

Sun shading can be created by making smart use of the core. This does not equal as an improvement in the thermal insulation properties, but it regulates the amount of sunlight coming in. This reduces the heat gain due to the sunlight (OKALUX, 2019).

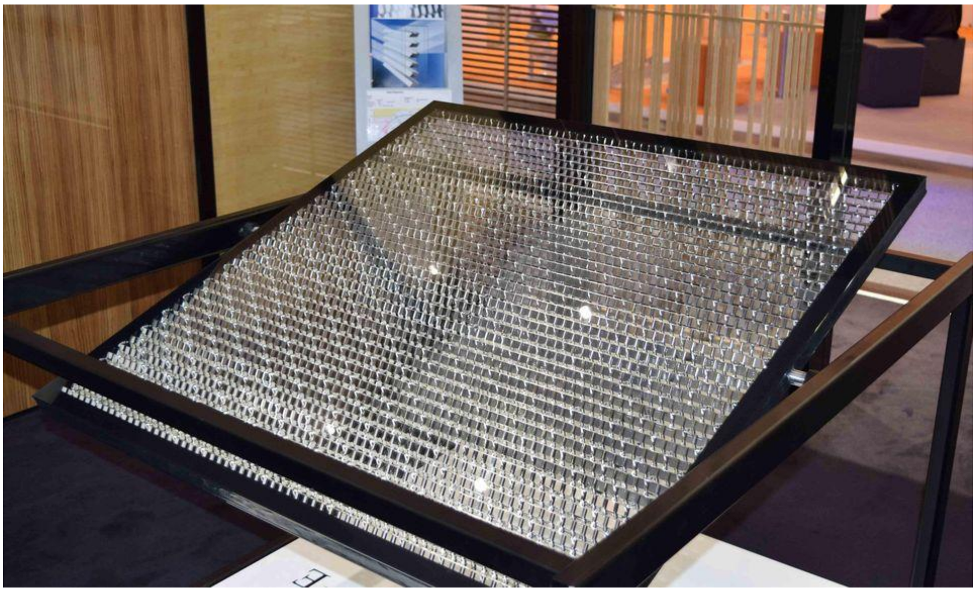


Image 103 - OKASOLAR panel from OKALUX.

9.2.2 Panel edge

Different types of spacers are used in traditional windows to keep the two glass panes separated. The spacers also has another function, namely absorbing moisture which is left in the cavity. The materials which can absorb the moisture are polypropylene and styrene acrylonitrile resin (Technoform, 2019) . The most used spacer, is the spacer on the right in Image 105. Aluminium is used in the edge of the glass panes, this is the only thing that separates the two glass layers. But in the case of the research, not only the spacer in the edge separates the two glass panes. Therefore it might not be necessary to use aluminium in the spacer. To stay within the scope of this research, a spacer of a different material is used; PA6. It is still important to integrate a material which will absorb the moisture and to use a material which has a very high young's modulus, comparable to aluminium. The spacer can also be used as a connector, to connect different panels and to connect panels to the building structure. Materials such as extruded nylon are very stiff and strong materials. CES EduPack writes:

> *"Nylon is a polyamide and is known for their strength, light-weight and durability. They range from the classic Nylon 6/6 to glass-filled polythalamide (metal replacement) to Kevlar (bullet proof vests). Proteins (which include silk) are natural polyamides."* (Granta Design, 2018)

Production techniques: extrusion, blow-moulding, injection molding, rotational molding and structural foam molding.
Joining: with acrylates or two-component EP resins and all forms of welding.

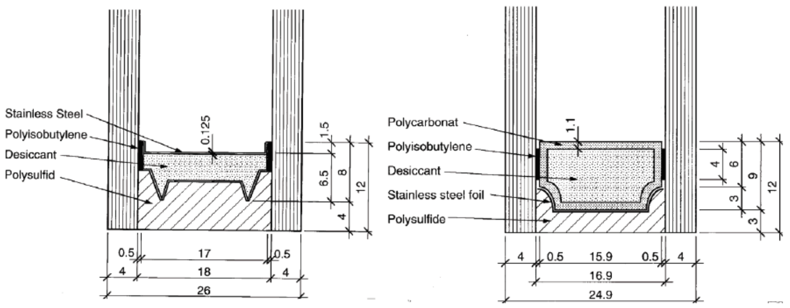


Image 105 - Example of spacers. Lecture notes Building Physics, R. Bokel. And section of the current panel.

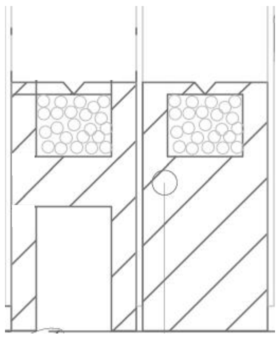


Image 104 - Double layer edge spacer. Own image.

9.2.3 Conclusion

The improvements which are most effective are highlighted in Table 21. These are a decrease of radiation (coating), the krypton and the added layers. The use of a different core material with a better lambda value and applying a wider grit are not very effective. These improvements are therefore not recommended. The U values with the recommended improvements are shown in the second row. Due to the glue it would not be possible to apply a soft coating. The U values are shown in the table below in the third row. The requirements of the 'Bouwbesluit' now state that the u value of windows need to be below 1,65 W/m²/K (BouwbesluitOnline, 2012). Table 21 shows that, in theory, it is possible to produce a panel with an U value below 1,65 W/m²/K. The spacer in the edge is going to be a newly designed spacer with moisture absorber which also functions as a connection, so no additional materials are needed.

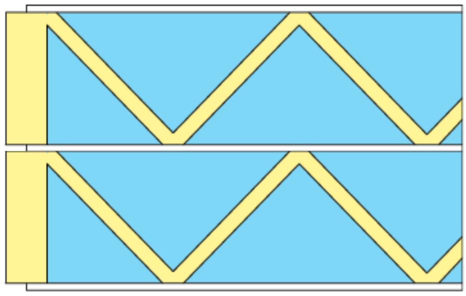


Image 107 - Section of the panel and location of the gas. Own image.

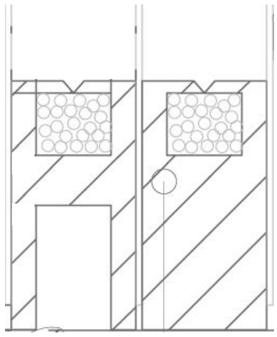


Image 106 - Double layer edge spacer. Own image.

Table 21 - Thermal improvements in combination with the U value.

Improvement	Thin glass			Normal glass	
	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,662	2,662	2,583	2,583
Decrease radiation (ε = 0,2)	2,066	2,066		1,907	
Krypton (λ = 0,009 W/m/K)	1,749	1,749	2,53	1,538	2,433
Woodfill (λ = 0,13 W/m/K)	1,690				
Wider grit (1/2%)	1,635				
Add one layer	1,038	1,13	1,88	0,961	1,779
Add two layers	0,761	0,84	1,50	0,699	1,402
Sun shading	-				

9.3 Structural properties

This sub-chapter starts with the conclusion of the compression test. After that the panel improvements are given. The improvements are limited by the boundaries of this research.

9.3.1 Panel improvements

Collapse mode of the panel in compression is dominated by delamination. A structure is not safe and therefore cannot be used as a structural component, when the collapse mode of a structure is dominated by delamination. The only way to make a safe load-bearing structure is to eliminate the glue. This will result in a completely different geometry of the panel. Unfortunately it is not possible to look into a different geometry, due to time. Another argument to not upscale this panel and to use is as a load-bearing façade is the life expectancy of the glue, due to UV-light degradation. The compression test learned that the panel can hold its self-weight when it is enlarged. The panel improvements are in line with this conclusion. The panel will not be used as a load-bearing structural element, a frame will take the loads. The panel now has to withstand it's self-weight and deflection due to the self-weight.

Self-weight

The maximum dimensions of a façade panel are 3,2 x 1,48 m. Table 22 shows the maximum sheet dimensions. The self-weight of the is shown in the Table 23 below. The density is calculated with the following formula, as explained in chapter 6.2.1:

$$G = \rho * t \tag{8}$$

Table 22 - Falcon glass, pane dimenions (AGC, 2019).

Standard thickness	Standard tolerance	Typical max sheet size
0,5 mm	+/- 0,05 mm	1245 x 3210 mm
0,7 mm		1350 x 3210 mm
0,9 mm		
1,1 mm		1480 x 3210 mm
1,3 mm		
1,6 mm	+/- 0,1 mm	1600 x 3210 mm

Table 23 - Self-weight of the panels.

Variables		Standard	Dense	Double
t_f [m]	0,0005	2x	2x	3x
t_f [m]	0,01	1x	1x	2x
ρ f [kg/m³]	2430			
ρ c [kg/m³]	1380			
Core %		0,26	0,29	(2*)0,26
Weight [kN/m²]		6,02	6,43	18,00
w [m]	1,245			
h [m]	3,2			
Weight [kN]		28,5	30,5	85,2

Deflection

Deflection of windows due to self-weight and expansion of the gasses in the cavity of the glass pane determine the view of the pane (Berkeley Lab, 2018). When the glass deforms, the reflection of the environment in the glass deforms (Image 108). This deflection should be avoided.

Image 108 - Deflection of glass in windows. University of California, Berkeley lab.

The option of optimizing the panel in terms of core pattern, material and glue area or another bonding method is most logical in this situation. In general this means, the more contact area, the better the structural performance of the panel. The use of more PET, especially to create more contact area results in big translucent sheets (Image 109). OKUALUX has some very nice examples of what this would look like (Image 110). Such translucent panes can be used in buildings where people want privacy and no distraction from outside, but still want natural light inside. These buildings could be libraries, bathhouses, museums, offices and factory workplaces. The structural improvements will be shown in a section of the panel as well. The standard pattern is again shown in Image 111 structural improvements are:

- Decrease delamination
- Decrease deformation
- Increase load resistance

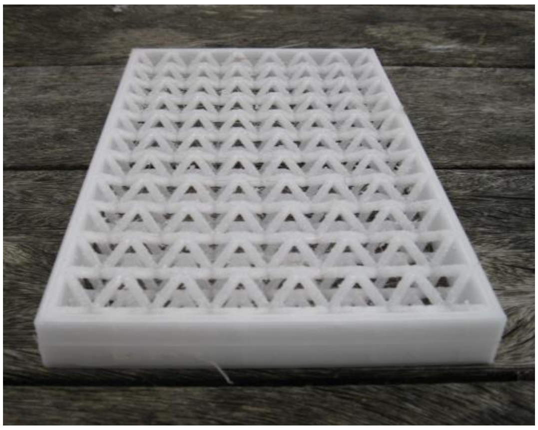


Image 109 - Slanted view of 'double layer' panel. Own image.

