Thin glass composite panel with 3D printed core

THERMAL AND STRUCTURAL PROPERTIES

STELLA BRUGMAN

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Content

List of abbreviations and file extensions

Abbreviations

AM: Additive Manufacturing
FDM: Fused Deposit Modelling
FEM: Finite Element Model
VIG Vacuum Insulated Glass
IGU: Insulated Glass Unit

File extensions

.stl: STereoLithography file
.dat: Data file

Nomenclature

Thermal

Symbol	Unity	Property
λ	W/m·K	Thermal conductivity (*warmtegeleidingscoëfficiënt)*
R	$K \cdot m^2/W$	Heat insulation
U	$W/m^2 \cdot K$	Thermal transmittance

Structural

Symbol	Unity	Property
E	N/mm^2	Youngs' Modulus
M	N·m	Bending moment
N	N	Normal force [Newton]

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 sheet 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 $<1{,}65\ W/m^2 \cdot K$. But in the near future, the new BENG regulations asks for a U value of $<0{,}6\ W/m^2 \cdot K$ (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 compare 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, of materials which need less material 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 (C. 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 CO2 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. 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.

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 (C. 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, 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 (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. All these researches focussed on the application of the composite as an window.

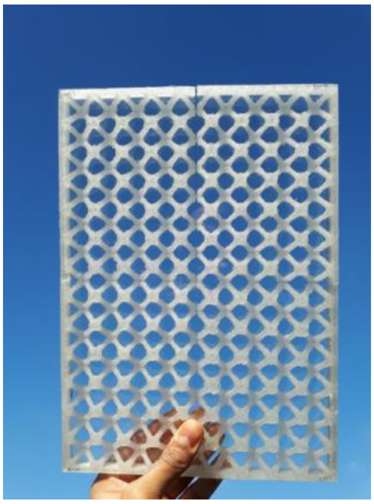

Image 1 - 11 mm core thickness. 0,7 mm thin glass (Akilo, 2018)

Image 2 - 8 mm core thickness. 1 mm thin glass (Neeskens, 2018)

Image 3 - 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 1, is a good example. The façade is going to support the roof and needs to be insulated to the standards of today, in the Netherlands.

Image 4 - 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/ 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 CO2 emission during the production. The ambition is to design a trussed 3D printed core in a thin glass composite panel which 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

Which 3D printed trussed pattern in a thin glass composite panel will lead to an optimal performance of the panel concerning thermal and structural properties?

1.5.2 Sub-questions

1. What is thin glass and how is it made?
2. What is the best sandwich structure in terms of structural properties and thermal conduction?
3. What is the best way to connect the thin glass and the core to obtain structural cohesion?
4. What parameters influence the structural properties of the composite panel?
5. How can the required stiffness be achieved by changing the parameters?
6. What parameters influence the thermal insulation properties of the composite panel?
7. How can the required thermal insulation be achieved by changing the parameters?
8. What is the relation between the parameters?
9. What are the criteria for the façade design?

Background question

1. What are the highlights in the development of glass?

Which 3D printed trussed pattern in a thin glass composite panel will lead to an optimal performance of the panel concerning thermal and structural properties?

1. What is (thin) glass and how is it made?
2. What is the best sandwich structure in terms of structural properties and thermal conduction?
3. What is the best way to bond the thin glass and the core to obtain structural cohesion?
4. Which production technique and material is most suitable to realize the core?
5. How can the thermal insulation value be determined?
6. How can the structural properties be determined?
7. Which test set-up can be used to test the panel?
8. What is the effect of a trussed pattern in a thin glass composite panel on the structural and thermal insulation properties of the panel?
9. Which aspects can be improved to give the composite panel better structural properties and thermal insulation properties?

1.6 Approach and methodology

Part one

Part one covers the sub-questions 1 till 3. There questions are going to be answered through literature research. The sources which are going to be used are ScienceDirect, Google Scholar and books from the library. The aim is to use papers from different writers, and if a paper is very useful, the references in that paper will also be used. 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

Part two covers the sub-questions 4 till 8. These questions are all about finding the right criteria for the pattern, performing analyses with the computer and perform hand calculations. The software that is going to be used is Rhino + Grasshopper, Karamba and an excel-sheet.

- Rhino + Grasshopper will be used to draw/ model the composite panel. Grasshopper, in particular, is a great program to use because it is easy to work with different parameters which can be adjusted later in the modelling process.
- Karamba is a plug-in for Grasshopper. Structural analyses can be performed with Karamba.
- Validation of Karamba with Diana.
- Excel-sheet, loaded in Grasshopper, 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 two panels will be tested.

Part three

Part three is about performing tests on two panel designs. At least 5 panels of each design will be tested to get a clear view on the behaviour of the panels. These tests are for validation the computer design. The results of the tests are input to improve the design. The pattern will be scanned with Recap from Autodesk before the tests will be performed because a 3D printed structure is never completely smooth. The layers of material are never completely on top of each other, which causes deviations in the structure. Even though these deviations are small and on a small scale, they can have a big consequence for the structure as a whole. The tests which are going to be performed are a compression test and a heat flow test.

Compression test

A compression test is going to be done to check the structural properties of the panel. 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 parameters which are going to be changed only relate to the trussed pattern.

The most important thing is that the panel can withstand the weight of the roof structure, snow load and dynamic load.

Needed materials:

- 6x panels
- Test machine

Heat flow sensors 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. (Antoniadis, 2011)(Zhao, Qian, Gu, Jajja, & Yang, 2016)

Needed materials:

- 2x heat flux sensor HFP01
- 4x thermocouples type T
- 2x voltmeter
- Heater/ cooler
- Laptop

3D printing

The core needs to be printed before the composite panels can be made and the tests can be performed. Two designs are going to be tested for at least three times, so in total 6 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.

Part four

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Part four covers question 9 and the conclusion is the final design. 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.

Multiobjective optimizations
PARETO FRONT from Vilfredo Pareto

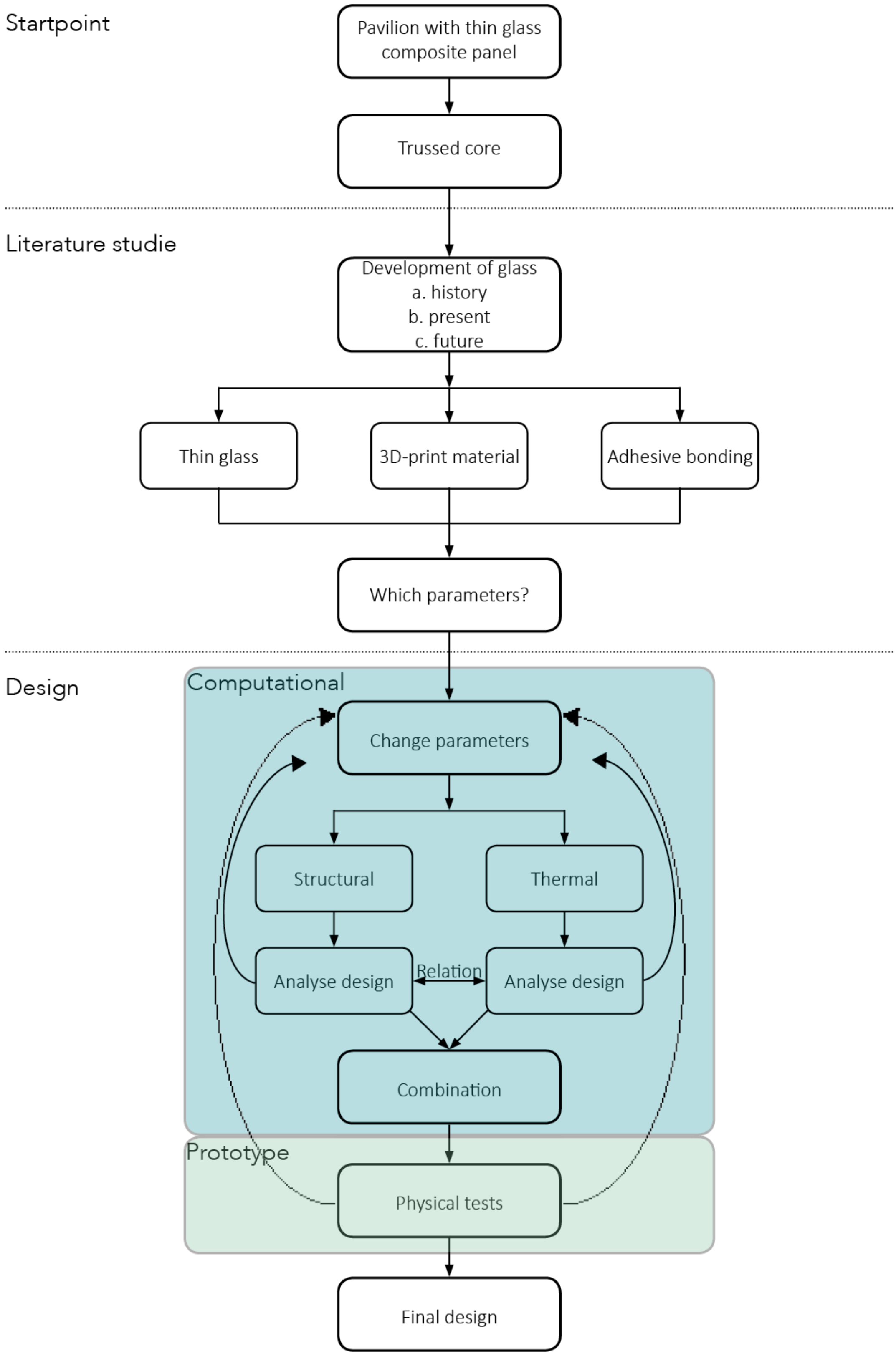

Figure 1 - Methodology scheme. Own figure.

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
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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 €??
Adhesive €??

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. And 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 is perspective is going to be described.

2.1 History

In the middle ages, from 500 – 1000, mainly small pieces of crown glass (image 5). 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. The top and the bottom are cut of, 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. These techniques are discussed in subchapter 2.2.

Image 5 - Crown glass. Photo: Edward Belding

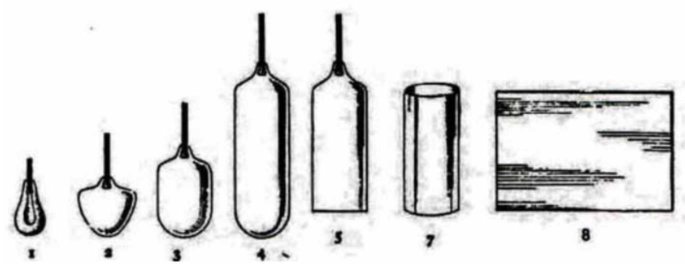


Image 6 - Making of cylinder glass. Image: A. Sauzay

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.

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.

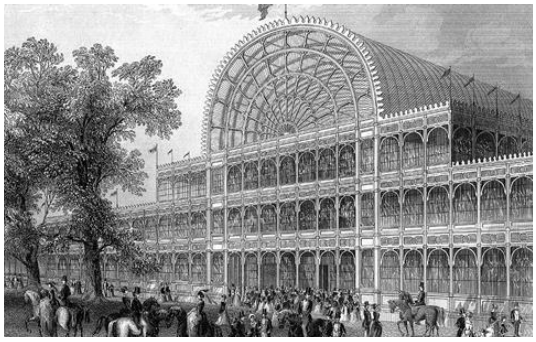


Image 7 - Crystal Palace, London 1851. Designer: Sir Joseph Paxton.

Image 6 - 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 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 9). 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 7 - The Apple House, New York. 2006. Photo: EOC

The Steve Jobs Theatre in California is a building with the newest structural glass application (image 10). 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 10 - Steve Job Theatre, California. 2018. Photo: Foster + Partners

The MAS museum in Antwerp gives the visitor an illusion of massive floating boxes (image 11). 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 11 - 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 12). 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 2,8 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 13) (Koninklijk Nederlands Normalisatie-Instituut, 2018). Appendix … show 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’. It is a Vacuum Insulating Glass (VIG) panel of two times 3 mm glass panes with a cavity of 0,1mm (image 14). As seen in image 14, 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.

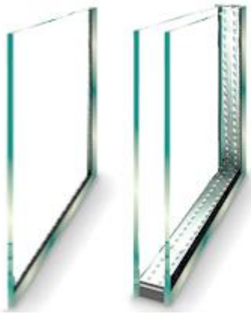


Image 12 - Single layer and double layer of glass in window pane. Image:

Image 13 - Triple layer of glass in window frame. Image: Reynaers.

Image 14 - VIG panel. 2 layers of 3mm glass with cavity of 0,1mm. Photo: AGC

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. To answer to this demand for high performance materials and products, new and innovative designs. 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, image …..

Image 86 - Thin glass screen on iPhone. Image: Apple.

Image 97 - Cold bent glass in the façade. Image: Carlym Simoen.

Image 108 - Pneumatic exoskeletonwindow. Image: Congrui Zha.

Part Ⅰ Literature study

3 (Thin) Glass

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

3.1 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...). Image... 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 ordenend 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.

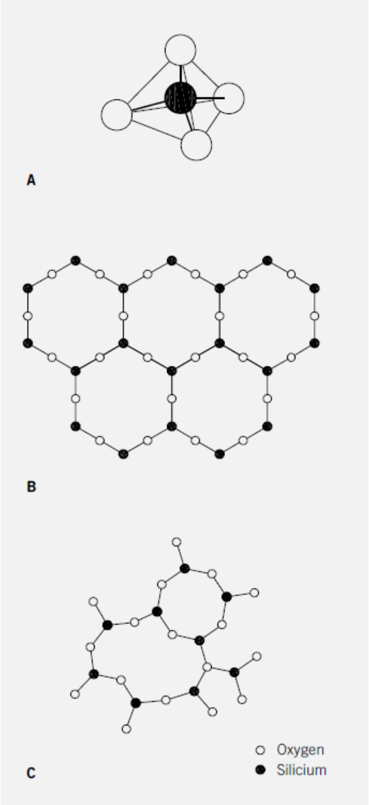


Image 11 - Chemical bond of glass. Wurm. 2007

Table... 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 (M. F. Ashby, 2013).

Table.. Composition of soda-lime glass

Material	Formula	Composition (%)
Silica	SiO_2	73
Soda	Na_2O	17
Lime	CaO	5
Magnesia	MgO	4
Alumina	Al_2O_3	1

Density = 2500 kg/m^3
Young's Modulus E = 70000 N/mm^2
Poisson ratio = 0,22

Table.... Composition of borosilicate glass

Material	Formula	Composition (%)
Silica	SiO_2	74
Boron oxide	B_2O_3	15
Lead oxide	PbO	5
Soda	Na_2O	4
Alumina	Al_2O_3	2

Table… Composition of aluminosilicate glass

Material	Formula	Composition (%)
Silica	SiO_2	60
Alumina	Al_2O_3	20
Boron oxide	B_2O_3	10
Lime	CaO	8
Soda	Na_2O	2

Glass behaves as a brittle material. There is no sign in the glass when it might possibly break, it just breaks. This is in contrast with most other materials which show pre-fracture behaviour, for example through cracks or deformation.

