Glass connections

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0 Introduction

Glass is a material that has been around for over 5000 years. People have been fascinated about it because of its appearance and its strength. Strong in the sense of durability, but even more in the sense of its ability to withhold big compression forces. Because of these aesthetic and structural properties, it is a preferable material for architects and engineers.
In the past there wasn't a lot of knowledge about manufacturing of glass. This is why it was mostly used for jewelry and other decorative products.
During the last years the body knowledge has increased a lot. As for many years it is used as windows and more and more it is used as a construction material.
The Apple Store at fifth avenue in New Yow is constructed entirely out of glass. The only thing that is not glass are the connections between the different glass panes.
This is already very impressive, but there is still a lot more to explore. Glass has actually a better compressive strength than concrete and wood, but one of the problems with glass is that is doesn't show signs of breakage. This is why people are "scared" to use it. Because of the the safety factor is around 5 – 10. For steel and concrete this safety factor lies around 1,5 and 1,7. This difference is absurd. For people to trust glass as a construction material research should be done. Research will increase the body of knowledge even more. This will give a good overview of how glass behaves.

This report will contribute to this knowledge by showing a research to a glass column that is connected to a glass wall, with a glass rod. The research that is done is specified to the connection between the glass rod and the column. Different connections are designed and tested. The results of these test will give an idea of the possibilities for this design.

1 Research framework

In this chapter the essence of this report is told. The problem statement is told and the research questions are introduced. Also the methodology of the whole report is mentioned. After this chapter the meaning of this report and how it will be presented should be clear.

Problem statement

Why

Most people are interested in light en sight. When searching for a new home, phrases as: “I love how light this room is” or “ I love the view” are used a lot. Studies also showed that a work environment with natural lighting is experienced as a better place than one that doesn’t. These are two of the many reasons architects are eager to design open spaces with a lot of natural light.
This often causes friction between the architect and the engineer. An engineer will be accused of doing a bad job if something breaks. This will lead for him/her to prefer a lot of good constructing elements.

How

To satisfy both parties, transparent construction elements are a good invention. The research after glass showed that there is a lot possible in the usage of this material. The problem however is the safety. Glass is brittle and will break without giving a sign. This causes some extreme safety regulations. When looked at steel or concrete, steel needs a 1.5 safety factor and concrete a 1.7. This means that they can handle at least 1.5 or 1.7 times the load case. For glass this safety factor is 5 to 10.

This shows that the lack of glass as a construction material is mostly because of a lack of knowledge. To increase this body of knowledge research must be done. The best way to know what the possibilities with glass are is to explore them.

What

The design that will be researched is an all glass connecting construction. A glass column will be connected to a glass sheet by a glass structural tube. The only other material in the first design is glue. The research will be done to see how far you can go with the usage of glass.
To do the first research the design is kept simple. A round column made of brick with a volume of 10-20 liters. A laminated sheet for safety reasons that consists out of 8 mm 15 mm 8 mm glass sheets. This pane will be 3,21 m by 6 m. The Glass rods have measurements of 22 mm diameter. The length of these are standardized at 1,5 meters but can be made longer on special request.
All these measurements are for the initial design and can be changed after the experiments have been done.
To connect the tube to the sheet, a "foot" is used. The foot is round so that there are no corners where the glue will loosen easier. The glue that will be used is a bison polymax. This is less strong than the blue light curing adhesive that is used in the Crystal house, but doesn't need the very high tolerance. This way production will be easier. The tests can again change this. If the adhesive is not strong enough, another one will be used.

Research questions

Is it possible to make an glass construction?

Sub questions:

What is glass?
Which connections can be used for glass?
How is glass made?
How do the connections work?
What are the aesthetic material properties of glass?
What are the structural material properties of glass?
What are the advantages of building with glass?
What is already been done?

Methodology

The report that is in front of you consists out of 6 parts. The fisrt part is a literature study after glass. This study will give an intel of how glass is made and what it is used for. The study also shows that glass is a relatively new construction material so that it is needed to research the material.
The second part is the design research. After getting the needed knowledge about glass, it is possible to start designing with it. In this part there is described what the critical areas are and possible ways how they can be fixed. In the end there is a choice made of what designs are going to be tested.
In the part of the final designs, the chosen designs are described. Here are the dimentions and the technical principles explained and is a prediction given of how the designs will perform.

When the designs are thought out, the testing can begin. To make the tests as easy as possible and not to expansive there is thought of a different way on how to test it. This still means that it is necessary to make some prototypes, just not the whole construction. So, in this part there is describes how the tests are done and how the prototypes are made. The results will be showed and discussed and in the end a conclusion will rise out of these tests.
The second last part is a review about the whole construction. The findings of the previous research are fed back to the original idea. Here will be described how the whole construction is made.
At last there are the conclusions. The conclusions will tell all the outcomes of the research and give advice over future researches.

Relevance

Glass is a relative new construction material. With this research the goal is to see if it is possible to make an all glass construction. This will give the future an insight in the possibilities of glass.

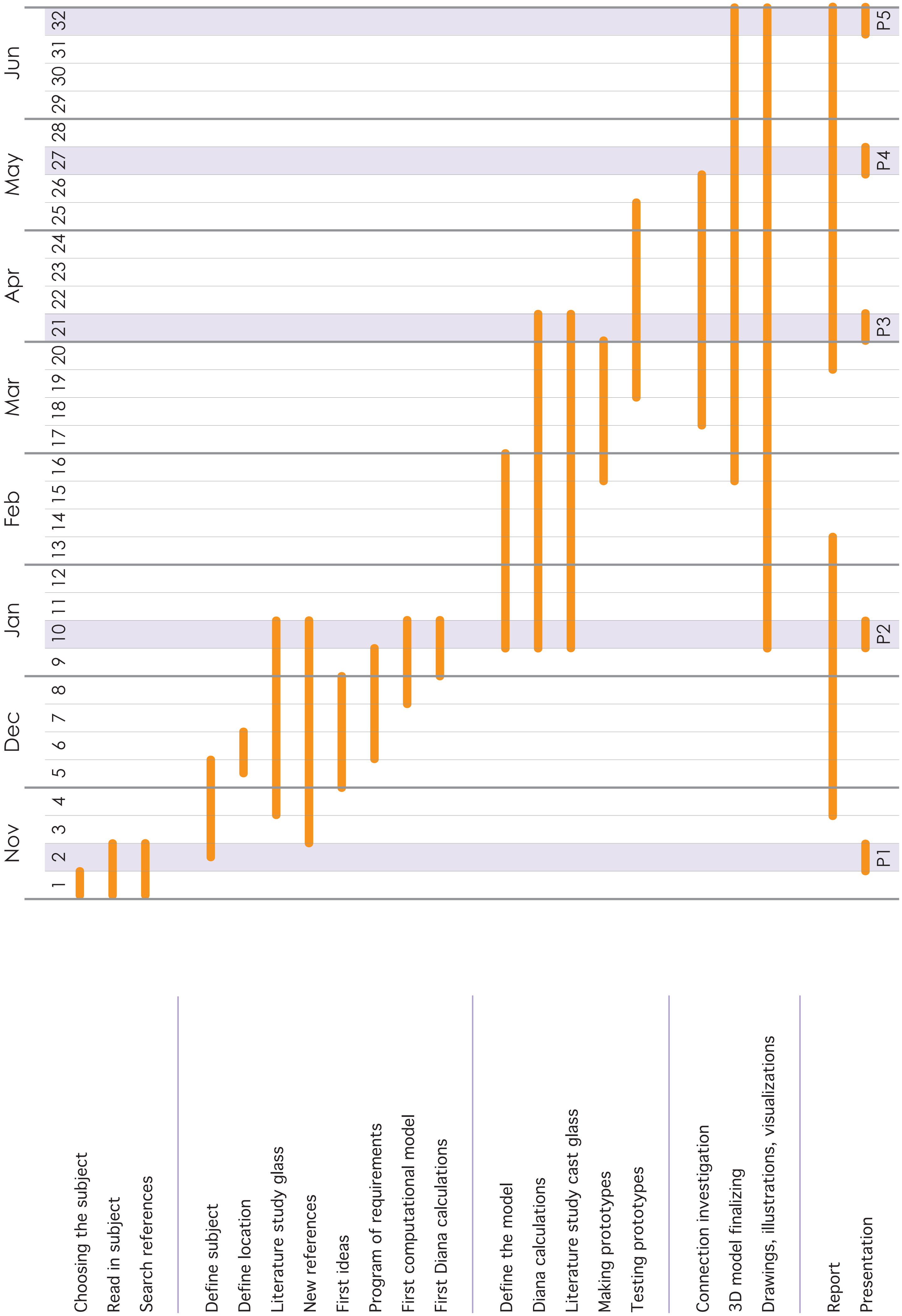


Figure 1.1 Time planning

list of figures

2 Literature study

This chapter is a literature study. This is a research after glass. The research is done on the basis of the previous told research questions. At the end of this chapter a few answers to those questions should be clear.

What is glass?

Glass consists out of a combination of molecules. This combination causes that it is not possible to give a chemical formula to glass. The molecules that are combined are arranged in a random order. There is no structure visible in the raster of the molecules. These characteristics cause glass to behave a certain way. The absence of the chemical formula causes that glass doesn't melt, but only changes form. The random arrangement of the molecules gives glass its transparency and is how glass distinguishes itself from crystals. Another result of this arrangement is the fact that the direction of the material doesn't change the properties. It does however cause that glass is less strong than crystal and more brittle. (Schittich, Staib et al. 2007)

Usage of glass

The first examples of glass being used by humans are 5000 years old. These consisted out of jewelry and other small objects and were made from solidified volcano lava. When it is hot it is possible to change the shape of glass, hence the usage of it. In the beginning glass was used for its transparency, but it is more and more used as a construction material. Nowadays glass is for 70 per cent used in new buildings or renovation of buildings

Silica glass		
Silicon oxide	(SiO2)	69-74 %
Calcium oxide	(CaO)	5-12 %
Sodium oxide	(Na2O)	12-16 %
Magnesium oxide	(MgO)	0-6 %
Aluminium oxide	(Al2O3)	0-3 %

Figure 2.1 Silica glass

How is glass made?

As said before glass is a mixture of materials. There are different mixtures that give another type of glass. The mainstream type of glass is the soda-lime-silica glass. Also known as silica glass or Quarts.
Silica glass has three main ingredients: Silicon dioxide (SiO2), Calcium oxide (CaO) and Sodium oxide (Na2O). These are the raw materials. SiO2 is the main component. This element comes from rocks and sand. Sand however, has to be purified first, because it contains a lot of color oxides. The sand that is suitable for the production of glass is only aloud to have a few impurities. The second biggest component is CaO. This is an element that is extracted from limestone. It is used in glass to make it harder.
The third main component is Na2O. Na2O can be extracted from soda ash. This element causes that the melting point of glass is lowered. This makes the production of glass easier.

To give the glass other specialized properties other materials can be added like: Magnesium oxide (MgO) and Aluminum oxide (Al2O3). When the proportions of the materials are changed, the behavior of the glass changes as well. The changes will mainly consist of changing the melting point or the strength of the glass. In EN 572 part 1 is described what aloud is. These boundaries make sure the glass has a certain quality and that it is save to use.

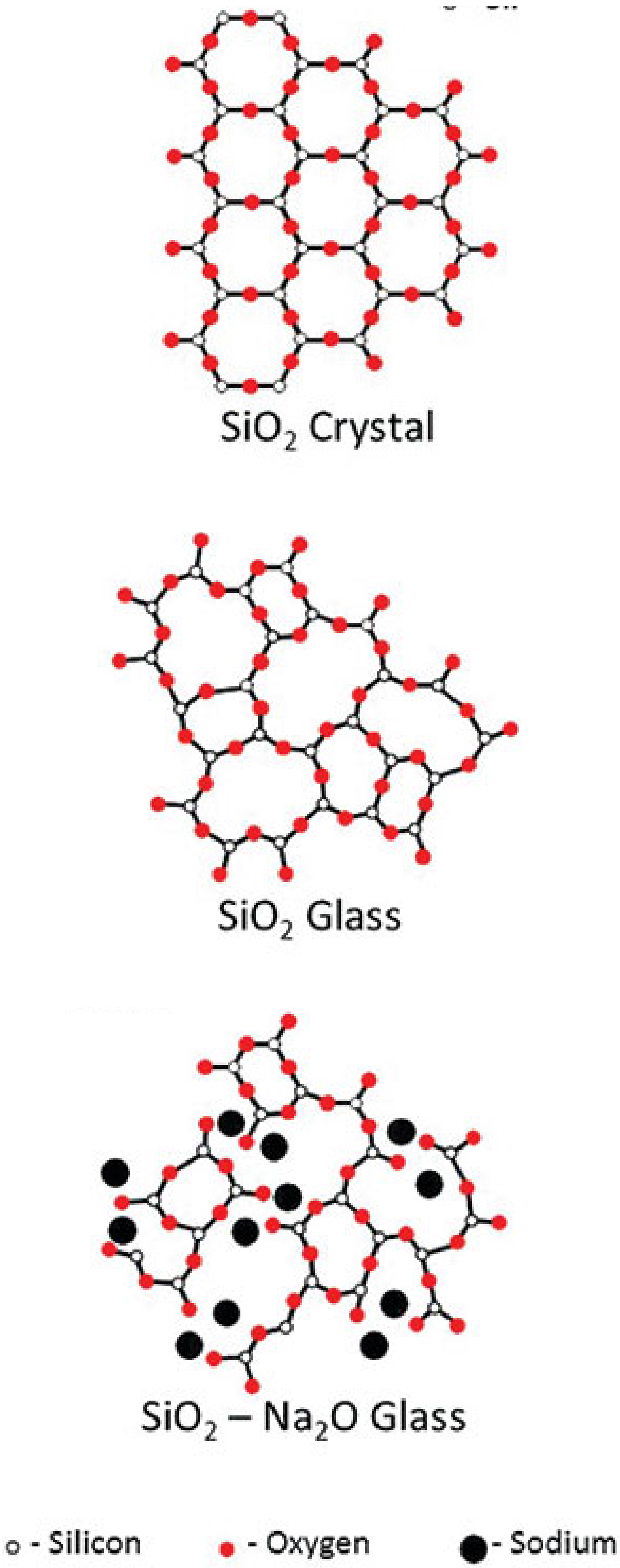


Figure 2.2 Silica glass chemical

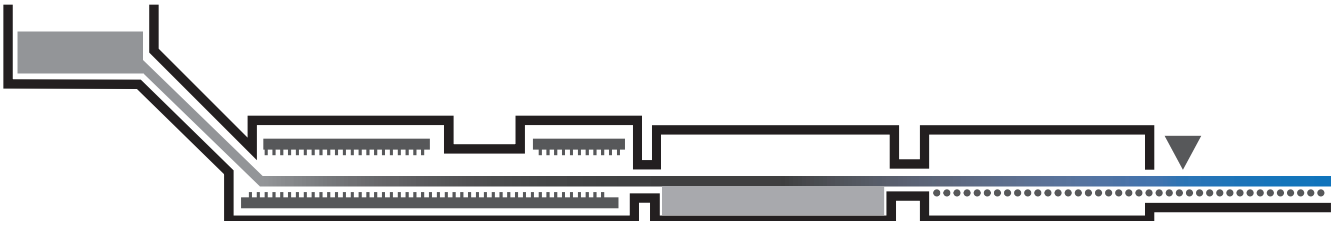


Figure 2.3 Production float glass

The main principle for the production of glass is that it is heating. This way it becomes viscous and can it be shaped. After this the glass will be cooled. The combination of these two actions causes the random arrangement. The molecules will not have time enough to make a crystalized structure. . (Schittich, Staib et al. 2007)

Float glass

Float glass is at the moment the mostly used production of glass and is developed bij Alastair Pilkington. The name already tells how this glass is manufactured. The raw material is melted and put on to a bath of liquid tin. The tin bath is about 50 meters long. The glass will go in at around 1100 C and floats on top of the tin until it solidifies at around 600 C. The thickness of this glass varies between 2 and 19 mm. The biggest normal produced glass sheet is 3,21 x 6 m. It is possible to get bigger sheets, but they have to be specially made. This and the fact that it is harder to transport these bigger sheets make it expansive. (Schittich, Staib et al. 2007)

Drawn sheet glass

There are two types of drawn sheet glass: The horizontal type and the vertical type. The raw material goes again in a melting tank, but is drawn out of it. The composition of the raw material is the same as floating glass. There is a difference in the visible aspect, because the rollers can leave a “mark” on the glass, which can cause a distorted reflection. (Wurm 2007)

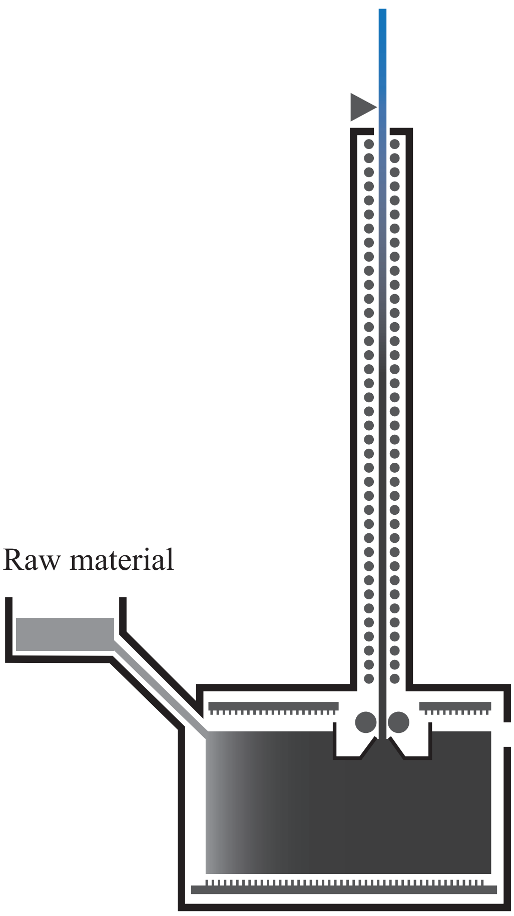


Figure 2.4 Production drawn glass

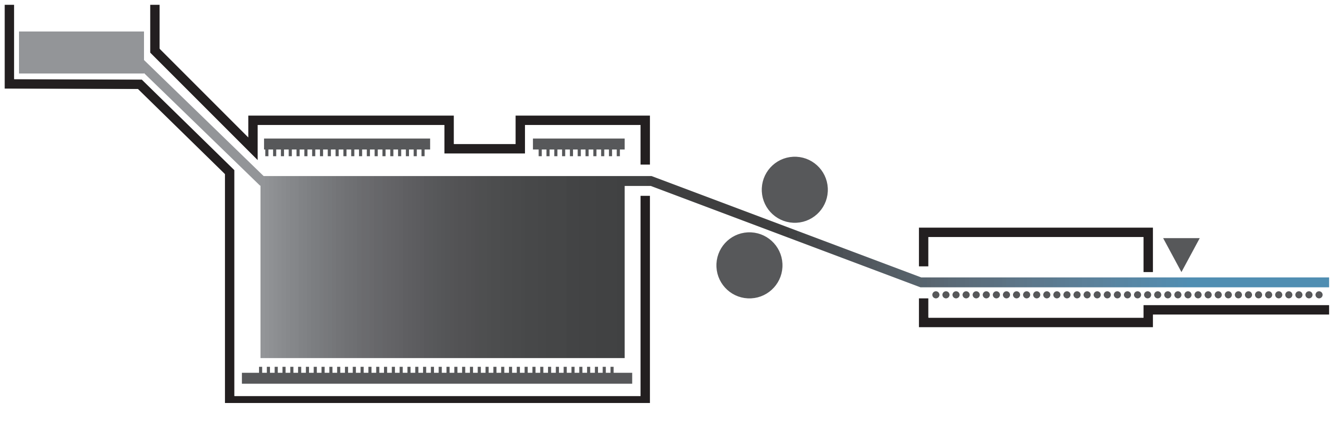


Figure 2.5 Production patterned or rolled glass

Patterned or rolled glass

With the production of patterned or rolled glass is again a bath used. In this case is there however no tin, but just the melted glass. This liquid glass flows over and is fed to rollers on the side. These rollers can give the surface texture. It is possible to make two textured surfaces, one, or one textured and one smooth surface. It is however not possible to make the glass as transparent as the float glass or the drawn glass. (Schittich, Staib et al. 2007)

Cast glass

Cast glass is used to make some more 3D shapes. Cast glass is the oldest way to make glass and is also the way to make shapes that are thicker than 25 mm. 25 mm is the maximum thickness of float glass.
The production of cast glass starts with a mold. The mold can be made out of different materials like sand, plaster, graphite and steel. The glass will be heated to 1200 C and casted in to the mold. The cooling of the glass needs to be done in the proper way. This has as result that it takes a long time (Cummings 2002)


Figure 2.6 Glass bricks, Crystal house Amsterdam

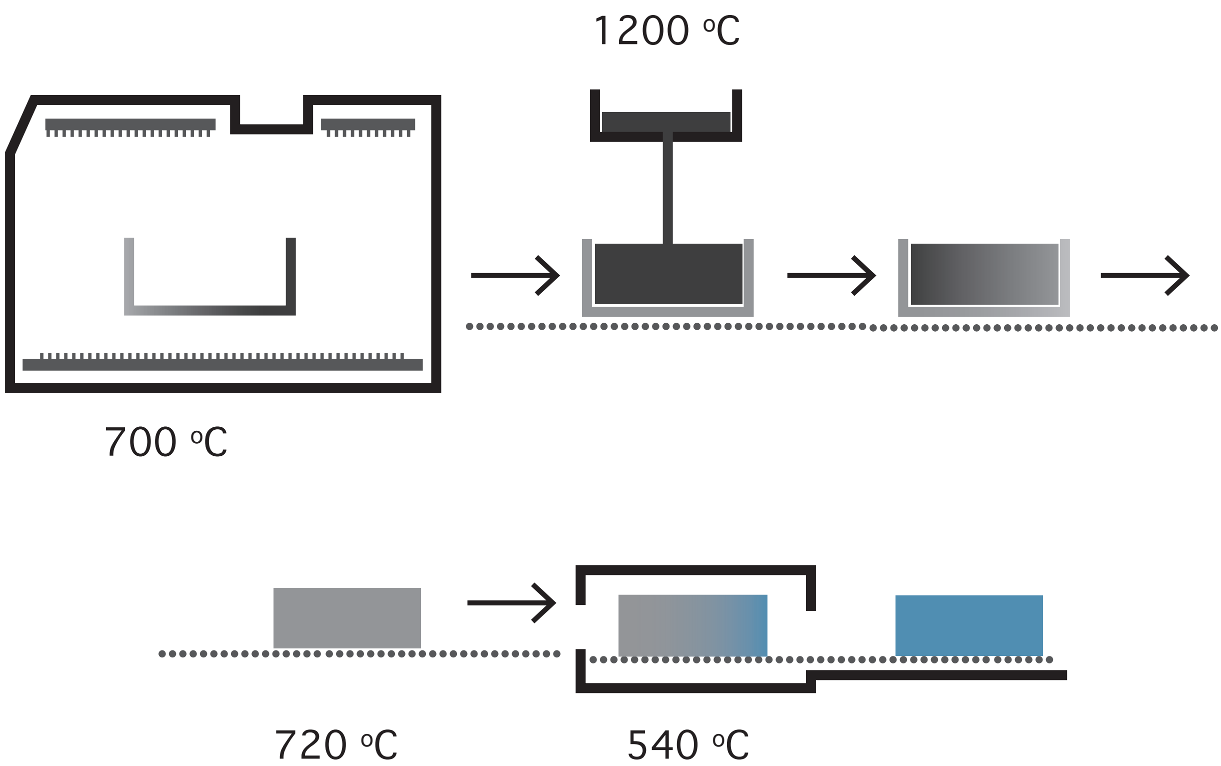


Figure 2.7 Production cast glass

Poesia bricks

As said there are multiple materials that can be used as a mold. (Oikonomopoulou, Bristogianni et al. 2017) used the poesia bricks. These bricks were made for the Crystal House in Amsterdam.
The poesia bricks were pored into a steel mold. This mold had to be preheated to 650-750 C so the glass wouldn't stick to it. It had also had to have a coating, so the glass would be able to get out easier.
The glass that is now in the mold will be cooled. To make sure is does not crystalize the glass is cooled to 720 C. The glass is now at it's softening point. This means that it would not deform under it's own weight (Shelby, 2005). The mold can be removed.
The brick will go into the oven to reach its annealing point. This is at around 540 C.
This is done so the residual stresses are relieved. The annealing time depends mostly one the dimensions of the brick. The environment and the oven can also play a part. Because of the non-uniform cooling the surface is convex. (Oikonomopoulou, Bristogianni et al. 2017)

Glass extrusion

Glass can as a lot of other materials also be extruded. This can be done in almost any cross section with diameters up to 75 mm. The lengths of these extruded rods have a standard of 1,5 meter. It is possible to get longer rods up to 10 meters. These are more expansive due to productions difficulties, but also because of the transportation.
A computer makes sure the glass goes with the right speed through the moulds. It can also regulate the heat of the rod so the rod will form in the right way. (Schott 2016)

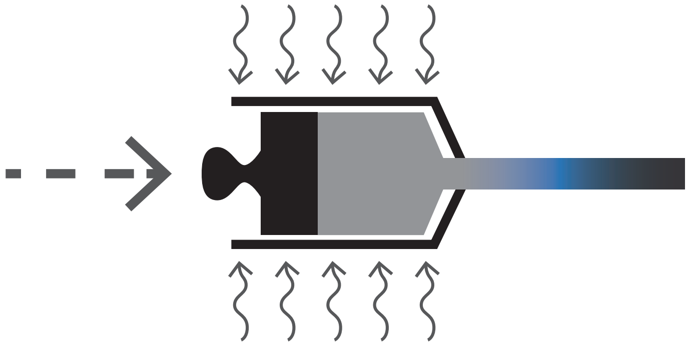


Figure 2.8 Production extruded glass

Blown glass

Blown glass is a production technique that has been practiced since before Christ. There is air blown into a blob of glass which will extend like a balloon. This can be done by a hand or with a machine. The manual technique is mostly used for artistic reasons. With special tools the glass is made into the desired shape.
With the machine, moulds are often used. The glass will be blown into this mould to let it get the desired shape. This is mostly used for everyday products like drinking glasses and lamps. (Haldmann, Luible et al. 2011).