Image 110 - OKALUX+ is a product from OKALUX.

Reference panel

The starting point is the panel with the standard spacer as shown in the image below (Image 111).

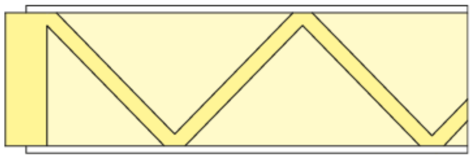


Image 111 - Section of the standard pattern. Own image.

Decrease delamination

Delamination can be decreased by an increase contact (glue) area and a better quality control considering the gluing process and 3D-printing (Image 112). This way there is more surface area for a good adhesive bonding. Another way to decrease delamination is to leave out the glue, but this will result in a completely different geometry and therefore this option does not fit within this research.

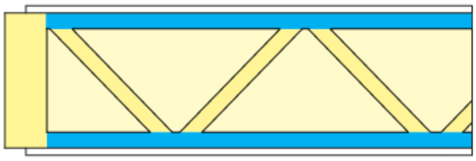


Image 112 - Section of the panel with increased glue area. Own image.

Decease deformation

When taking a look at the compression test, most panels deformed at the bottom or top of the panel (Image 113). This means that the forces concentrate at the top and bottom. The section of the beams at these locations need to be increased to withstand these force. Deformation can also be decreased through two other principles: with the increase of contact area (Image 114) and the use a different core material with higher shear resistance. This material could be aluminium for example. The yield strength of PET is 56.5 - 62.3 MPa (Ashby, 2013) and the yield strength of aluminium is 150 – 175 MPa.

Image 113 - Standard pattern 1 deformation due to compression. Own image.

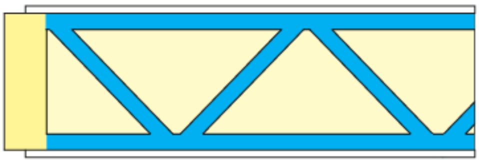


Image 114 - Section of the panel with changed core material for higher shear stiffness. Own image.

Increase load resistance

The improvement with the biggest impact considering the load resistance is an increase of the second moment area of the panel/ increase of the thickness of the panel (Image 115). This is done the quest by adding layers. The formula for the second moment area is also discussed in chapter 6.2.2 'Structural behaviour', formula 18. From this formula it is derived that doubling the thickness of the cross section, the t, results in a I to the power of 3.

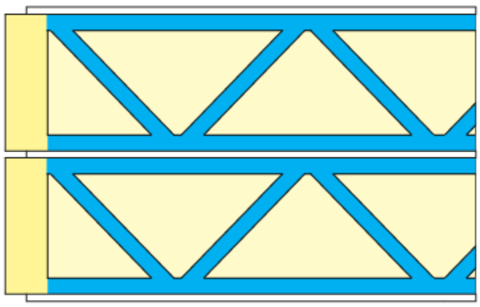


Image 115 - Section of the panel with increased second moment area. Own image.

$$I = \frac{1}{12} b t^3 \tag{11}$$

With:
b = width of the section [mm]
t = the thickness of the section [mm]

9.3.2 Structural safety

The compression tests learned that the failure mode of the panel is dominated by delamination, the panel will therefore be placed in a frame. When the panel is placed in a frame, the focus of the improvements shifts a bit. It is now important to decrease the deformation due to self-weight.

Chemical strengthening makes the glass brake in small pieces. Structural glass elements generally consist of multiple laminated layers to remain the integrity of the structure when a pane is broken. In case of this research, the glass is bonded to the core. This means that when a glass layer breaks, all the little pieces will stick to the core, but that specific layer cannot take any forces anymore. Since a frame is needed to support the panel and the panel only needs to support its self-weight, the safety standards are not that high. There is no extra glass layer needed.

9.3.3 Conclusion

A frame is needed to support the composite panels. The best way to decease delamination and deformation is the apply more contact are between the core and the glass. This is done by applying beams along the surfaces of the glass which connect all the contact points of the truss. The stiffness of the panel is significantly increased when a layer is added (Image 116).

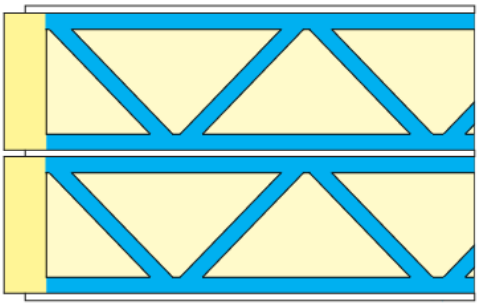


Image 116 - Section of the panel with increased second moment area. Own image.

To remain the integrity, an extra glass layer is needed in case the glass breaks. When there is no added glass layer, the little broken glass pieces will still stick to the core due to the glue.

9.4 Conclusion

To what extent can a thin glass composite panel, with a polymeric 3D-printed trussed core, be improved to meet the thermal insulation and structural regulations of today, to be used as a façade element in the building industry?

The improvements which are most effective are highlighted in Table 24 - Thermal improvements in combination with the U value.. These are a decrease of radiation (coating), the krypton and the added layers. The use of a different core material with a better lambda value and applying a wider grit are not very effective. These improvements are therefore not recommended. The U values with the recommended improvements are shown in the second row. Due to the glue it would not be possible to apply a soft coating. The u values are shown in the table below in the third row. The requirements of the 'Bouwbesluit' now state that the u value of windows need to be below 1,65 W/m²/K (BouwbesluitOnline, 2012). The spacer is in the edge is going to be a newly designed spacer with moisture absorber which also functions as a connection, so no additional structure is needed.

Table 24 - Thermal improvements in combination with the U value.

Improvement	Thin glass			Normal glass	
	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,662	2,662	2,583	2,583
Decrease radiation (ε = 0,2)	2,066	2,066		1,907	
Krypton (λ = 0,009 W/m/K)	1,749	1,749	2,53	1,538	2,433
Woodfill (λ = 0,13 W/m/K)	1,690				
Wider grit (1/2%)	1,635				
Add one layer	1,038	1,13	1,88	0,961	1,779
Add two layers	0,761	0,84	1,50	0,699	1,402
Sun shading	-				

A frame is needed to support the composite panels. The best way to decease delamination and deformation is the apply more contact are between the core and the glass. This is done by applying beams along the surfaces of the glass which connect all the contact points of the truss. The stiffness of the panel is significantly increased when a layer is added (Image 117). To remain the integrity, an extra glass layer is needed in case the glass breaks. When there is no added glass layer, the little broken glass pieces will still stick to the core due to the glue.

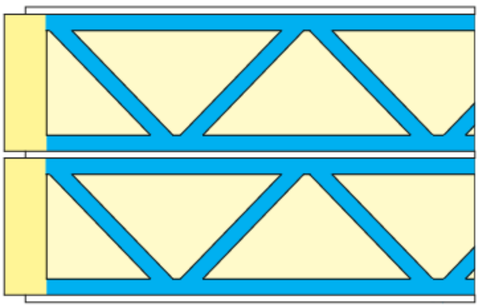


Image 117 - Section of the panel with increased second moment area. Own image.

To conclude, the type of pattern is determined by the size of the glass sheet. When the biggest glass sheet is used (3,2 x 1,245m) extra beams are needed to create a stiff panel. This results in a lower U value. The grid can be wider and the beams can be decreased when smaller glass sheets are used. This results in a better U value and it might be possible to apply a coating.

The conclusion in short:
High thermal insulation -> wide grid -> low structural properties -> small panels
High structural properties -> very dense grid -> lower thermal insulation -> big panel

10 DESIGN PROPOSAL

The tropical fruit company is located in Dublin (Image 118). It used to be the location where tropical fruit came in in bulk and then got packed in smaller packages to be distributed over the country. The building does not have this function anymore, today it is used as an office building. The website of the building is: https://tropicalfruitwarehouse.com/. As can be seen on the image to the right, a new extension is going to be built on the existing building. This is a case where it is favourable to use a lightweight structure.

Image 118 - The tropical fruit company in Dublin. Image from: https://tropicalfruitwarehouse.com.

The façade is a double façade (Image 119). This means that there is a big gap between the two glass layers where the air is conditioned to ensure a good indoor climate. This is prefect for the sandwich panel to be placed on the inside. This way there is no wind load on the panel and therefore it is possible to completely focus on the thermal insulation. The only structural thing that needs to be considered is accidental damage of the glass due to cleaning (during vacuuming for example). Currently, for the inside glass panels, a pane with one cavity, but four glass layers, two on each side, is used.

Image 119 - Image from the inside of the building. Image from https://tropicalfruitwarehouse.com.

The size of the inside glass panels have the dimensions of the free floor height, 3,2m and the maximum width is 1,245m. There is still wind pressure on the indoor panels. The wind pressure is transferred via the air layer between the panels, this means that extra vertical beams are needed to prevent deflection.

10.1.1 Combing thermal insulation and structural properties

The most realistic improvements for the thermal insulation of the panel are using a gas, krypton, in the cavity and to add one layer, this gives a u value of 1,88 W/m²/K. The spacer is in the edge is going to be PA6 re-designed frame with moisture absorber. Since the dimensions of the glass pane are 1,245 x 3,2 m, the best way to decease delamination and deformation is the apply more contact are between the core and the glass. This is done by applying beams along the surfaces of the glass which connect all the contact points of the truss. More contact area will slightly decrease u value (0,05 W/m²/k). This will result in a U value of 1,93 W/m²/K. The stiffness of the panel is significantly increased when a layer is added (Image 117). Image 121 shows the panel as it is (double layer and extra beams). The colour blue is just a background colour to show the transparency of the panel. Note that the dimensions of the panel in this image are 250 x 150 mm! Image 120 shows the transparency of a full scale panel (3,2 x 1,245 m).