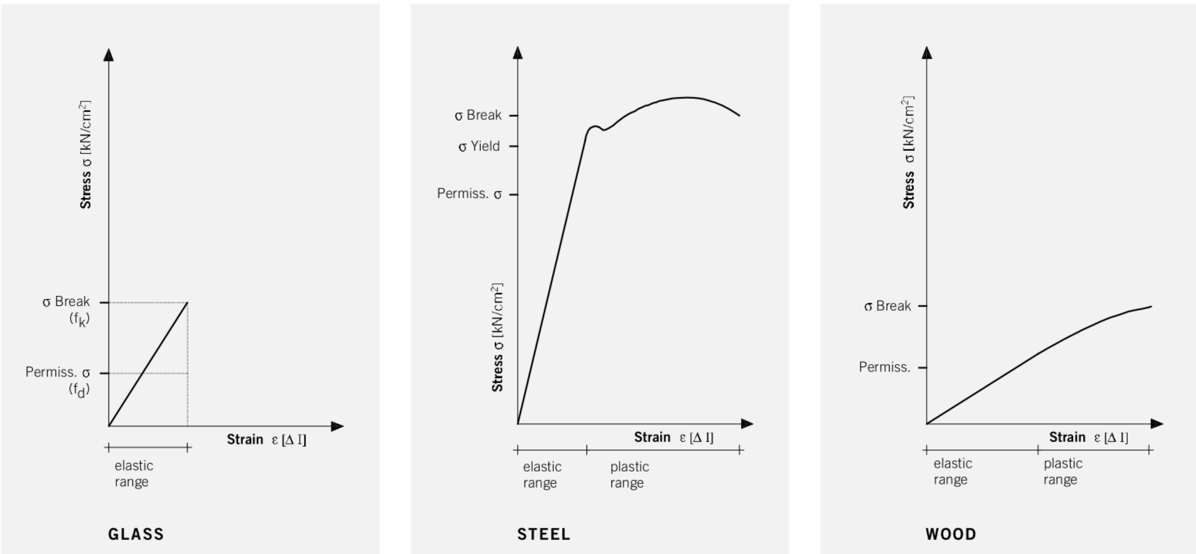


Image 12 - Stress/ strain curvature for glass, steel and wood (Wurm, 2007).

3.2 Primary production process

Glass producers have always tried to make the production process better and cheaper. Over the years different kind of process have been tried and there is still development of new production techniques.

Float glass

Float glass is a production technique which is mostly used. The image below (image 9) 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 thin 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

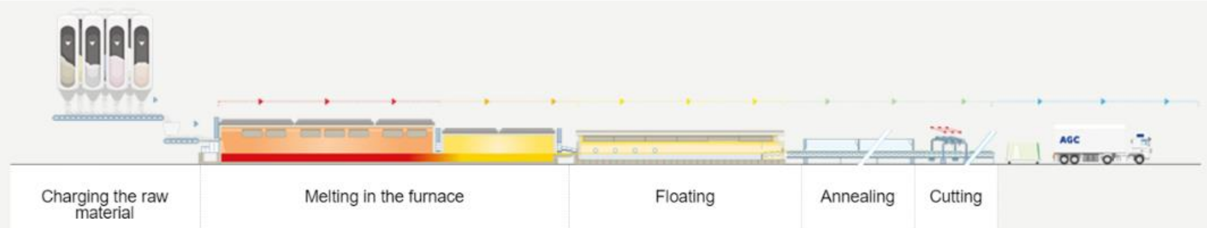


Image 13 - Production process of float glass. Image: AGC.

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, 2019).

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 of the rolls in the glass.

Overflow and down-draw

The overflow and down-draw process are very 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. The flow speed is controlled by a slot. the glass flow down to the tip where the two glass sides meet each other. At the tip the glass is cooled with water. The cooled glass sheet is guided down by rolls. This method is first used to produce car shields.

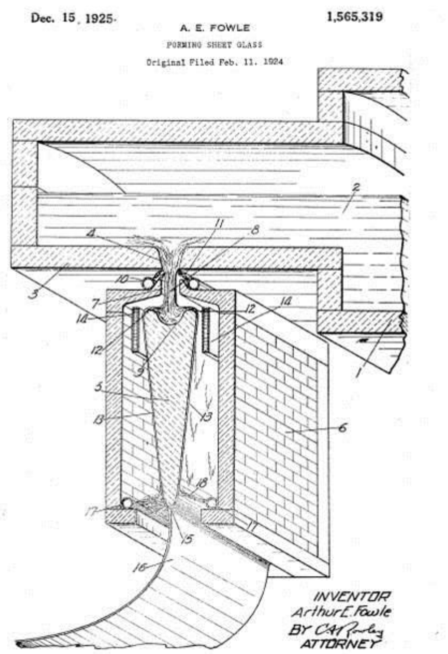


Image 21 - Down-draw process. Image: A. Fowle.

Corning re-invented the down-draw process.
DOOR SCHRIJVEN

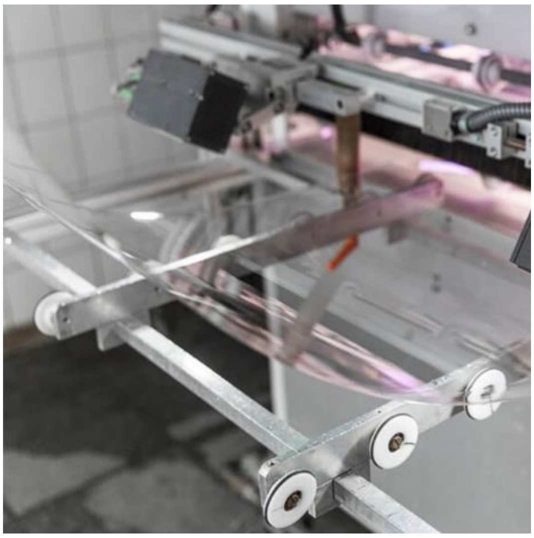


Image 20 - Down-draw of thin glass. Photo SCHOTT.

3.3 Post processing

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.

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.

Annealed glass breaks in large pieces (image 22). 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/mm² to 52N/mm². 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 (image 22).

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/mm² and 150N/mm². The glass must be between 4 mm and 19 mm thick. When the glass brakes, it shatters in small pieces (image 22). 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.

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.

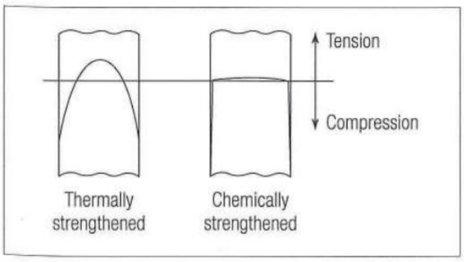


Figure 2.9 Section through toughened glass showing comparison between the stresses in thermal and chemical processes

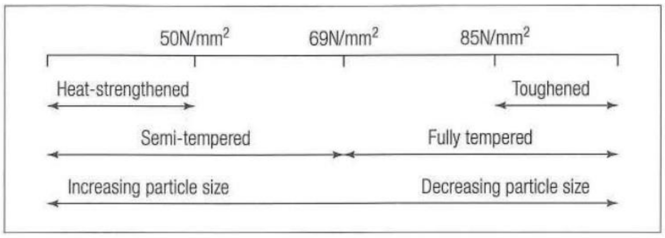


Figure 2.10 Chart of glass types comparing their strength and particle size following failure

The different treatments can be identified by the break pattern of glass (image 22), but a break pattern does not only show the treatment it got, but it also shows the weak spot.

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

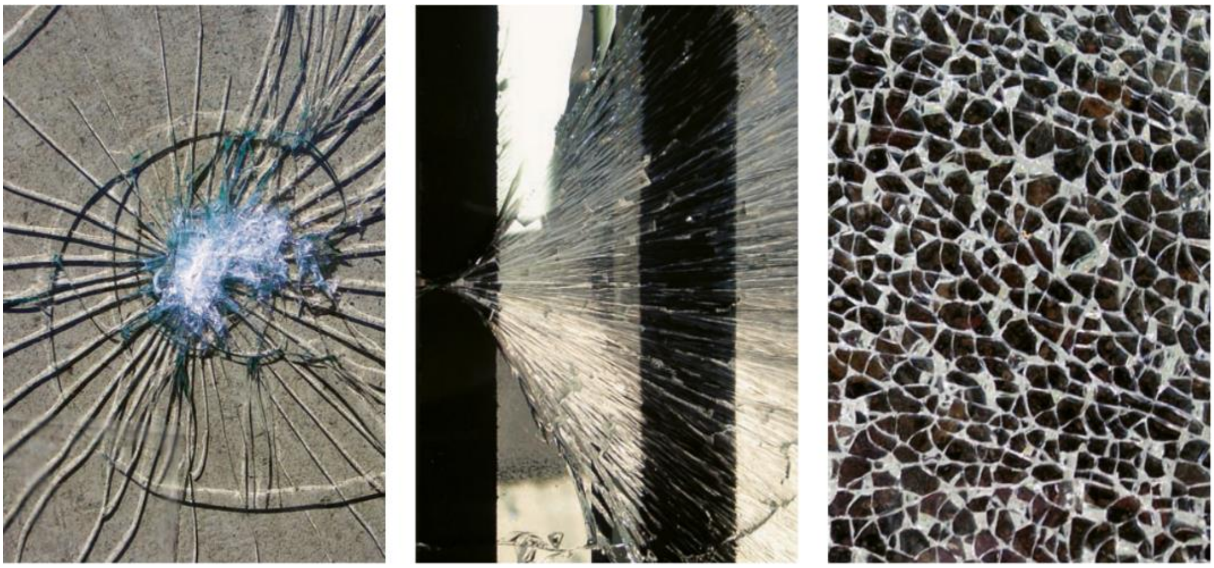


Image 22 - Break pattern of glass. Wurm, 2017.

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 water.

Cutting the glass means that the surface is scratched. Scratching the surface means distortion of the compressive layer and therefore the glass is weakened.

Curved glass

Glass can be bent in two different ways: hot bent and cold bent (O'Regan, 2014; Wurm, 2007).

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 fluid sheet takes to 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.

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).

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). 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.

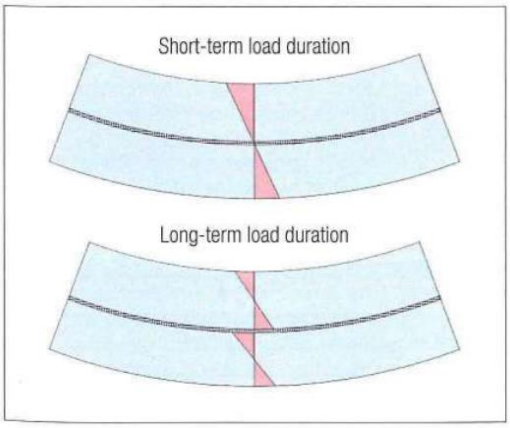


Figure 2.12 Section through laminated glass indicating bending stress within plies for short-term and long-term conditions

3.4 Thin glass – potential applications

Properties of the material

Table…. Properties of thin glass from AGC

Properties	Parameters	1,6mm	0,5mm
Optical	LT	91,6	92,1
	ET	91,5	92,1
	Refractive index (visible	1,515 +/- 0,005	
	Photo elastic constant	27,227,2nm/cm/MPa	
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
Chemical resistance	Hydrolytic class	2

Table… Size of the glass

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

The edge of the material is very sensitive. This has to be taken in account when designing the edge connection.

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/cm^3
	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

3.5 Conclusion

Thin glass is a glass sheet with a thickness of 0,1 – 2,0mm (AGC Glass, 2017). Thin glass can be produced in three different ways, float glass, down-draw and overflow. Because the thinness of the glass it can only be chemically strengthened (Wurm, 2007).

It is not possible yet to apply a coating on thin glass. Experiments are done to apply a soft coating at this moment. In theory it would be possible to apply a coating on to float glass. But applying a coating during the overflow process is not possible.

4 Sandwich structures

What is the best sandwich structure in terms of structural properties and thermal conduction?

4.1 General properties of sandwich structures

The topological design of multifunctional cellular metals Evans (Evans, Hutchinson, & Fleck, 2001)

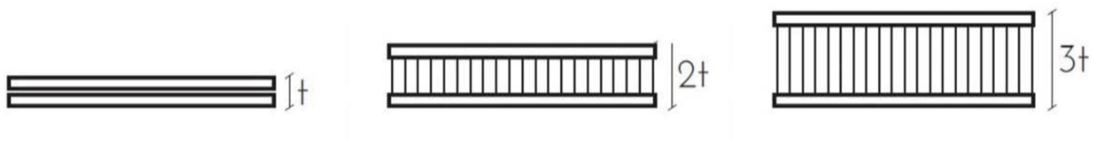
> *"The underlying concept is to design the topology of the structural alloy to carry load, conduct heat (and so on) in the most efficient manner (that is, at lowest weight): whereupon, the intervening space can be used to enable other functionalities, such has passages for flowing fluids that remove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

Carry load, conduct heat -> lowest weight
Distribute plastic deformations that absorb energy.

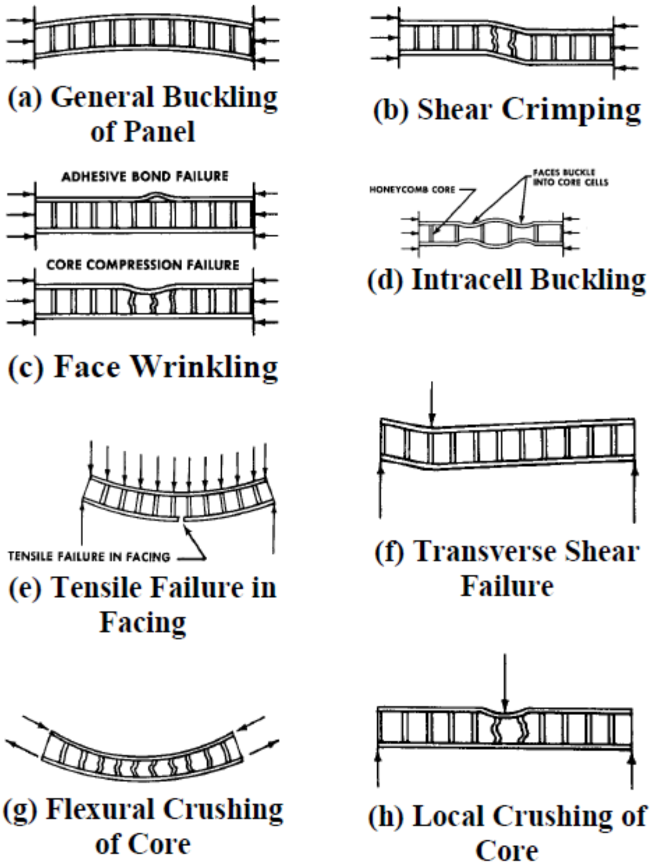
Choice for periodic -> truss pattern

Design and Experimental Testing of All Glass Sandwich Panels : An Experimental and Numerical Study for the Glass Floors of the Acropolis Museum

(Vitalis, Veer, & Oikonomopoulou, 2018)