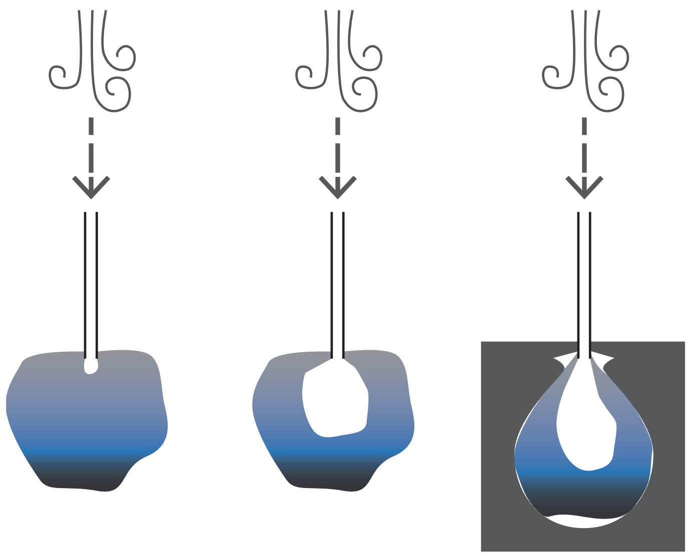


Figure 2.9 Production blown glass

Viscosity		Temeparture	
		SLSG	BSG
(dPa’s)		ºC	ºC
10^3	Working point	1040	1280
$10^{6.6}$	Softening point	720	830
10^{12}	Annealing point	540	570
$10^{12.3}$	Transition point	530	560
$10^{13.5}$	Strain point	506	530

Figure 2.10 Viscosity of glass

Types of glass

Borosilicate glass

Borosilicate glass has an other mixture of materials than the ones discussed before. Borosilicate glass has 7–15% Boron in it. This gives the glass a lower coefficient of thermal expansion. The Boron also causes a higher resistance against alkaline solutions and acids. Borosilicate glass can be produced by all three given production processes. (Wurm 2007)

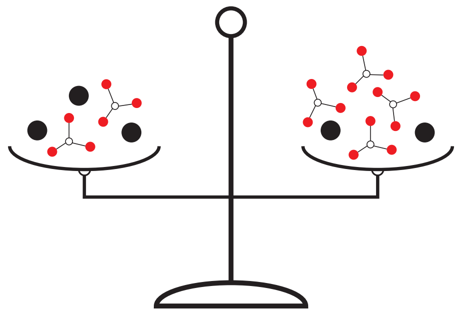


Figure 2.11 Different mixtures

Borosilica glass		
Silicon oxide	(SiO)	70-80 %
Boron oxide	(B2O3)	7-15 %
Sodium oxide	(Na2O)	1-8 %
Potassium oxide	(MgO)	1-8 %
Aluminium oxide	(Al2O3)	1-8 %
Silica glass		
Silicon oxide	(SiO2)	69-74 %
Calcium oxide	(CaO)	5-12 %
Sodium oxide	(Na2O)	12-16 %
Magnesium oxide	(MgO)	0-6 %
Aluminium oxide	(Al2O3)	0-3 %

Figure 2.12 Borosilica and silica glass

Alkaline earth glass

Alkaline earth glass is again a variation of the silicate glass. This glass has a higher density and a lower coefficient of thermal expansion. This glass can be used in fire resistance situations when it is subjected to a special thermal toughening process. (Wurm 2007)

Aluminosilicate glass

This type of glass contains 16-27% aluminum trioxide(AL2O3) and around 15% Alkaline earth. This causes a high temperature resistance so this glass is used for fire resistant glazing. The glass is produced by the float glass production. (Schittich, Staib et al. 2007)

Production method

Polished wired glass

During the manufacturing of this glass there is a wire mesh inserted. Although it might seem like that would increase the safety of the glass, this is mostly done for esthetic reasons. (Schittich, Staib et al. 2007)

Profiled glass

After the melt tank the glass is passed in to a mold that lifts the sides. This way the glass has a profile. This glass can be constructed in three ways. The first is the standard method where the panels all face the same way. The second, the panels are alternately facing the other way. At the third method there is a double layer of panels that face both ways. This last one has the best thermal insulation.(Schittich, Staib et al. 2007)

Treatment of glass

Glass ceramics

Glass ceramics are almost never used as a construction material. With glass ceramics the crystallization of the glass is controlled. The structure is partly or even completely crystalized. This way it is actually not glass anymore, but it is still possible to make it transparent. It is produced with the float glass or drawn glass process. Glass ceramics are mostly used in the cooking industry. (Schittich, Staib et al. 2007)

Thermally toughened safety glass

A method to toughen glass is trough thermally threaten it. The pane will be heated to the transformation at minimal 640 C. After this it will be suddenly cooled. The surface will this way be cooled quicker than the core. This causes the surface to contract quicker than the core witch increases the bending strength. Because of the additional compressive stresses at the surface, the pane brakes when the surface is broken. This causes that it is not possible to treat the pane any further. Any edge finishing or other shape changes has to be done before this process.
Sometimes there are nickel sulphide(NiS) molecules in the pane. In a normal pane this would not be a problem, but in the thermally toughened one this can. Because of the abrupt cooling, this molecule can not as quickly return to their original crystalline form, because it has a smaller specific volume. This will lead to stresses in the glass cross-section witch will cause that the pane eventually breaks. (Schittich, Staib et al. 2007)

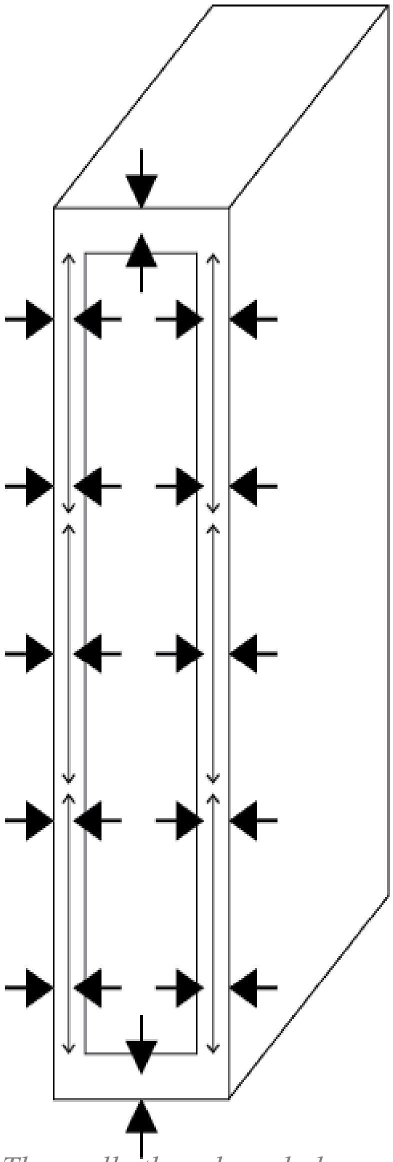


Figure 2.13 Thermally thoughened glass

Properties	
Density at 18 °C	2500 kg/m^3
Modulus of elasticity	7e10 Pa
Poison’s ratio	0.2
Specific heat capacity	0.72e3 J/(kg * K)
Average coefficient of thermal expansion	9e-6 K^{-1}
Thermal conductivity	1 W/(m * K)

Figure 2.14 Properties of glass

Heat-strengthened glass

This glass is similar to the thermally toughened safety glass. The difference is that this pane is less quick cooled. This gives the glass pane a lower surface strength. Because of this is, it breaks quicker and can not be called a safety glass.(Schittich, Staib et al. 2007)

Breakage of glass

There are three ways a glass pane can break. Most glass panes break in big pieces that have sharp edges. Wired glass breaks, but stays together because of the wire mesh. There will still be sharp edges. The upside of these two is that there are not a lot of pieces, which will make it easier to clean.
Heat-strengthened glass
Tempered glass will break in a lot of very small pieces. The upside to this breakage is that the parts are not that sharp. .(Schittich, Staib et al. 2007)

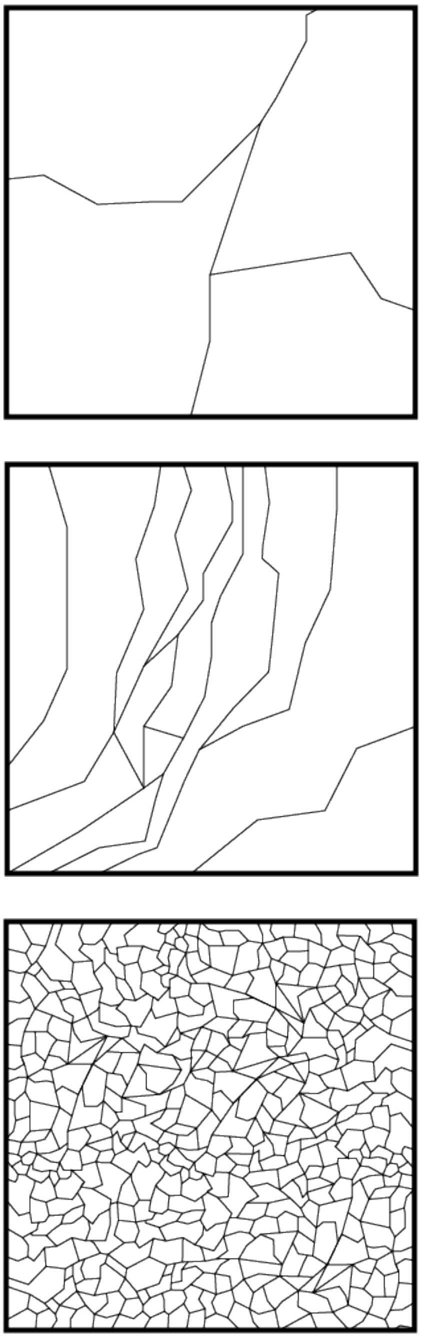


Figure 2.15 Breakage of glass

Laminated glass

Laminated glass is, as the name tells, at least two glass panels that are laminated together. There are two types of laminated glass: “normal” and safety. Normal laminated glass can be used for sound insulation purposes and decorative purposes. Because it doesn’t have a safety purpose the interlayer doesn’t need to have other functions other than making sure the panes don’t touch.
The safety laminated glass can be used for example for balcony balustrade. Here the interlayer needs to hold the layers together. This causes the glass to act as a thicker pane. Because there are multiple layers it is less of a problem when one of them breaks. The interlayer also makes sure the broken pieces are attached to it, so there are less sharp edges. (Schittich, Staib et al. 2007)

Durability

Glass has the great property that is can be recycled. When it is reheated it can be used again without losing it strength. Another aspect of glass is that it is resistant against a lot of chemicals and elements of nature. (Wurm 2007)

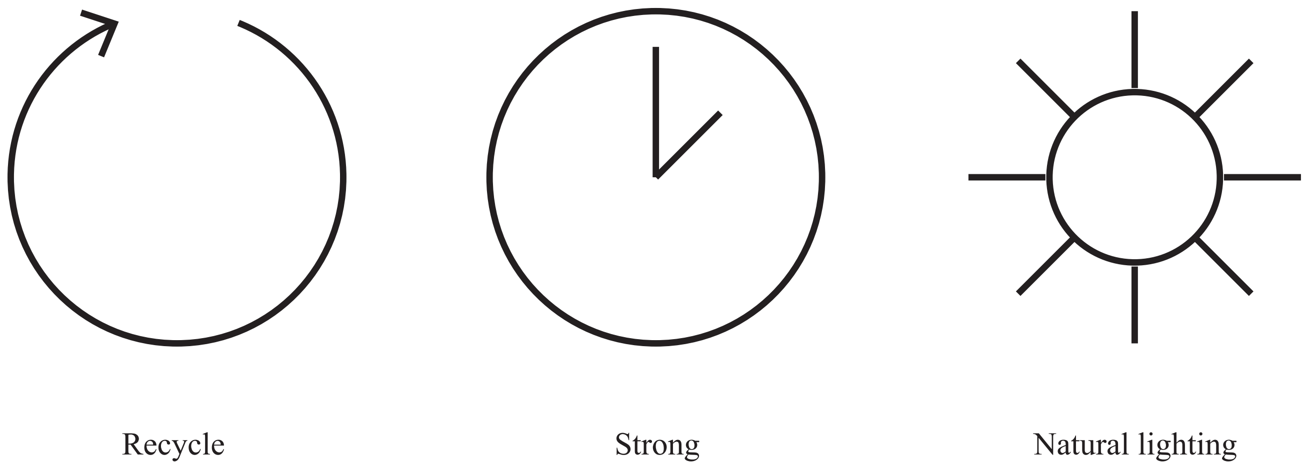


Figure 2.16 Durability

What has been done?

3 different kind of glass is used: laminated glass, a glass tube and cast glass. Because laminated glass is already used a lot, the references will be mainly focused on a glass façade and glass columns.

Glass facades

Maison Hermes, Tokyo 2013
Architect: Piano

Maison Hermes has a façade out of hollow glass bricks. These are used to make the impression of a magic lamp. Hollow bricks don't have structural purposes, so there is a steel structure behind it. This structure is established at the concrete bearing structure. The steel structure keeps a gap between the glass brick façade and the concrete structure. This way the façade gives the impression that it stands on its own (Kido 2013)

Figure 2.17 Maison Hermes, Tokyo

Optical house, Hiroshima 2012
Architect: Nakamura

The façade of the optical house in Hiroshima is made out of Casted glass bricks. These bricks are structural and carry the load. The problem is that the wall is 8,6 meters high. The glass bricks could not stand on its own with this height. This is why there were steel bars introduced. The steel bars go trough the bricks. The bars are very slim in comparison to the brick, so they are almost not visible from the outside.(Nakamura, 2012)

Figure 2.18 Optical house, Hiroshima

Atocha memorial, Madrid 2007
Architect: Lomholt

Atocha memorial is a glass tower in Madrid. This tower is 11 meter high and completely made out of glass bricks. The bricks have round and convex ends. This way the bricks were able to build up in a circular way. This is what makes the tower stable. To hold the bricks together an acrylic adhesive is used(Paech and Goppert 2008)

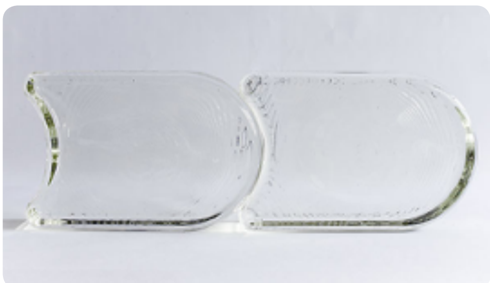


Figure 2.19 Cast glass bricks

Figure 2.20 Atocha memorial, Madrid

Figure 2.21 Crystal house, Amsterdam

Crystal house, Amsterdam 2016
Architect: Oikonomopoulou

The façade of the Crystal house in Amsterdam consist out of casted glass elements. The bricks that are used are the same size as the usual bricks. This way the glass bricks could flow over in the normal bricks. The façade is 10 meters high, but was strong enough to stand on its own. The glue that was used for this construction is a UV-modified acrylic one. This glue is a very washy one. Because of this the bricks were only aloud to have a tolerance of ± 0,25.mm, which is really hard to get with cast glass. (Oikonomopoulou, Bristogianni et al. 2017)

Glass columns

Glass columns exists different forms: the layered cylinder, the bundled column, the layers sheets, the profiled column and the poured column.

Layered cylinder

Tower place, London 2002
Architect: Arup façade engineering

Glass cylinders are in this building used for compression. There are steel cables reinforced to take up all the tensile stresses.

Layered cylinder, TU-Delft 2005
Architect: Nieuwenhuijzen

This is a research after a column that consists of two cylinder tubes. These are glued together to make it stronger. There research found out that is very hard to make sure the adhesive is evenly spread. This caused problems. (Nieuwenhuijzen, 2005)

Figure 2.22 Tower place, London

Bundled column

Bundled column, TU-Delft 2015
Architect: Oikonomopoulou

The bundled column is another research of the TU-Delft. This column consists out of multiple columns. These are glued together with a transparent adhesive. The multiple usages of columns provide safety. If one of them breaks the rest is able to carry the load. (Oikonomopoulou, Bristogianni et al. 2016)

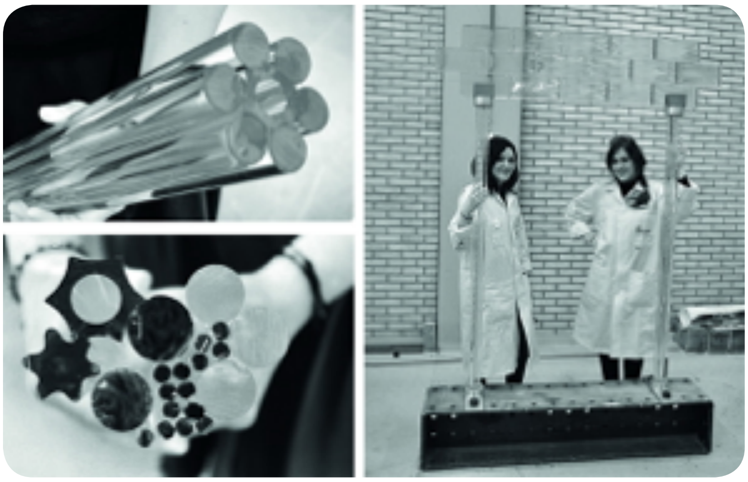


Figure 2.23 Bundled column, Delft

Layered sheets

Laminata house of glass, Leerdam 2001
Architect: Knuunenberg Architecten

The layered sheets are here more used as a wall. The layers are glued in a horizontal way. Because all the edges are visible the wall that is totally out of glass, is more translucent that transparent. (Richards 2006),

Figure 2.24 Laminata house of glass, Leerdam

The pompano park water feature, Florida 2006
Architect: Carey Jones

The pompano park water feature is actually a sculpture. It does exist of four columns that are connected on top. Stacking glass plates on top of each other makes the columns. Bigger plates that go from one column to another make the connection.

Figure 2.25 The pampano park water feature, Florida

Profiled

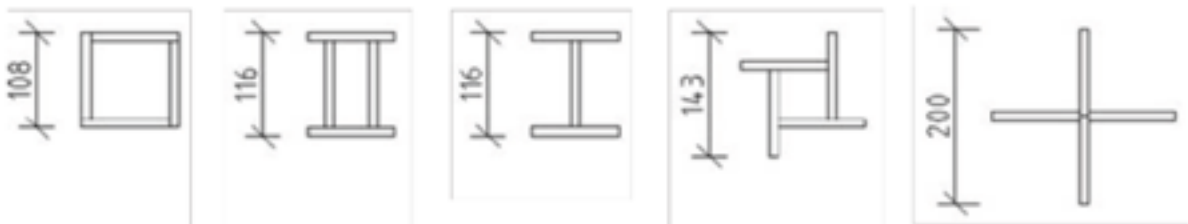
Town hall, Saint-Germain-en-Laye 2000
Architect: Brunet Saunier, Architecture

This design has 8 glass columns. They all have measurements of 220 x 220 mm. They are cruciform and consist of laminated panes. The columns are fixed on the bottom and top with steel caps. When the columns break there is a steel tension ring that will carry the load(archdaily 2009).

Figure 2.26 Town hall, Saint-Germain-en-Laye

Several profiled columns, Delft 2011
Architect: Ouwerkerk

Again there is a research done at the TU-Delft. This research looked at different kind of profiles. The profiles that are studied are different shapes of panes that have a 100 mm length and 8 mm thickness. In the table beneath the test results are shown. (Ouwerkerk 2011)



Type	Failure load (kN)	Compressive strength at failure load (MPa)	Failure mode
Profiled square column	111.6	34.9	Crack
Profiled double-web column	145.3	45.5	Crack and buckling
Profiled H-profile column	121.9	50.8	Buckling
Profiled Zappi column	128.0	40.0	Buckling
Profiled Cruciform column	83.2	26.0	Crack and buckling

Figure 2.27 Profiled columns, Delft

Poured

Solid water, Venice 2010
Architect: Roni Horn

This is not really a column. This is made by a artist and so more of an art project. The main this about this project is that it shows that there are limitations of the sizes cast glass. The element had to be annealed for 12 months.

Figure 2.28 Solid water, Venice

Buildings such as the Apple stores and the Optical house use a lot of steel for their connections. This is done so that the steel parts can with hold the tensile stresses.

The top picture shows connections bet-weem glass panes.These connections are made as small as possible to “hide” them.

The bottom facade is made out of cast glass with holes. Through these holes steel cables are placed. Even though the facade is more transparent that normal. The cables are visible.

Figure 2.29 Steel connections

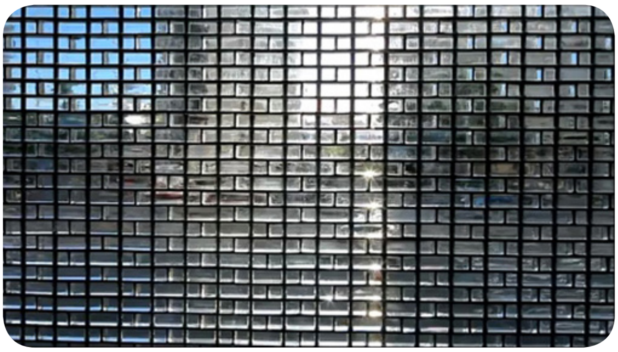


Figure 2.30 Steel cables

To make an innovative design the steel should be minimalized, and preferable discharged. To get to such a design the production of glass is taken under the loop. This shows that each production process will give another shape of glass.