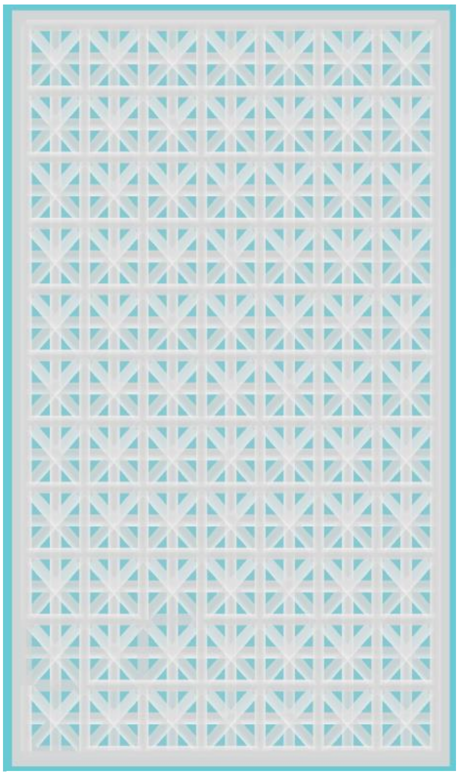


Image 121 - Image of the panel. Dimensions 250 x 150 mm. Own image.

Image 120 - Full scale panel, 3,2 x 1,245 m. Own image.

10.1.2 Production and end-of-life of the panel

There are roughly two steps to produce a panel, the production of the different materials/ elements and the assembly of the elements.

Embodied energy for production of materials and elements

Energy is needed for the production of materials and the elements. The following numbers are derived from CES EduPack, 2018. These are just rough number to give an indication for the amount of energy needed. The amount of energy needed for the production is split in primary and secondary production. The primary energy is the energy needed to compose a good material with the right properties and the secondary production is the energy needed to form the right elements (Granta Design, 2018). Table 25 shows, roughly, the total amount of energy needed to produce one, double layered, façade panel. A lot of energy is needed to produce the PET core (the underlined numbers are used in the calculation). This is the reason that the newly designed façade panel is not more sustainable than a normal façade panel. The panel would be more sustainable if the energy needed for the PET core is decreased.

Table 25 - Energy needed for the production of materials and elements. CES EduPack, 2018.

	Thin glass	PET	PA6 (25% glass fiber)	Soda-lime glass	Aluminium
Amount of material [m³]	0,0005 x 3,2 x 1,245 x 3 = 0,0060	0,01 x 3,2 x 1,245 x 0,30 x 2 = 0,024	0,01 x 0,02 x 3,2 x 1,245 x 2 = 0,0016	0,006 x 3,2 x 1,245 x 3 = 0,072	0,01 x 0,015 x 2x (3,2 x 1,245) x 0,10 = 0,00012
Density [kg/m³]	2480	1380	1250	2450	2700
Energy primary production [MJ/kg]	24	Recycled: 28 New: 80	110	10,5	200
Energy secondary production [MJ/kg]	-	Molding: 20 Extrusion: 6	6	-	4,7
Total [MJ]	357	1683	231	1209,1	0,26
Total glass pane [MJ]	**2171**			**1845**	

Assembly

The full-scale panel production has the same steps as the prototype production. The following steps need to be followed to produce one panel.

1. Connect the core with the spacer.
2. Clean one glass plate and one side of the core.
3. Apply glue on one side of the core.
4. Place the glass on the core and cure with UV light.
5. Flip the panel.
6. Clean the other side of the core and the second glass layer.
7. Apply glue on the cleaned side of the core.
8. Put the structure in a chamber filled with Krypton.
9. Place the second glass plate on the core and cure with UV light.
10. Kit the edges where the core is connected to the glass.

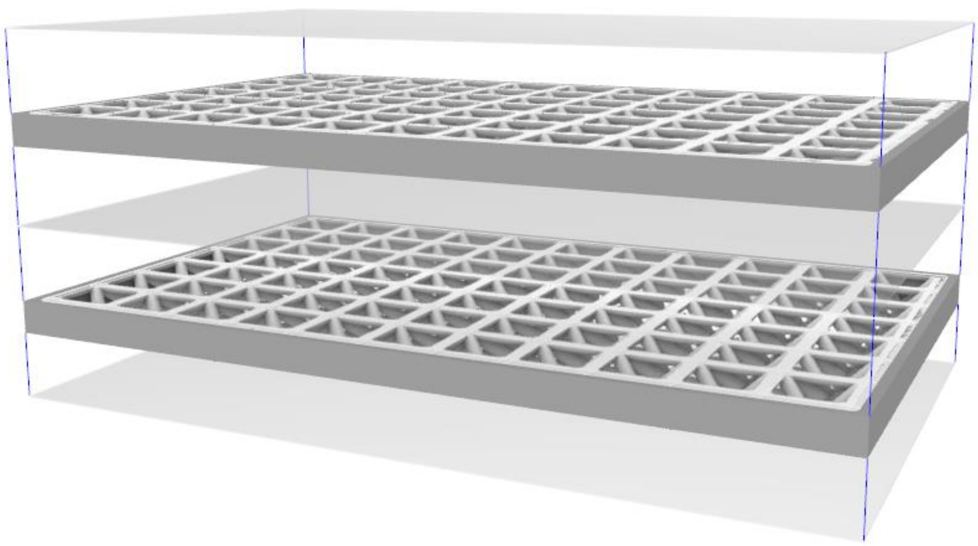


Image 122 - 3D exploded view of the panel (250 x 150 mm). Own image.

End of life

All the separate materials can easily be recycled. The panel is designed in such way that the it can be dismounted completely, so all the materials can be reused except for the glue. But, the glue can be removed by using a scraper to scrape the glue of the surface or by using a dissolver such as acetone or more specific and professional glue remover products (MESA Products, 2018).

10.1.3 Drawings

The principle of structural glass (Raico, 2019) is used to solve the connections. Two principle details are drawn with the vertical and horizontal connection.

- Detail 1 – vertical detail
- Detail 2 – horizontal detail

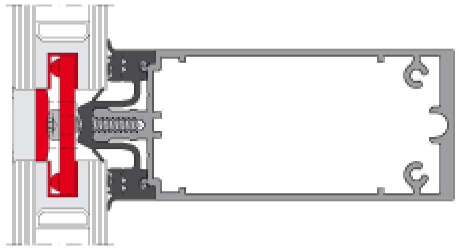
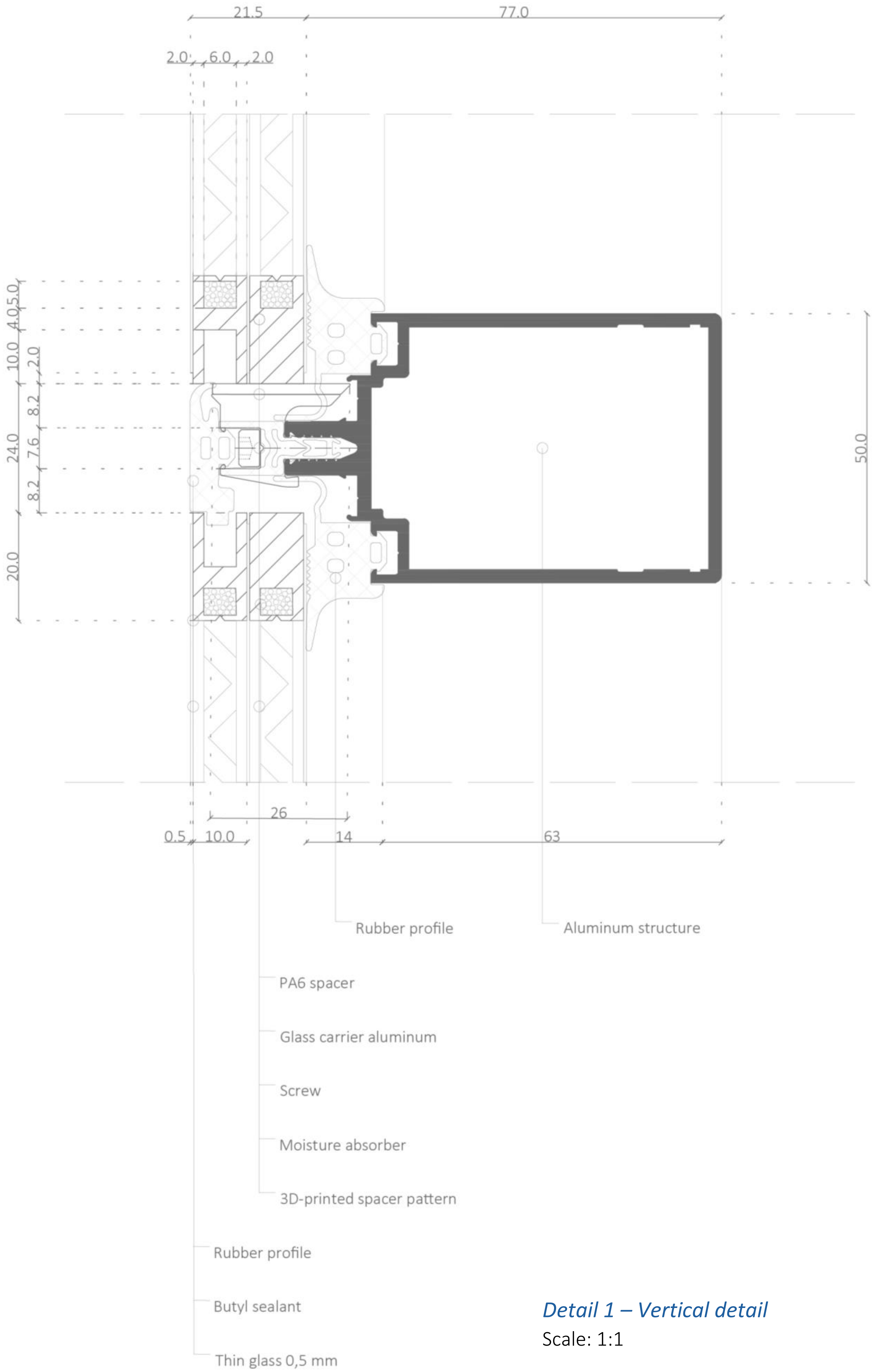
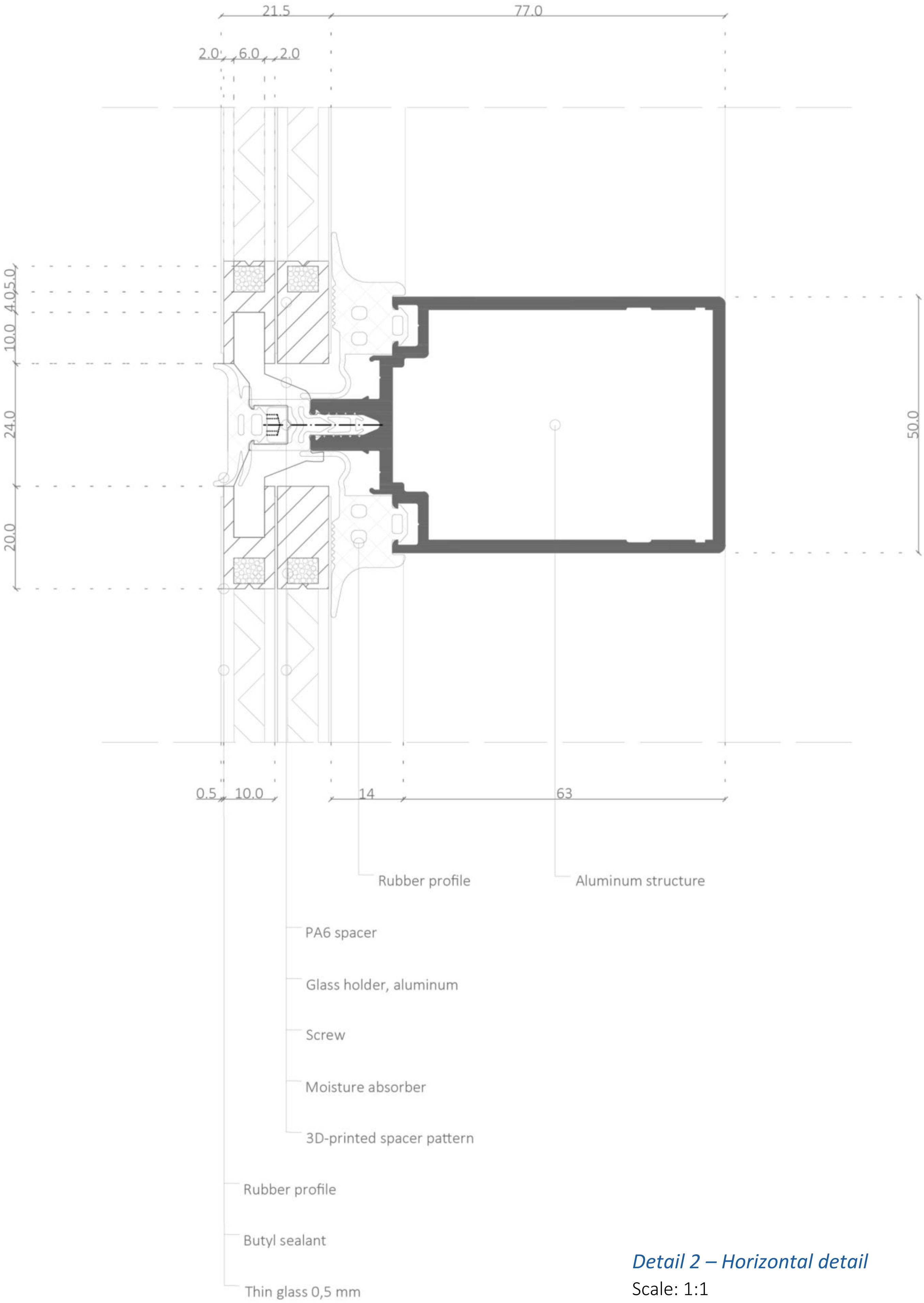