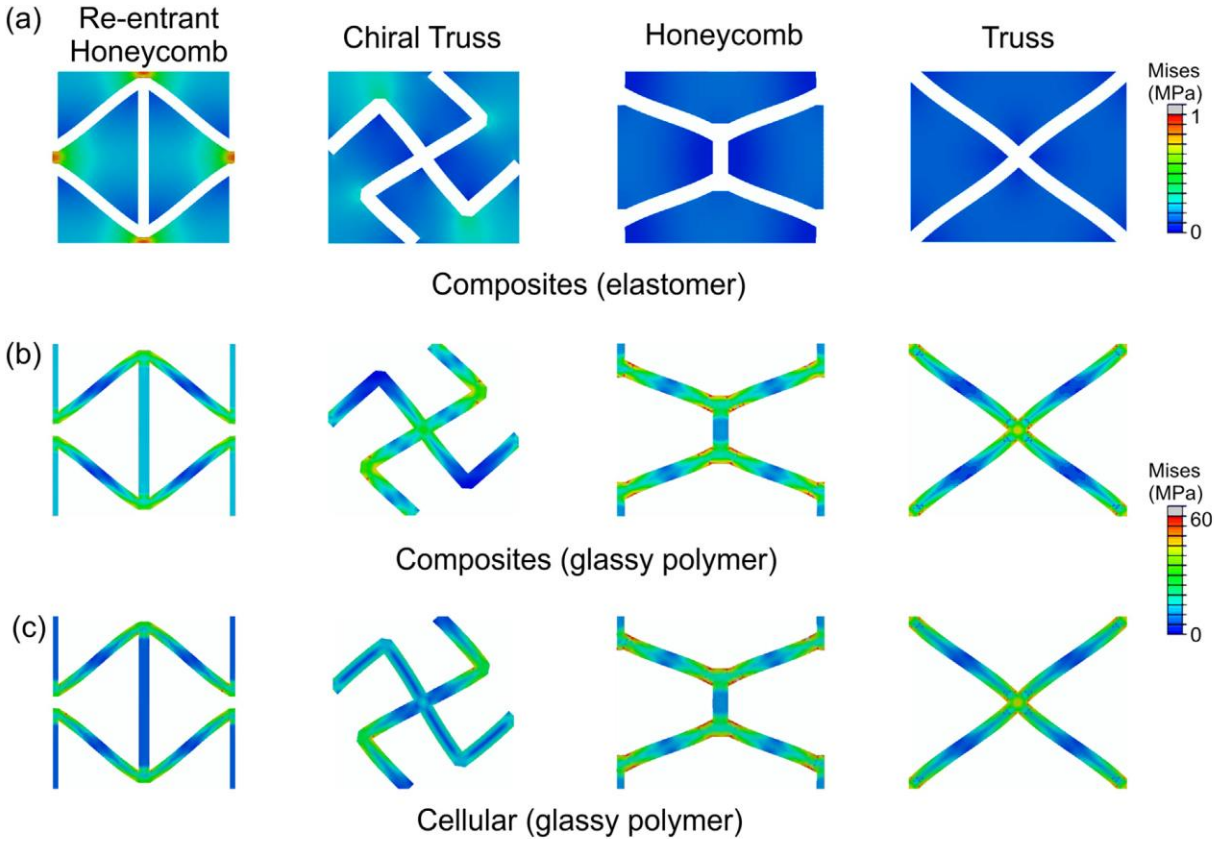
Relative Weight			
	1	1.2	1.4
Relative Bending Stiffness			
	1	5	15
Relative Strength			
	1	2.5	6.5

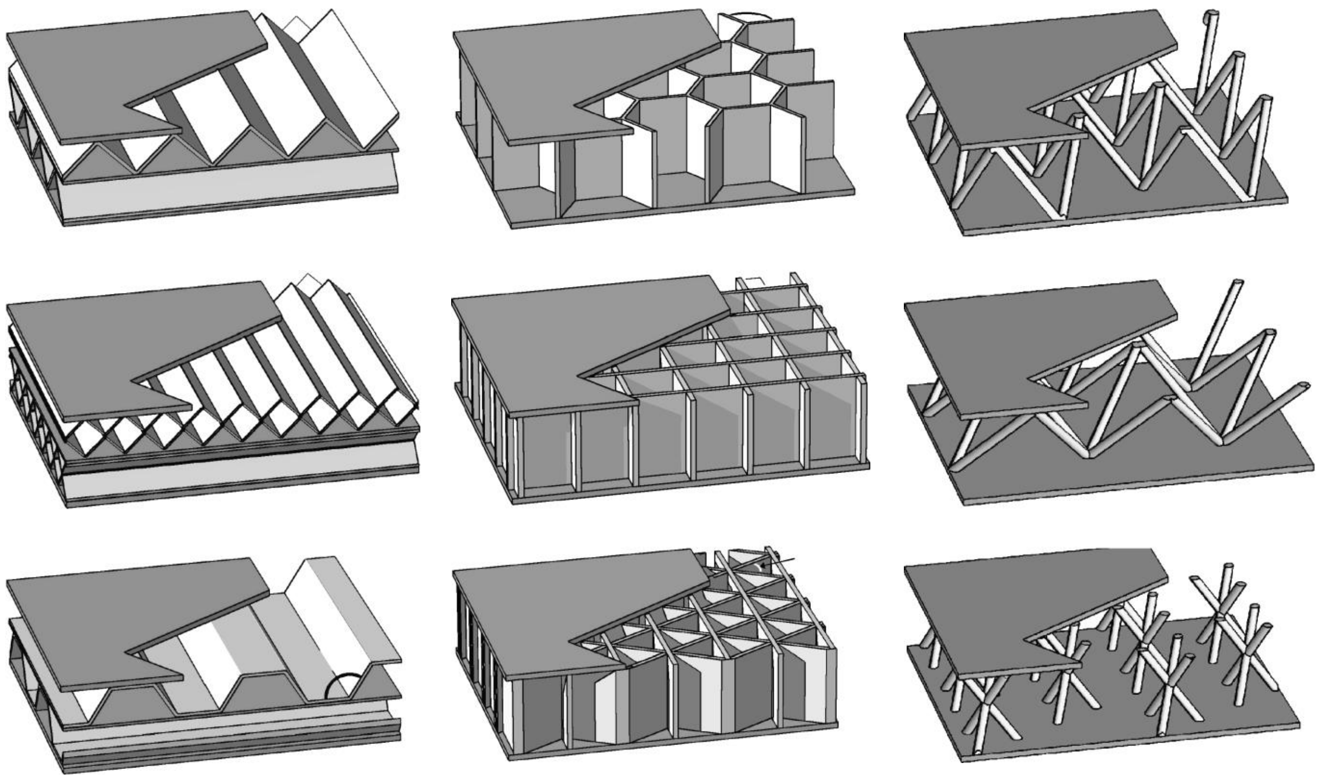


(Ratwani, 2010)

4.2 Pattern

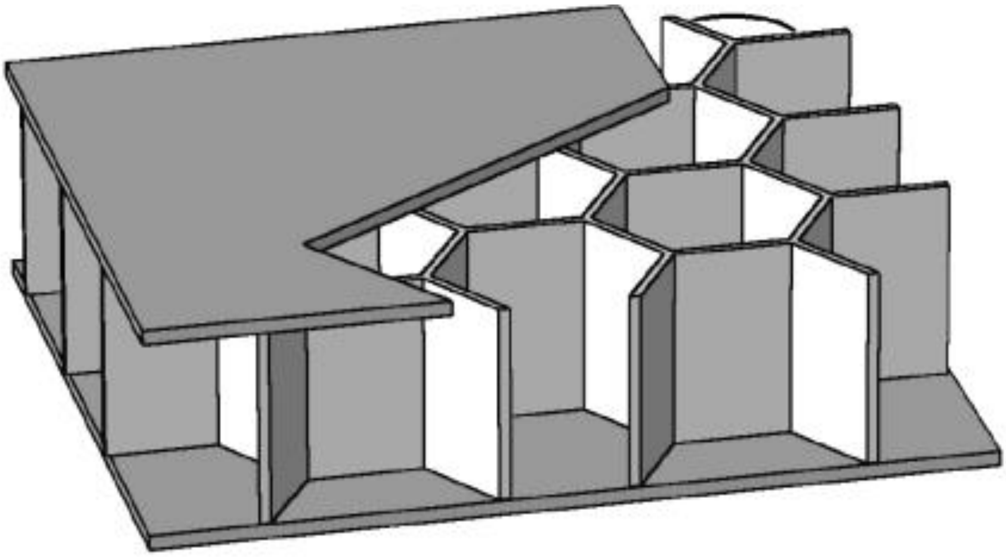
(Li, Chen, Hu, Li, & Wang, 2018) In summary, we have investigated the macroscopic mechanical responses of the auxetic lattice reinforced composites through a combination of 3D printing, experiments, and numerical analyses. We have shown that auxetic lattice reinforced composites have enhanced mechanical performance, achieving a unique combination of stiffness and energy absorption, compared with the non-auxetic lattice reinforced composites. In particular, by harnessing the negative Poisson's ratio effect in the lattice reinforcements, we find that the mutual constraints between the auxetic reinforcement and matrix enable enhanced mechanical properties by gaining additional support from the matrix phase. We further quantify the effect of Poisson's ratio on the other mechanical properties of various honeycomb reinforced composites, indicating that the degree of auxetic behaviour could be used to tune the stiffness and energy absorption of the lattice reinforced composites. Finally, we use scaling law to evaluate the effect of volume fraction of the reinforcement phase in the composites, showing that the re-entrant honeycomb reinforced composite exhibit nearly linear scaling. These results provide guidelines for engineering and developing a new class of auxetic reinforced composites with enhanced mechanical performance for a wide range of applications and further creating multifunctional materials.

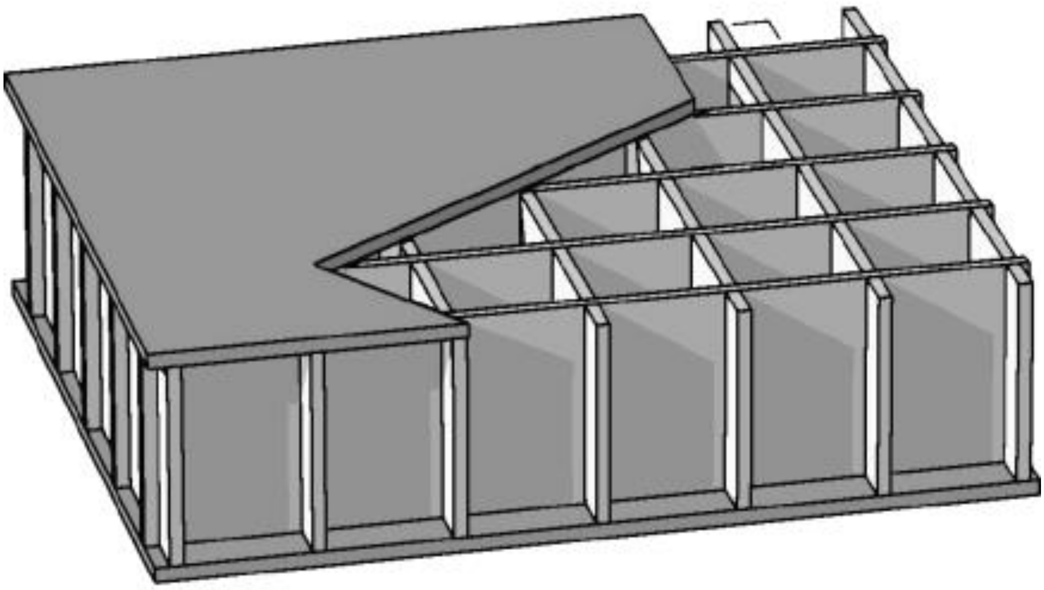

(a)
Re-entrant Honeycomb
Chiral Truss
Honeycomb
Truss
Mises (MPa)
1
0
Composites (elastomer)
(b)
Mises (MPa)
60
0
Composites (glassy polymer)
(c)
Cellular (glassy polymer)

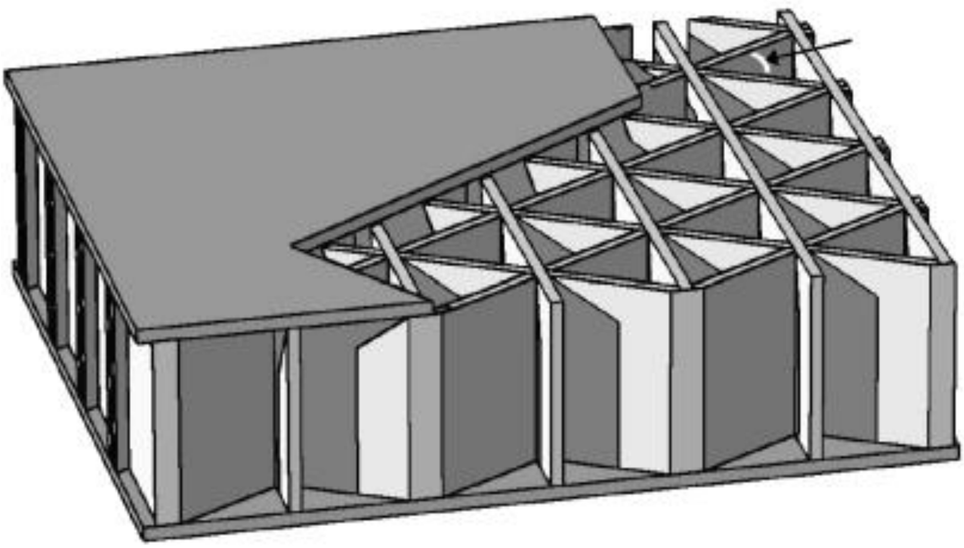


(Wadley, 2006)

4.2.1 Conclusion







4.3 Bonding

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

4.3.1 Lamination

PolyVinyl Butyral (PVB), SentryGlass (SG), TPU & Ethylene Vinyl Acetate (EVA) interlayer
Lamination is done with an Autoclave. The layers which need to be bonded (glass, interlayer and core) need to be put on each other, in a vacuum bag. Than the materials are put in an oven and heated till 135 ˚C.

4.3.2 Adhesive bonding

An adhesive is needed 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 (C. 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 (Christian Louter, 2017).MOOI VERHAAL VAN MAKEN

Epoxy

Types

- Generally: 2-components: an epoxide resin and a polyamide hardener
- Curing: UV-curing, cold curing and hot curing variants
- Hybrid epoxy with increased elasticity (toughened epoxy)

General properties

- High strength and stiffness
- Small optimal thickness (generally less than 0,5mm)

Structural applications

- E.g. aircrafts, boats, metal structures ….

Acrylate

Types

- Cyanoacrylate, methacrylate (2-compnents) and UV-curing acrylate

General properties

- In general a high shear strength
- Small optimal thickness (generally less than 0,5mm)
- Methacrylate's: good durability
- U-acrylates: some durability problems, transparent
- Brittle

Structural applications

- E.g. adhesive layers in structural double-sided tape
- E.g. indoor applications like bonded door hinges etc.

Silicone

Types
- One component (air curing) and 2-component (chemical curing)
- Hot curing film (TSSA)

General properties
- Low strength and stiffness (exception: TSSA)
- Thickness: >6mm
- High durability, UV as well as humidity

Structural applications
- Structural sealant glazing (ETAG 002)

Polyurethane

Types
- Physical and chemical curing variants
- 1-component and 2-component

General properties
- Medium strength and stiffness
- Stronger than silicone and MS-polymers, less brittle than epoxies and acrylates
- Used to have low UV resistance (UV-blocking primers)

Structural applications
- In automotive, e.g. windshield bonding
- E.g. bonding non-transparent façade panels or external insulation

Table…. Summary of adhesive properties

	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 U-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
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.