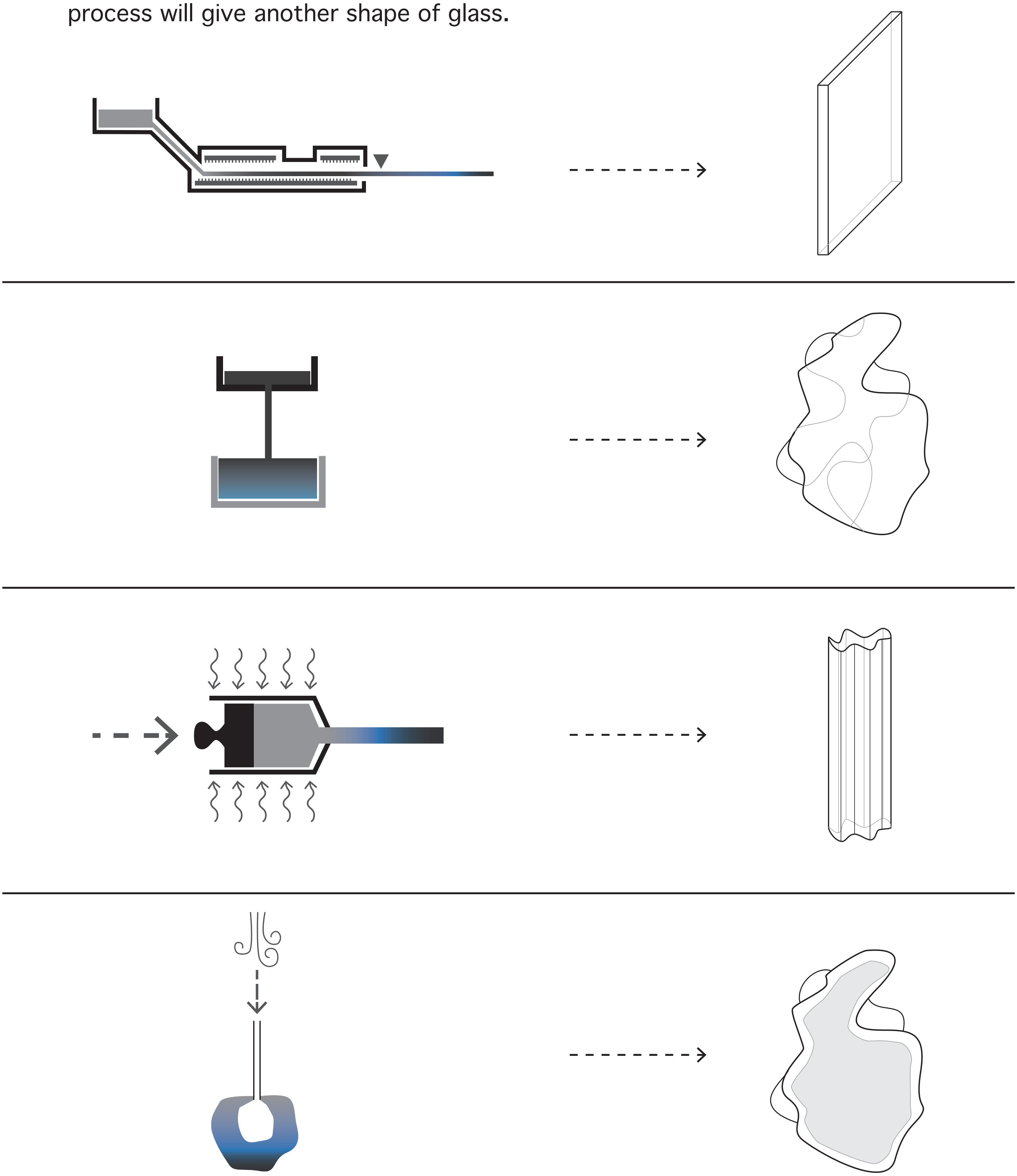


Figure 2.31 Shapes of glass productions

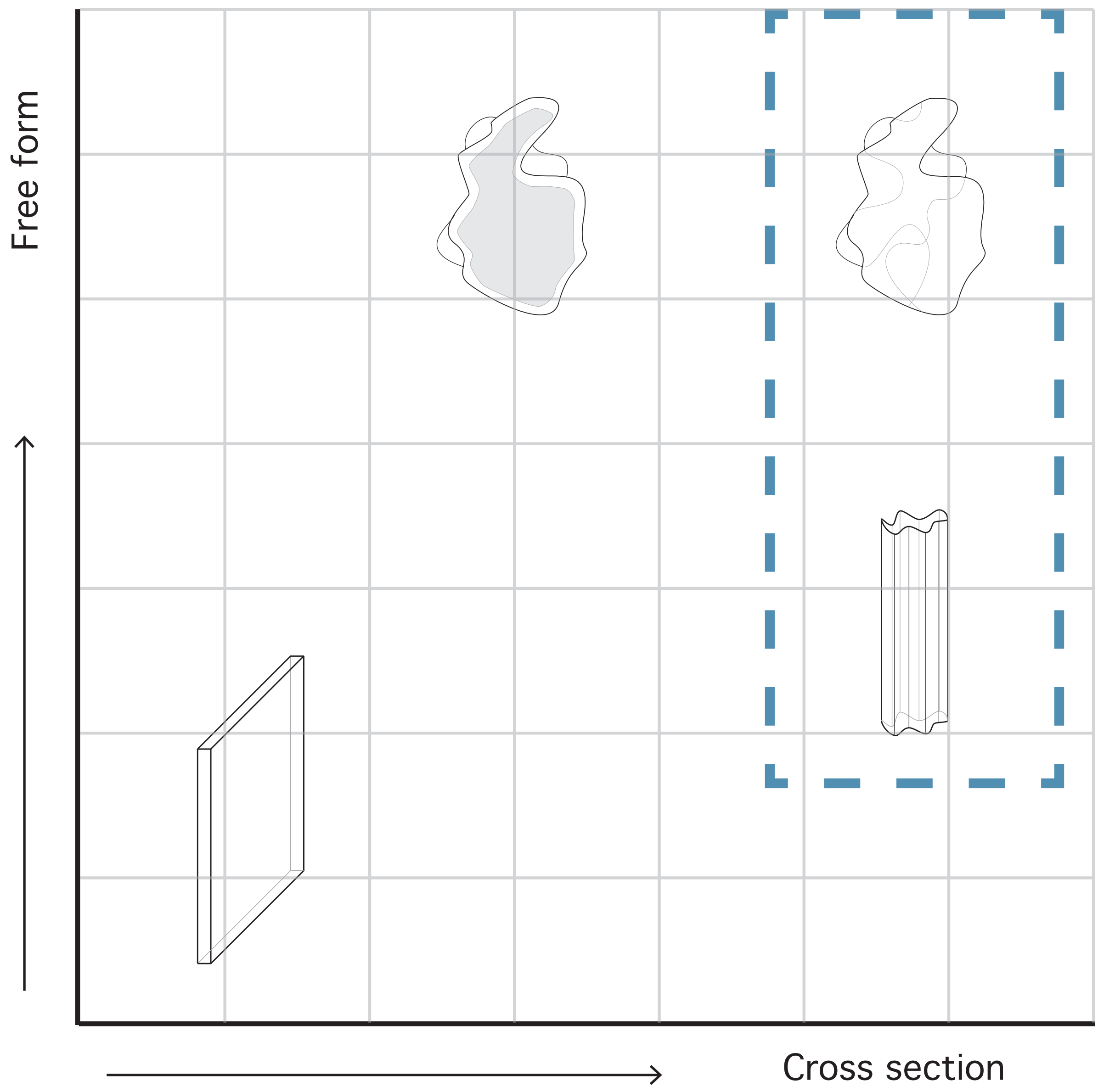


Figure 2.32 Shapes in relation to free form and cross section

For this design to function, it is needed to choose a production technique that gives shaped with a high cross section. This is because the glass is structural stronger. The second criteria is the freedom of shape. Some production techniques are able to make any shape desired, others are more limited. It helps when the shape is changeable to be able to get to more and better designs.

archdaily (2009). from https://http://www.archdaily.com/29755/civic-center-in-st-germain-philippe-harden

Cummings, K. (2002). A history of glassforming, University of Pennsylvania Press.

Kido, E. M. (2013). "The new steel-glass architecture of buildings in Japan." Steel Construction 6(3): 229-237.

Oikonomopoulou, F., et al. (2016). "Developing the bundled glass column." Structures and Architecture Beyond their Limits.

Oikonomopoulou, F., et al. (2017). "The construction of the Crystal Houses façade: challenges and innovations." Glass Structures & Engineering: 1-22.

Ouwerkerk, E. (2011). "Glass Columns: A fundamental study to slender glass columns assembled from rectangular monolithic flat glass plates under compression as a basis to design a structural glass column for a pavilion."

Paech, C. and K. Goppert (2008). Innovative Glass Joints—The 11 March Memorial in Madrid. Challenging Glass: Conference on Architectural and Structural Applications of Glass.

Richards, B. (2006). New glass architecture, Laurence King Publishing.

Schittich, C., et al. (2007). Glass construction manual, Walter de Gruyter.

Wurm, J. (2007). Glass structures: design and construction of self-supporting skins, Walter de Gruyter.

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Figure 2.27 Profiled columns, Delft

Figure 2.28 Solid water, Venice

Figure 2.29 Steel connections

Figure 2.30 Steel cables

Figure 2.31 Shapes of glass productions

Figure 2.32 Shapes in relation to free form and cross section

3 Design research

Figure 3.1 Topic

Chapter 3 is another research. This time it is one after the connections. This is a design research instead of a literature one. In this chapter multiple connections are designs and compared to each other. The research should give an inside of the connections that are possible and show which connections work in this particular case.

Problem areas

To figure out what to analyze there is looked at the problem areas of the design. A lot of parts of the design are already tested in other researches. The problems for this design lie especially at the connection points with the glass tube. At one end the tube is connected to the pane with a foot, and at the other it is connected in the glass column brick. To make the connection strong it is decided to make a notch in the brick. This part will have a lot of forces to process, so this part will be analyzed.

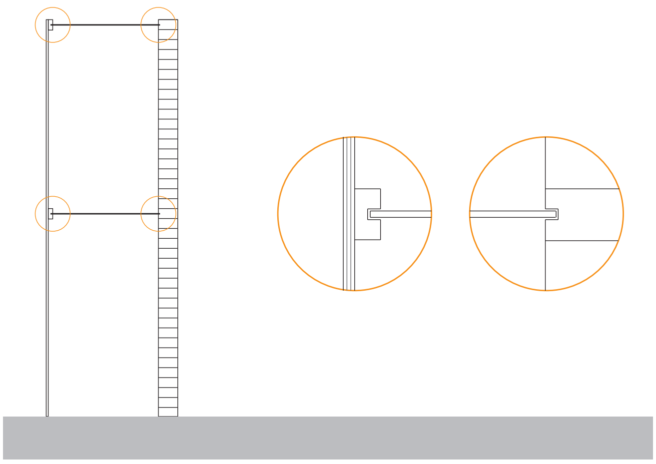


Figure 3.2 Problem area

Design criteria

Transparency

The most special thing about glass is that it is transparent yet strong. For this design the goal is to highlight both these features.

Challenging

This research is part of a graduation project at the Technical University of Delft. The TU-Delft consists of a lot of testing equipment and tutors that are specialized in particular areas. This means that a lot is possible. To make the project as interesting as possible and to stretch the possibilities with the material it is necessary to make a challenging design.

Manufactural criteria

Manufactural ease/costs

Even though there is a lot possible, it is unnecessary to stretch the costs of the project. This is the same with the manufactural ease. The best projects are the simplest. There is also a matter of time, if the production is complicated it tends to take a while.

Stress concentrations

Glass can process a lot of compression loads, but one of the flaws of the glass is processing stresses. Glass is able to work some stresses, but not a lot. This means that the designs need to be reviewed on stress concentrations. These will be the weak points of the design.

Tolerances

The manufacture of glass depends on a lot of factors. This causes that glass never really behaves as you want is. The cooling process for instance can cause shrinkage. So to make the design easier to make, tolerances should be reviewed.

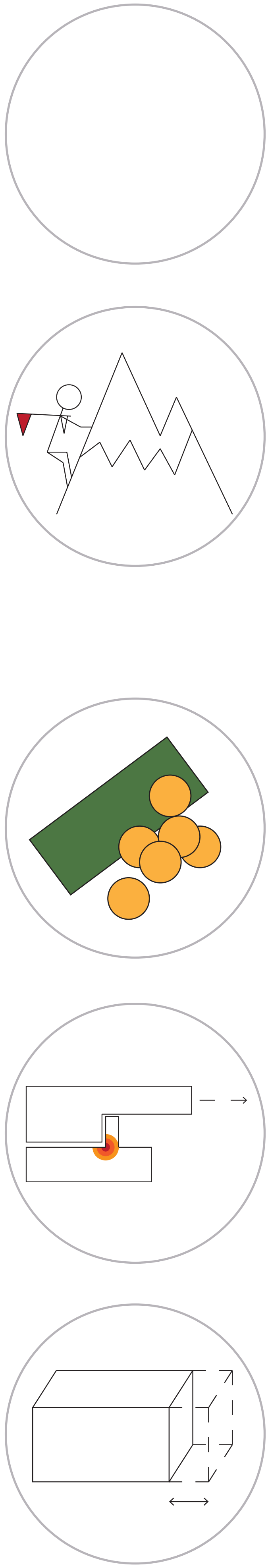


Figure 3.3 Design criteria

Connections

To make a new connection there is first looked at existing ones. One of the obvious connections is the bold and screw. This is a frequent used connection in almost every structure and there are a lot of variations to this connection. Another one is the Japanese wood connection. This, again exists in many variations. Both these connections are designed with the same sort of principle: Two or more profiled part that fit perfectly into each other.

Another obvious one makes use of an adhesive. There are multiple adhesives possible, but the main principle is the same. This principle is used frequently in the glass industry.

When looking further at glass connections you will find a lot of steel or aluminum parts that connect two or more glass panes. It is good to look at these connections to see what is in the field, but because this part of the design does not make use of a pane, it is not very relevant.

After these connections there is done some further research into the use of glass in other fields. So is found that in chemistry they sand glass and use this to close an Erlenmeyer.

From these connections three main principles rise: Profile, Adhesive and Sanding. With these the main design is taken back into account. So how can we use these principles to connect a rod to a brick build column.

Profiled connection

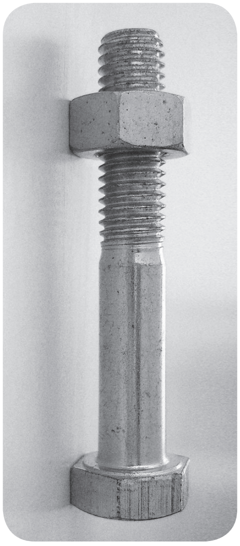


Figure 3.4 Bolt and nut

Figure 3.5 Japanese wood connections

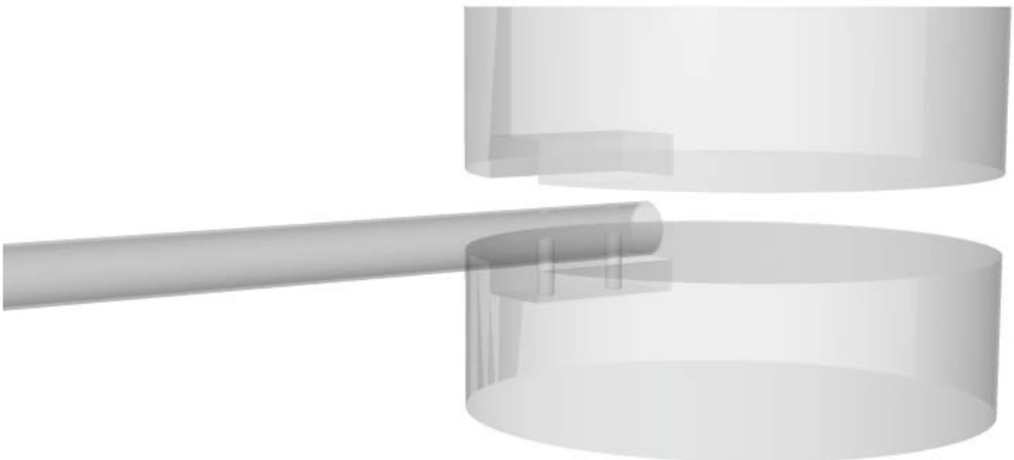


Figure 3.6 Profiled design

Use of adhesives

Figure 3.7 Polymax

Figure 3.8 Acrylic glue

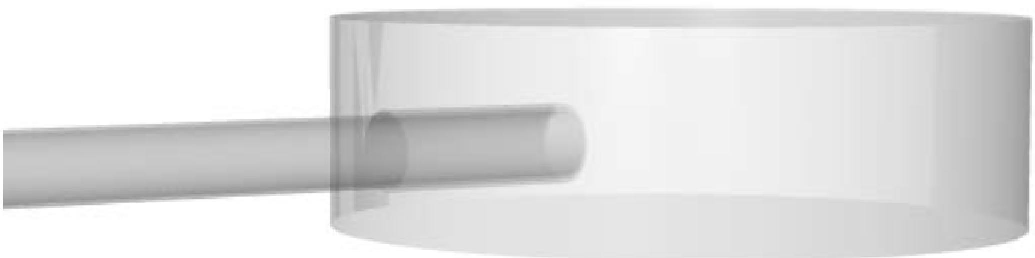


Figure 3.9 Glued design

Sanded connections

Figure 3.10 Sanded connection

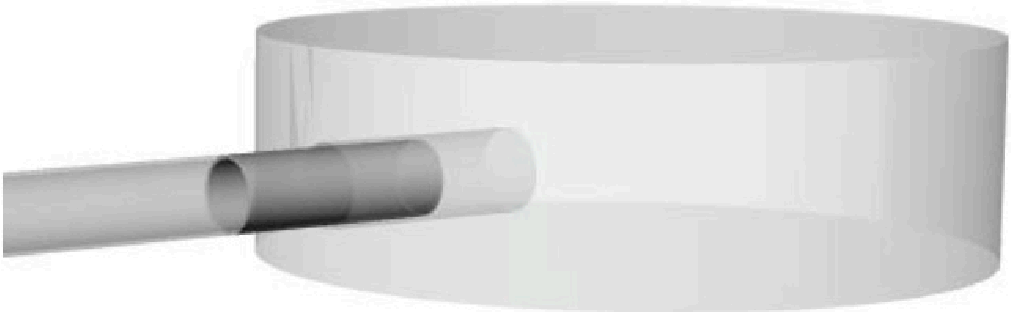


Figure 3.11 Sanded design

Connections for glass panes

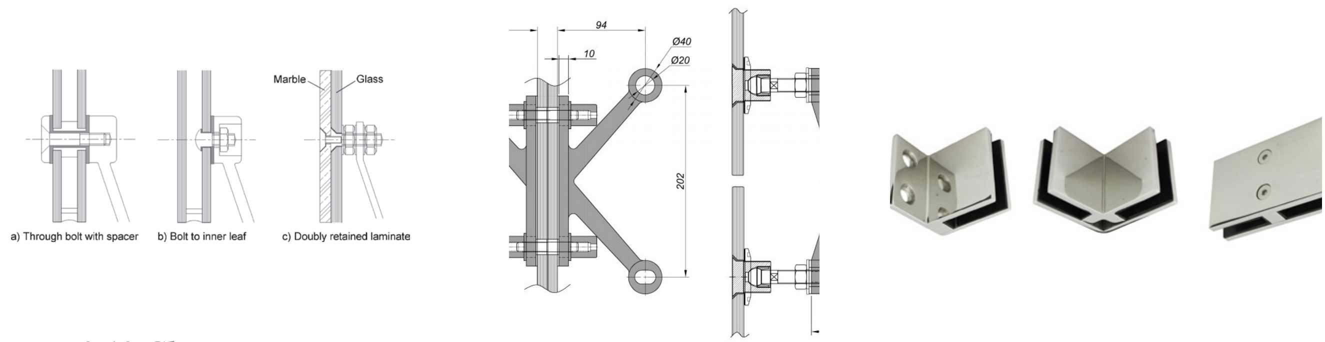
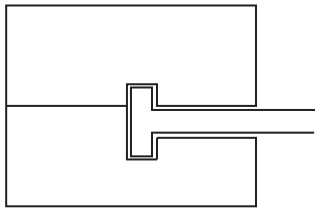


Figure 3.12 Glass pane connections

Seven designs rose from this:

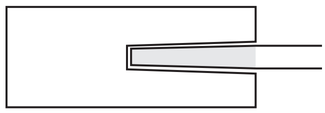
Pressure

This is also a profiled design, At the end of the rod is something added that fits in the bricks of the column. This added part might not be super strong, so the design relies on the fact that the bricks on top of the used bricks will give it enough pressure.



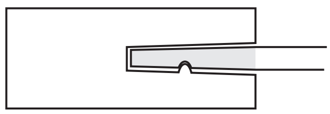
Sanded

The sanded principle is like said used a lot in the chemistry field. However not much in the building industry. In the chemistry world when a stop doesn't go off of the Erlenmeyer, they call it a frozen connection. For this design it was the idea to make use of this frozen connection and see if it can be used in a different field.



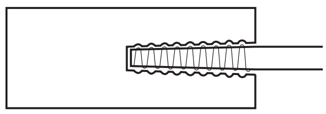
Sanded with nod

The sanded with nod connection relies on the same principle. This just has an extra nod that keeps on hooking to a groove in the brick. So it is actually a combination between the profile and the sanded principle.



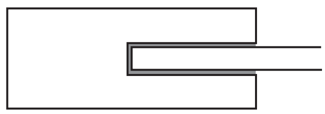
Swirl

The swirl Is actually a normal bold and screw connection, but made out of glass. If you turn is far enough it won't turn back and unscrew. Here is again made use of the profiled connection.



Adhesive

The adhesive does not have a special shape or finishing from the glass. This is a very straight forward design.



Profile with glass
The profile with glass is a connection that is like a puzzle. It is a similar design as the pompression design, but here there is not something added to the rod, but made some cuts.

Profile with steel
This design is one that uses another material. Glass is known for not handling stresses very well. This design responds to this to add a material that is known for its ability to handle these.

Because we looked at the problem areas and decided that the part with the column and the rod is the part that needed to be fixed, does not mean that the other side should be ignored. The end goal is to make the whole structure, so all parts should be thought of.
To design the other side of the rod, the designs of the column side are back linked to the wall side. They are changed where they had to and stayed the same where possible.

Not all designs can work with each other. Some are very precise which makes it hard to connect them in the same way on the other side. Because the wall is made out of glass panes and the column out of casted bricks, it is not possible to work them the same.To. make the same connections on both sides is it possible to make a cast glass foot. This will then be glued to the glass pane.

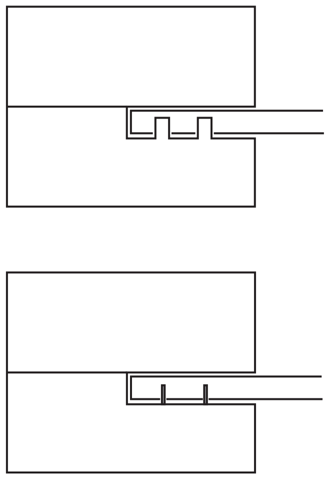


Figure 3.13 Designed connections

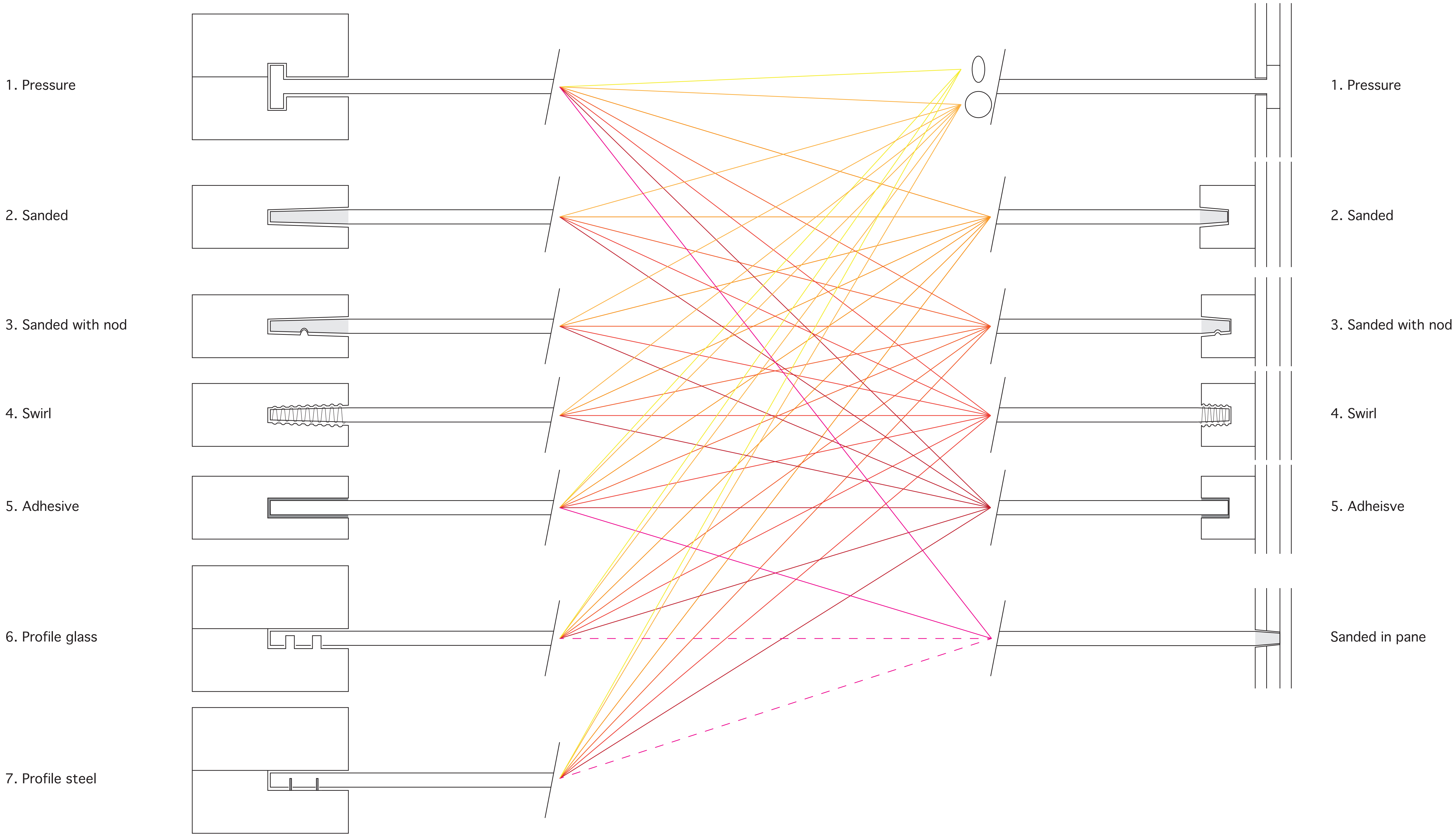


Figure 3.14 connecting the designs

Choosing connections

There are now multiple options and there are multiple criteria's. To choose the best option the criteria are linked to the designs.

The first criterium is the stress concentration. There is no design that has a very good solution for the stress concentrations, just because glass and stresses don't go together. The option with the steel profiles that should solve this, still has the glass around the steel that will be pulled at. For the other designs applies that the ones with a profile works less than the other ones. If the glass is relatively thick in the places where the stresses occur, the problem would be less. Sharp edges are also a problem when it comes to stresses. So it is best to avoid these.

The second one is manufacturing ease/ costs. This is mainly caused by how the rod should be worked with. The rod has its shape that cannot be changed easily. It is not easy to attach something to the rod, this makes the pressure option and the swirl less doable. Sanding the rod is not that hard, but to also add a nod that is pretty precise is more difficult. The profiled design with glass with the two bricks does not have to be super precise. This makes it verily easy to make. The one with the steel causes a process that combines two materials together. This is doable, but not the easiest.

Tolerances is an important one. In the previous criterium is already described that the designs that need a lot of preciseness is hard to produce. The sanded options have small tolerances because the principle relies on a lot of surface contact. Here the adhesive one depends on the adhesive that is used. There are two main types of glues that are used with glass and are transparent. The Ultra violet glue is aqueous what will cause for a maximum tolerance of around 0.25 mm. The other glue is a Polymax. This allows a bigger tolerance, it is just less strong.

Last but not least there is looked at the challenging part of the project that will rise out of the chosen option. This mostly means that the use of an adhesive might work and a be a good option, but it doesn't stretch the possibilities that are possible with glass. The use of steel will also reduce the challenging part.