Image 123 - Structural glass detail from Raico, 2019.



Detail 1 – Vertical detail
Scale: 1:1



Detail 2 – Horizontal detail

Scale: 1:1

CONCLUSIONS & RECOMMENDATIONS

11 CONCLUSIONS

First all the sub-questions are answered, after that the main-question is answered.

What is a sandwich structure and which typologies are used to create a stiff and lightweight structure?

The most important factors to make use of a sandwich structure are the weight and smart use of the structure. The pyramidical lattice structure is the most lightweight. Therefore this structure is chosen in this research as starting point. Because the glass needs to be bonded to a thermoplastic, it is best to use an UV-curing acrylate. When the panel, as described earlier in this thesis, is loaded in-plane, it is probably going to buckle. When the panel buckles, the core needs to withstand the occurring shear forces.

What is (thin) glass and how is it made?

In general, glass is a brittle material, very week in tension but very strong in compression. But glass has different chemical compositions and because of that different characteristics. This is shown in the composition of soda-lime glass and aluminosilicate glass, the silica sand is replaced by alumina. This gives the aluminosilicate glass a higher melting point.

There are several different production processes for the production of a glass sheet, the most common one is 'float glass'. Thin glass is a glass sheet with a thickness of 0,5 – 1,6mm (AGC Glass, 2017) and is produced as float glass and through the overflow process. Due to its thinness it can only be chemically strengthened. Strengthening is a process to create tension in the surface area (Wurm, 2007). The edges of a sheet are very sensitive due to this strengthening. It is not possible yet to apply a coating on thin glass. Experiments are done to apply a off-line, soft coating at this moment.

Which production technique and material is most suitable to realize the core?

3D printing is an AM process for rapid prototyping. This production process is used to produce the core of the sandwich structure. The big advantage of 3D printing is that almost any freeform can be printed, relative easily and cheap. But 3D printing also has various limitations, such as: the production speed, the layered production/ material deposits, material use and the limited the size of the product. For this research it is a good process to quickly produce the cores. But for future mass production, another production process is recommended. The material that is going to be used for 3D printing is PET. PET has good yield and tensile strength, in comparison with the other materials. Even though the lambda value (λ = 0,29 W/mK) is a bit worse, it is a good starting point for the calculations. Other important factors are that the material can easily be glued, acrylic glue is not a problem and the PET is recyclable. Injection molding is most suitable for future mass production. The mold can produce almost any freeform and can be re-used multiple times. The physical tests will prove if the PET is suitable as core material.

How can the thermal insulation value and structural properties theoretically be determined?

By performing different calculations (optimistic, pessimistic, Excel, Trisco) and taking into account all the different factors which can influence the thermal insulation properties. The calculations show a small decrease of 0,2 $W/m^2{\cdot}K$ in comparison with air filled, double glass windows. The panel has to withstand at least all the permanent and variable loads. The possible failure modes of a panel are expected to be delamination, core shear, buckling and tension in the glass faces.

Prototype

Unfortunately it was not possible to print the panel as a whole. The print is split in two, at the location where the contact points are at the bed. This means that the two pieces need to be put together. This can be done in several ways, one way is to glue and the other way is to weld the parts. At the faculty of

Industrial Design and Engineering, Don van Eeden recommended two types of glue, a fast drying glue and a two-component glue. The parts can also be weld together, this is done by melting the material with heat, or chemically melt with dichloromethane. Because it was not possible to solve this error, the decision was made to order the panels at a professional 3D-printing company. Considering the criteria: ease to use, preparation of the surface, visibility of the bond, the Kunststoffkleber, Loctite and two-component Griffon are chosen to use for the tensile test. Because these glues were easy to use, allowed for small flaws on the surface which needed to be glued and they are all transparent, or at least translucent. In general it is best to prevent the use of glue, because it can take approximately half the stress of a normal/ complete dog-bone. But if there is no other option than to use the glue, it is best to use the Loctite because it is easy in use and gave the best results.

What is the actual effect of a trussed pattern in a thin glass composite panel on the thermal insulation and structural properties of the panel?

More PET contact points, standard versus dense pattern, is not equal to worse thermal conduction. This only applies when the difference in amount of PET is bigger. The effect of the contact points solely, with these patterns, is very small because the points are too close to each other. The effect of a single contact point will be increased when the grid size is increased. This is also shown in the double panel, the increase of the insulation value is not in line with the expected insulation value in the hand calculations. The results of the tests are better than the 'percentage hand calculation', this could be explained by the simplification of reality in the hand calculations and inaccuracies during the physical testing.

The first dip in the curve announces the start of delamination. Delamination probably goes on till the panel breaks. The amount of load the panel can take before the lamination starts equals to a glue connection of good quality. The failure mode is dominated by delamination because that it the first thing that occurs during the compression test. After that the panel fails due to shear in the core. The difference in deformation can be explained by the quality and the surface area of the glue. The better the glue quality and the more surface area, the least deformation. But more surface area is not equal to a higher strength. To conclude, the panel is not safe to use as a load-bearing structure, because the failure mode is dominated by delamination. But the panels can take their self-weight. The worst panel can take almost double that weight before it starts delaminating. Thus the compression tests proved that the panels can carry their self-weight, when the size of the panels is increased to 2,5 x 3,2m.

Main question:

To what extent can a thin glass composite panel, with a polymeric 3D-printed trussed core, be improved to meet the thermal insulation and structural regulations of today, to be used as a façade element in the building industry?

The improvements which are most effective are highlighted in Table 26. These are a decrease of radiation (coating), the krypton and the added layers. The use of a different core material with a better lambda value and applying a wider grit are not very effective. These improvements are therefore not recommended. The U values with the recommended improvements are shown in the second row. Due to the glue it would not be possible to apply a soft coating. The u values are shown in the table below in the third row. The requirements of the 'Bouwbesluit' now state that the u value of windows need to be below 1,65 W/m²/K (BouwbesluitOnline, 2012). The spacer is in the edge is going to be a newly designed spacer with moisture absorber which also functions as a connection, so no additional structure is needed.

Table 26 - Thermal improvements in combination with the U value.

Improvement	Thin glass			Normal glass	
	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]	U [W/m²/K]
Start point	2,662	2,662	2,662	2,583	2,583
Decrease radiation (ε = 0,2)	2,066	2,066		1,907	
Krypton (λ = 0,009 W/m/K)	1,749	1,749	2,53	1,538	2,433
Woodfill (λ = 0,13 W/m/K)	1,690				
Wider grit (1/2%)	1,635				
Add one layer	1,038	1,13	1,88	0,961	1,779
Add two layers	0,761	0,84	1,50	0,699	1,402
Sun shading	-				

A frame is needed to support the composite panels. The best way to decease delamination and deformation is the apply more contact are between the core and the glass. This is done by applying beams along the surfaces of the glass which connect all the contact points of the truss. The stiffness of the panel is significantly increased when a layer is added. To remain the integrity, an extra glass layer is needed in case the glass breaks. When there is no added glass layer, the little broken glass pieces will still stick to the core due to the glue.