Type of adhesive (Machalická & Eliášová, 2017)
1-component PU 2-component PU
2-component acrylate UV – curing acrylate UV – curing acrylate
Ageing resistance

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 (M. Ashby, Shercliff, & Cebon, 2014).

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

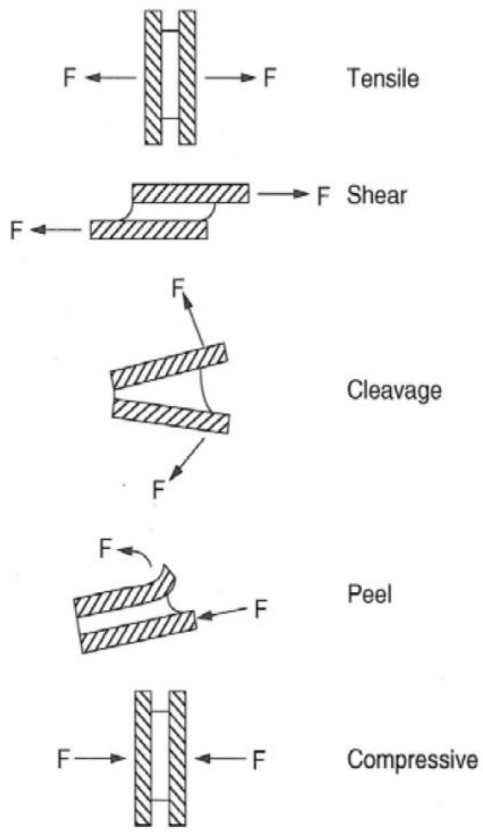


Image 14 - Different loads on adhesive bonds.

4.3.3 Conclusion

5 Additive manufacturing

Fused Deposit Modelling (FDM) is an Additive Manufacturing (AM) process. This means that
https://www.3dhubs.com/knowledge-base/advantages-3d-printing
Additive manufacturing techniques

https://www.3dhubs.com/get/am-technologies/

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. This chapter concludes with information about the available printers at the Technical University of Delft and what this means for the design of the core.

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. In this way, layer by layer, an object is printed. Everyone can by or make a printer themselves. With a bit of 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. 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 good connected to the bed and the print moves, the layers of material cannot be put on each other. The result is a distorted print.

Image 154 - Ultimaker 3. From 3dninja.nl

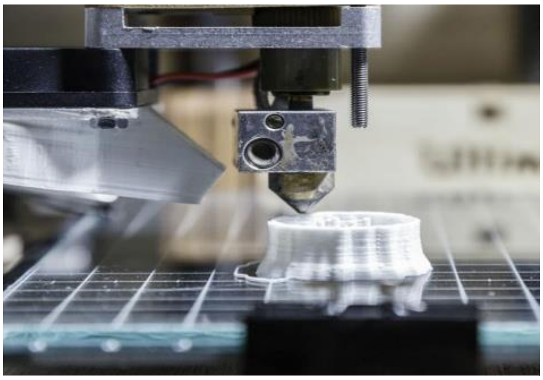


Image 165 - FDM/ 3D printing. Image: Industry week.

https://www.3dhubs.com/knowledge-base/selecting-right-3d-printing-process

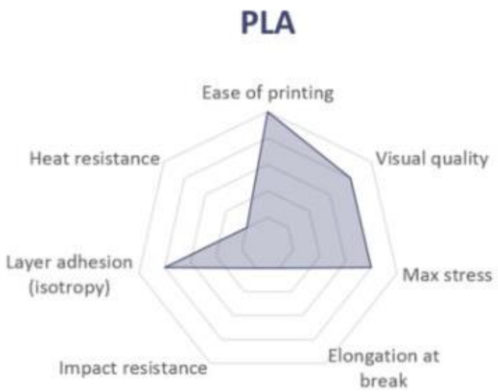
Print technique

The printer deposits layers of flued material on top of each other.
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 rectangles

Model
Before the geometry in Rhino can be printed, it need to be checked is al 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'.

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, Schöffer, & Garret, 2017).

PLA = polylactic acid
Very rigid
Biodegradable, Odourless, Sanding is ok & painting is ok met acrylics, Good against UV
Low humidity resistance, Not good with glue in general
λ = 0,13 W/mK (Make it from, 2018; Sd3D.com, 2015)



ASHBY(M. F. Ashby, 2013)
General properties

Density	1,210	- 1,250 kg/m3
Price	2.4	- 3 USD/kg

Mechanical properties

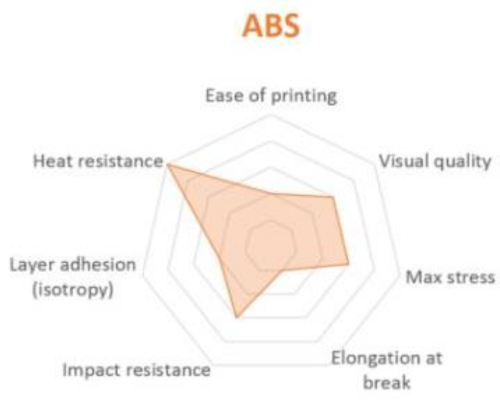
Young's modulus	3.45	- 3.83 GPa
Yield strength (elastic limit)	48	- 60 MPa
Tensile strength	48	- 60 MPa
Compressive strength	48	- 60 MPa
Elongation	5	- 7 %
Hardness—Vickers	14	- 18 HV
Fatigue strength at 107 cycles	14	- 18 MPa
Fracture toughness	0.7	- 1.1 MPa · $m^{1/2}$

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

ABS = acrylonitrile butadiene styrene
Rigid
Post process: Acetone for glossy finish, Sanding and glue with acrylics, Good with epoxies & acetone glue, Good abrasion resistance
UV sensitive, Odour when printing, potentially high fume emissions
λ = 0,173 W/mK



https://www.sd3d.com/portfolio/abs/

ASHBY
General properties

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

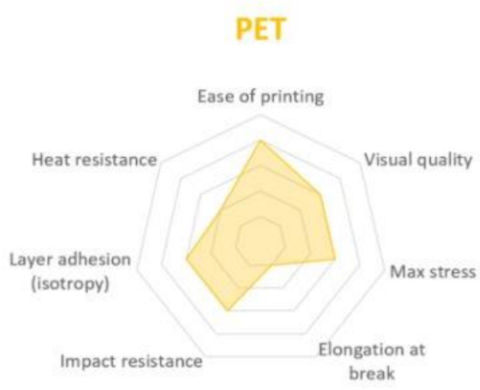
Mechanical properties

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

PET (recycled) = polyethylene terephthalate
Fairly rigid
Food safe, high humidity resistance, high chemical resistance, recyclable, good abrasion resistance, good with sanding and acrylic paint, can be glued, good with acrylic glue (cyanoacrylate)
λ = 0,29 W/mK



https://www.sd3d.com/portfolio/pet/

ASHBY
General properties

Density	1,290	- 1,400 kg/m^3

Error! Use the Home tab to apply Kop 1 to the text that you want to appear here.

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 · $m^{1/2}$

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

Support material
PVA (PolyVinylAlcohol), can be dissolved in water

Other materials based on PLA/ PHA
Corkfill https://colorfabb.com/corkfill
PLA 70%, cork 30%
Cork λ = 0,046 W/mK (Weersink, Zeegers, Erdtsieck, Van der Linden, & Keizer, 2006)
PLA λ = 0,13 W/mK
(7*0,13 + 3*0,046) / 10 = 0,1 W/mK

Woodfill https://colorfabb.com/woodfill
PLA 70%, wood 30%
Softwood λ = 0,14 W/mK (Weersink et al., 2006)
PLA λ = 0,13 W/mK
(7*0,13 + 3*0,14)/ 10 = 0,13 W/mK

https://www.3dhubs.com/knowledge-base/fdm-3d-printing-materials-compared

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. 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).
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 (Martikka, Kärki, & Wu, 2018).

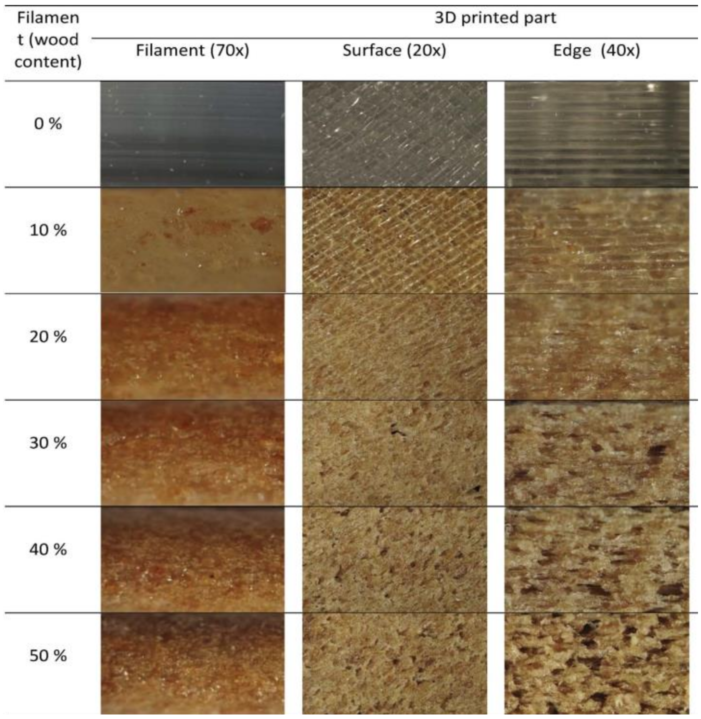


Image 17 - PLA - wood filament (Kariz, Sernek, Obucina & Kuzman, 2018)

Table… Properties of the 3D print materials.

	Young's Modulus (GPa)	Yield strength (MPa)	Tensile strength (MPa)	Shear strength (GPa)	Glass temperature (˚C)	Thermal expansion coefficient (µstrain/ ˚C)	Thermal conductivity (λ = W/mK)	Poisson's ratio
PLA	3,3 – 3,6	55 – 72	47 – 70	1,2 – 1,29	52 - 60	126 - 145	0,13	0,38 – 0,4
ABS	2 – 2,9	29,6 – 44,1	30 – 50	0,319 – 1,03	88 - 120	126 - 145	0,173	0,38 – 0,4
PET	2,8 – 3	50 – 55	55 – 60	0,994 – 1,49	60 – 84	115 - 119	0,29	0,381 – 0,396
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		142 - 158	120 - 125	0,189 – 0,205	0,391 – 0,407
Woodfill	Wood: 10 – 12	32,5 – 39,8	47 – 70	6,5 – 7,9	77 – 102	2 – 11	0,13	0,35 – 0,4
Corkfill	Cork: 0,025 – 0,05	1,1 – 2,2	47 – 70	0,55 – 1,1	77 – 102	120 - 180	0,13	0,08 – 0,4

5.2 Conclusion

To conclude this subchapter, the material PET is going to be used.
Because it has a good yield and tensile strength and even though the Lambda value (λ = 0,29 W/mK) is not that good. The material can easily be glued, acrylic glue is not a problem. Another advantage is the recyclability of the material.

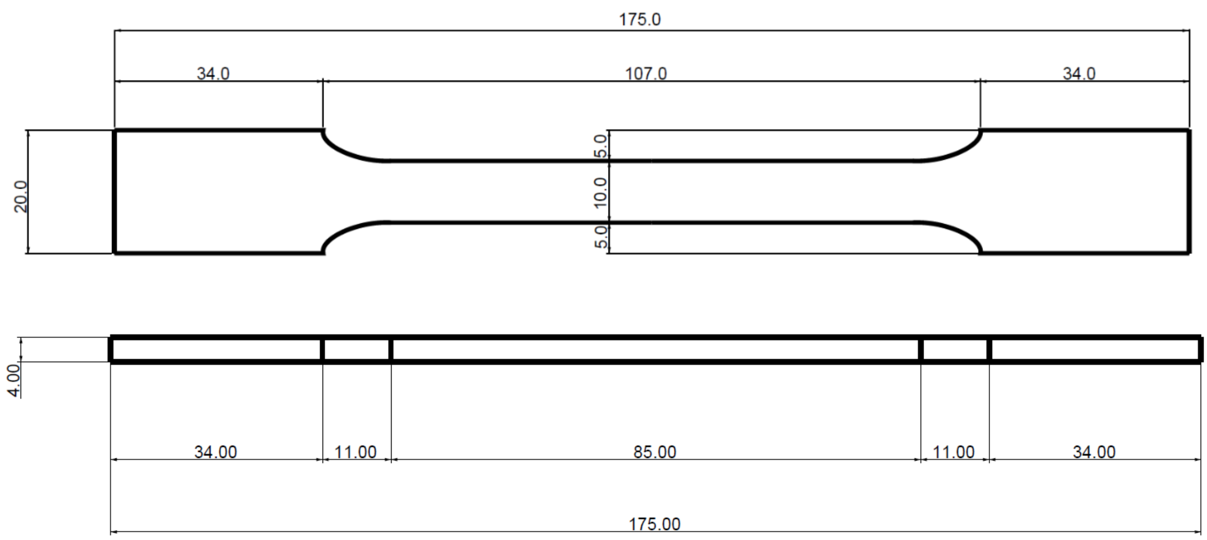
Part ⅠⅠ Preliminary design

Image 18 - Thin glass. Photo: SCHOTT

6 Structural properties

How can the structural properties be determined and achieved?

6.1 Dog bones



https://www.mcpp-3dp.com/products/pet-g/#1509706806250-04692060-e054

6.2 Loads

Dead weight + life load

SCHEMA's MET DE LOADS

It is extremely difficult to calculate the exact second moment of area of a composite panel. That is the reason to only give theoretical arguments, not based on numbers, about the performance of the panel.

BUCKLING
SHEAR CRIMPING
DELAMINATION
FACE WRINKLING

https://www.structx.com/plates.html

Euler buckling of slender columns:

$$P_e = \frac{\pi^2 \cdot E \cdot I}{L^2}$$

Where

E = Young's Modulus
I = Second moment of area
L = effective length of the column

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':

$$EI_{eq} = \frac{E_f \cdot b \cdot t^3}{2} + \frac{E_f \cdot b \cdot t^3}{6} + \frac{E_c \cdot b \cdot c^3}{12}$$

Where

Ef = Young's modulus of the face
Ec = Young's modulus of the core
b = width of the material
t = thickness of material

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).