When looked at the scheme, the profiled with glass and the sanded design score the highest. The profiled option scores higher, but the sanded design is more innovative, so there is decided to give both these options a try.

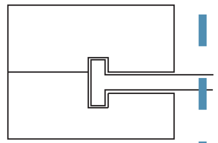
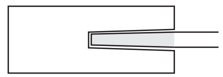
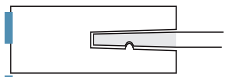
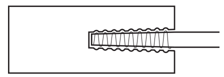
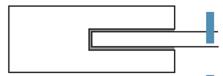
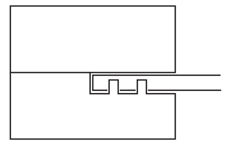
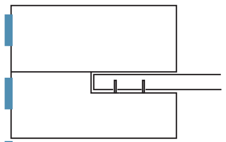
							
Stress concentrations	●●●○○	●●●●○	●●○○○	●○○○○	●●●●○	●○○○○	●○○○○
Manufacturing ease / cost	●○○○○	●●●●●	●●●○○	●○○○○	●●●●●	●●●●●	●●●○○
Tolerences	●●●●●	●○○○○	●○○○○	●○○○○	●●●○○	●●●●●	●●●●●
Challenging	●●●●○	●●●●●	●●●●●	●●●●●	●○○○○	●●●●●	●○○○○

Figure 3.15 Criticizing connections

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4 Final designs

Design 1 profile

The final chosen profile design is changed. The option that was compared to the other had a problem with the stress concentrations. It is not possible to completely discard this problem but changing the shape does help. This made that the cut outs of the rod are now made into a more smooth and round shape.
the hollow cut out would go 1/3th into the rod. This way there is still enough glass left, but would it also have enough grip.

Structural principles

The shape is designed by thinking about the production of the rod and the brick. The rod is a standard rod and so it cannot be ordered in any shape you desire.

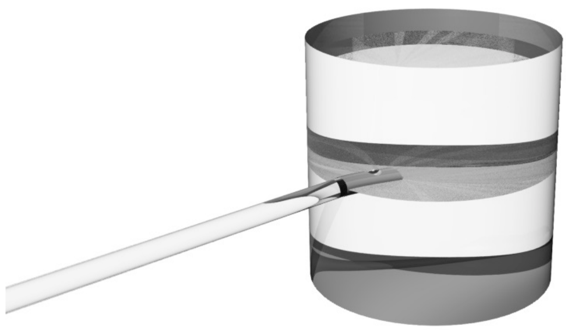
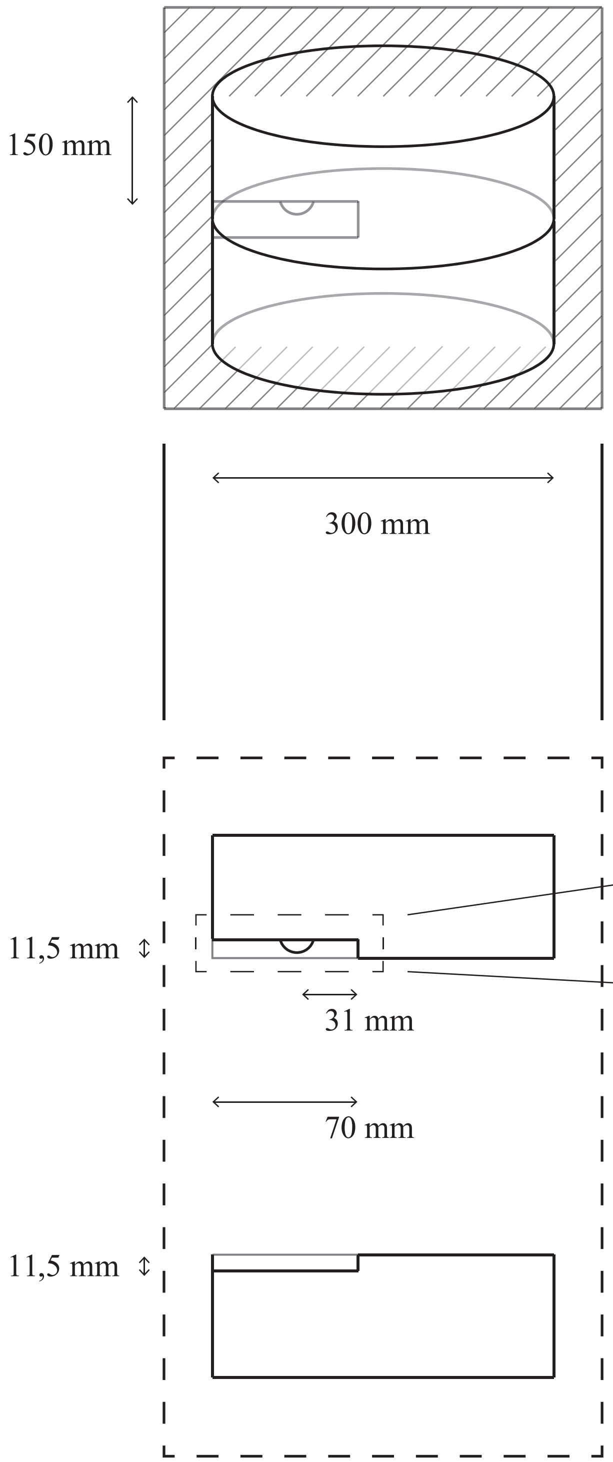


Figure 4.1 Profiled design

Figure 4.2 Exploded vieuw profiled design



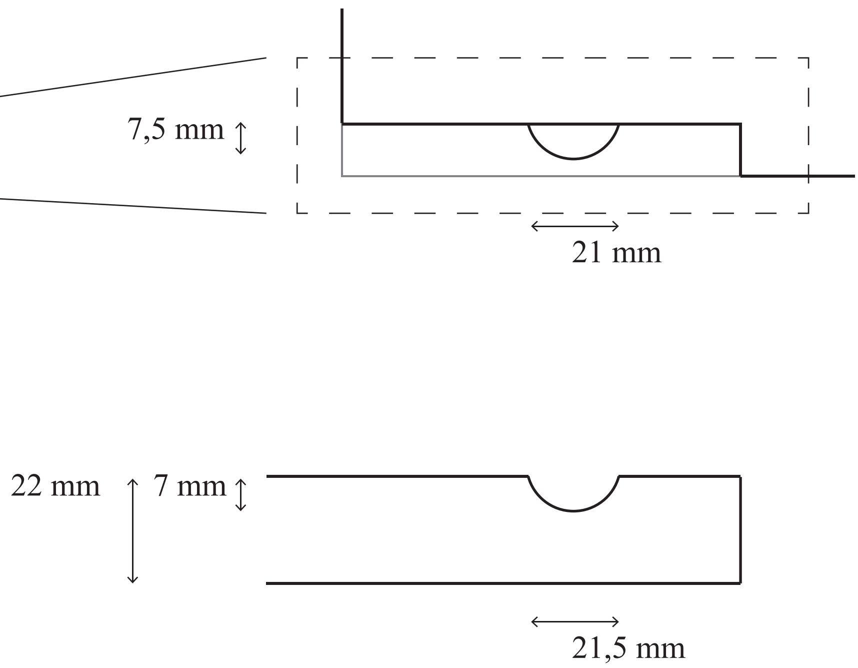


Figure 4.3 Dimensions profiled design

Design 2 sanded

The sanded design is almost left the same. Looking at the chemistry stops the shape stands out. All the stops are cone shaped. This makes that the design is able to be less precise. The slopes have to be the same, but it is less of a problem when one is bigger than the other.

Structural principles

Sanding a connection means that is makes use of friction. To optimize this friction principle there will be made use of liquids.

Figure 4.4 Sanded design

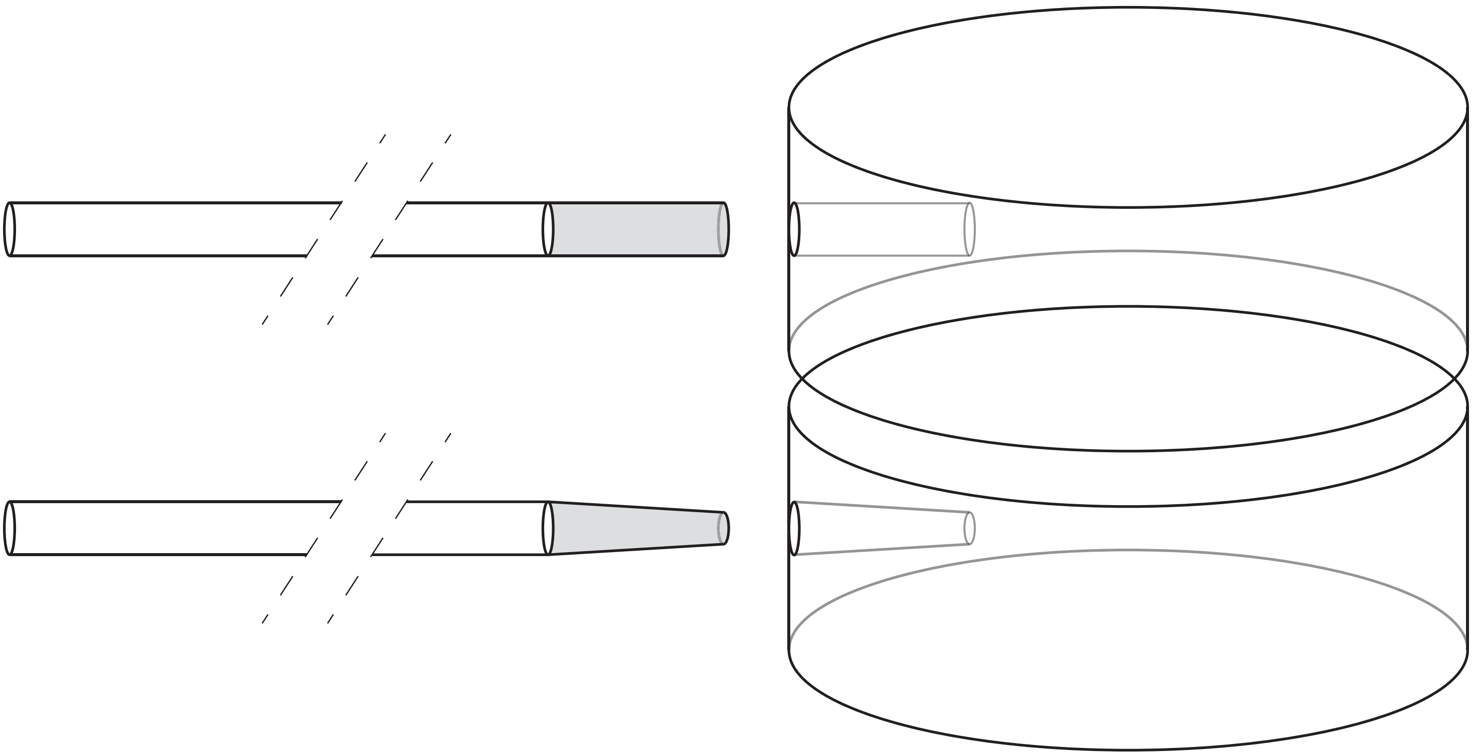


Figure 4.5 Cone shape sanded design

Comparing

+ More tolerances

+ Connecting capacity

- Peak stresses

- Less production ease

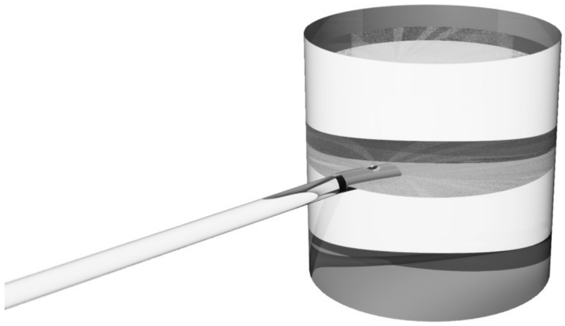


Figure 4.6 Profiled design

- Full accuracy

- Unsure mechanical connection

+ Homogenous stress distribution

+ Production ease

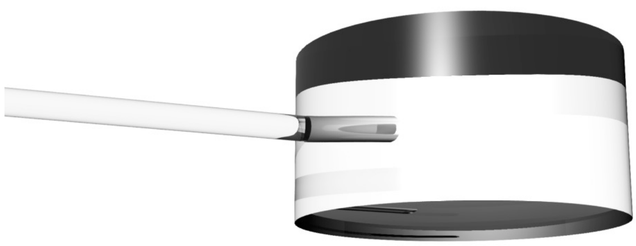


Figure 4.6 Sanded design

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5 Experiments

In this chapter the experiments are done. Because there are two designs chosen there are two different sets of experiments done. Both designs are simplified to make the tests easier. After this chapter is should be clear how the different designs are made, how they are tested and how they performed during these tests.

Tests set up

Profile design

During the design process there was already thought of manufacturing of this option. The two bricks will be casted, and the rod will be shaped so that there is a hole in the right place. A simplified roadmap to cast glass has 9 steps.

Glass takes a very long time to cool. To speed up this process the model that is made will have a maximum of 3 liters. The size rod cannot be changed, so it is not possible to make a scaled model. Resulting in that the brick had to be cut. This is actually convenient because this will give flat surfaces where it can be attached to a machine. Of course, it should be taken into account that there is still enough glass to hold the forces.

The rod will be made by lowering a hot steel ball. This requires a mould that holds the rod and lets the ball go down to the right point and in the right place. This mould will be made out of gypsum with, of course, a steel ball. This will be discussed and made with Kees from the Dreamhall at civil engineering.

1: A computer model is made. This can be done with different programs for instance SketchUp or rhinoceros. For a prototype the model should have a volume under 3 liters.
2: The comper model is 3D printed. To make glass out of it, it is needed that the model has a good kwalaty so it has as small as possible lines. It will still have some lines. So, take notice of which way the model is arranged. This wil get some parts smoother than others.
3: Around the 3D-printed model a silicon mould is made. This is done so it is possible to make multiple bricks with the same mould. This will lessen the costs and the fabrication time.
4: Around the silicon mould is a gypsum mould made. This makes sure the silicon mould will stay the shape you want.
5: In the silicon mould is now wax pored.
6: To speed up the process it is possible to slice the wax when the sides have a thickness of around 8 cm. This will give enough force for the second gypsum mould.
7: The second gypsum mould is the mould where the glass will eventually poured into.
8: To put glass in this mould, the wax should get out. This is done by melting it. The melted wax can later be used again for the next brick.
9: Step nine is getting melted glass in the second gypsum mould and let it cool off by a specific cooling process.

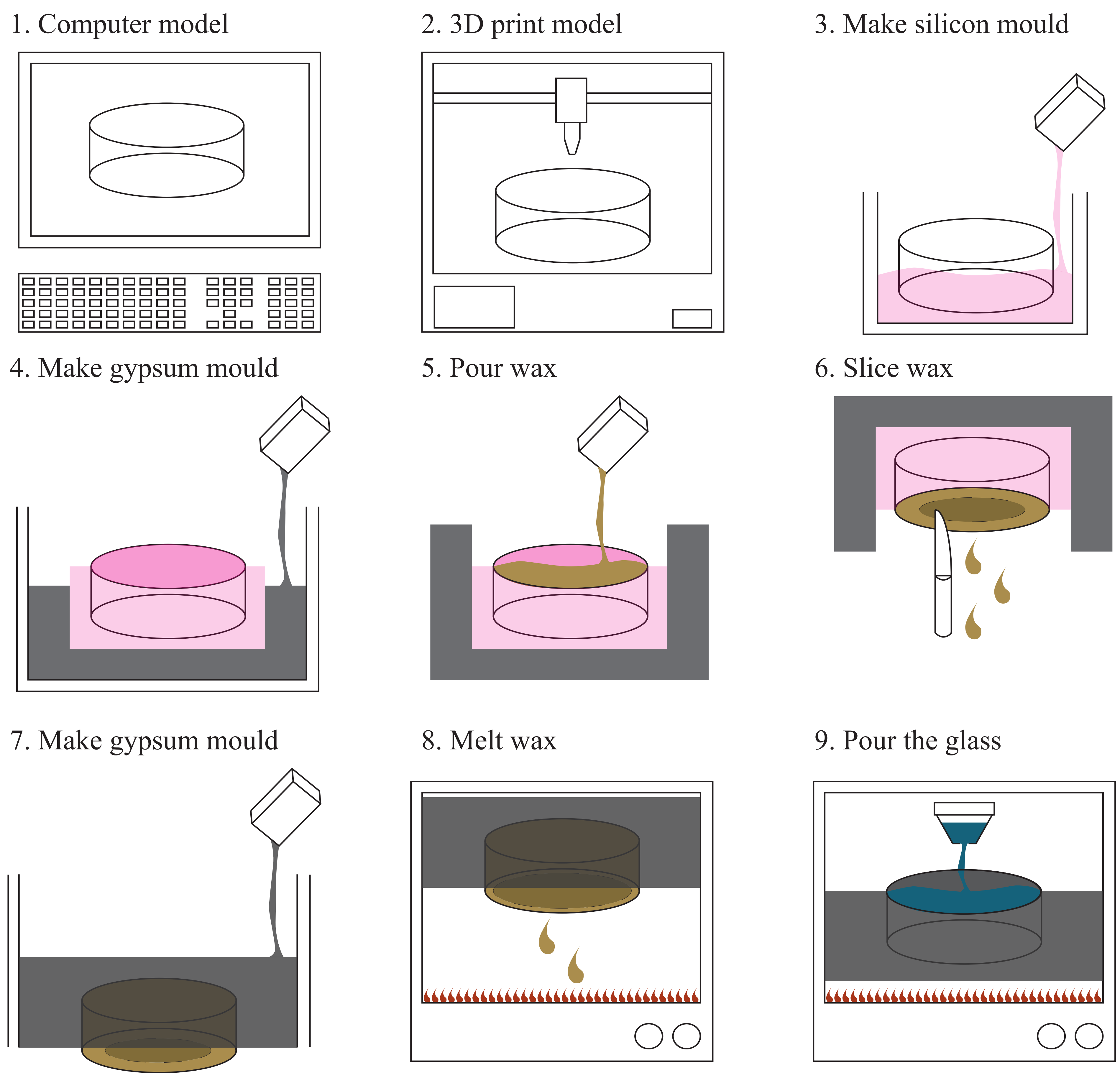


Figure 5.1 Making of glass

Figure 5.2 Making equipment

Figure 5.3 Equipment for sanded design

To make the rod feasible for the pulling machine, it has to be shortened. Also, an aluminum tube has to be glues around it with a wired rod attached to it, so that it is able to pull on it.

Sanded design

The research after connections gave us the connection of the Erlenmeyers and their stops. To make the project easier, cheaper and faster the decision was made to test these. This way there was no need to make new glass. It was however necessary to make aquipment to make the tests feasible.

This extra equipment is hand made and fits therefore perfectly. There are made aluminum holds for the stops and the tubes that are going to be used. These have again a wired rod at the end to use in the pulling machine.

Prototype manufacture

Making of the glass

The computer model

Melted cast glass can’t get in places smaller than 6 mm. This also means that it is hard to make very sharp edges, if the glass isn’t worked afterwards. In rhinoceros it is possible to filet the edges to get ahead of this problem. For further production of the glass the model is made half a cm higher for the kley to stick to the table. Make sure that the volume is not to much, in between 1 or 2 liters. This makes that the brick has to be cut. This is convenient for the tests, but it is nessecery that there is enough glass around so it won’t break.

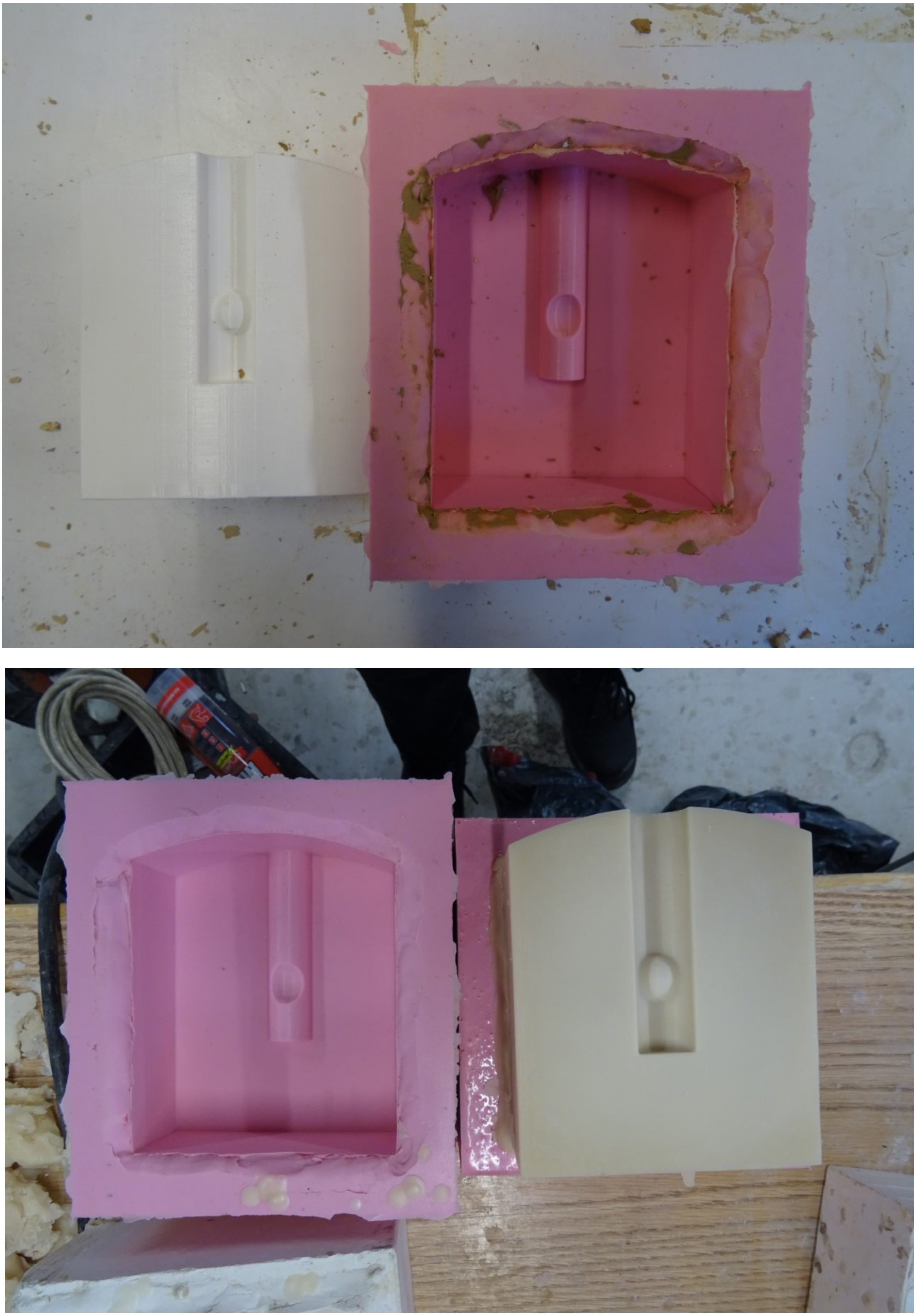


Figure 5.4 From 3D printed model, to silicon mould, to wax model

3D print the models
Place the models in the right way. This means that the bottom might shrink a little bit because of gravity. Also the round parts should be as round as possible. Every little groove is visible in the glass so make sure that the smallest noosle is used. If there are still a few mistakes, sand the model

Make the silicon mould
The 3D printed modelis cleaned and sprayed with Vaseline. Repeat 3 times with a 3-5 minute break. Now the model is clayed to a surface and space is left around it for the frame and the silicon. The silicon is a mixture with a 1:10 rate, stired well with a silicon cooking stirrer. This is cleaned afterwards because the silicon will stick to the other silicon. Because of the expanses, only one mould is made. The bulb can be sculped out of the waxen model.

Make the wax model
Normally a gypsum mould is made to make sure the shape doesn't change because of the weigth, but for this model there are put other moulds around it and it was made sure the silicon was thick enough. The wax is made into liquid and gotten out with a normal paper cup. The wax is filled all the way to the top with even a little overflow in the edges where the clay was. This is done so the wax model can be clayed to the surface again. This is done twice. For the second one the bubble is removed with a scalp. As said before the glass will show everything so the wax mould are looked at and the small imperfections are fixed with another sort of clay.