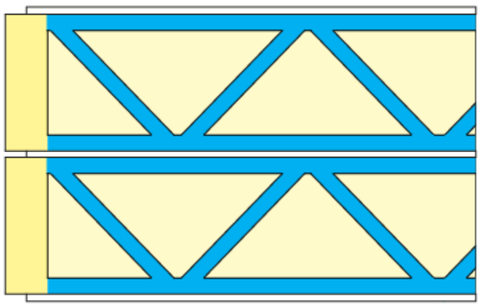


Image 124 - Section of the panel with increased second moment area. Own image.

To conclude, the type of pattern is determined by the size of the glass sheet. When the biggest glass sheet is used (3,2 x 1,245m) extra beams are needed to create a stiff panel. This results in a lower U value. The grid can be wider and the beams can be decreased when smaller glass sheets are used. This results in a better U value and it might be possible to apply a coating. The conclusion in short:
High thermal insulation -> wide grid -> low structural properties -> small panels
High structural properties -> very dense grid -> lower thermal insulation -> big panel

12 RECOMMENDATIONS

General

A general conclusion can be drawn that the 'double layer' panels are better than single layer panels. This can be interpreted in such way that adding more and more layers would improve the properties with every layer. This is probably not true, there will be a point where adding more layers is not improving the panel anymore. Thus it can be recommended to research to what extend it would be valuable to add extra layers.

To make the 3D-printing process easier it would be better to choose another core pattern. By choosing a pattern which can be printed in one, fluent line movement without lifting the printhead. The printing time will be significantly shorter, with less failures during printing and better quality.

To go more into the 'Design Informatics' direction, it can be recommended to do research into 1 mm extrusions with a robot arm to produce the trussed core. This way it would be possible to produce a core with really thin beams, without all the layers in the structure and without all the failures of the 3D-printing.

Thermal insulation

Coatings are one of the most essential elements to improve the thermal insulation value of a window. At this moment it is not possible to apply a hard / on-line coating on thin glass due to the overflow production process. Further research needs to be done to apply a soft/ off-line coating on the thin glass, but an off-line coating and a sandwich panel is not the best combination. The glue might damage the coating.

The use of the 3D-printing material PLA and wood fibre is very interesting in terms of thermal insulation, because of the lambda value of 0,13 W/m/K. Further research needs to be done with the PLA and wood fibre in combination with moisture. Also, the type of glue needs to be tested. A good glue for PLA is non-existing at this moment. But the combination of PLA and wood fibre might change the glue ability of the material.

Changing the gas in de cavity is very effective for its thermal insulation. But it is not so easy to put a different gas in the cavity. The spacer at the edge of the panel needs to be designed in such way that it can keep the gas inside. More research needs to be done to design a proper spacer for the edge of the panel.

Structural properties

The use of another bonding method leads to the use of another material in the core because the PET cannot be heated till 150 ˚C for lamination. To improve the structural properties of the material it would be useful to use another material as core material. Not only because the for bonding reasons, also for shear strength. The PET has low shear strength when compared to other materials such as steel or aluminium. And the 3D-printing production process does not allow for high shear stresses.

The only way to make the sandwich panels structurally safe to be in-plane loaded would be by eliminating the glue or used a stronger glue, so that the collapse mode is not dominated by delamination anymore. Leaving out the glue would result in a different geometry. This would probably result in a thick layer of glass which transfers all the forces. The sandwich part (core and second, thin, face) could be added to provide thermal insulation. And more research needs to be done into glues or bonding methods. To improve this failure mode of delamination.

It might just be better to not load sandwich panels in-plane (Miura & Pellegrino, n.d.).The purpose of sandwich panel seems to be loaded out of plane. It is recommended to read structural concepts and their theoretical foundations from Miura and Pellegrino n.d. considering optimisation a.k.a. 'shape efficiency' of the core (Image 125).

> *"To understand the key effects that need to be analysed, it is useful to think initially of making a lightweight core out of a given material in the following idealised way."*(Miura & Pellegrino, n.d.) *(page 159)*

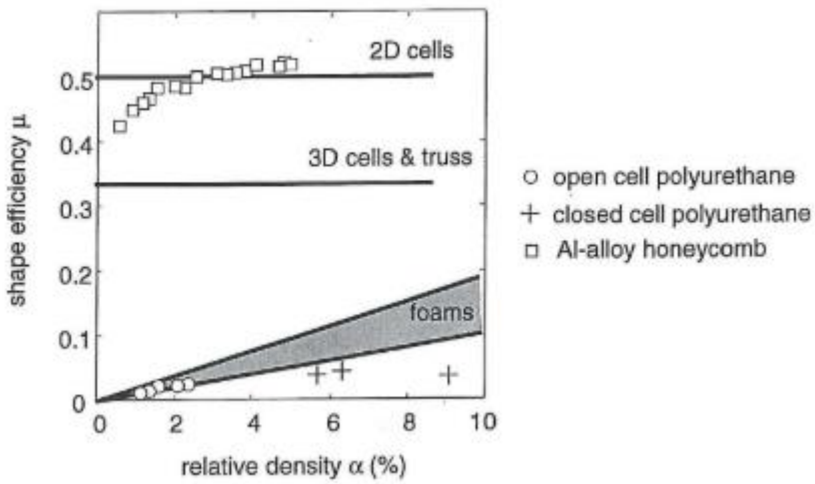


Image 125 - shape efficiency of plates with different types of core. Miura, Pellegrino n.d..

13 REFLECTION

The Building Technology track focuses on research, technological design and innovation, dealing with the newest technology and interacting with the current market to contribute to smart buildings that are sustainable, comfortable and environmentally intelligent. The track offers fours specialisations: structural design, climate design, façade & production design and design informatics. This research touches the specialisation of structural design and climate design while making use of design informatics to create a sustainable and comfortable façade element by using the newest production techniques.

Thin glass is a relatively new material in the built environment. The flexibility of the material is a challenge because it asks for a different approach to apply the material in a correct way. The same goes for 3D printing. It is not a very common production technique and needs a lot of improvement before it can actually be used in the built environment. This research will be one of the stepping stones in the bigger picture of research on application of new materials in de built environment.

The use of thin glass and 3D printing allows for a more freeform and minimalistic form of architecture while contributing to environmental sustainability. With the use of thin glass, the use of raw materials is decreased from 3 – 6 mm till 0,5 mm and PET is a well-known plastic which accounts for a big amount of waste nowadays. The reduction of glass and re-use of PET results in a lower energy consumption for the production and CO_2 emission, which is better for the environment.

At the beginning, the approach of the research was 'research through design'. A computer model would be made and analysed to produce two panels which then would be tested of their structural and thermal insulation properties. But at a very early stage in the research, the feedback was given to start doing experiments instead of trying to calculate the structural part first. This resulted in a more experimental approach towards the research. This changed the process and research questions in such way that the analysis of the design shifted from before the panel production till after the panel production. It became an analysis of the test results. The advantage of this approach is that the consequences of design decisions become more clear in the tests results, rather than in the computer model. The limitations of your design are directly visible and tangible. It took some time to adjust to this new approach, but this approach payed back in results of the tests.

A lot of unforeseen decisions had to be made during the research, especially in the field of 3D-printing. These decisions were the result of unfortune events during the 3D-printing process. This resulted in a delay of about three weeks, before the actual tests could be performed. These unforeseen decisions mainly have to do with the production of the core of the panels, it took a week to make the patterns printable and then still two weeks to produce all the panels. But, due to small errors during the printing, such as warping or jumping, the printer keeps on failing to print the patterns correct. The failures had most to do with the difficult pattern. After a while of trying to print, the decision was made to order the patterns at a professional 3D-printing company. This was the best decision made during this research because the failures of 3D-printing caused a lot stress. Even though the 3D-printing caused a delay in the planning, it was still a valuable process. Because a lot of new 3D-printing skills were gained. For the next time it would be better to pick a pattern which is more easily to print, or just order the products at a professional company. Next to that there are a lot of things which influence the test results, such as quality of the prints, gluing & curing and moisture.

The actual testing time went really fast. The thermal test took one day and the structural test took two hours, which went as planned. No errors occurred during the tests. It felt a bit odd to put so much time into something that is done so quickly. After the tests it was time to process the results, and it became clear that it is not so simple to interpret the results correct. The results show that the core and the multiple layers have a big impact on its thermal and structural properties and the bond mainly has a big impact on the structural properties. The impact of the core contradicts between the two functionalities. This way it is impossible to find one solution for both functionalities. The initial final design is going to be adjusted according to these findings.

The thermal tests showed that the panel performs better than the hand calculations predicted and as good as Trisco predicted. It seems that the formulas for the hand calculations have a build-in safety factor so that the panel will always perform at least at the calculated number. The test results of the 'double layer' get even closer to the reference value of air-filled triple glass. This could mean that the negative value of the PET becomes negligible when multiple layers of glass are applied.

The compression tests showed that the core had to take a high shear forces, which were transferred to the glue. It would have been good to do a compression test on the core without the glass, as a reference. If the core without the glass was tested, it would have been clear what strength the glass adds to the sandwich panel. The failure mode of the sandwich panel is dominated by delamination. This means that the panel is not structurally safe to use as an in-plane, loadbearing façade element. Due to this result, the initial idea of designing a panel for the small one-floored building, is not possible. But the compression tests also showed that the panel is stiff and strong enough the carry its self-weight, when enlarged to a façade element of 2,5 x 3,2 m. This means that the panel has potential to be used as a lightweight façade element with the least amount of materials needed. But the panel needs a structure load-bearing structure around it. The aim now is to find a suitable application of the panel, one optimized for the thermal insulation, one optimized for structural application and one 'in between' panel. These results and conclusions are in line with the results of previous theses. The panel can be used as a lightweight window, it still needs a frame.