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

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

where

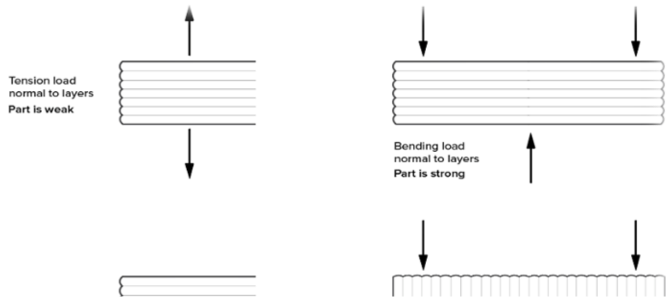
a = t+h/2
c = (t+h)/2
d = h/2
Es = the Young modulus of the skin
Ec = Young's modulus of the core
Gs = the shear modulus of the skin
Gc = the shear modulus of the core

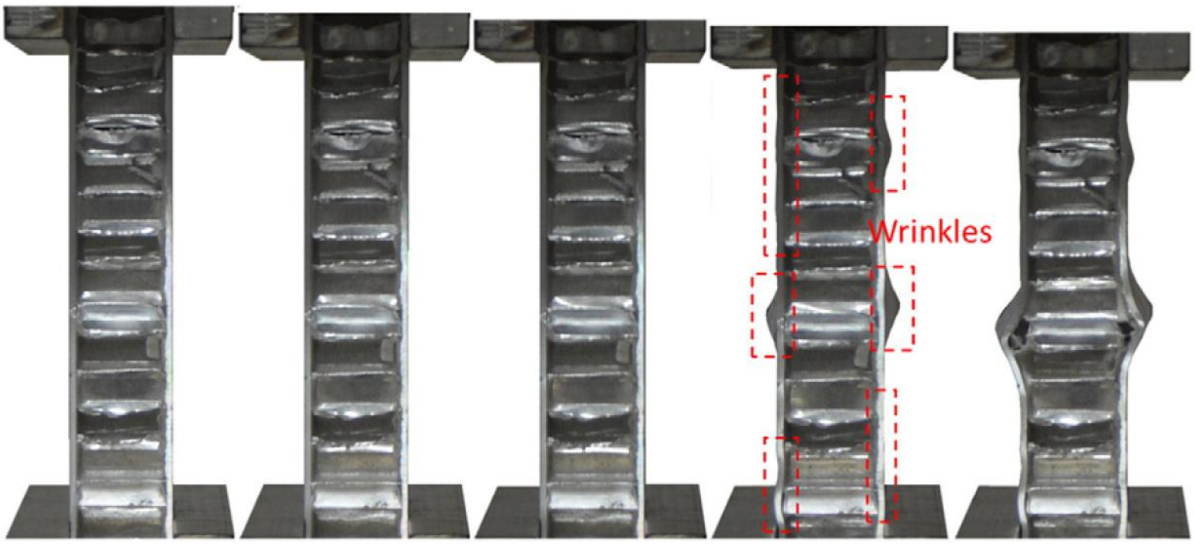
Because the equivalent stiffness defined in Eqs. , takes into account the bending and shear stiffnesses of the skins, the skins are modelled by isoparametric four-node elements, and such elements are also used to model the core. Due to its finite thickness, the skin makes a non-vanishing but small contribution to the overall shear stiffness of the column. The core, similarly, makes a non-vanishing but small contribution to the overall bending stiffness of the column. The geometry of the columns analysed and the mesh used in the computation are shown in Fig. 4 on the right (the real mesh was finer than shown) (Bažant & Beghini, 2004).

http://www.mse.mtu.edu/~drjohn/my4150/sandwich/sp2.html
https://www.inholland.nl/media/12081/composieten_basiskennis-2e_druk.pdf
https://apps.dtic.mil/dtic/tr/fulltext/u2/a571921.pdf
http://openaccess.iyte.edu.tr/bitstream/handle/11147/3947/T000703.pdf?sequence=1

Isotropic: glass, steel uniform in all directions (x, y, z)
Anisotropic: Layered structure. Good in one direction, worse in the other (concrete)
Orthotropic: Subset of anisotropic. Different properties in the three axes.

3D printing is Anisotropic/ orthotropic.
A trussed pattern is anisotropic, because it does not have the same pattern in all three directions. Only in two directions.





(Sun, Huo, Chen, & Li, 2017)

Sandwich theory

Dear Stella,

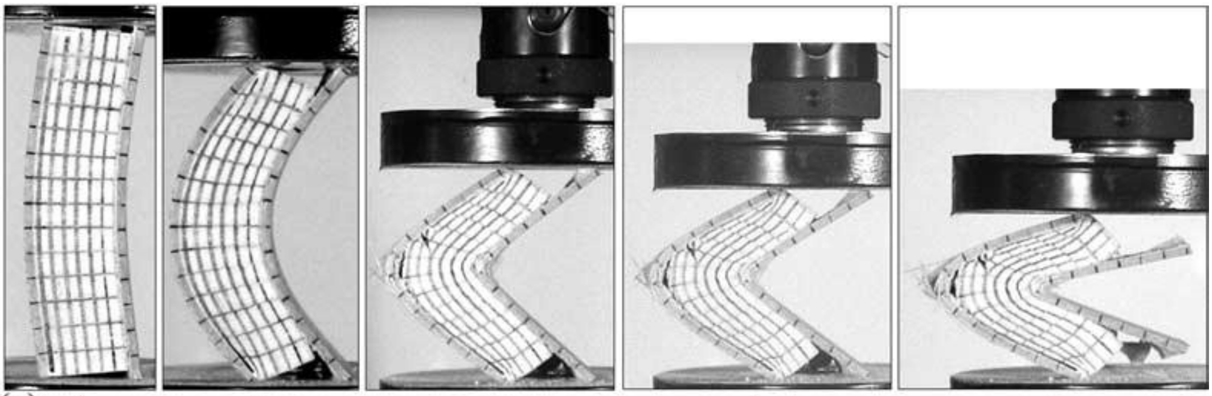
I have used the theory of Allen as well, attached you can find the book of reference.

In Chapter 2, you can find the formula for the EI of a sandwich panel, see the paragraph with thin faces (your case).

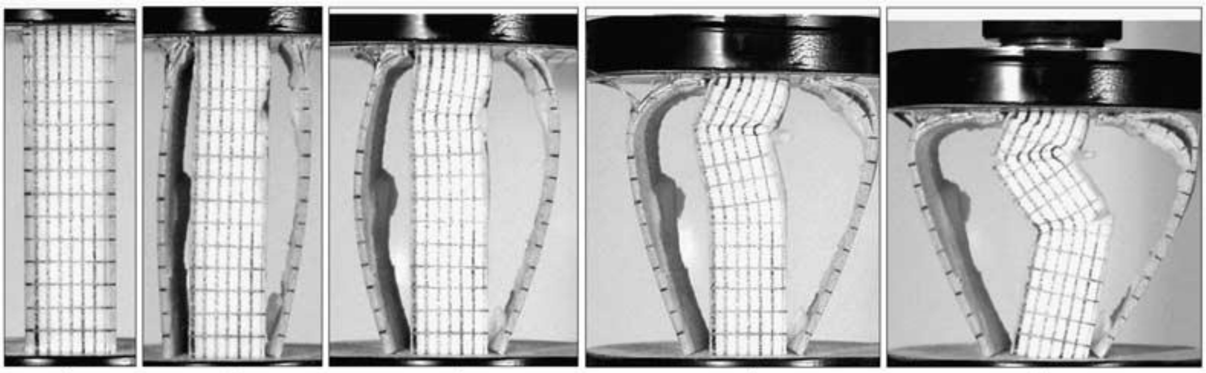
Remember that this formula is for a sandwich panel with a full core, while the Truss that you are using will have a slightly different stiffness.

As a first approximation this formula is perfectly fine for your hand calculations.

When you will run the analysis on Diana/Femap, you will find out the exact stiffness of your panel.



(a) 1 2 3 4 5

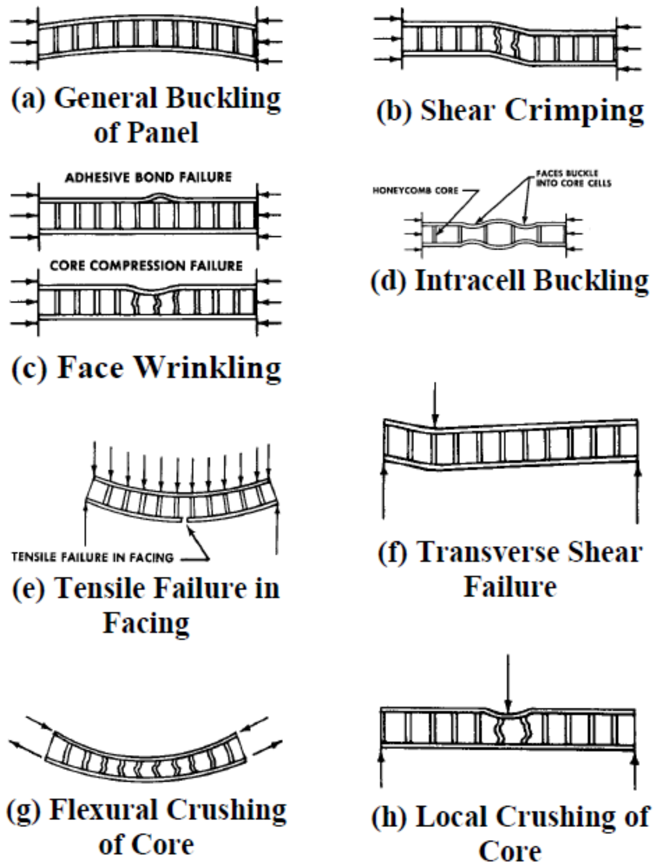


1 2 3 4 5

6.3 WHAT TO EXPECT FROM THE TEST

The bigger the I (second moment of area), the better the structural properties.
The more contact area of the truss with the glass, the better the structural properties.

Glue can fail (delamination)
PET can fail (shear in core, core compression fail)
Glass can fail (tensile fail)



7 Thermal insulation

How can a good thermal insulation value be achieved?

7.1 IGU

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.

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. PLAATJE + MEEST GEBRUIKTE SPACERS EN WAARDES ERBIJ -> VIG VAN TENPIERIK

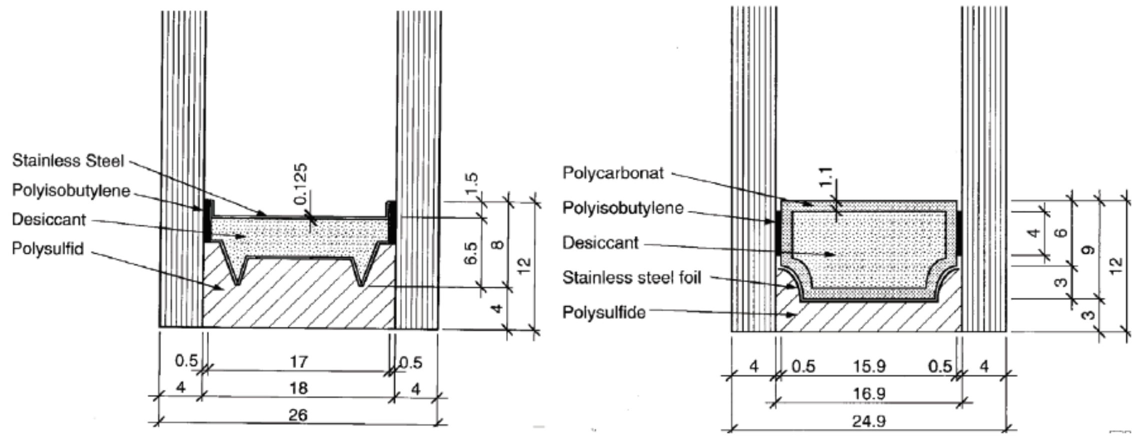


Image 19 - Example of spacers. Lecture notes Building Physics, R. Bokel.

And thermal expansion of the air/ gas in the cavity makes the glass curved (Buddenberg, Hof, & Oechsner, 2016).

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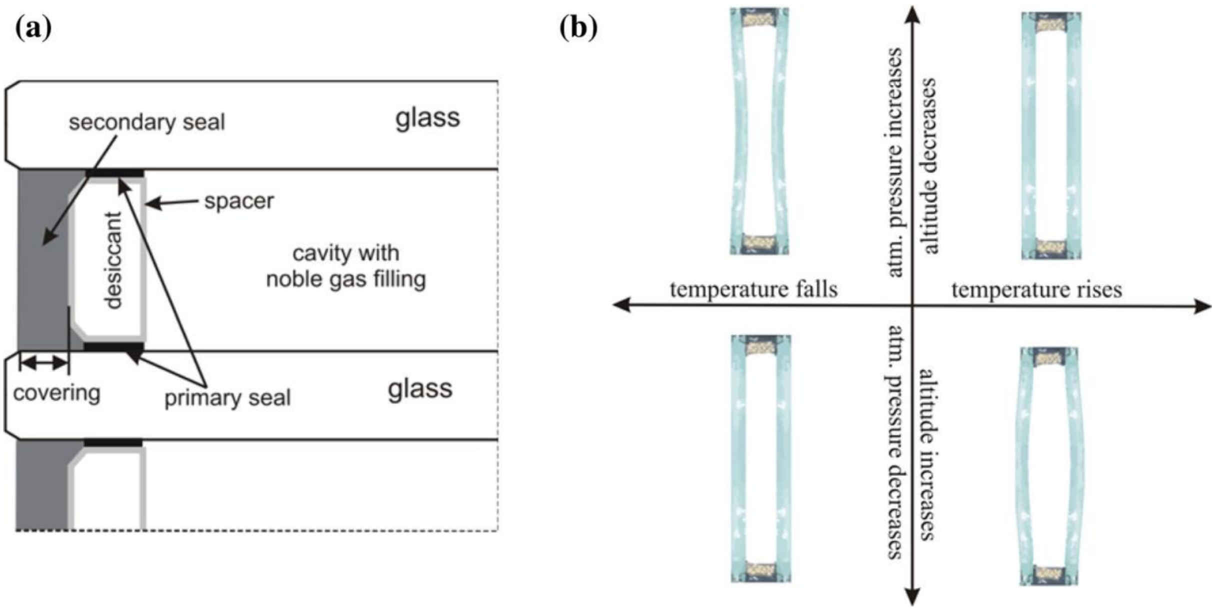


Image 23 - Thermal expansion in IGU. Image: S. Buddenberg, P. Hof, M. Oeschner.

Coating
Low-E coating

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

Two types of Low-E coatings: sputtered (off-line) and pyrolytic (on-line).
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. KLEINE CONCLUSIE BIJ SCHRIJVEN.
http://www.ravenwindow.com/smart-window-technology

When you do not have background information of 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 can not 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. 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 15 - Check reflection with lighter. Image:

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). MEER INFO OVER GAS

7.2 Heat transfer

Conduction
Convection
Radiation

U = 1/ R

R = λ · d

Enz. ….

Overall calculation of the thermal insulation
U value of the panel is calculated as the inverse R value. The R value is calculated by dividing the thickness of the material by the thermal conductivity of the material (λ).

Cavity
The spacers transport heat from one side of the panel to the other side.