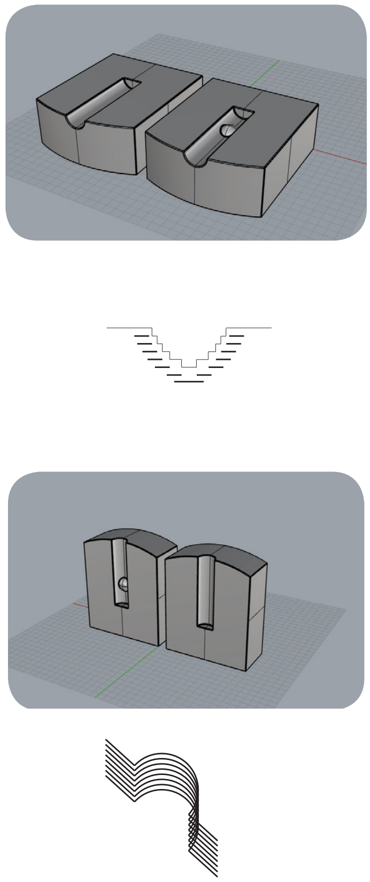


Figure 5.5 Print direction

Figure 5.6 From wax model to gypsum mould

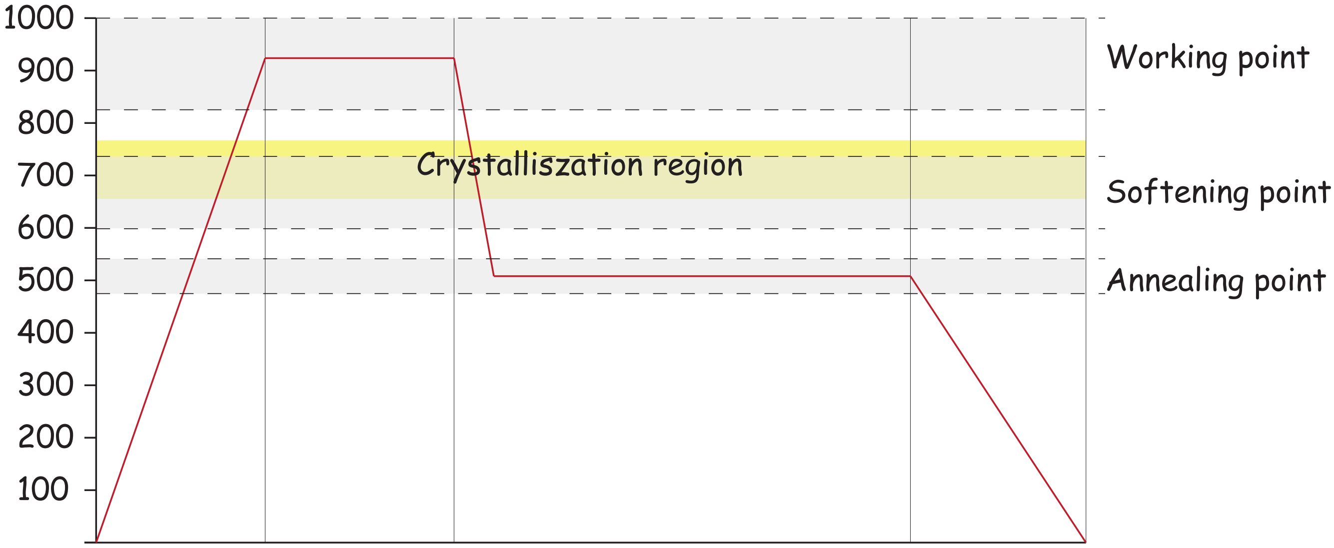


Figure 5.7 Glass temperature

Make the gypsum moulds.
The gypsum mould is made with plaster powder and water. The rate is 1/7. This actually dries quick so when it the plaster and the water is put together it has to be stired and poured within 10 minutes. After 1,5 hour this will be dry and it is possible to take the wax out.

Steam the mould
The wax will be removed by steaming it. In a bucket water and some brickes are placed. The would will be put upside down on the bricks. The steaming machine goes in, and it is necessary that the bucket is covered very well. The steaming process depands on how big of a model it is and how big the opening is where the wax can flow out. In my case the opening was very big so it did not take a long time.

How much glass
Beforehand there is a small calculation made on how much glass will probably be needed. This is done by multiply the volume times the weight of glass. You have to make sure you now take off the half a centimeter that was used to stick the clay. After this the mould is put on a scale and set to 0. Now water is added up until the part the glass needs to be. At this point it was decided to make the models a little bit slimmer because the calculations told us we would need too much glass. The water tells us the volume that the mould actualy did get so we can again do the calculations. Now that

Figure 5.8 From glass lenses to glass bricks

it is known how much glass is needed it is put a bucket on the scale and set it to 0 again. The glass that is used are lenses from SCHOTT. In the bucket is a plastic bag. In the back the amount of glass that is needed is put in.

Glass in the oven.

Because the mould is a very open one, it was not necessary to use the flowerpots. It was possible to just put the glass inside and let it heat up.

Remove the gypsum mould.

To remove the gypsum mould of the glass you have to put the whole thing in water. This will make the gypsum brittle and soft, so it is possible to just break it off.

Make the glass rod:

At first the thought was to make the rod with the hole in it by letting a hot steel ball slowly into the rod. This would mean that there should be a big mould all the way around the rod. At the end would be a little bit of space for the material that would be at the hole. After discussion it was decided that this was a little too much. So it was suggested that there would cut slices off giving it a sort of round shape. After this was done it was noticed that the ball would give a different shape than the slices. But is was still possible to use this rod to test the connection.

Figure 5.9 Removing the mould

Erlenmeyers

For the tests it was decided to experiment with Erlenmeyers with different peripheries. Also, a stopper and a glass tube were used for the tests. To perform the test, glue was used to fasten the Erlenmeyers to a wooden plank so that is can be fixed with glue clamps to the pulling machine. This is done with a 2-component glue which is very strong. To be able to pull the stoppers out of the flasks, there was an aluminum device designed. There where three different sizes of the stoppers so there are made three different "heads".
To pull the glass tubes an aluminum rod is glued into the tubes. This is done with an ultra violet glue that dries very quick and also very strong.

Experiments

As said the tests for the sanded design are done with Erlenmeyers, stops, tubes and a pulling machine. The machine is set to give the results for the forces in Newton and the displacement in mm. To give an idea of what the results tell us it is needed to know that 100 Newton is 10 Kilos. Also, for a typical Dutch building the wind-load on a wall is calculated with 1 kN/m2.
There are four different sizes of Erlenmeyers used to give as many results as possible. On the next page there is a visual of the names that where given to them.

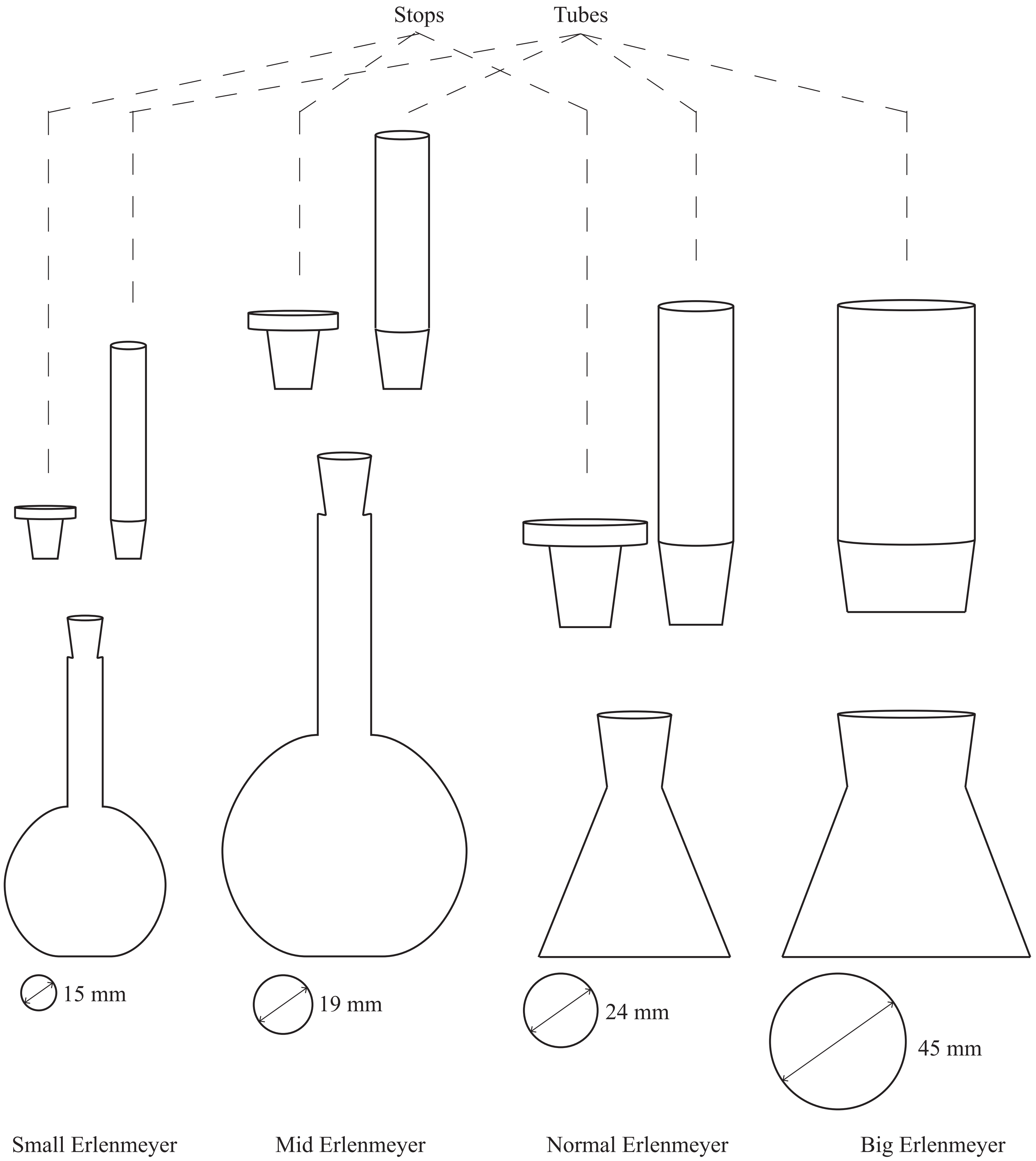
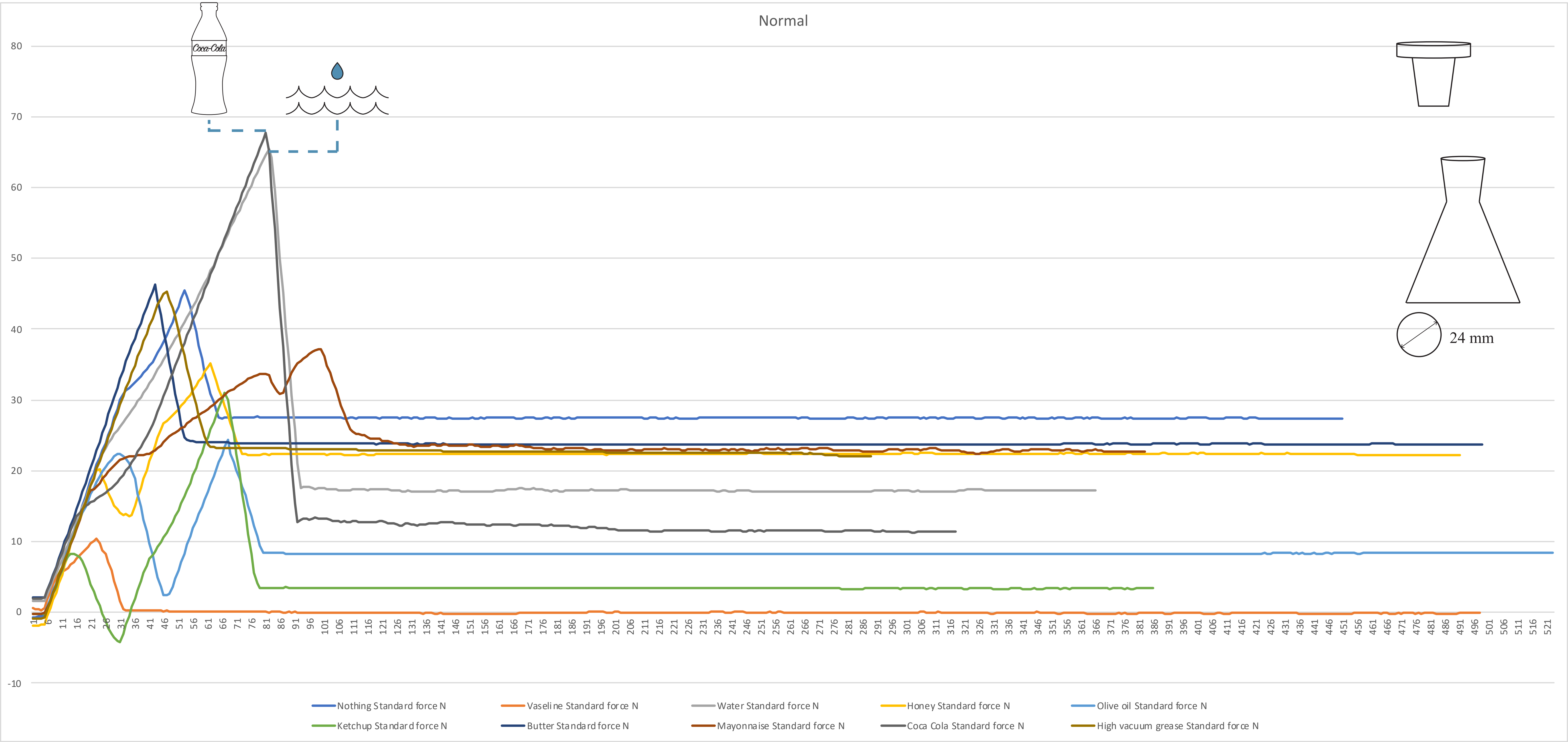


Figure 5.10 Different used erlenmeyers

Figure 5.11 Test set up, sanded design



The first tests that are done were to see how different liquids would behave when in between two surfaces of glass. Some of the liquids are known for their ability to stick very good, others to vacuum the space in between.
Looking at the peak forces, Coca Cola and water work the best. These are both water based. These test results gave the idea to do the next experiments with water-based liquids.
In this figure it is visible that Coca Cola works a bit better than water. The reason behind this could be sugar. Sugar gives water a different viscosity what can relate to the better results. This is worth testing.

Water is a very interesting substance in many ways. For instance, it expands when getting colder. Normally molecules move faster when they get hot and slow down when cooled. This makes that materials expand when heated and shrink when cooled. Water expands when it is frozen because of hydrogen bridges. These are attractions between the positive side of the water molecule and the negative side. This comes from the shape of the molecule. The molecule consists of one oxygen and two hydrogen atoms. The hydrogen atoms are arranged in an angle of 107o. This makes that the molecule is uneven. The hydrogen bridges keep the molecules apart when it is frozen.

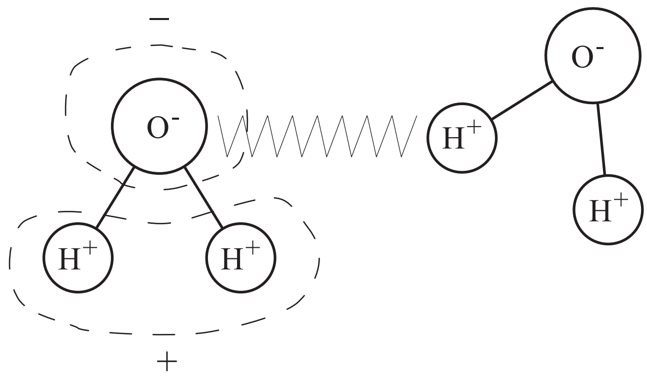


Figure 5.12 Hydrogen bridges

Salt is a water-soluble substance. It consists of Natrium and Calcium. The positive and negative side of the water molecule plays again a big role in this process. The positive part attracts to the negative loaded Calcium atoms and the negative part to the positive loaded Natrium atoms. Because there is a lot of the attractions between the water molecule they take the salt atoms apart.

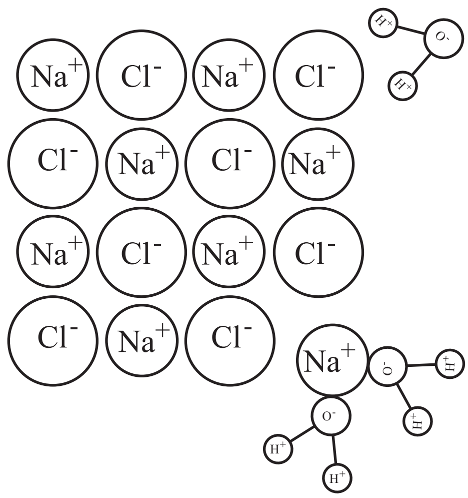


Figure 5.13 Behaviour of salt in water

Glass consist as said mostly of Silicon, Oxygen and Natrium and has as said an amorph pattern. When in contact with water, the water molecules can again attract the Natrium atoms. This causes negatively loaded oxygen atoms to be exposed. Water can in this case make hydrogen bridges with these atoms.

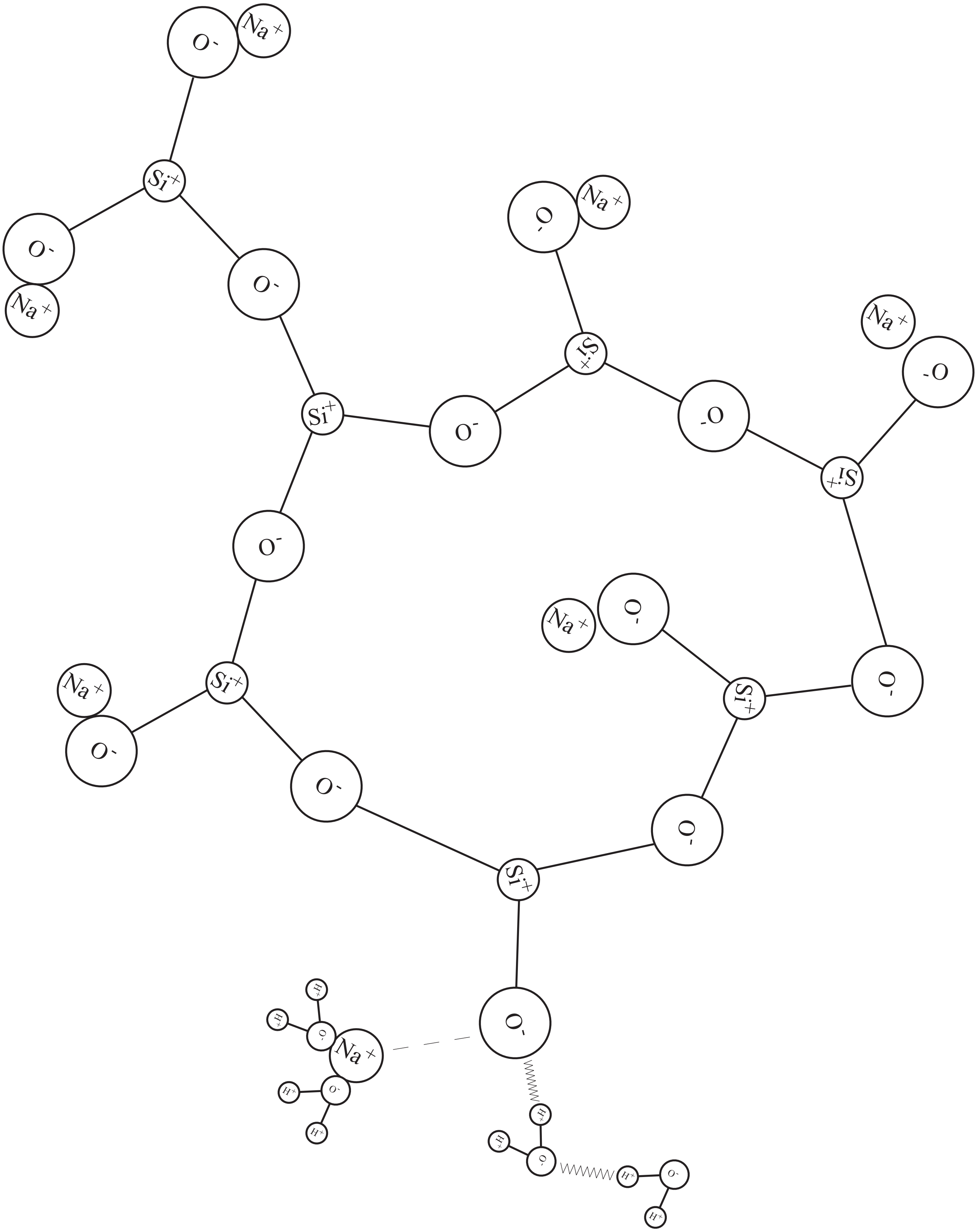
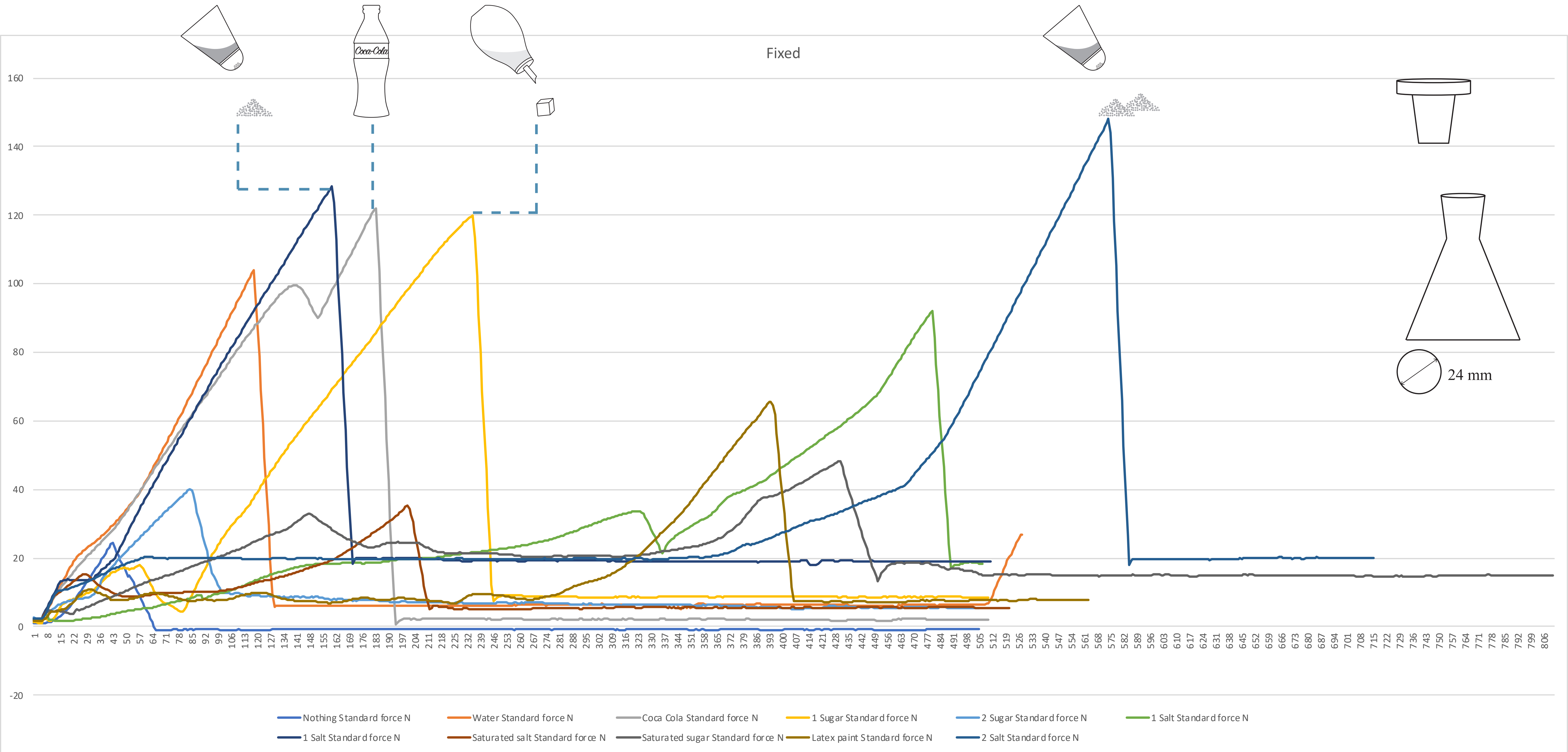
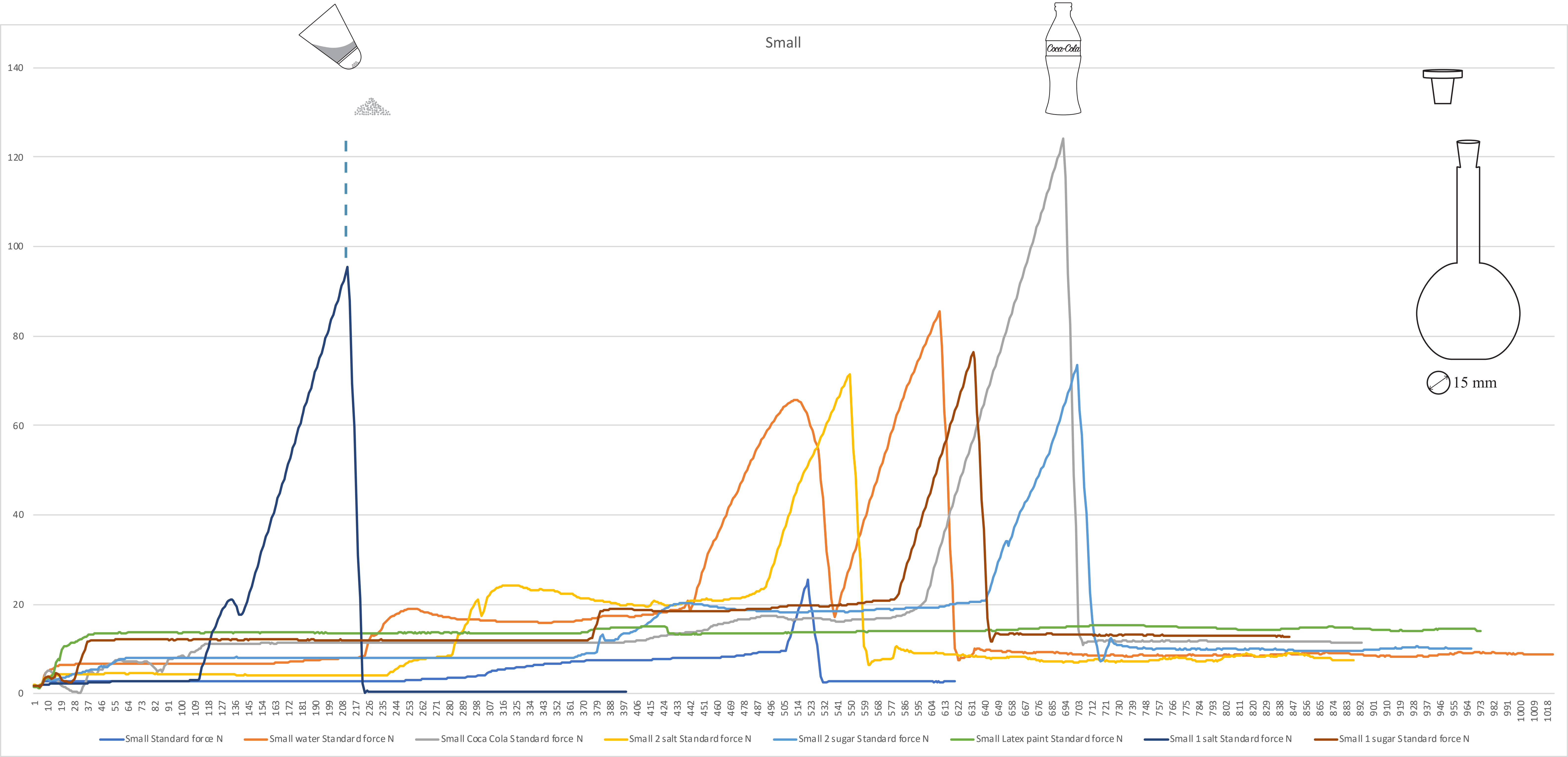