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15 APPENDIX

15.1 Bouwbesluit 2012 – Artikel 5.3. Thermische isolatie

1. Een verticale uitwendige scheidingsconstructie van een verblijfsgebied, een toiletruimte of een badruimte, heeft een volgens NEN 1068 bepaalde warmteweerstand van ten minste de in tabel 5.1 gegeven waarde.
2. In afwijking van het eerste lid heeft de uitwendige scheidingsconstructie van een drijvend bouwwerk op een op 1 januari 2018 bestaande ligplaatslocatie een volgens NEN 1068 bepaalde warmteweerstand van ten minste 3,5 m^2•K/W.
3. Een horizontale of schuine uitwendige scheidingsconstructie van een verblijfsgebied, een toiletruimte of een badruimte, heeft een volgens NEN 1068 bepaalde warmteweerstand van ten minste de in tabel 5.1 gegeven waarde.
4. In afwijking van het derde lid heeft de uitwendige scheidingsconstructie van een drijvend bouwwerk op een op 1 januari 2018 bestaande ligplaatslocatie een volgens NEN 1068 bepaalde warmteweerstand van ten minste 4,5 m^2•K/W.
5. Een constructie die de scheiding vormt tussen een verblijfsgebied, een toiletruimte of een badruimte en een kruipruimte, met inbegrip van de op die constructie aansluitende delen van andere constructies, voor zover die delen van invloed zijn op de warmteweerstand, heeft een volgens NEN 1068 bepaalde warmteweerstand van ten minste de in tabel 5.1 gegeven waarde.
6. Een uitwendige scheidingsconstructie die de scheiding vormt tussen een verblijfsgebied, een toiletruimte of een badruimte en de grond of het water, met inbegrip van de op die constructie aansluitende delen van andere constructies, voor zover die delen van invloed zijn op de warmteweerstand, heeft een volgens NEN 1068 bepaalde warmteweerstand van ten minste de in tabel 5.1 gegeven waarde.
7. In afwijking van het eerste, tweede en zesde lid heeft de uitwendige scheidingsconstructie van het drijflichaam van een drijvend bouwwerk een volgens NEN 1068 bepaalde warmteweerstand van ten minste 3,5 m^2•K/W en bij een op 1 januari 2018 bestaande ligplaatslocatie een warmteweerstand van ten minste 2,5 m^2•K/W.
8. Een inwendige scheidingsconstructie die de scheiding vormt tussen een verblijfsgebied, een toiletruimte of een badruimte, en een ruimte die niet wordt verwarmd of die wordt verwarmd voor uitsluitend een ander doel dan het verblijven van personen, heeft een volgens NEN 1068 bepaalde warmteweerstand van ten minste de in tabel 5.1 gegeven waarde.
9. Ramen, deuren en kozijnen in een in het eerste tot en met achtste lid bedoelde scheidingsconstructie hebben een volgens NEN 1068 bepaalde warmtedoorgangscoëfficiënt van ten hoogste 2,2 W/m^2•K. De gemiddelde warmtedoorgangscoëfficiënt van de ramen, deuren en kozijnen in de in het eerste tot en met achtste lid bedoelde scheidingsconstructies van een bouwwerk is, bepaald volgens een bij ministeriële regeling gegeven bepalingsmethode, ten hoogste 1,65 W/m^2•K.
10. Met ramen, deuren en kozijnen gelijk te stellen constructieonderdelen in een in het eerste tot en met achtste lid bedoelde scheidingsconstructie hebben een volgens NEN 1068 bepaalde warmtedoorgangscoëfficiënt van ten hoogste 1,65 W/m^2•K.
11. Het eerste tot en met het achtste lid zijn niet van toepassing op een oppervlakte aan scheidingsconstructies, waarvan de getalwaarde niet groter is dan 2% van de gebruiksoppervlakte van de gebruiksfunctie.

15.2 AGC Fineo product information

AGC

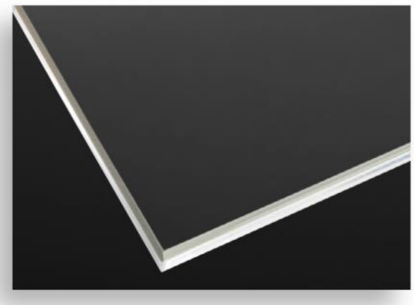
e-photo library

Download Summary

Picture Information
Id: 10893
Name: Vacuum Glazing
Organization Year: 2018
Country: Belgium
Caption: As the fruit of a joint development agreement between AGC and Panasonic, AGC Glass Europe is to invest in production of vacuum glazing at its plant in Lodelinsart (Belgium), a technology that offers very high energy performance.
Caption2: Press release on www.agc-glass.eu
Photographer: Jean-Michel Byl
Photo Year: 2018
Courtesy Notice: © AGC Glass Europe

15.3 AGC Falcon glass product information

Falcon glass **AGC** GLASS UNLIMITED for thin and lightweight applications

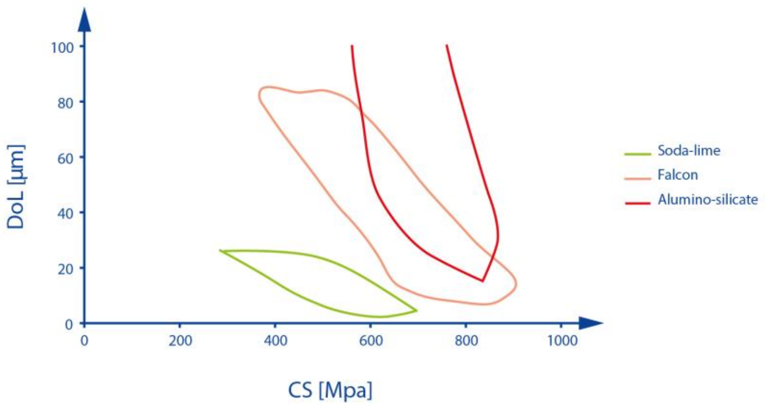


AGC's Falcon glass is a new type of alumino-silicate thin glass suitable for chemical toughening and produced by the very high quality, cost efficient float process.
From mobile devices to high-performance assemblies in building and transportation, Falcon offers the highest performance at an affordable cost.

Falcon glass

What's so special about it?	What does this mean for you?
Available in very low thicknesses	Reduces weight, opening up new possibilities in the design of high-strength, lightweight structures at a reasonable cost
Very strong after toughening	Excellent mechanical strength: 5 times stronger than conventional thermally toughened soda-lime glass
	Damage-resistant
High transmission and neutrality	High luminance and exceptional colour rendering while ensuring low power consumption
Beautiful surface appearance	Beautiful, pristine finish and high scratch-resistance compared with resin
Unique anti-warping treatment	AGC's unique anti-warping treatment guarantees no deformation of the glass after chemical toughening, allowing it to keep perfect flatness
Easy to thermoform	Opens up new possibilities in shapes and design
Available in large dimensions	Makes it possible to create large-dimension toughened glass covers for touchscreens or any other large format application

What can you use it for	. . . be inspired
Electronics	Smartphones, tablets, laptops, interactive displays, etc.
Transportation	Trains, aerospace, automotive, etc (interior and exterior)
Building	Lightweight assemblies, creative designs, etc.



Performances

Thickness	0.5 mm with AW*	0.7 mm	0.7 mm with AW*	1.1 mm	2.1 mm
TL (D 65, 2°)	92.1	91.9	92	91.8	91.6
TE (ISO 9050)	92.1	91.8	92	91.7	91.5
L**	96.85	96.77	96.83	96.74	96.66
a**	0.01	0.01	0.01	0.02	0.04
b**	0.15	0.15	0.15	0.14	0.11

* AW refers to the unique AGC anti-warping treatment applied to Falcon allowing it to keep perfect flatness after chemical toughening

** A Lab colour space is a colour-opponent space with dimensions L for lightness and a and b for the colour-opponent dimensions

Chemical strengthening properties	Compressive stress (@ 20µm DoL)	> 800 MPa
	Depth of Layer (in 8h)	> 40 µm
	Reinforcement (for 15µm defect)	> 600 MPa
	Warpage (in 0.7mm – 420°C/4h)	< 0.05%
Mechanical properties	Density	~ 2.48 g/cm³
	Young's Modulus*	~73 GPa
	Poisson's ratio*	~ 0.22
	Shear Modulus*	~ 30 GPa
Optical properties	Refractive index* (630 nm)	1.514
	Photo elastic constant*	~ 27.2 nm/cm/MPa
Thermal properties	Softening point	~ 665 °C
	Tg	~ 575 °C
	Coefficient of thermal expansion	~ 9.10⁻⁶ (25-300°C)
	Thermal conductivity*	~ 0.95 W/(m.°C)
Chemical resistance	Hydrolytic class*	2

* Computed values

Processing options

Safety	Toughening (thermal and chemical)
Cutting	Straight or circular
Shaping and edge finishing	Edge grinding, drilling
Special treatments	Anti-warping
	Silkscreen printing
	Bending (thermo-forming and cold-bending)
	Acid etching (single or double)
	Anti-reflective coating
	Wet coating application (anti-fingerprint/hydrophobic coating)
	Safe foil application
	UV adhesive bonding

Availability

Thickness	Size
0.5 mm	Up to 1.245 x 3.21 m
0.7 mm	Up to 1.35 x 3.21 m
1.1 mm	Up to 1.48 x 3.21 m
2.1 mm	Up to 1.60 x 3.21 m

Other thicknesses and dimensions are available upon request.