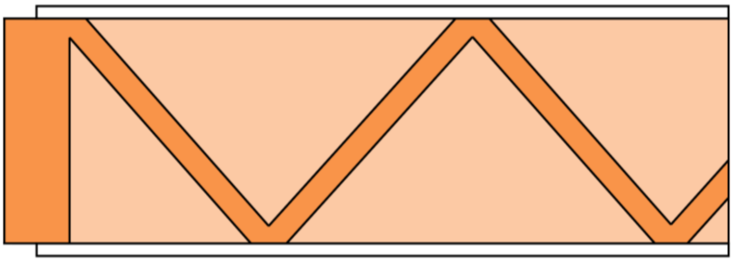
Radiation: The glass and the spacers are black body radiators. Ɛ = 0,9
Convection: no convection when the cavity is less than 12 mm wide.
Conduction:

Normal U calculation (Bokel, 2017) for the overall U value (including the edge)

$$U_\omega = \frac{\Sigma A_g \cdot u_y + \Sigma A_f u_f + \Sigma l_g \cdot \psi_g}{\Sigma A_g + \sum A_f}$$

$$R = \frac{1}{\alpha_i \cdot A} + \left[\left(\frac{2t}{\lambda \cdot A} + \frac{1}{a \cdot A} \right)^{-1} + 2\lambda r \right]^{-1} + \frac{1}{\alpha_0 \cdot A}$$

7.3 Hand calculations



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

λ (W/m/K)	
Glass	0,95
PET	0,29
Woodfill	0,14
Glue	0,48
Air	0,025

α con. + cond. = 1 W/m²/k
α rad = 6 Ɛres = 1/0,9 + 1/0,9 – 1 = 4,8 W/m²/K

VIG panel (Tenpierik & Cauberg, 2007)

$$\psi_{\mathrm{vip,edge}} = \frac{1}{1+(\lambda_c/\alpha_1 d_p)+(\lambda_c/\alpha_2 d_p)} \times \left[\frac{\alpha_1 (N_2^2 - B)}{\frac{\varphi d_p \lambda_f}{\lambda'_f}(N_1^2 N_2^2 - B^2) - \lambda_1 \sqrt{N_1^2 N_2^2 - B^2}\left(\frac{2B}{\sqrt{D}}+1\right) - \lambda_2 \sqrt{N_1^2 N_2^2 - B^2}\left(1-\frac{2B}{\sqrt{D}}\right)} \right], \quad (5)$$

in which λ'_f ($\mathrm{W\,m^{-1}\,K^{-1}}$) is the thermal conductivity of the laminate at the panel edge. The parameters N_1, N_2, and B are calculated as:

$$N_i = \sqrt{\frac{\alpha_i}{t_f \lambda_f} + \frac{\lambda_c}{t_f \lambda_f d_p}}, \quad (6a)$$

$$B = \frac{\lambda_c}{t_f \lambda_f d_p}, \quad (6b)$$

$$\lambda_1 = -\sqrt{\frac{(N_1^2 + N_2^2) - \sqrt{(N_1^2 - N_2^2)^2 + 4B^2}}{2}},$$

$$\lambda_2 = -\sqrt{\frac{(N_1^2 + N_2^2) + \sqrt{(N_1^2 - N_2^2)^2 + 4B^2}}{2}},$$

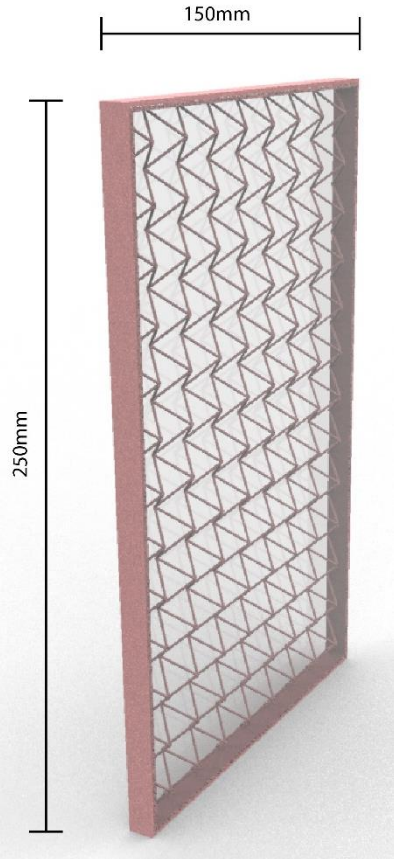
7.4 Trisco

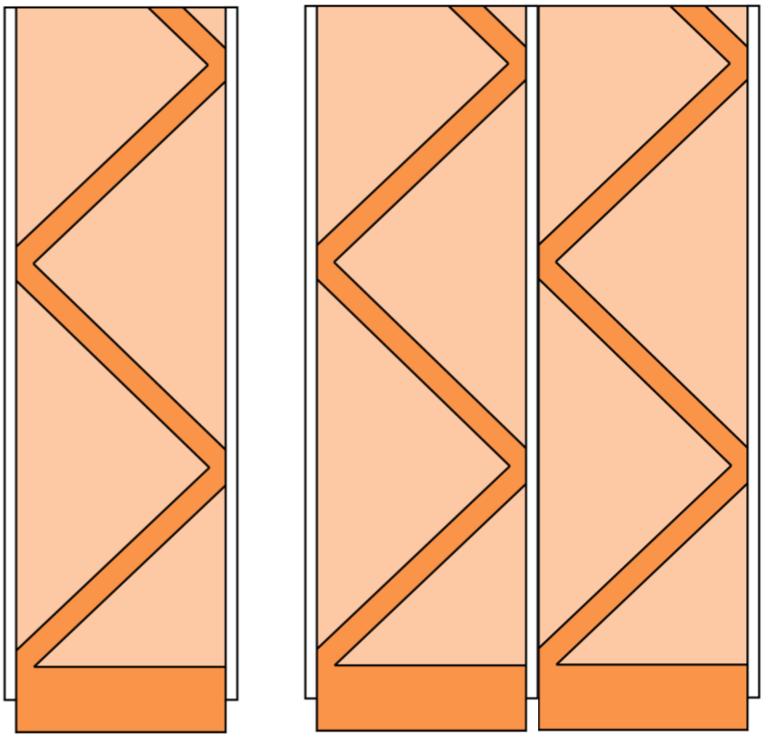
7.5 Conclusion

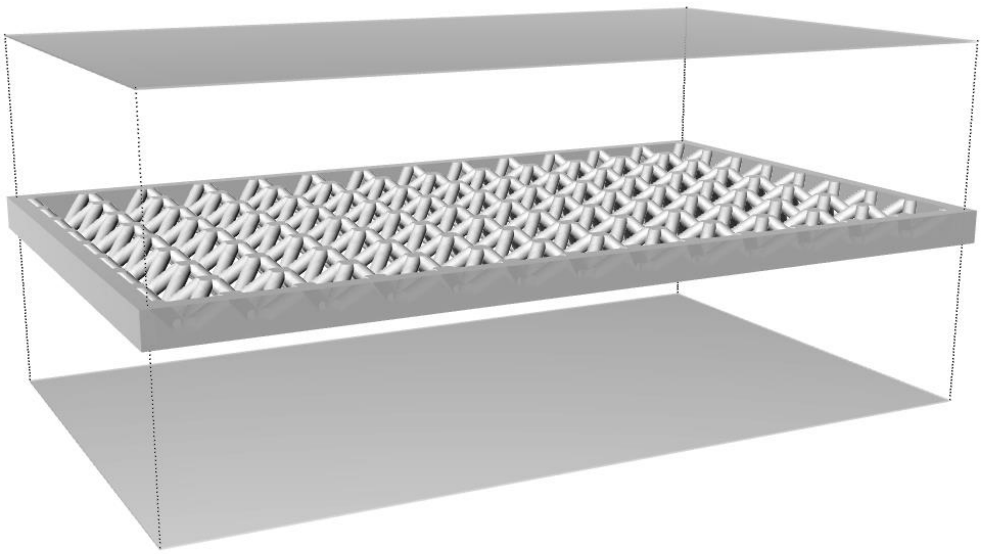
Not possible to apply coating and glass.
Therefore the overall R value of the panel will be comparable to normal double layer glass, or worse due to the contact points.

Due to thermal expansion it would be smart to use glue and a spacer material which is a little bit flexible.

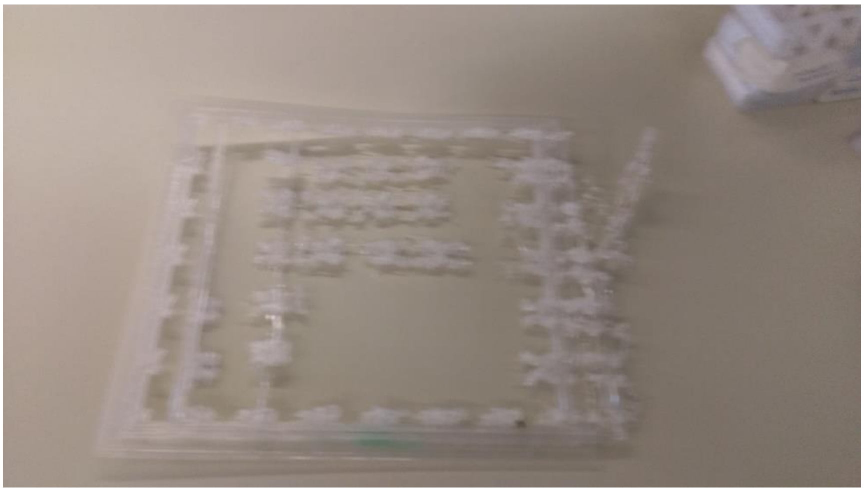
8 The composite panel







Part Ⅰ Ⅰ Ⅰ Practical analysis



9 Prototype

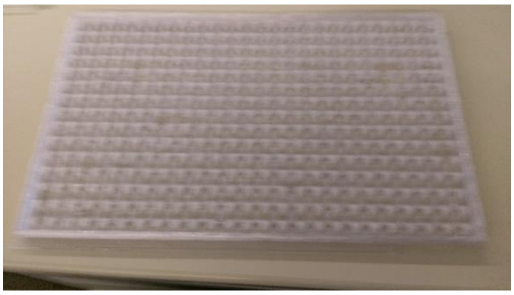
Which test set-up can be used to test the panel?

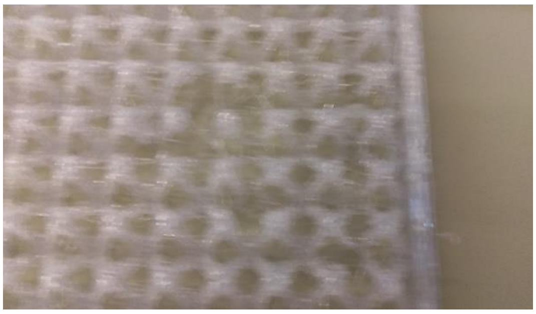
9.1 Glass

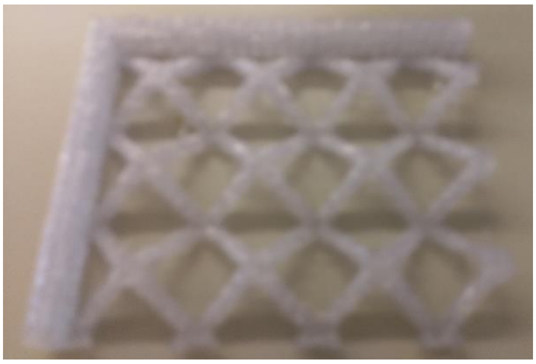
9.2 Panel fabrication

9.2.1 3D printing the core

The beams in the initial pattern were first 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. The robot arm can extrude the filament, go around the corner and continue with extruding to finish the model.
The diameter of the beams increased to 3mm. This is still very small with a 1mm nozzle and resulted in a poor quality panel. Therefore the diameter is increased to 4mm.







Filament printed at 230 ˚C. No heated bed, but some type of foil. Print speed 20 mm/s. Fan speed layer 1 = 0%, layer 2 = 35%, layer 3 = 50%, layer 4 = 75%. The print speed can be increased when the first few layers are already printed.

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 (not in the air).

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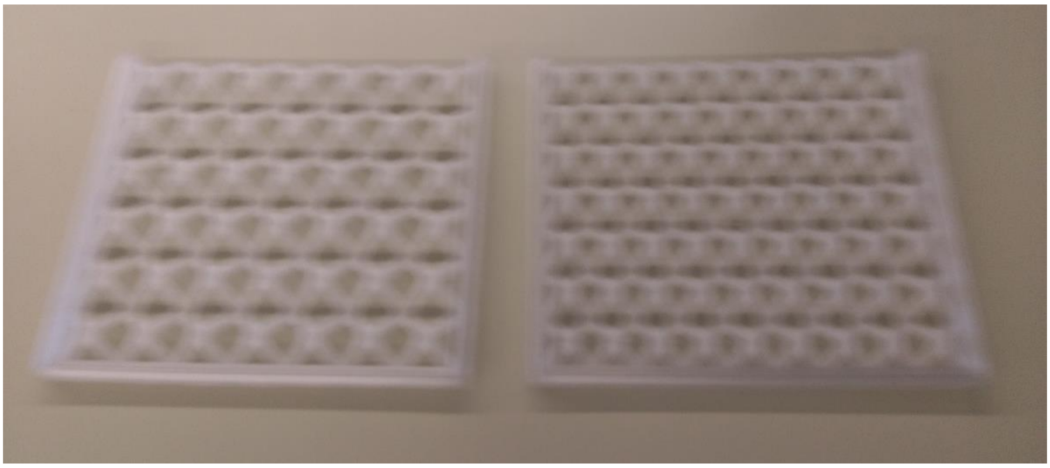


This means that the two pieces need to be glued together. This can be done in several ways, one way is to glue and the other way is to weld the parts. At the UNI there are two types of glue, fast glue and a two-component glue. To weld can be done by melting the material with heat, of to chemically melt with dichloromethane or KLEBER

Unfortunately a lot of panels failed because various reasons. The prints did not want to stick to the bed, warping. 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.

Because it was still very difficult to print correct panel. I ordered them.

9.2.2 Gluing the panel

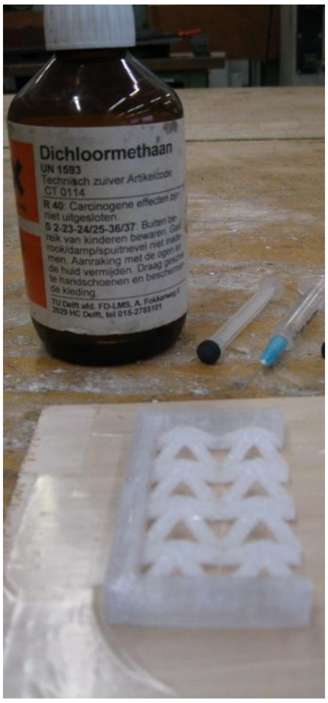
Bond
Dissolving the material

- Heat
- Dichloromethane
- …..

Glue the material

- Loctite
- Two component

https://forum.simplify3d.com/viewtopic.php?f=8&t=9281&sid=4aa1e8a377949446bd560d7ccc15952f&start=10
https://www.amazon.com/gp/product/B003HNFLMY/ref=od_aui_detailpages00?ie=UTF8&psc=1

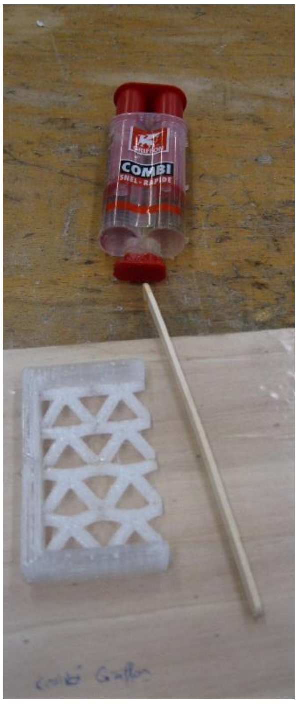


Dichloromethane (dissolver):
Perfect connection in terms of structural properties.
Easy to work with. Just lay the two pieces down next to each other and drip the fluid on the joints.
The pieces need to be perfect prepared. The to be glue surfaces need to be perfectly smooth, this is very difficult to accomplish.
Because the fluid is very thin, it is hard to put enough in between the joints.