Figure 5.14 Behaviour of salt water and glass



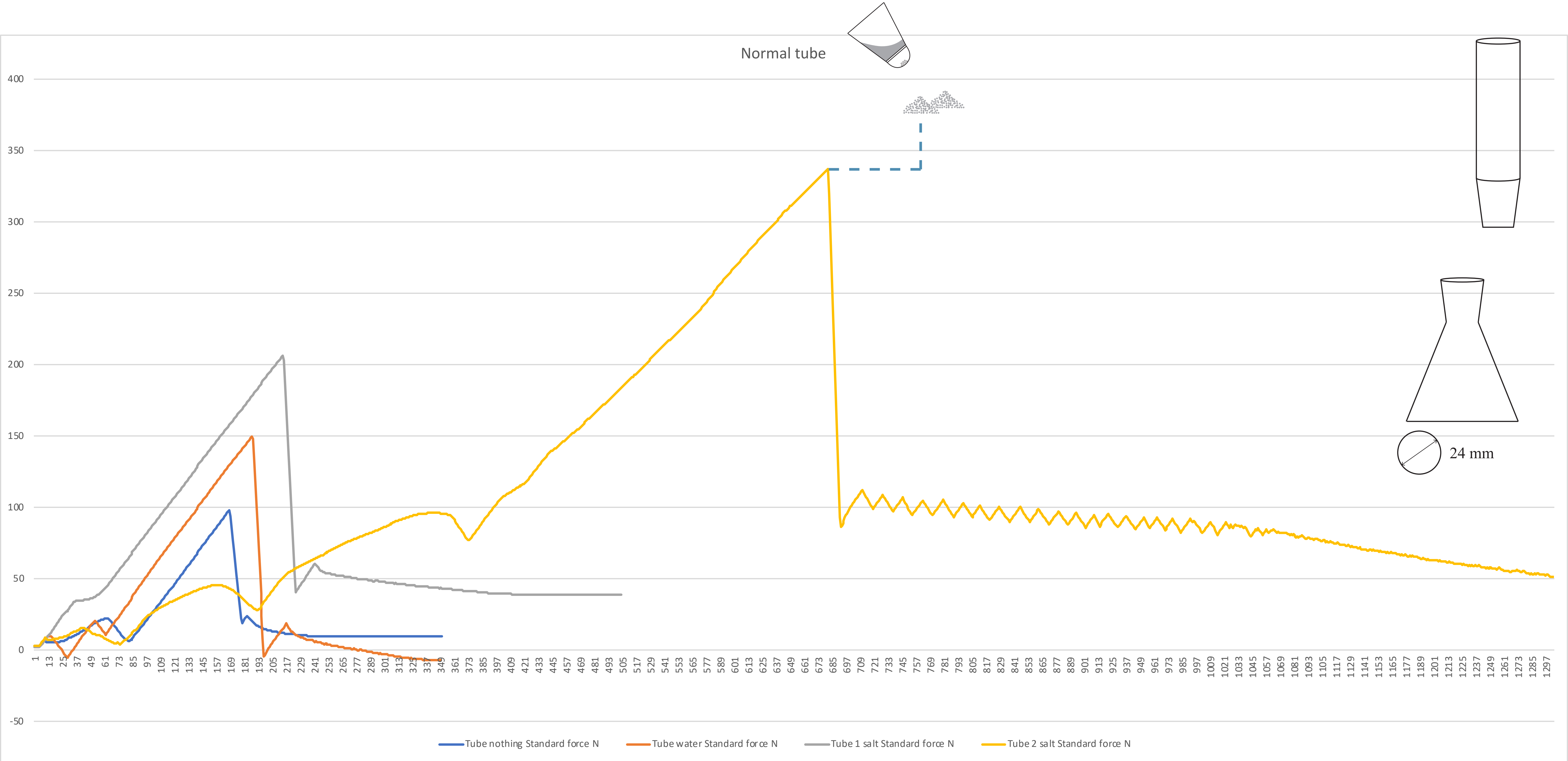
During the second test session the stops are pushed into the Erlenmeyer. This way the frozen connections that are explained before are imitated. The forces will for this be higher than the previous tests.
Visible in this graph is that two bags of salt work very well. One bag of salt is also performing fine. Water with 1 bag of sugar and Coca Cola work just as good. All the better working liquids are around 130 N. This is higher than the first tests, but still not workable in a construction.
Saturaded salt doesn’t work at all, because all the water molecules are already atracted to a Natrium or Calcium ion.

The next set of tests is done to see if there is a difference when it comes to surface. An Erlenmeyer with a slimmer neck is used. The amount of surface is less what might give lower results, due to less contact friction.



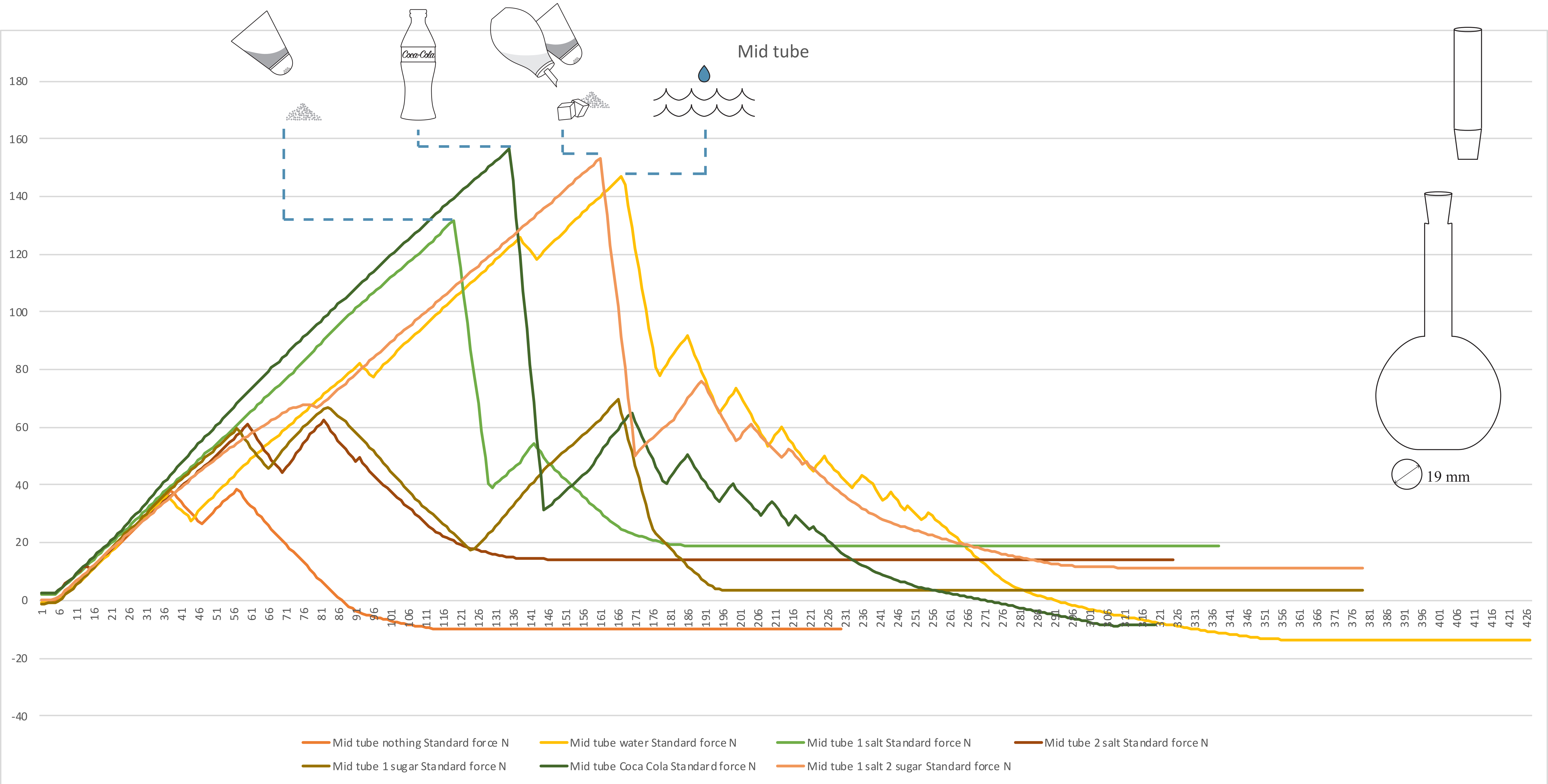
Here Coca Cola works the best. It works almost as good as with the bigger neck. The rest of the liquids work less good. The second one is 1 salt. What is weird is that 2 salt don't really work here. This might be because there is less surface the water with salt can connect to

The next tests will show us if a tube behaves differently than a stop.

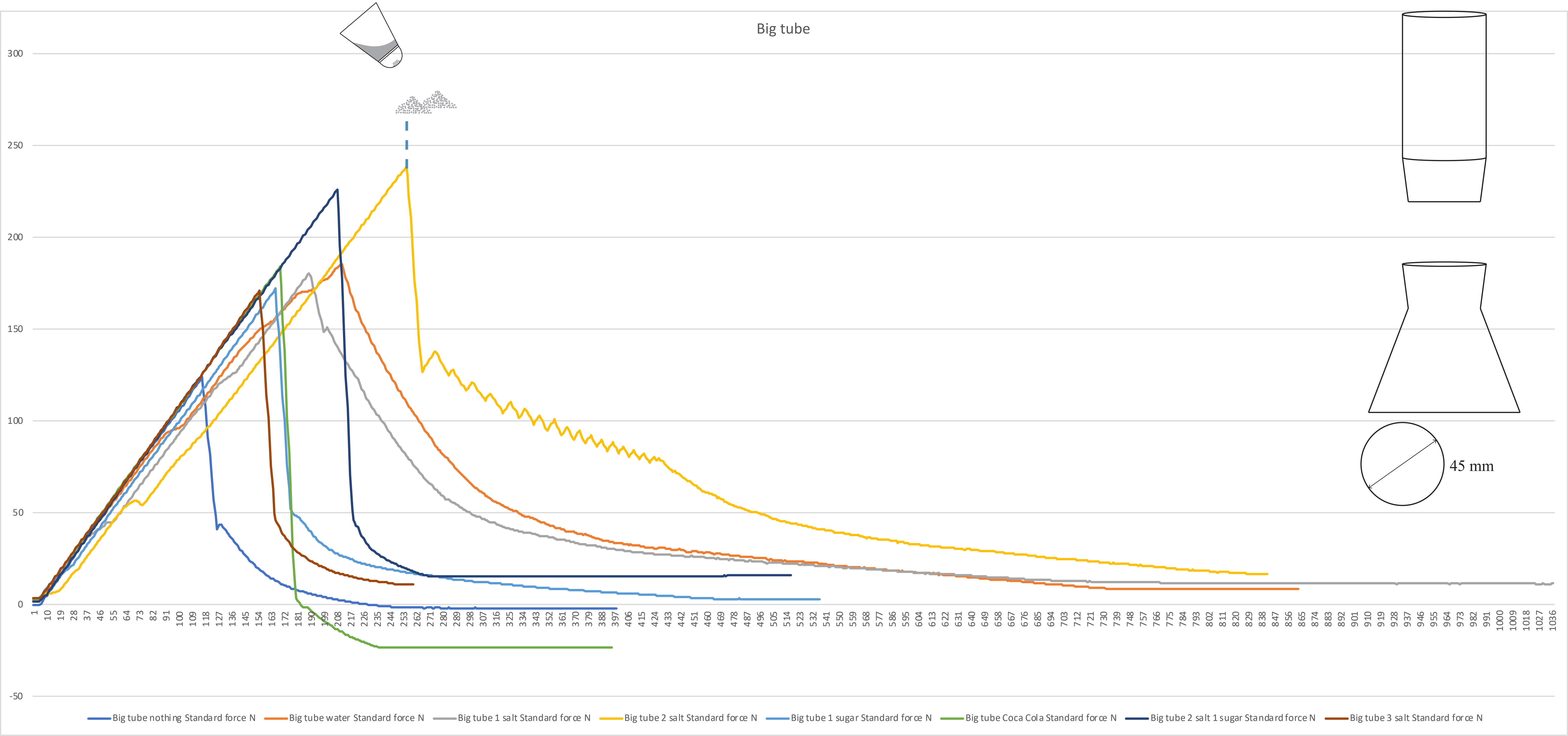


During this set of tests the last Erlenmeyer with these sizes broke. This means that there are not many results. It does give the new record. Again 2 bags of salt work well and give us a result of around 320 N, So, around 32 Kilograms. The results also show that a tube seems to be working better than a stop. This can still be because of many reasons. For instance, it was signifyingly warmer that day, than the previous test days.

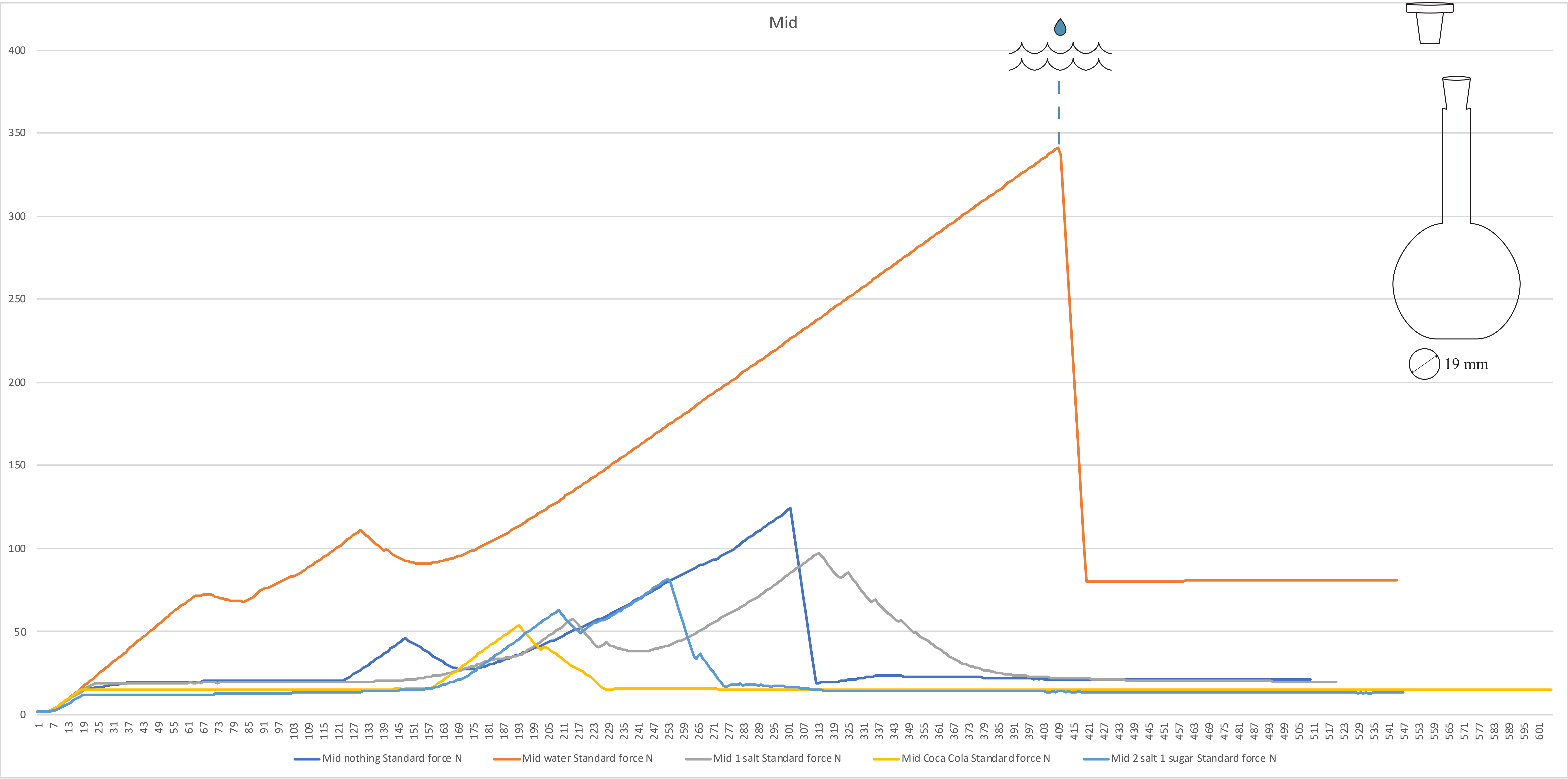
The next test will be done with a Erlenmeyer with sizes that are close to this one. This might give results that can be compared to the first stop tests.



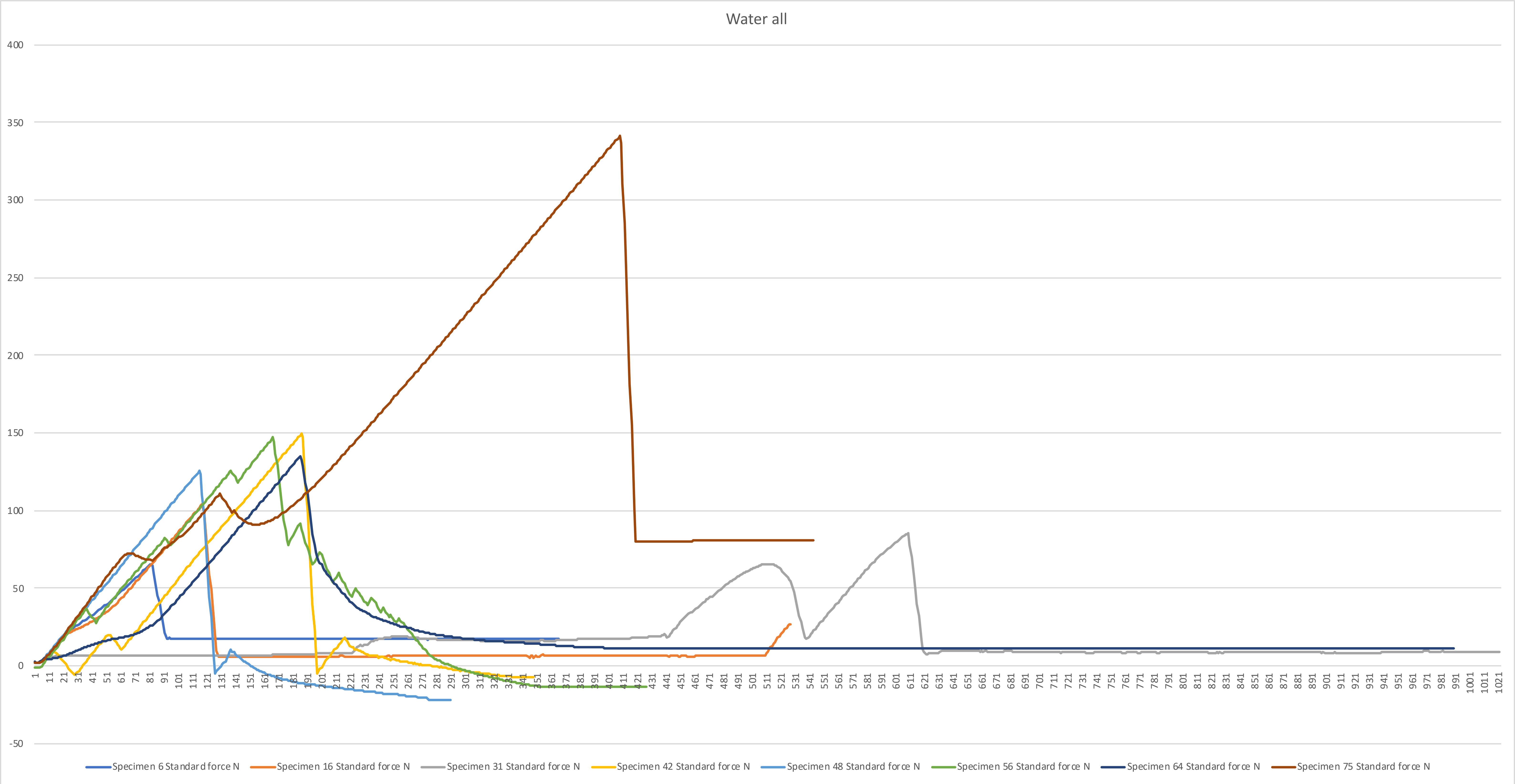
The results are not very promising. The top results give a maximum force of 150 N. It does stand out that 2 bags of salt didn't work well. This might still be because there is less surface. Because salt and sugar are giving pretty well results, the thought occurred to combine these two. Maybe, when the water is made less aqueous and eclectically charged with the salt, the results would increase.
This did give one of the better results, but not higher than others that perform good.



To look at the differences in results compared to the amount of surface, there are tests done with a bigger neck. This means that there now 3 sizes to compare. The results are higher than the small tube, and it stands out that 2 bags of salt again works well. This approves the theory that there is now again more surface to hold on to. Because this also has more surface than the normal Erlenmeyer there is a test done with three bags of salt. This is apparently to much salt.



The mid Erlenmeyer has the closest diameter to the real rod. It is good to properly test this one. That is why even though the tests with the tube gave a better result than the stop ones, the stops are still tested. These tests did show surprising results. Water gave an extremely good result and second in line is nothing.
The results depend on a lot of different things, but to try an explanation for these results, the glass of the mid Erlenmeyer and the tube and the stop will be tested.



Even though there are more than 80 tests done, it is hard to give a conclusion. Water gave a pretty constant result. So, this graph shows how all the different sizes worked with water. One of the conclusions that can get out of this, is that it is possible to get a high result like the 350 N. It is just not a constant result. It is better to assume to get a result around 150 N.

Figure 5.15 Breaking glass

To try to explain the different results a glass test is done. For this test is was necessary to have a flat glass surface of 5 cm or powdered glass. All our samples where round so to get powdered glass we had to break it. To make sure the glass wouldn't go everywhere when broken a towel was used.

At 3mE there is a machine that can see what the glass is made of by the use of a laser.

Results glass test

Materials Science and Engineering
TUDelft, Faculty of 3mE
Mekelweg 2
2628CD Delft, The Netherlands
Tel. 015 27 82244/89459
Email: R.W.A. Hendrikx@tudelft.nl

X- ray diffraction facilities

Experimental conditions:

For XRF analysis the measurements were performed with a Panalytical Axios Max WD-XRF spectrometer and data evaluation was done with SuperQ5.0i/Omnian software. 18/12/2015 09:37:03

25/05/2018 13:27:15

PANalytical

Quantification of sample Veerle, sample "colf" 25may18

Sum before normalization: 64.0 wt%

Normalised to: 100.0 wt%

Sample type: Pressed powder

Initial sample weight (g): 2.000

Weight after pressing (g): 3.000

Correction applied for medium: No

Correction applied for film: No

Used Compound list: Oxides

Results database: omnian 4kw 27mm

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	SiO2	81.291	0.1
2	BaO	9.4	0.09
3	Na2O	4.698	0.06
4	Al2O3	3.617	0.06
5	As2O3	0.528	0.02
6	Fe2O3	0.152	0.01
7	Cl	0.102	0.01
8	CaO	0.089	0.009
9	K2O	0.059	0.007
10	SO3	0.024	0.005
11	SrO	0.018	0.004
12	ZnO	0.011	0.003
13	P2O5	0.011	0.003

The results don’t show the difference between Boron and Silica. The previous tables show that silica glass only has 75-80% silica. This means that this is Boron-silicate glass.
The difference between these pieces of glass lies in the Na2O. This is a 1% difference. Because it only contains around 5% this difference is around 20%. This might explain the different test results.