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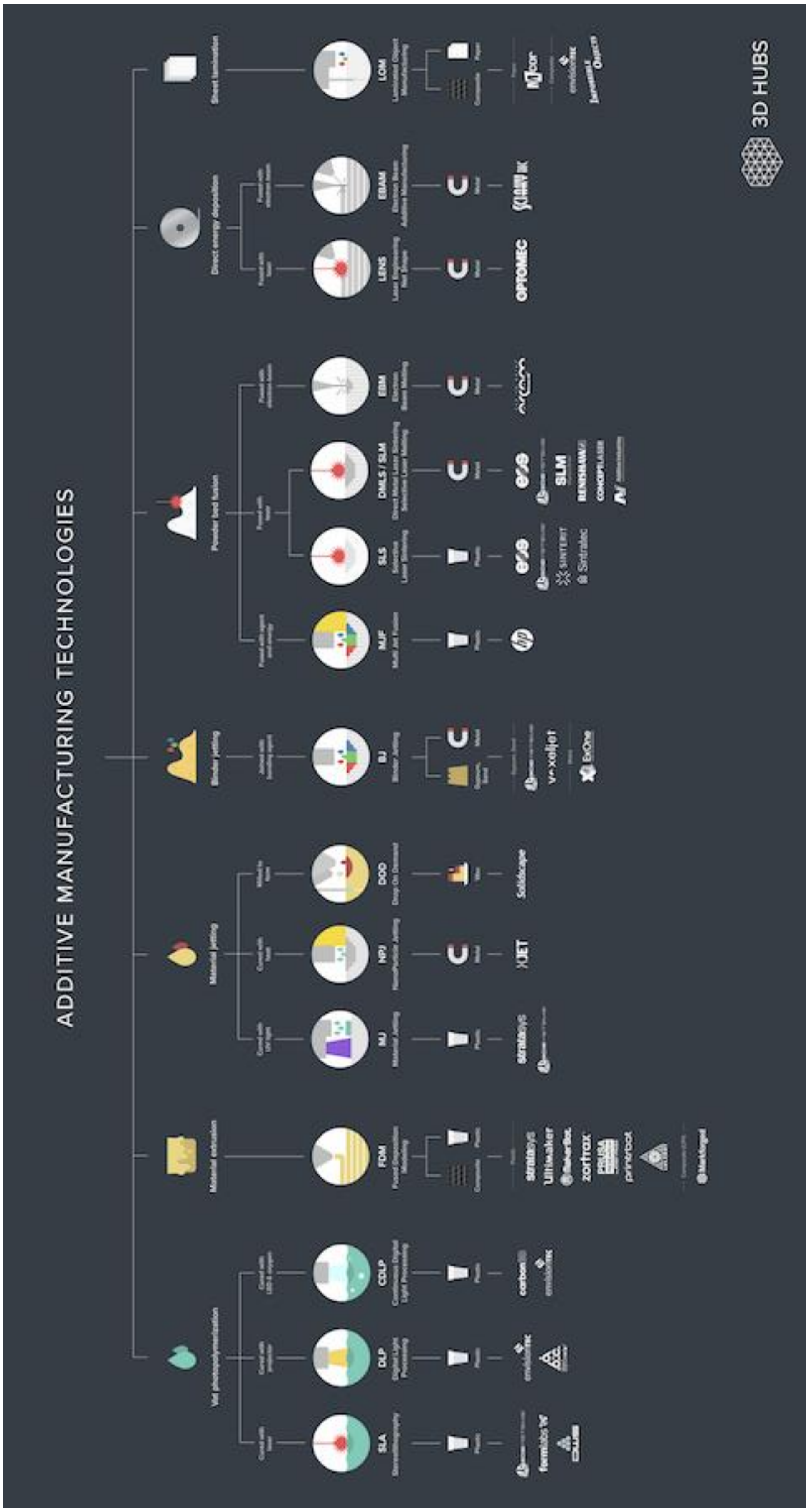
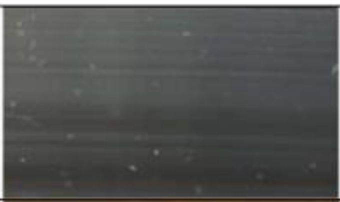
15.4 Additive manufacturing techniques

(3D HUBS, 2019a)



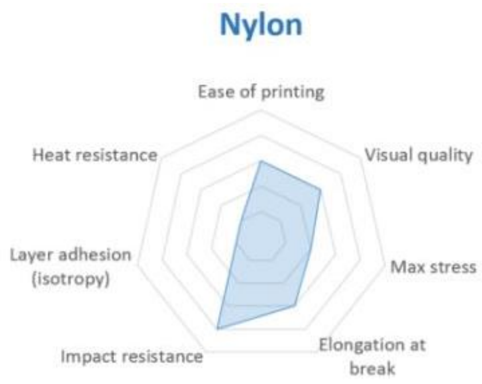
15.5 PLA – wood filament

(Kariz et al., 2018)

Filament (wood content)	3D printed part		
	Filament (70x)	Surface (20x)	Edge (40x)
0 %			
10 %			
20 %			
30 %			
40 %			
50 %			

15.6 Properties of materials for 3D printing

Nylon



Soft, low friction (Redwood et al., 2017)
Good chemical resistance
Very low humidity resistance, potentially high fume emission

General properties (Ashby, 2013)

Density	1,120	- 1,140 kg/m^3
Price	3.9	- 4.3 USD/kg

Mechanical properties

Young's modulus	2.62	- 3.2 GPa
Yield strength (elastic limit)	50	- 94.8 MPa
Tensile strength	90	- 165 MPa
Elongation	30	- 100 %
Hardness—Vickers	25.8	- 28.4 HV
Fatigue strength at 107 cycles	36	- 66 MPa
Fracture toughness	2.2	- 5.6 MPa · m$^{1/2}$

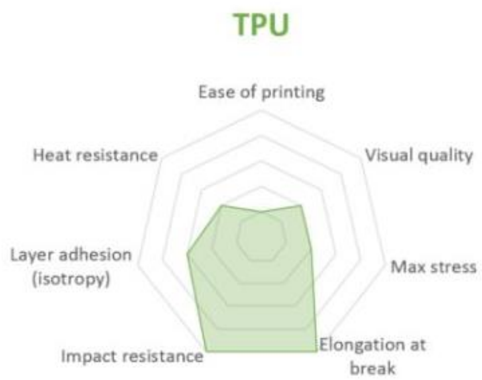
Thermal properties

Melting point	210	- 220 ˚C
Maximum service temperature	110	- 140 ˚C

Thermal conductor or insulator? Good insulator

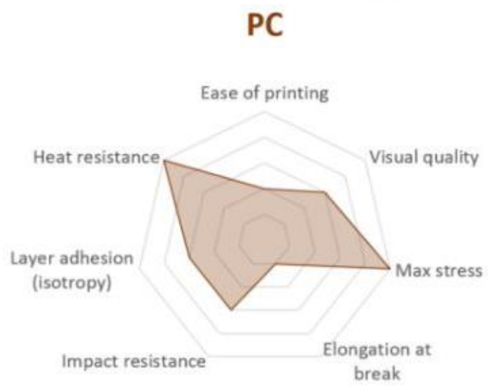
Thermal conductivity	0.23	- 0.25 W/m · K
Specific heat capacity	1,600	- 1,660 J/kg · K
Thermal expansion coefficient	144	- 149 µstrain/ ˚C

TPU



Flexible (Redwood et al., 2017)
Good abrasion resistance, good resistance to oil and grease
Difficult to post process, not easily glued

Polycarbonate (PC)



Very rigid (Redwood et al., 2017)
Can be sterilized, easy to post-process (sanding)
UV sensitive

General properties(Ashby, 2013)

Density	1,140	- 1,210 kg/m^3
Price	3.8	- 4.2 USD/kg

Mechanical properties

Young's modulus	2	- 2.44 GPa
Yield strength (elastic limit)	59	- 70 MPa
Tensile strength	60	- 72.4 MPa
Compressive strength	69	- 86.9 MPa
Elongation	70	- 150 %
Hardness—Vickers	17.7	- 21.7 HV
Fatigue strength at 107 cycles	22.1	- 30.8 MPa
Fracture toughness	2.1	- 4.6 MPa · m$^{1/2}$

Thermal properties

Glass temperature	142	- 205 ˚C
Maximum service temperature	101	- 144 ˚C
Thermal conductor or insulator?	Good insulator	
Thermal conductivity	0.189	- 0.218 W/m · K
Specific heat capacity	1,530	- 1,630 J/kg · K
Thermal expansion coefficient	120	- 137 µstrain/ ˚C

15.7 Standard value IGU panels

(Koninklijk Nederlands Normalisatie-Instituut, 2018)

Soort				U_{gl} W/(m²·K)				
Enkel glas				5,8				
Meervoudige beglazing				**Soort spouwvulling (gasconcentratie > 90 %)**				
Type	**Coating glaslaag**	**Emissiviteit ε_n [a]**	**Laagdiktes mm [b]**	**Lucht**	**Argon**	**Krypton**	**SF_6**	**Xenon**
Dubbel glas	Geen (normaal glas)	0,89	4-6-4	3,3	3,0	2,8	3	2,6
			4-8-4	3,1	2,9	2,7	3,1	2,6
			4-12-4	2,8	2,7	2,6	3,1	2,6
			4-16-4	2,7	2,6	2,6	3,1	2,6
			4-20-4	2,7	2,6	2,6	3,1	2,6
	Een ruit met warmte-reflecterende coating	≤ 0,20	4-6-4	2,7	2,3	1,9	2,3	1,6
			4-8-4	2,4	2,1	1,7	2,4	1,6
			4-12-4	2,0	1,8	1,6	2,4	1,6
			4-16-4	1,8	1,6	1,6	2,5	1,6
			4-20-4	1,8	1,7	1,6	2,5	1,7
		≤ 0,15	4-6-4	2,6	2,3	1,8	2,2	1,5
			4-8-4	2,3	2,0	1,6	2,3	1,4
			4-12-4	1,9	1,6	1,5	2,3	1,5
			4-16-4	1,7	1,5	1,5	2,4	1,5
			4-20-4	1,7	1,5	1,5	2,4	1,5
		≤ 0,10	4-6-4	2,6	2,2	1,7	2,1	1,4
			4-8-4	2,2	1,9	1,4	2,2	1,3
			4-12-4	1,8	1,5	1,3	2,3	1,3
			4-16-4	1,6	1,4	1,3	2,3	1,4
			4-20-4	1,6	1,4	1,4	2,3	1,4