Kunststoffkleber (dissolver):
The fluid is a bit thicker than the dichloromethane, this makes it easier to apply on the right surface and there is enough time to put the parts together.
It is still very important to prepare the pieces, the surfaces need to be smooth.

Heating (dissolving):
Perfect connection in terms of structural properties.
Not easy to do, you have to be very quick to put the two parts together. The materials cools down very fast.

Loctite (glue):
The glue is a bit thick and fills the gaps.
The two pieces need to be put together in one flow, there is no second change to adjust the joints.



Two component 'Griffon'
Very thick fluid, easy to apply and fills up gaps. Glue is a little bit visible, but still transparent. Does not dry fast, so there is time to adjust the joints.

Ease to use	-> thickness fluid
	-> time to dry
	-> how to apply
Preparation models	-> Neat and smooth or 'fills the gaps'

Glue the core and the glass

The glue used for this research is DELO photobond 4494 (image....). This is an acrylic, one component, transparent, UV-curing glue. MORE INFO ON THE 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.

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

10 Thermal 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. (Antoniadis, 2011)(Zhao et al., 2016)
Needed materials:

- 2x heat flux sensor HFP01
- 4x thermocouples type T
- 2x voltmeter
- Heater/ cooler
- Laptop

10.1 Test set-up

mV
Heat flux * 1000/ de weerstand van de kabel

The edge of the panel is not very important for the test because the area of the measurement is very specific.

Heat flux sensors have to be calibrated in order to relate their output signals [µV] to heat flux values [W/(m2·K)]. Heat flux * 1000/ de weerstand van de kabel

10.2 Results

11 Structural test

A compression test is going to be done to check the structural properties of the panel. 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 parameters which are going to be changed only relate to the trussed pattern.

The most important thing is that the panel can withstand the weight of the roof structure, snow load and dynamic load.

Needed materials:

- 5x panels
- Test machine

11.1 Results

12 Results??

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

Part Ⅳ Final design

13 Criteria façade

Which aspects can be improved to give the composite panel better structural and thermal insulation properties?

This chapter is about the further criteria for the façade design, such as weathertightness and the connection of the composite panel to the roof.

Image 2 - The Glass House, designed by Philip Johnson. Photo: Michael Biondo

14 Conclusion

15 Discussion

The standard truss is chosen as base point. The structural test is done without solid calculations due to time.

16 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 for the research. This changed the process and the research questions in such way that the analysis of the design shifted from before producing the panels to analysis of the test results.

A lot of unforeseen decisions had to be made during the research. This resulted in a delay of about three weeks for the actual tests on the panels. These unforeseen decisions mainly have to do with the production of the panels, it took a week to make the panel printable and then still two weeks to produce all the panels. Next to that there are a lot of things which influence the test results, such as quality of the prints, gluing & curing and moisture.

Further steps which need to be done till P4 are performing the tests (thermal & structural), analyse the results and find the difference between the panels and make an improved panel. Furthermore it is important to keep on writing the report and to understand the place of this research in the broader context.

- Your understanding on the "how and why"
- Your reflection upon the feedback that was given by your mentors
- How you have translated the feedback into your work
- How you've learned from your own work
- Further steps
- Aspect 5 Discuss the ethical issues and dilemmas you may have encountered in (i) doing the research, (ii, if applicable) elaborating the design and (iii) potential applications of the results in practice.

17 Recommendation

The use of PLA/ woodfill is very interesting in terms of thermal insulation, but the woodfibres are sceptical for moisture. Therefore the PLA/ woodfill needs to be tested on its behaviour due to moisture. Also gluing the material is hard. This needs to be tested.

18 References

3D Matter. (2019). FDM 3D Printing materials compared | 3D Hubs. Retrieved January 23, 2019, from https://www.3dhubs.com/knowledge-base/fdm-3d-printing-materials-compared

ABT. (2019). Museum aan de Stroom - ABT | Ingenieurs in bouwtechniek. Retrieved February 13, 2019, from https://www.abt.eu/projecten/museum-aan-de-stroom-mas-antwerpen.aspx

AGC Glass. (2017). Thin and ultra-thin glass for an extended range of applications.

AGC Glass. (2019). From sand to glass | AGC Glass Europe. Retrieved January 9, 2019, from http://www.agc-glass.eu/en/products/sand-glass

Akilo, M. (2018). *Design and analysis of a composite panel with ultra-thin glass faces and a 3D-printed polymeric core*. University of Bologna.

Antoniadis, K. D. (2011). *Measurement of the Thermal Conductivity of composite solid materials*. *Thessaloniki*. https://doi.org/10.1111/j.1151-2916.1943.tb14456.x

Ashby, M. F. (2013). Material profiles. *Materials and the Environment*, 459–595. https://doi.org/10.1016/B978-0-12-385971-6.00015-4

Ashby, M., Shercliff, H., & Cebon, D. (2014). *Materials: Engineering, Science, Processing and Design*. Elsevier Science & Technology.

Bažant, Z. P., & Beghini, A. (2004). Sandwich buckling formulas and applicability of standard computational algorithm for finite strain. *Composites Part B: Engineering*, *35*(6–8), 573–581. https://doi.org/10.1016/j.compositesb.2003.11.009

Bokel, R. (2017). Lecture note: Building Physics.

Buddenberg, S., Hof, P., & Oechsner, M. (2016). Climate loads in insulating glass units: comparison of theory and experimental results. *Glass Structures & Engineering*, *1*(1), 301–313. https://doi.org/10.1007/s40940-016-0028-z

Eckersley O'Callaghan. (2018). Eckersley O'Callaghan - Steve Jobs Theater. Retrieved December 13, 2018, from https://www.eocengineers.com/en/projects/steve-jobs-theater-293

Eckersley O'Callaghan. (2019). Apple Fifth Avenue Mark II. Retrieved February 13, 2019, from https://www.eocengineers.com/en/projects/apple-fifth-avenue-mark-ii-100

Evans, A. G., Hutchinson, J. W., & Fleck, N. A. (2001). The topological design of multifunctional cellular metals. *Progress in Materials Science*, *46*, 309–327. https://doi.org/10.1016/S0079-6425(00)00016-5

Hees, R. Van, Bommel, B. Van, Lubelli, B., Naldini, S., Quist, W., & Vries, D. J. De. (2018). Construction History AR0014, (February).

Kariz, M., Sernek, M., Obućina, M., & Kuzman, M. K. (2018). Effect of wood content in FDM filament on properties of 3D printed parts. *Materials Today Communications*, *14*(September 2017), 135–140. https://doi.org/10.1016/j.mtcomm.2017.12.016

Koninklijk Nederlands Normalisatie-Instituut. Nederlandse Technische Afspraak 8800; Energieprestatie van gebouwen - bepalingsmethode, Pub. L. No. NTA 8800, 8800 944 (2018). Netherlands: NEN.

Li, T., Chen, Y., Hu, X., Li, Y., & Wang, L. (2018). Exploiting negative Poisson's ratio to design 3D-printed composites with enhanced mechanical properties. *Materials and Design*, *142*(March), 247–258. https://doi.org/10.1016/j.matdes.2018.01.034

Louter, C. (2017). Technoledge – Structural Glass.

Louter, C., Akilo, M. A., Miri, B., Neeskens, T., Ribeiro Silveira, R., Tpcu, Ö., … O'Callaghan, J. (2018). Adaptive and composite thin glass concepts for architectural applications. *Heron*, *63*(1/ 2), 199–218.

Louter, C., Veer, F., & Belis, J. (2008). Redundancy of reinforced glass beams; temperature, moisture and time dependent behaviour of the adhesive bond. *Challenging Glass*, (April 2015). https://doi.org/10.1002/pola.20650

Machalická, K., & Eliášová, M. (2017). Adhesive joints in glass structures: effects of various materials in the connection, thickness of the adhesive layer, and ageing. *International Journal of Adhesion and Adhesives*, *72*(September 2016), 10–22. https://doi.org/10.1016/j.ijadhadh.2016.09.007

Make it from. (2018). Polylactic Acid (PLA, Polylactide). Retrieved January 23, 2019, from https://www.makeitfrom.com/material-properties/Polylactic-Acid-PLA-Polylactide

Mamalis, A. G., Manolakos, D. E., Ioannidis, M. B., & Papapostolou, D. P. (2005). On the crushing response of composite sandwich panels subjected to edgewise compression: Experimental. *Composite Structures*, *71*(2), 246–257. https://doi.org/10.1016/j.compstruct.2004.10.006

Martikka, O., Kärki, T., & Wu, Q. (2018). Mechanical properties of 3D-printed wood-plastic composites. *Key Engineering Materials*, *777 KEM*, 499–507. https://doi.org/10.4028/www.scientific.net/KEM.777.499

Murr, L. E. (2015). *Handbook of materials structures, properties, processing and performance*. *Handbook of Materials Structures, Properties, Processing and Performance*. Springer. https://doi.org/10.1007/978-3-319-01815-7

Neeskens, T. (2018). *Thin Glass*. Technical University Delft.

O'Regan, C. (2014). *Structural use of glass in buildings (second edition)* (2nd ed.). London: The Institution of Structural Engineers.

Ratwani, M. M. (2010). Composite Materials and Sandwich Structures – A Primer. *Rto-En-Avt*, *156*, 1–16.

Redwood, B., Schöffer, F., & Garret, B. (2017). *The 3D printing handbook*. Amsterdam: Coers & Roest.

Sauzay, A. (1875). *Wonders of glass-making in all ages*. New York: Scribner, Armstrong & co.

Sd3D.com. (2015). Technical data sheet - PLA.

Strauß, H., & Knaack, U. (2015). Additive Manufacturing for Future Facades: The potential of 3D printed parts for the building envelope. *Journal of Facade Design and Engineering*, *3*(3–4), 225–235. https://doi.org/10.3233/FDE-150042

Sun, G., Huo, X., Chen, D., & Li, Q. (2017). Experimental and numerical study on honeycomb sandwich panels under bending and in-panel compression. *Materials and Design*, *133*, 154–168. https://doi.org/10.1016/j.matdes.2017.07.057

Tenpierik, M., & Cauberg, H. (2007). Analytical models for calculating thermal bridge effects caused by thin high barrier envelopes around vacuum insulation panels. *Journal of Building Physics*, *30*(3), 185–215. https://doi.org/10.1177/1744259107073160

van der Heide, J., Vreeman, H. L., & Haytink, T. G. (2016). *Bijna EnergieNeutrale Gebouwen*. Retrieved from https://www.royalhaskoningdhv.com/nl-nl/nederland/diensten/diensten-van-a-tot-z/bijna-energieneutrale-gebouwen-toelichting/394

Van der Weijde, I. (2017). *Ultra lightweight, insulating thin glass facade panel*. Technical University Delft.

Vitalis, D., Veer, F., & Oikonomopoulou, F. (2018). Design and Experimental Testing of All Glass Sandwich Panels : An Experimental and Numerical Study for the Glass Floors of the Acropolis Museum. *Challenging Glass 6*, (May).

Wadley, H. N. G. (2006). Multifunctional periodic cellular metals. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *364*(1838), 31–68. https://doi.org/10.1098/rsta.2005.1697

Weersink, A. M. S., Zeegers, A., Erdtsieck, P., Van der Linden, A. C., & Keizer, F. A. J. (2006). *Bouwfysica tabellen en formules*.

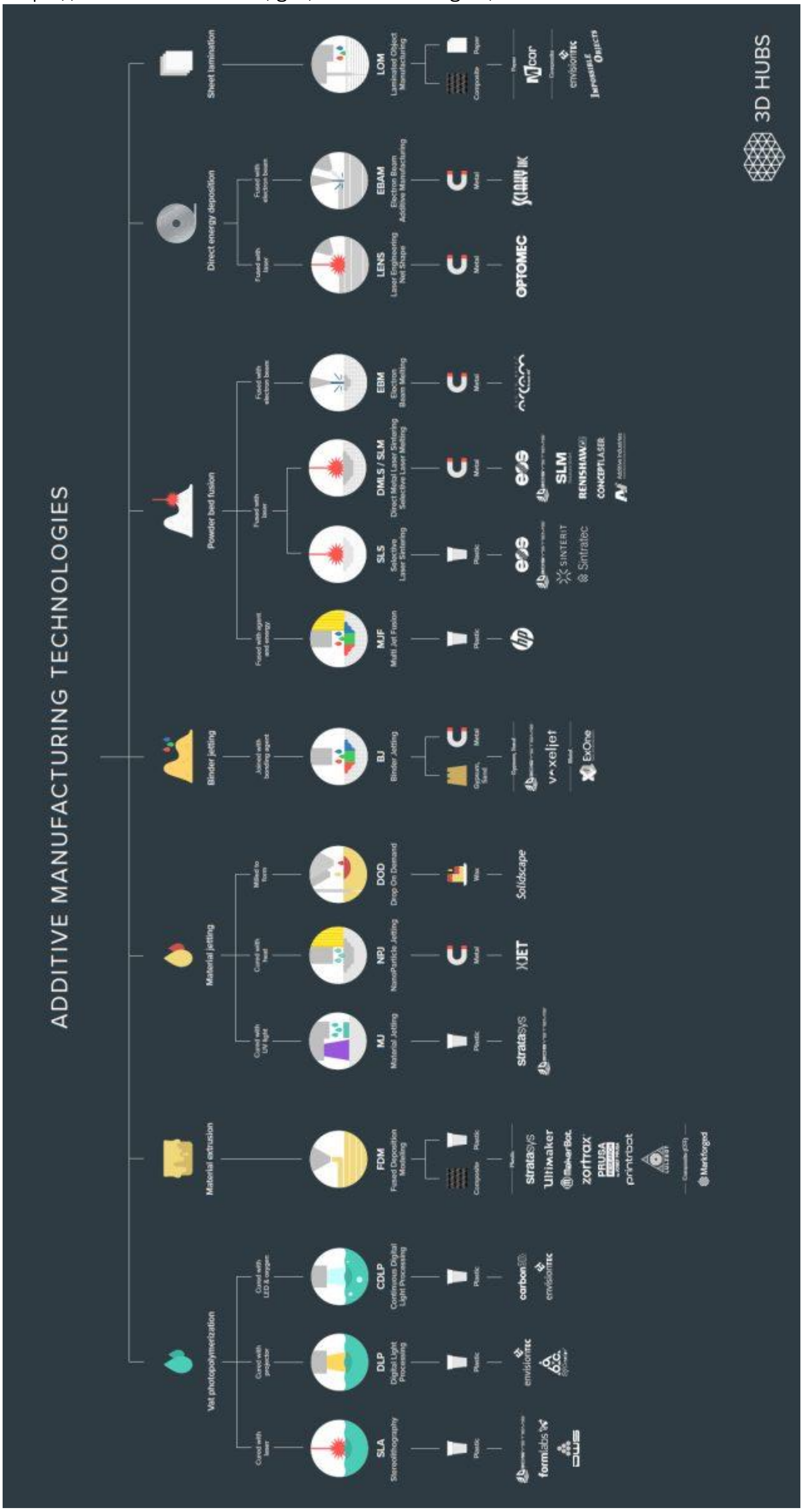
Wurm, J. (2007). *Glass Structures*. Basel: Birkhäuser.