25/05/2018 13:29:23

PANalytical

Quantification of sample Veerle, sample "stop" 25may18

Sum before normalization: 48.5 wt%

Normalised to: 100.0 wt%

Sample type: Pressed powder

Initial sample weight (g): 2.000

Weight after pressing (g): 3.000

Oxygen validation factor: 0.00

Correction applied for medium: No

Correction applied for film: No

Used Compound list: Oxides

Results database: omnian 4kw 27mm

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	SiO2	91.736	0.1
2	Na2O	5.263	0.07
3	Al2O3	2.258	0.04
4	Cl	0.184	0.01
5	ZrO2	0.097	0.009
6	Fe2O3	0.09	0.009
7	CaO	0.079	0.008
8	MgO	0.074	0.008
9	K2O	0.051	0.007
10	SO3	0.05	0.007
11	CeO2	0.042	0.006
12	TiO2	0.028	0.005
13	P2O5	0.019	0.004
14	Cr2O3	0.012	0.003
15	CuO	0.008	0.003
16	ZnO	0.007	0.002
17	SrO	0.002	0.001

25/05/2018 13:30:48

PANalytical

Quantification of sample Veerle, sample "tube" 25may18

Sum before normalization: 53.5 wt%

Normalised to: 100.0 wt%

Sample type: Pressed powder

Initial sample weight (g): 2.000

Weight after pressing (g): 3.000

Oxygen validation factor: 0.00

Correction applied for medium: No

Correction applied for film: No

Used Compound list: Oxides

Results database: omnian 4kw 27mm

Results database in: c:\panalytical\superq\userdata

	Compound Name	Conc. (wt%)	Absolute Error (wt%)
1	SiO2	92.154	0.1
2	Na2O	4.158	0.06
3	Al2O3	2.725	0.05
4	K2O	0.542	0.02
5	Cl	0.101	0.01
6	ZrO2	0.09	0.009
7	Fe2O3	0.071	0.008
8	CaO	0.059	0.007
9	MgO	0.037	0.006
10	TiO2	0.026	0.005
11	SO3	0.026	0.005
12	P2O5	0.01	0.003

Conclusion

The highest results of these tests were around 150 N this is around 0,15 kN. A standard that is set for wind is 1kN/m^2. This means that the connection will probably not be strong enough o hold a wall. Under some circumstances is might be possible, but there needs to be found out how much forces it exactly has to hold. For now it showed that there definately is a connection, but not for this design. The connection can be used for for instance a coffeetable.

Figure 5.15 Glass coffee table

Test results profiled design

With polarized glasses it is possible to see the stresses in cast glass. Most imperfections are already visible in the pictures, but some bigger stresses were only visible with the glasses on. In the pictures from the front and the back, we see that there is something strange going on with the three circles. In the pictures below, you can see that there are a lot of stresses because of the thickness. This might actually be a problem because these are only parts of bricks. When the bricks get bigger it is likely to get more stresses.

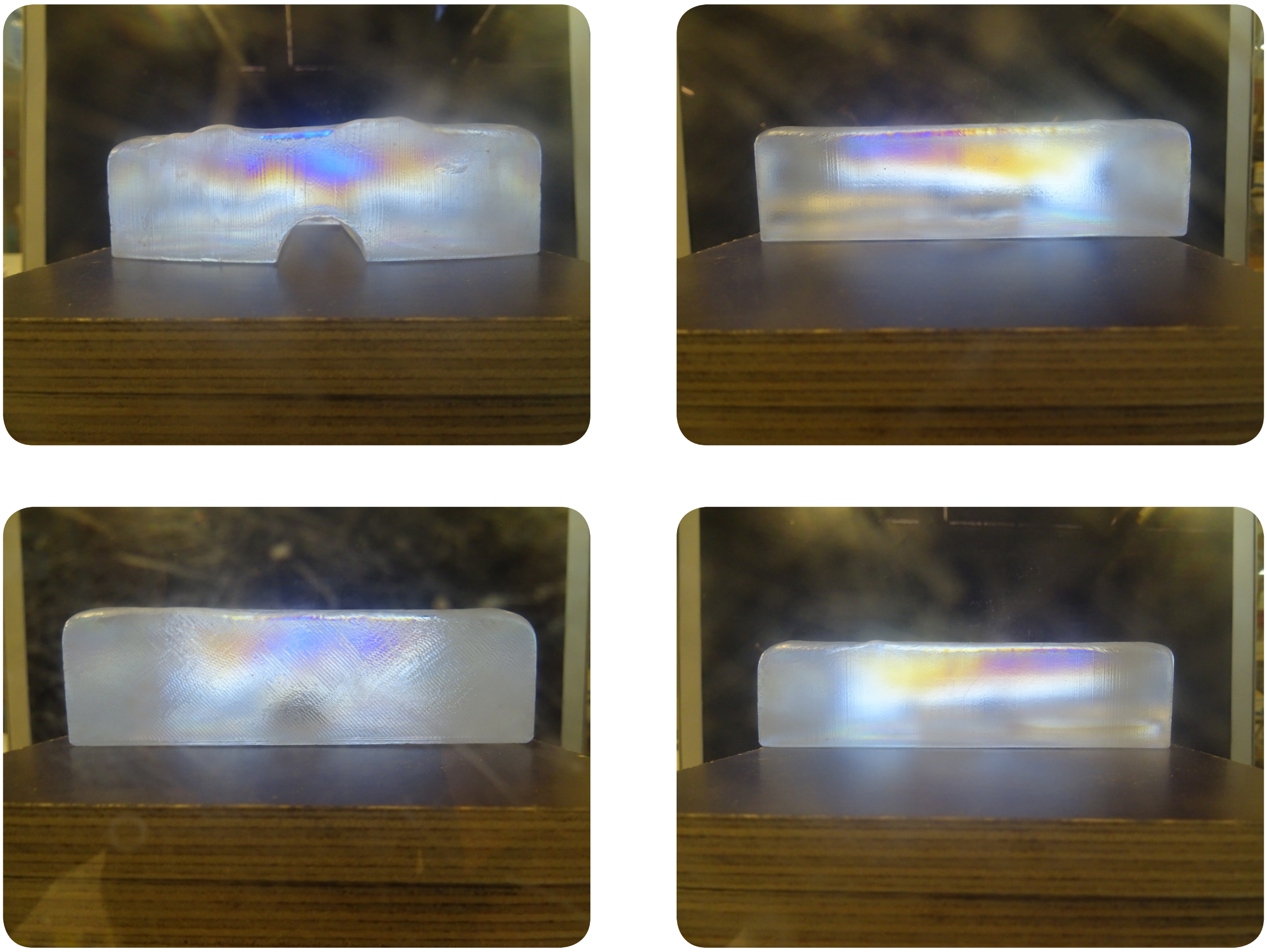


Figure 5.16 Stresses in glass brick

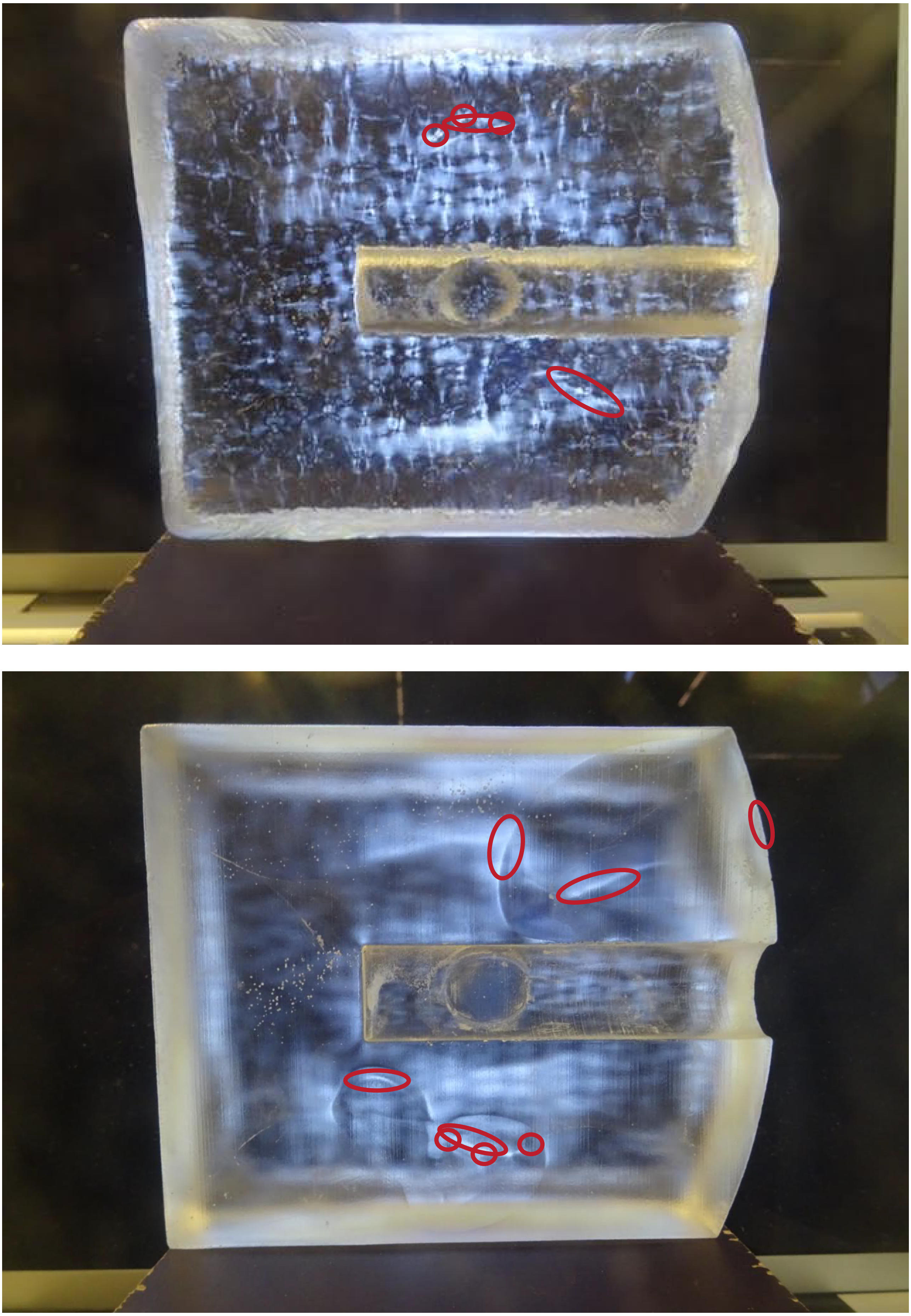


Figure 5.17 Stresses in brick

This part of the brick is less thick, and it is visible that is has less stresses. The reason for this, might be the way of casting, because other, bigger, bricks have less stresses. The other brick mostly use the flower pot process. Because the mould was a very open one, we decided to put the glass already in.

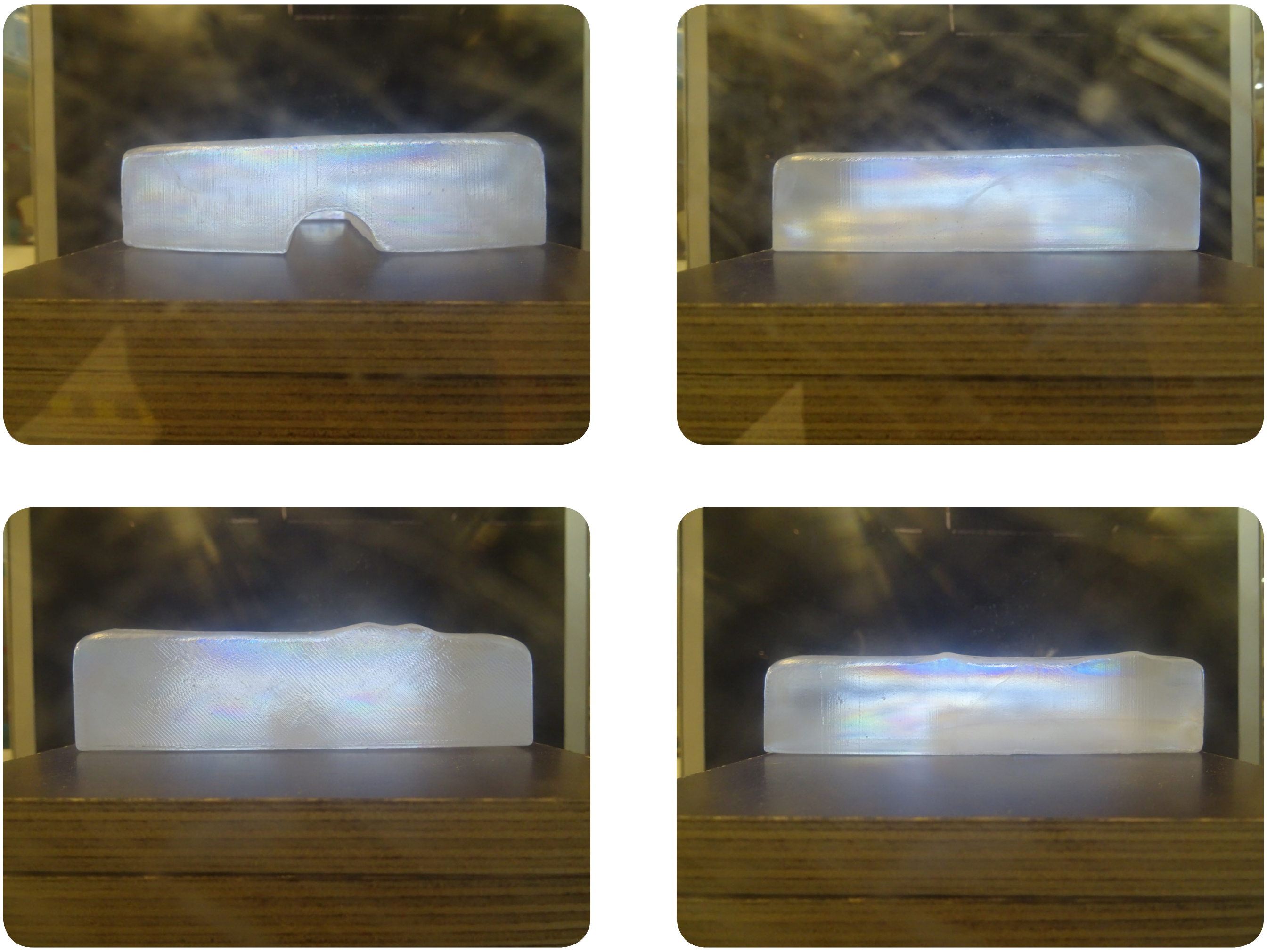


Figure 5.18 Stresses in brick

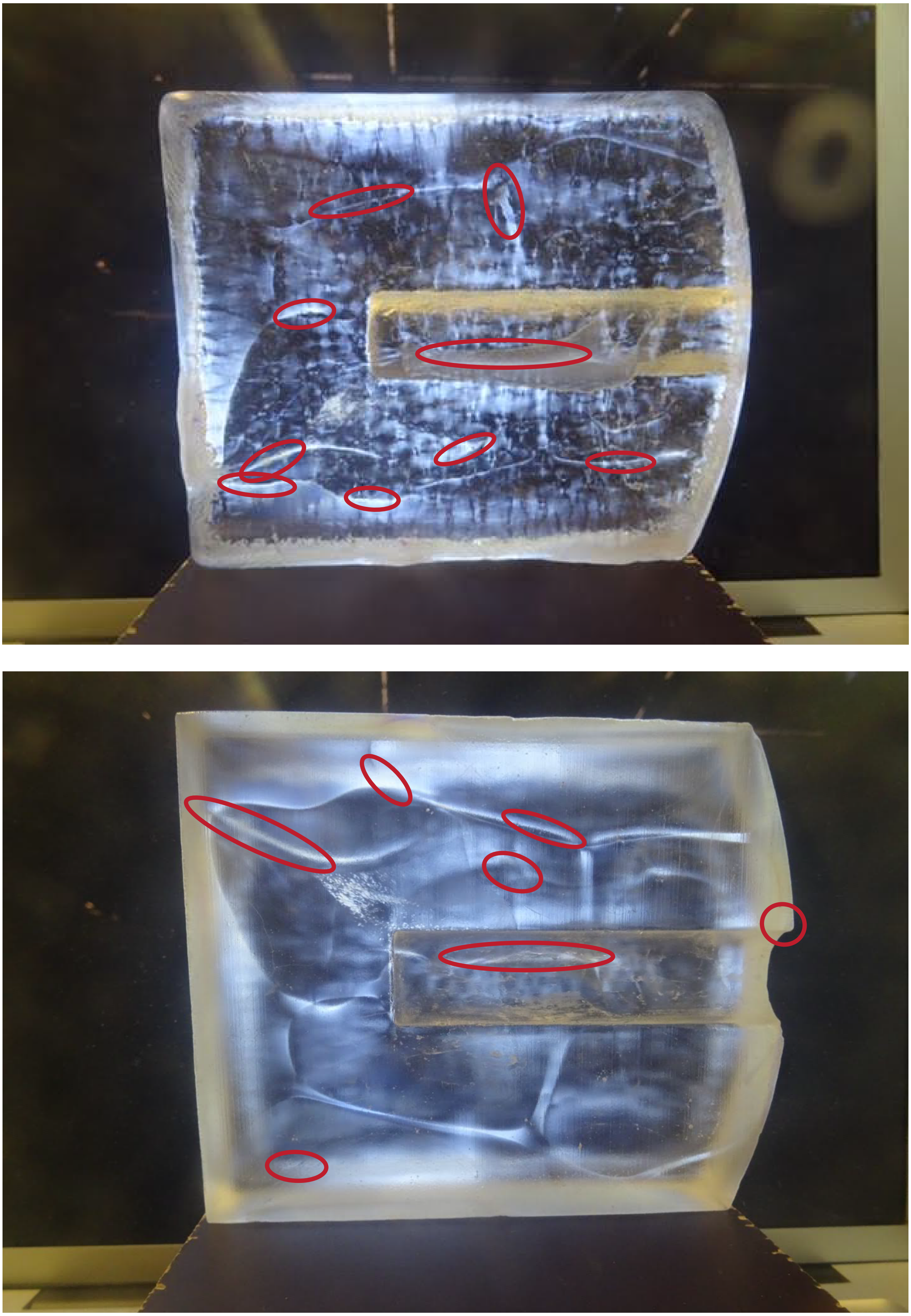


Figure 5.19 Stresses in brick

Here is clearly visible that the thicker brick has more stresses than the thinner one.

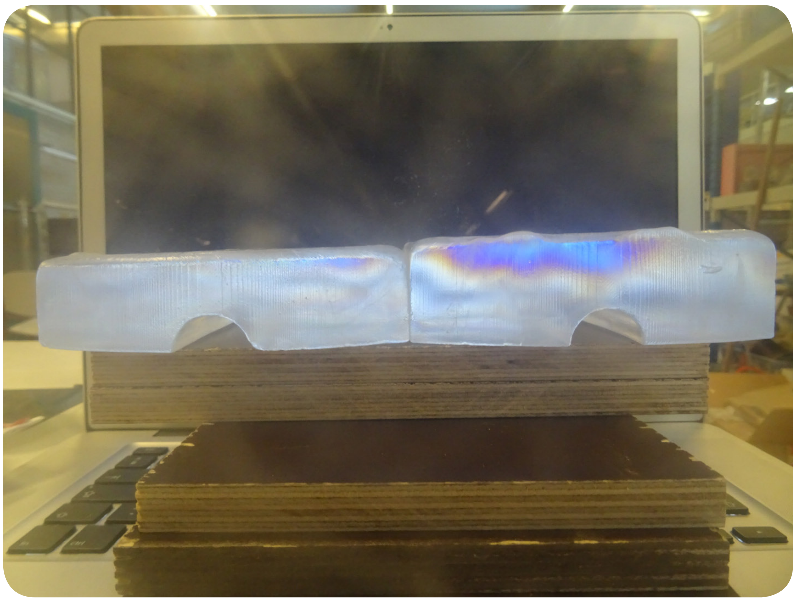


Figure 5.20 Stress comparison

In this picture you can see that the surface got convex. Normally this is because of the cooling process of the glass, but in this case it is more likely that it is because of the wax model

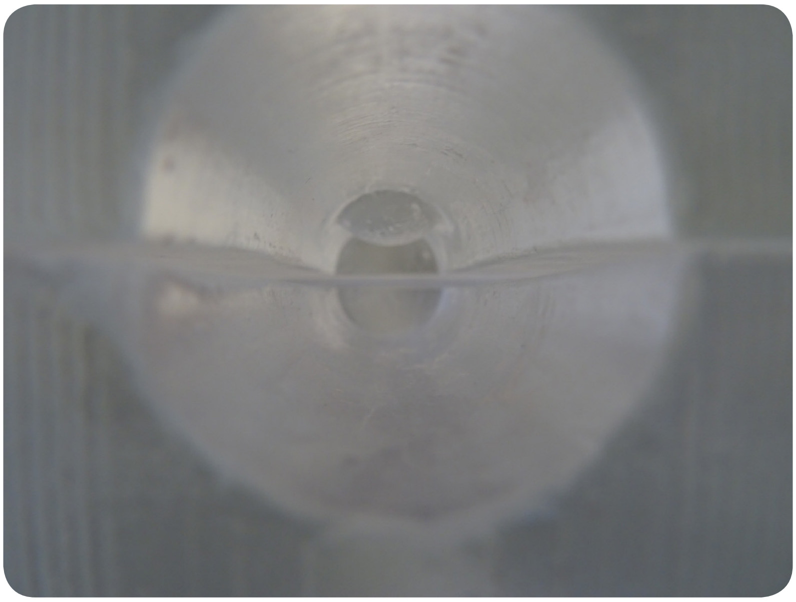


Figure 5.21 Convex

It is not the cleanness fix, but the bricks fit and even the rod is able to go in as well.

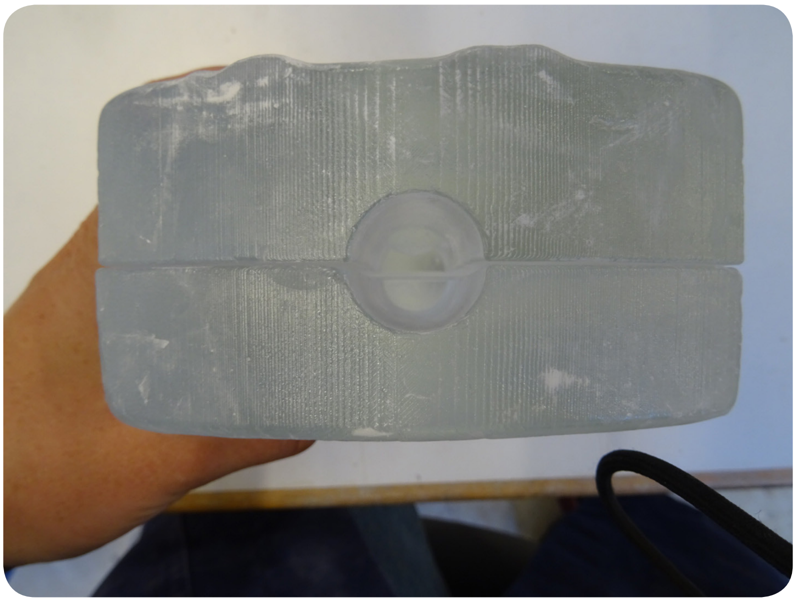
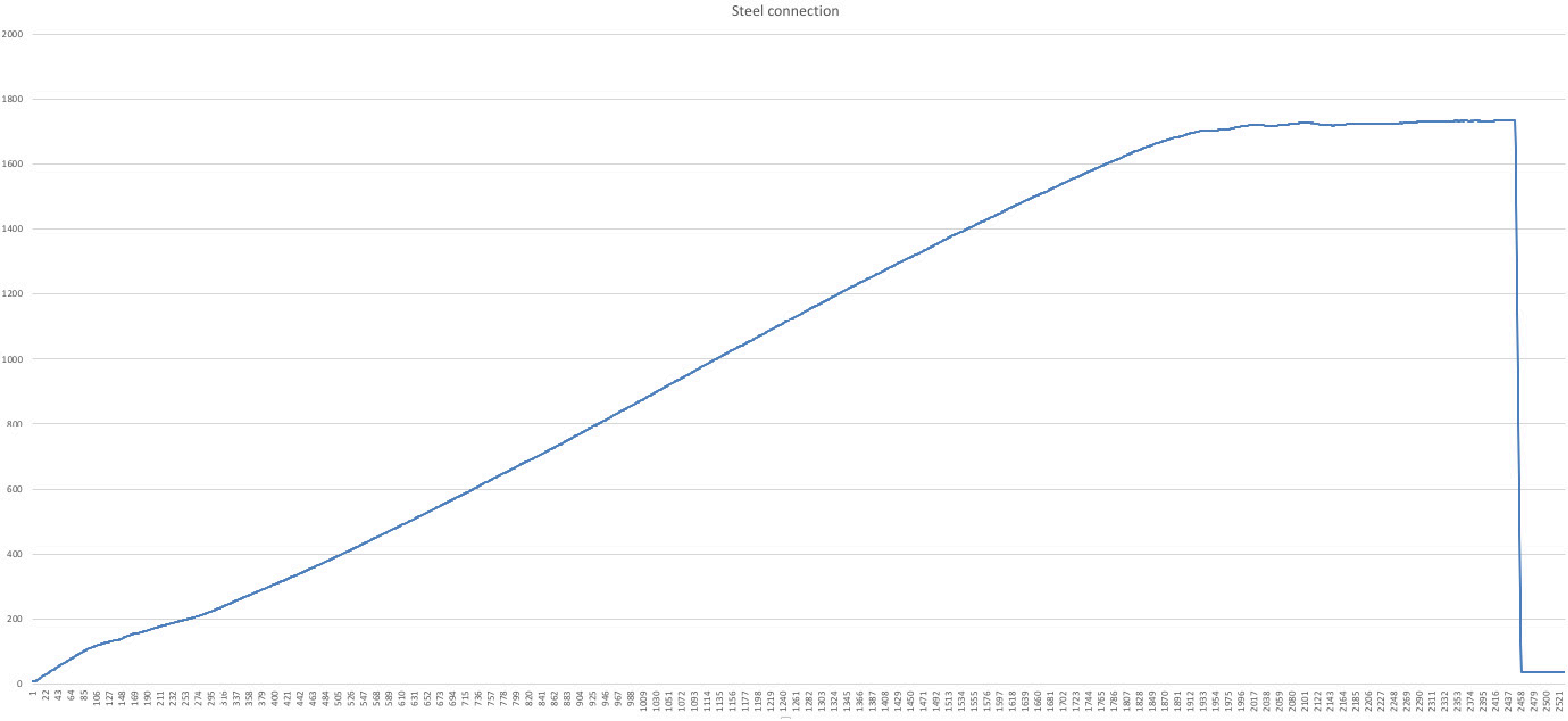


Figure 5.22 Imperfections

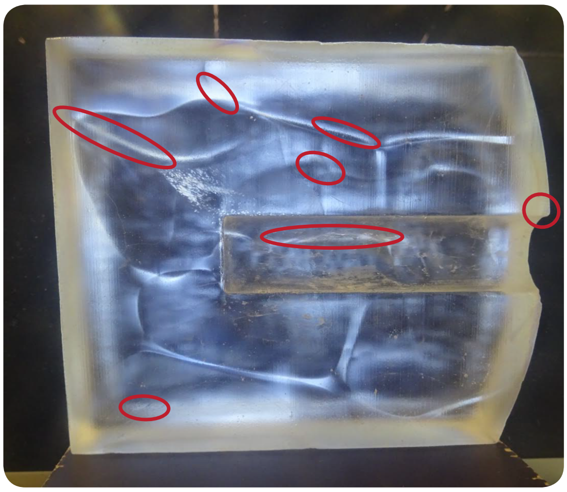
Figure 5.23 Test set up profiled design



The first tests that are done with this design is done with a glass rod and a steel connection piece. The results were higher than the sanded design. The problem with this test was that the prototype broke where the glass rod was connected with the steel connection piece. This was not a part of the connection we wanted to test.