		≤ 0,05	4-6-4	2,5	2,1	1,5	2,0	1,2
			4-*8*-4	2,1	1,7	1,3	2,1	1,1
			4-*12*-4	1,7	1,3	1,1	2,1	1,2
			4-*16*-4	1,4	1,2	1,2	2,2	1,2
			4-*20*-4	1,5	1,2	1,2	2,2	1,2
Soort				**U_{gl} W/(m²·K)**				
Meervoudige beglazing				**Soort spouwvulling (gasconcentratie > 90 %)**				
Type	**Coating glaslaag**	**Emissiviteit ε_n [a]**	**Laagdiktes mm [b]**	**Lucht**	**Argon**	**Krypton**	**SF_6**	**Xenon**
Drievoudige beglazing	Geen (normaal glas)	≤ 0,89	4-6-4-6-4	2,3	2,1	1,8	1,9	1,7
			4-*8*-4-*8*-4	2,1	1,9	1,7	1,9	1,6
			4-*12*-4-*12*-4	1,9	1,8	1,6	2	1,6
	Twee ruiten met warmtereflecterende coating	≤ 0,20	4-6-4-6-4	1,8	1,5	1,1	1,3	0,9
			4-*8*-4-*8*-4	1,5	1,3	1,0	1,3	0,8
			4-*12*-4-*12*-4	1,2	1,0	0,8	1,3	0,8
		≤ 0,15	4-6-4-6-4	1,7	1,4	1,1	1,2	0,9
			4-*8*-4-*8*-4	1,5	1,2	0,9	1,2	0,8
			4-*12*-4-*12*-4	1,2	1,0	0,7	1,3	0,7
		≤ 0,10	4-6-4-6-4	1,7	1,3	1,0	1,1	0,8
			4-*8*-4-*8*-4	1,4	1,1	0,8	1,1	0,7
			4-*12*-4-*12*-4	1,1	0,9	0,6	1,2	0,6
		≤ 0,05	4-6-4-6-4	1,6	1,2	0,9	1,1	0,7
			4-*8*-4-*8*-4	1,3	1,0	0,7	1,1	0,5
			4-*12*-4-*12*-4	1,0	0,8	0,5	1,1	0,5

OPMERKING 1 Deze tabel is gebaseerd op tabel C.2 van NEN-EN-ISO 10077-1:2006.

OPMERKING 2 De gegeven warmtedoorgangscoëfficiënten zijn berekend met NEN-EN 673 op basis van de gegeven emissiviteit en gasconcentraties groter dan 90 %. Emissiviteit en gasconcentratie van beglazing kan in de tijd veranderen. Procedures voor de berekening van het effect van veroudering op de thermische prestatie van beglazing worden beschreven in NEN-EN 1279-1 en NEN-EN 1279-3.

[a] ε_n is de emissiviteit voor normaalstraling volgens A.1 van NEN-EN 673.

[b] De cursief weergegeven waarde is de spouwbreedte.

15.8 Design thermal values for materials in general building applications

(Koninklijk Nederlands Normalisatie-Instituut, 2008)

Material group or application		Density ρ kg/m^3	Design thermal conductivity λ W/(m·K)	Specific heat capacity c_p J/(kg·K)	Water vapour resistance factor μ dry	wet
Asphalt		2 100	0,70	1 000	50 000	50 000
Bitumen	Pure	1 050	0,17	1 000	50 000	50 000
	Felt/sheet	1 100	0,23	1 000	50 000	50 000
Concrete [a]	Medium density	1 800	1,15	1 000	100	60
		2 000	1,35	1 000	100	60
		2 200	1,65	1 000	120	70
	High density	2 400	2,00	1 000	130	80
	Reinforced (with 1 % of steel)	2 300	2,3	1 000	130	80
	Reinforced (with 2 % of steel)	2 400	2,5	1 000	130	80
Floor coverings	Rubber	1 200	0,17	1 400	10 000	10 000
	Plastic	1 700	0,25	1 400	10 000	10 000
	Underlay, cellular rubber or plastic	270	0,10	1 400	10 000	10 000
	Underlay, felt	120	0,05	1 300	20	15
	Underlay, wool	200	0,06	1 300	20	15
	Underlay, cork	< 200	0,05	1 500	20	10
	Tiles, cork	> 400	0,065	1 500	40	20
	Carpet / textile flooring	200	0,06	1 300	5	5
	Linoleum	1 200	0,17	1 400	1 000	800
Gases	Air	1,23	0,025	1 008	1	1
	Carbon dioxide	1,95	0,014	820	1	1
	Argon	1,70	0,017	519	1	1
	Sulphur hexafluoride	6,36	0,013	614	1	1
	Krypton	3,56	0,009 0	245	1	1
	Xenon	5,68	0,005 4	160	1	1
Glass	Soda lime glass (including "float glass")	2 500	1,00	750	∞	∞
	Quartz glass	2 200	1,40	750	∞	∞
	Glass mosaic	2 000	1,20	750	∞	∞
Water	Ice at –10 °C	920	2,30	2 000	—	—
	Ice at 0 °C	900	2,20	2 000	—	—
	Snow, freshly fallen (< 30 mm)	100	0,05	2 000	—	—
	Snow, soft (30 to 70 mm)	200	0,12	2 000	—	—
	Snow, slightly compacted (70 to 100 mm)	300	0,23	2 000	—	—
	Snow, compacted (< 200 mm)	500	0,60	2 000	—	—
	Water at 10 °C	1 000	0,60	4 190	—	—
	Water at 40 °C	990	0,63	4 190	—	—
	Water at 80 °C	970	0,67	4 190	—	—
Metals	Aluminium alloys	2 800	160	880	∞	∞
	Bronze	8 700	65	380	∞	∞
	Brass	8 400	120	380	∞	∞
	Copper	8 900	380	380	∞	∞
	Iron, cast	7 500	50	450	∞	∞
	Lead	11 300	35	130	∞	∞
	Steel	7 800	50	450	∞	∞
	Stainless steel [b], austenitic or austenitic-ferritic	7 900	17	500	∞	∞
	Stainless steel [b], ferritic or martensitic	7 900	30	460	∞	∞
	Zinc	7 200	110	380	∞	∞

15.9 Calculation thermal bridge effect

Lambda air	0,025				N1	155,9116	
lambda_cavity (air…)	0,037465	W/m/K			N2	155,9116	
cavity thickness [m]	0,01	m			lambda1	-128,145	
					lambda2	-179,432	
lg*tg	4,75E-04	Wm2/K			D	2,49E+08	
ls*effectievebreeftespacers	8,68E-04	Wm/K			B	7,89E+03	
alpha 1	7,8	W/m2/K					
alpha 2	7,8	W/m2/K					
length panel	0,25	m					
width panel	0,15	m					
			psi	0,0074	W/K		psi-value of thermal bridge
lambda_glass	0,95	W/m/K	Ucop	1,907	W/m2/K		unbridged U-value
thickness_glass	5,00E-04	m	Ueff	2,066	W/m2/K		bridged U-value
Surfacearea_panel	0,0375	m2	Double	1,412			
lambda_spacer	0,29	W/m/K	Triple	1,073			
Surfacearea_spacer	0,002395	m2					
			Double	1,268			
			Triple	0,950			

(orange)	input
(green)	output

alpha_rad_spouw	1,2465	W/m2/K
alpha_conv+cond_spouw	2,50E+00	W/m2/K
Rspouw	0,266916	m2K/W
Lambda_spouw	0,037465	W/m/K
eps1	0,2	
eps2	0,9	
eps_res	0,195652	

15.10 Nusselt number

(Jóhannesson, 2006)

$$Nu = \frac{h_c \cdot l}{\lambda}$$

Nusselt : Actual heat transfer coefficient h_c in relation to that of still air over a given characteristic length l. When the air is standing still the Nusselt number will be equal to 1. With increasing air movements either due to temperature differences or to external forces the Nusselt number will increase.

$$Gr = \frac{g \cdot \beta \cdot l^3 \cdot \Delta T}{\nu^2}$$

Grashof: Criterium for fluid movements due to natural convection. As gravity g, volume expansion coefficient **β** and the kinematic viscosity **ν** for air are fairly constant in the normal temperature range the Grashof number will depend strongly on the geometry represented by the characteristic length l and the temperature difference **ΔT**.

$$Re = \frac{u \cdot l}{\nu}$$

Reynolds: Properties of the flow at forced convection. For a given fluid and geometry Reynolds number will increase linearly with the velocity of the fluid. With increasing velocity, when the Reynolds number reaches a certain limit, we will have transition from laminar to turbulent flow.

$$Pr = \frac{\nu \cdot \rho \cdot c}{\lambda}$$

Prandtl: Properties of the flowing medium. For applications to building air flow the Prandtl number can normally be set equal to 0.7.

g = acceleration of gravity 9.81 m/s^2

β = volume expansion coefficient K^{-1}

l = characteristic length, m, that can be the hydraulic diameter in forced duct flow or the length of the surface in the direction of the flow for air flow along exposed surfaces.

u = air velocity, m/s

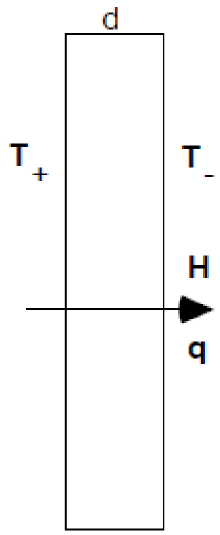
ν = kinematic viscosity, m^2/s

h_c = the coefficient of surface heat transfer due to conduction and convection, W/m^{2}K.

When the Nusselt number has been calculated for a given characteristic length l the convective surface heat transfer coefficient can be calculated as

$$h_c = Nu \cdot \lambda / l \qquad (6.5)$$

6.4.7.2 *Vertical gap with limited height H and horizontal heat flow*



The thickness of the gap, d, m , is the characteristic length to be used in the calculation of the Grashof number

$2 \cdot 10^4 < \mathbf{Gr} < 2 \cdot 10^5 \quad H > 3d$ (6.25)

$\mathbf{Nu} = 0.18 \cdot \mathbf{Gr}^{1/4} (\mathbf{H/d})^{-1/9}$

$2 \cdot 10^5 < \mathbf{Gr} < 2 \cdot 10^7 \quad H > 3d$ (6.26)

$\mathbf{Nu} = 0.065 \cdot \mathbf{Gr}^{1/3} (\mathbf{H/d})^{-1/9}$

Expressions (6.25) and (6.26) are used for instance for the calculation of the convective heat transfer between the panes of a multi-glazed window.

The heat transfer coefficient is given as

$$h_c = \frac{Nu \cdot \lambda}{d} \qquad (6.27)$$

and the average density of heat flow rate between the surfaces can be calculated as

$$q = h_c \cdot (T_+ - T_-) \qquad (6.28)$$

At high Grashof numbers the air in the cavity will start rotating due to the density differences and we can assume that we have downward flow of air on the cold side and upward flow of air on the warm side. This means that there will be a temperature and heat flow gradient along the surfaces.