Zhao, D., Qian, X., Gu, X., Jajja, S. A., & Yang, R. (2016). Measurement Techniques for Thermal Conductivity and Interfacial Thermal Conductance of Bulk and Thin Film Materials. *Journal of Electronic Packaging*, *138*(4), 040802. https://doi.org/10.1115/1.4034605

19 Appendix

19.1 Additive manufacturing techniques

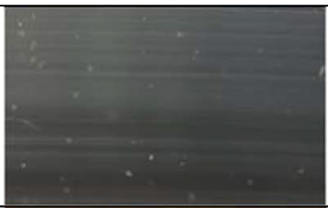
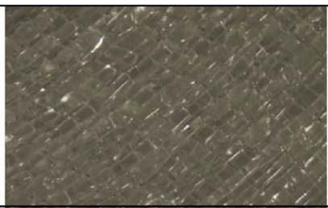
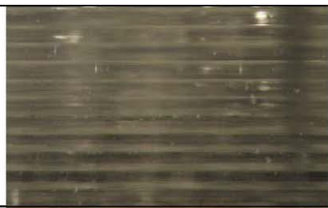
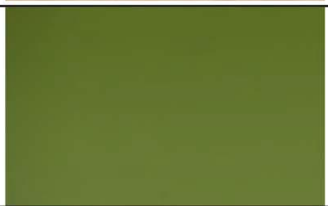
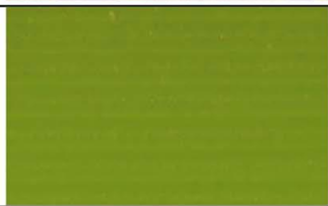
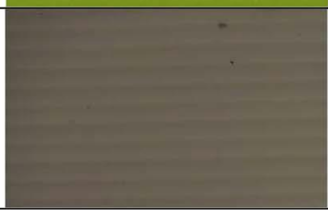
https://www.3dhubs.com/get/am-technologies/



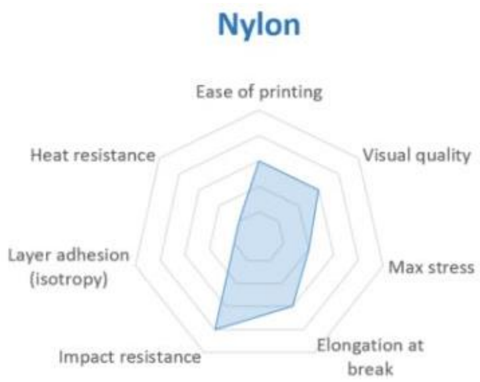
19.2 Bouwbesluit 2012 – Artikel 5.3. Thermische isolatie

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.

19.3 PLA – wood filament

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

Nylon
Soft, low friction
Good chemical resistance
Very low humidity resistance, potentially high fume emission

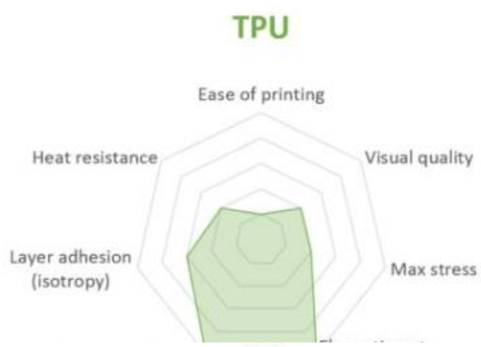


General properties
Density 1,120 - 1,140 kg/m^3
Price 3.9 - 4.3 USD/kg

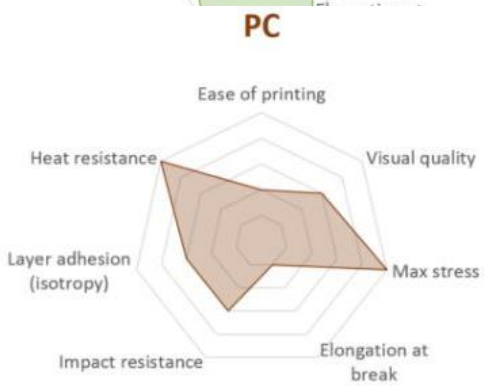
Mechanical properties
Young’s modulus 2.62 - 3.2 GPa
Yield strength (elastic limit) 50 - 94.8 MPa
Tensile strength 90 - 165 MPa
Elongation 30 - 100 %
Hardness—Vickers 25.8 - 28.4 HV
Fatigue strength at 107 cycles 36 - 66 MPa
Fracture toughness 2.2 - 5.6 MPa · $m^{1/2}$

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
Good abrasion resistance, good resistance to oil and grease
Difficult to post process, not easily glued



Polycarbonate (PC)
Very rigid
Can be sterilized, easy to post-process (sanding)
UV sensitive



General properties
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

19.4 Young's modulus, shear modulus, bulk modulus and Poisson's ratio

Definition and measurement. Figure 1 shows a typical tensile stress-strain curve. The initial part, up to the yield strength σ_y or elastic limit σ_{el}, defined under *Yield strength (elastic limit)*, is linear (Hooke's law), and it is elastic, meaning that the strain is recoverable – the material returns to its original shape when the stress is removed. Stresses above the elastic limit cause permanent deformation or fracture (see notes for *Yield strength (elastic limit)* and *Fracture toughness*).

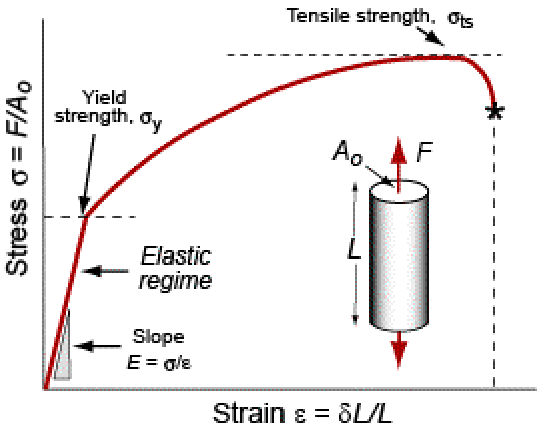


Figure 1. A tensile stress-strain curve.

Within the linear elastic regime, strain is proportional to stress, but stress can be applied in more than one way (Figure 2). The tensile stress σ produces a proportional tensile strain ε:

$$\sigma = E\,\varepsilon$$

and the same is true in compression. The constant of proportionality, *E*, is called Young's modulus. Similarly, a shear stress σ_s causes a proportional shear strain γ

$$\sigma_s = G\,\gamma$$

and a pressure *p* results in a proportional fractional volume change (or "dilatation") Δ:

$$p = K\,\Delta$$

where *G* is the shear modulus and *K* the bulk modulus. All three of these moduli have the same dimensions as stress, that of force per unit area (N/m^2 or Pa). It is convenient to use a larger unit, that of 10^9 Pa, Giga-Pascals, or GPa.

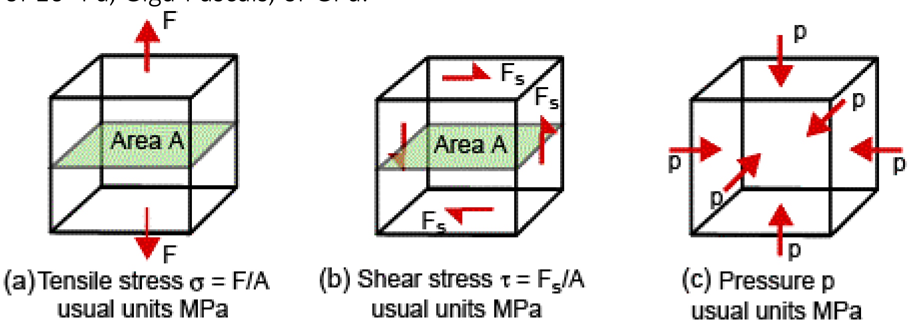


Figure 2. (a) Tensile stress. (b) Shear stress. (c) Hydrostatic pressure.

Young's modulus, the shear modulus, and the bulk modulus are related, but to relate them we need one more quantity, Poisson's ratio. When stretched in one direction, a material generally contracts in the other two directions. Poisson's ratio, ν, is the negative of the ratio of the lateral or transverse strain, ε_{tr}, to the axial strain, ε, in tensile loading:

$$\nu = -\frac{\varepsilon_{tr}}{\varepsilon}$$

You might think that the way to measure the elastic modulus of a material would be to apply a small stress (to be sure to remain in the linear-elastic region of the stress-strain curve), measure the strain, and divide one by the other. In reality, moduli measured as slopes of stress-strain curves are inaccurate, often by a factor of 2 or more, because of contributions to the strain from material creep or deflection of the test machine. Accurate moduli are measured dynamically: by exciting the natural vibrations of a beam or wire, or by measuring the velocity of longitudinal or shear sound waves in the material.

Top

Drilling down: the origins of moduli. Atoms bond together, some weakly, some strongly. If they bind strongly enough they form solids; the stronger the bond, the higher is the melting point of the solid. Think of the bonds as little springs (Figure 3). The atoms have an equilibrium spacing a_o; a force F pulls them apart a little, to $a_o + \delta$, but when it is released they jump back to their original spacing. The same happens in compression because the energy of the bond increases no matter in which direction the force is applied, as the lower part of the figure suggests. The bond energy is a minimum at the equilibrium spacing. A spring that stretches by δ under a force *F* has a stiffness, *S*, defined by

$$S = \frac{F}{\delta}$$

and this is the same in compression as in tension.

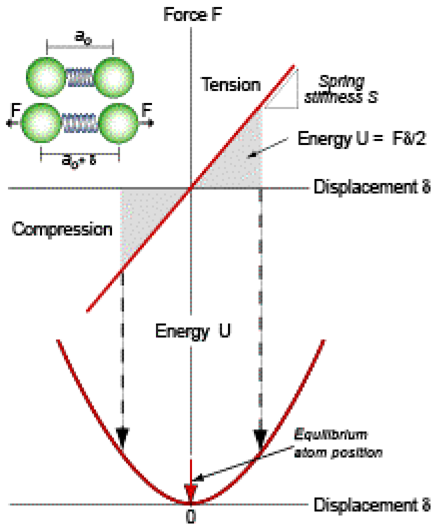


Figure 3. Stretching or compressing an atomic bond raises its energy. Its resistance to stretch is its stiffness, S.

Table 1 lists the stiffnesses of the different bond types; these stiffnesses largely determine the value of the modulus, E. The covalent bond is particularly stiff (*S* = 20–200 N/m); diamond, for instance, has a very high modulus because the carbon atom is small (giving a high bond density) and its atoms are linked by the stiffest springs (*S* = 200 N/m). The metallic bond is a little less stiff (*S* =15–100 N/m) and metal atoms are often close-packed, giving metals high moduli too, though not as high as that of diamond. Ionic bonds, found in many ceramics, have stiffnesses comparable with those of metals, giving them, also, high moduli. Polymers contain both strong diamond-like covalent bonds along the polymer chain and weak hydrogen or Van-der-Waals bonds (*S* = 0.5–2 N/m) between the chains; it is the weak bonds that stretch when the polymer is deformed, giving them low moduli.

When a force F is applied to a pair of atoms, they stretch apart by δ. A force F applied to an atom corresponds to a stress $\sigma = F/a_o^2$ where a_o is the atom spacing. A stretch δ between two atoms separated by a_o corresponds to a strain $\varepsilon = \delta / a_o$. Substituting these into the last equation gives

$$\sigma = \frac{S}{a_o}\varepsilon$$

Table 1 Bond stiffnesses, S

Bond type	Examples	Bond Stiffness S (N/m)	Young's Modulus E (GPa)
Covalent Metallic Ionic Hydrogen bond	Carbon-carbon bond All metals Alumina, Al_2O_3	50 – 180 15 – 75 8 – 24 6 – 3	200 – 1000 60 – 300 32 – 96 2 – 12

Bond type	Examples	Bond Stiffness S (N/m)	Young's Modulus E (GPa)
Van der Walls	Polyethylene Waxes	0.5 - 1	1 - 4

Comparing this with the definition of Young's modulus reveals that *E* is roughly

$$E = \frac{S}{a_o}$$

The largest atoms (a_o = 4 x 10^{-10} m) bonded with the weakest bonds (*S* = 0.5 N/m) will have a modulus of roughly

$$E = \frac{0.5}{4 \times 10^{-10}} \approx 1\,GPa$$

This is the *lower limit* for true solids and many polymers do have moduli of about this value; metals and ceramics have values 50–1000 times larger because, as Table 1 shows, their bonds are stiffer.

One class of materials – elastomers (rubber) – have moduli that are much less than 1 GPa. An elastomer is a tangle of long-chain molecules with occasional cross-links, as in Figure 4 (a), as explained in [Density and atom packing](). The bonds between the molecules, apart from the cross-links, are weak – so weak that, at room temperature, they have melted. We describe this by saying that the glass temperature T_g of the elastomer – the temperature at which the bonds first start to melt – is below room temperature. Segments are free to slide over each other, and were it not for the cross-links, the material would have no stiffness at all.

Temperature favors randomness. That is why crystals melt into disordered fluids at their melting point. The tangle of Figure 4 (a) has high randomness, or expressed in the terms of thermodynamics, its *entropy* is high. Stretching it, as at (b), aligns the molecules – some parts of it now begin to resemble the crystallites shown in the notes on [Density and atom packing](). Crystals are ordered, the opposite of randomness; their entropy is low. The effect of temperature is to try to restore disorder, making the material try to revert to a random tangle, and the cross-links give it a "memory" of the disordered shape it had to start with. So there is a resistance to stretching – a stiffness – that has nothing to do with bond-stretching, but with strain-induced ordering. A full theory is complicated – it involves the statistical mechanics of long-chain tangles – so it is not easy to calculate the value of the modulus. The main thing to know is that the moduli of elastomers are low because they have this strange origin and that they increase with temperature (because of the increasing tendency to randomness), whereas those of true solids decrease (because of thermal expansion).

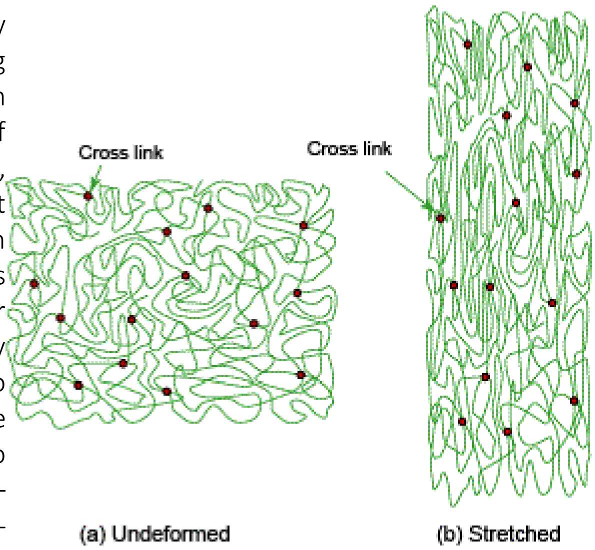


Figure 4. The stretching of an elastomer causes alignment, producing crystal-like regions. Thermal vibration drives the structure back to the one on the left, restoring its shape.

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Further reading.

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