Breakage of connection

Even though the components stayed struturaly whole, there was a piece chiped off. To know why this cracked here there is looked at the previous stress analyzes. Here is visible that there was indeed a weak spot.



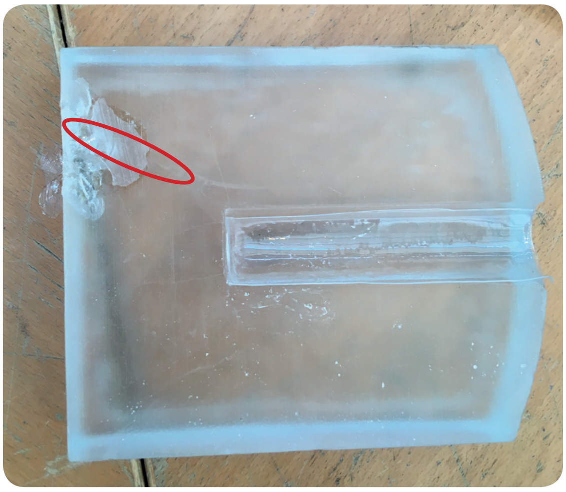
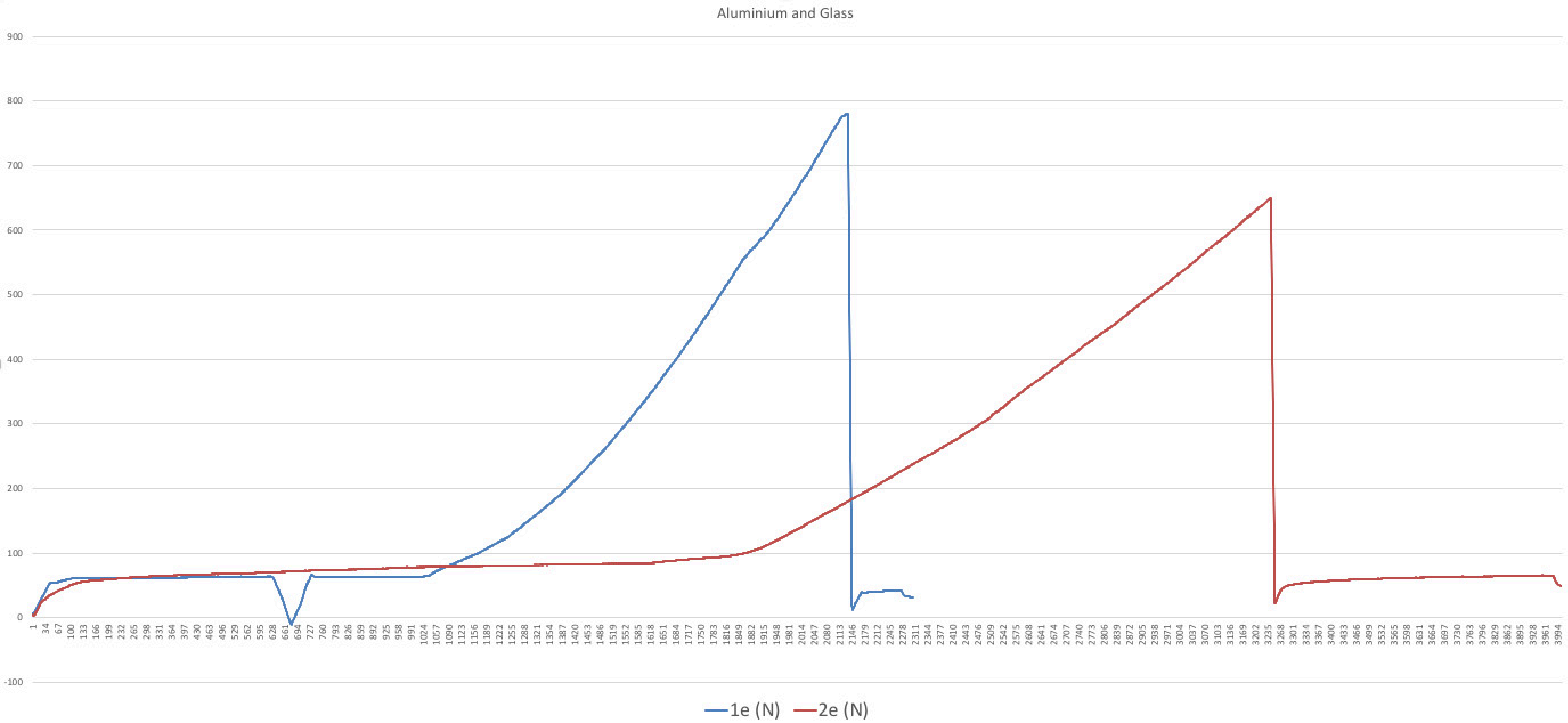


Figure 5.25 Breakage of connection

Figure 5.24 Stress compared to crack

Figure 5.26 From steel connection piece to an aluminum one



To make sure the prototype wouldn't again break at this point, an aluminum connection piece is made. This and also making the length of this piece longer will cause the tension difference in the glass to decrease. This will hopefully dissolve the problem.

The results of this test were actually disappointing. Because these were even lower than the previous test, there was looked for another explanation. The first thing that came to mind was the finish of the hole in the rod.
The hole is made by sawing of slices. This leaves sharp edges and imperfections. It is also visible that this is where the rod broke.

Breakage of the rod

Figure 5.27 Breakage of the rod

Figure 5.28 Imperfect hole

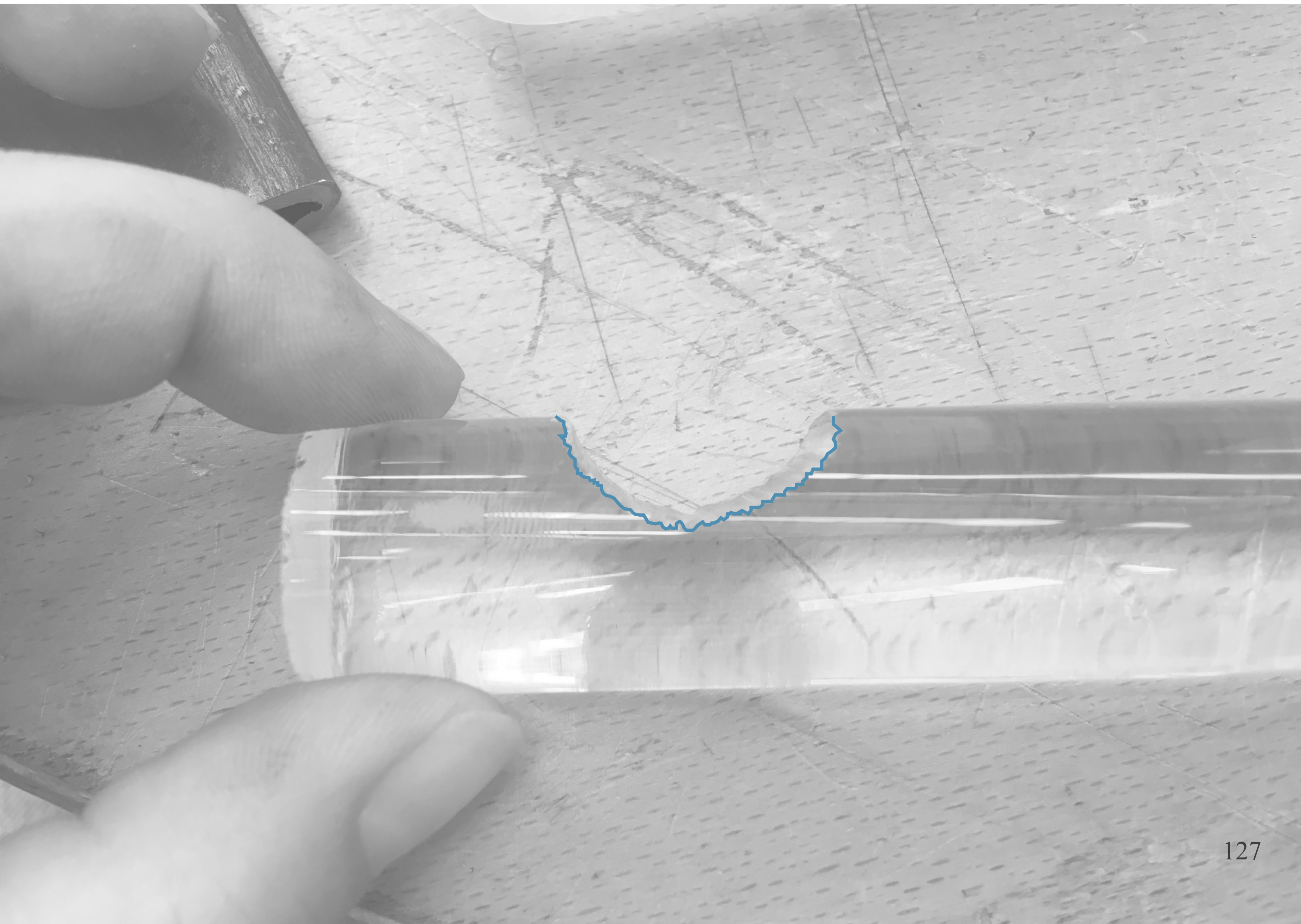


Figure 5.29 From aluminum plus glass connection piece to an all aluminum one

There was not enough time to make a new rod that had a better finishing. This made the decision to make an all-aluminum rod, to test what loads can be put on the bricks.
The results for these tests were the highest of all the tests. Still there occurred a problem. The test set up, was not strong enough to withstand the forces. The glass bricks did not break, but they moved. For the second test the glue clamps were tightened, but the bricks still moved.

Figure 5.30 Movement of brick

Figure 5.31 Microscope on glass brick

Studies after the surface crack behavior of glass is well documented. The crack front spreads through the material and makes a fraction features known as mirror, mist and hackle. The first flaw origin spreads into a mirrorlike breakage. However, after the breakage fastened the fraction is unstable and causes a dimpled surface that is named mist. This instable behavior causes that the fracture branch out creating the rough hackle region. The hackle marks point to the origin flaw.

Looking at the component through a mis-croscope, showes that these small flaws caused the component to fracture.

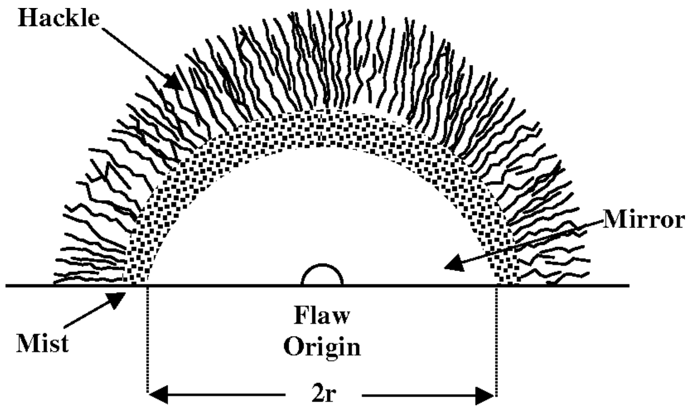


Figure 5.32 Mirror mist and hackle breakage

Figure 5.33 Mirror mist and hackle breakage in brick

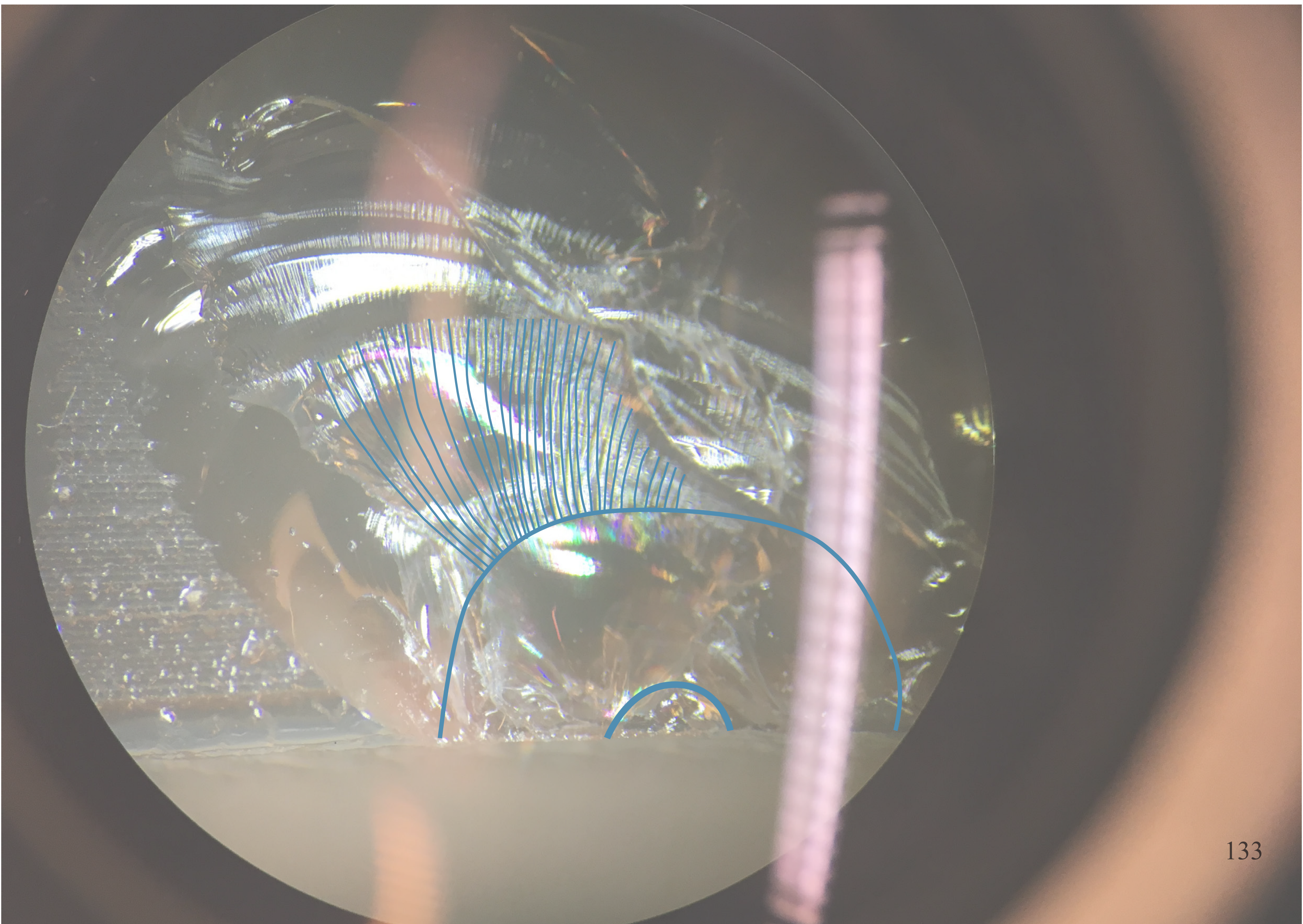


Figure 5.34 Impression of increased usage of rods

Conclusions

The test results show that the profiled design is a better connection. Even though the tests it is still unclear how the connection exactly will behave, the forced it could withstand were fine. With the profiled design it is possible to make a strong connection.
These results gave a maximum of 2 kN. For wind a standard is set for 1kN/m^2. This means that the design is already possible, but with more rods as is shown above.

Reccomendations

For the next tests it is nessecery to finish the rods properly. It might be needed to produce the rod in a different way so that the edges will be smoother.
If the glass bricks are interlocked with each other as well the bricks will move less. It is then nessecery to test the shear stresses in these bricks.
To better the connection it is a possibility to make an extra hole and bulge. This will divide the forced over more surfaces. The problem with this will probably be the rod. If it is made thinner at two places, it will be more fragile at two places.

Figure 5.35 Used test material

list of figures

6 Feasibility

This chapter will show how the whole design is build. The choices that are made during this research are taken back to the original idea. This chapter will make clear that it is possible to make it.

The other side

In the third chapter there is a chart made that showed which connections could interact. Looking back at this chart the best option would be the connection with the adhesive. The main problems of this choise are that it is less sustainable and less challenging

Figure 6.1 Impression

Calculations

To build this design, the column needs to take up all the pressure force. Some handcalculations are done to calculate if this is possible. Because of the dimensions the design is not going to be placed at 3Me anymore. Therefore there is a three storey high residence building assumened.

For the buckling number, the hinged column is used. This is done, because the column exsist of all different components.

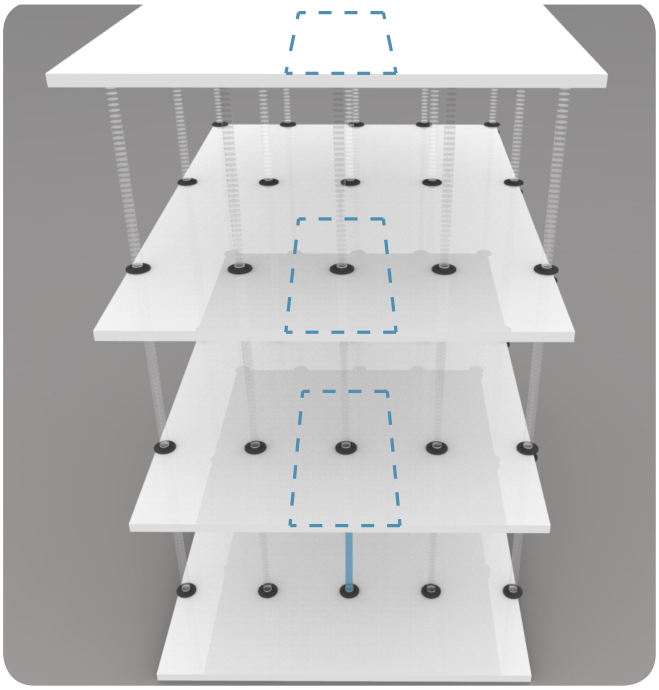


Figure 6.2 Calculated area

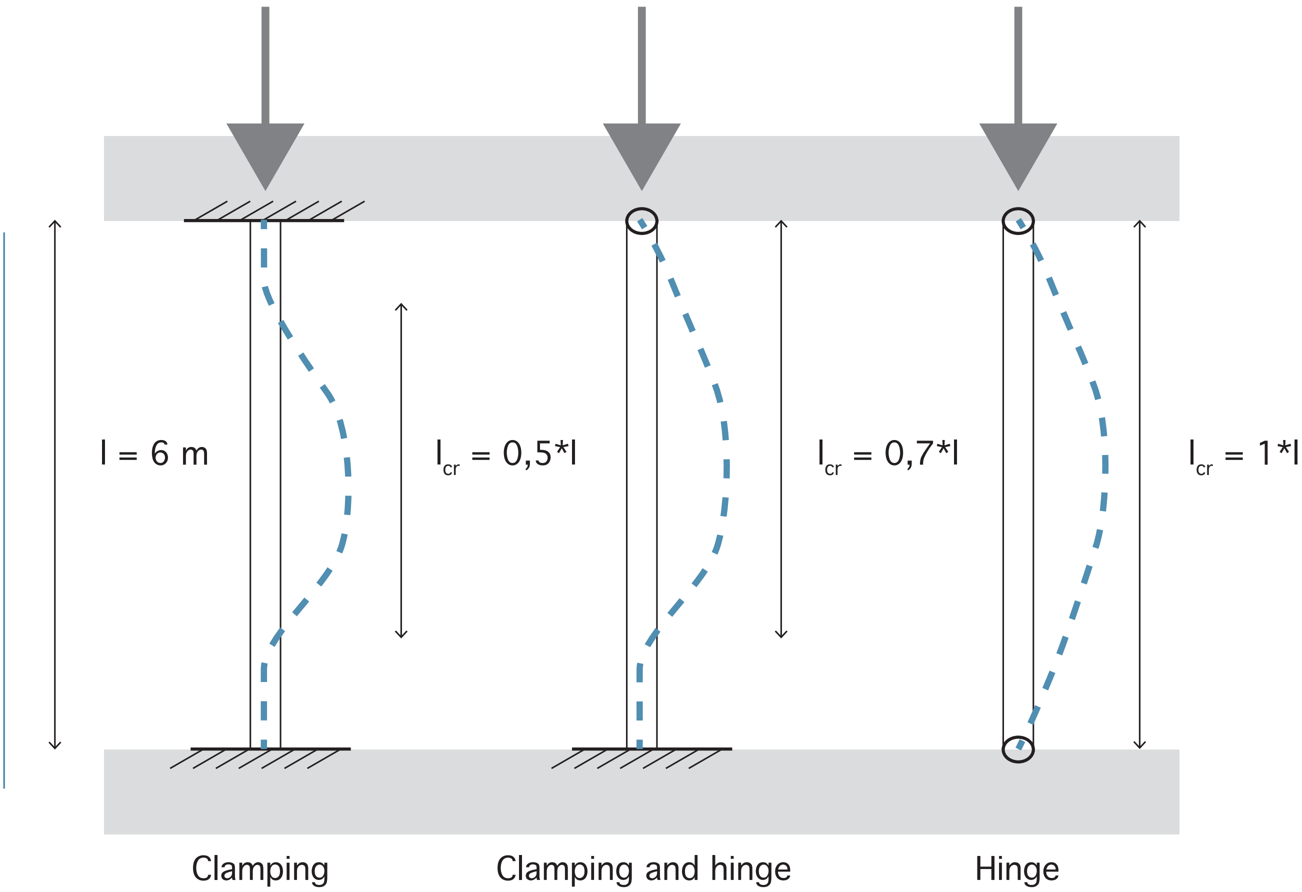


Figure 6.3 Rules for buckling number

		300 x 150 mm^2	200 x 100 mm^2
I_y	$(\pi*r^{4)}/4$	397607820,2	7853981,34
E		72000	72000
l_{cr} hinge		1	1
l		6000	6000
r		150	100
Pi		3,14159...	3,14159...
EI		2,8627E+10	5,65487E+12
F_{cr}	$(\pi^2 * EI)/l_{cr}^{\ 2}$	7848463,785 N	1550313,834 N
		7848,463785 kN	1550,313834 kN
Safety	$F_{cr}/5$	1569,692757 kN	310,0627668 kN

Figure 6.4 Calculations of acceptabel loads

Example	kg/m^3	kg/m^3
Water	1000	10
Wood	800	8
Plaster work	2000	20
Concrete	2400	24
Glass	2500	25
Steel	7850	78,5

Figure 6.5 Examples of own weight

		kN/m^2
Roof		1
Residence		1,75
Ofiices		2,5 - 3,5
Stores		4
Theater		5,0 - 7,0

Figure 6.6 Examples of weight of functions

Safety factor rest	1,2
Safety factor variable	1,5

		kN/m³
Surface 3000 x 7500 mm^2	22,5 m^2	
Concrete 300 mm	0,3 m	7,2
Concrete deck floor 60 mm	0,06 m	1,44
Floor finish		0,5
Roof		0,5
Instalations		0,25
Total		9,89

		kN
Roof	Rest	267,03
	Variable	33,75
Residence	Rest	267,03
	Variable	59,06
Residence	Rest	267,03
	Variable	59,06
Total		953 kN

Figure 6.7 Calculations of load

The results of these hand calculations show that the column can carry a 3 storey high residence building.

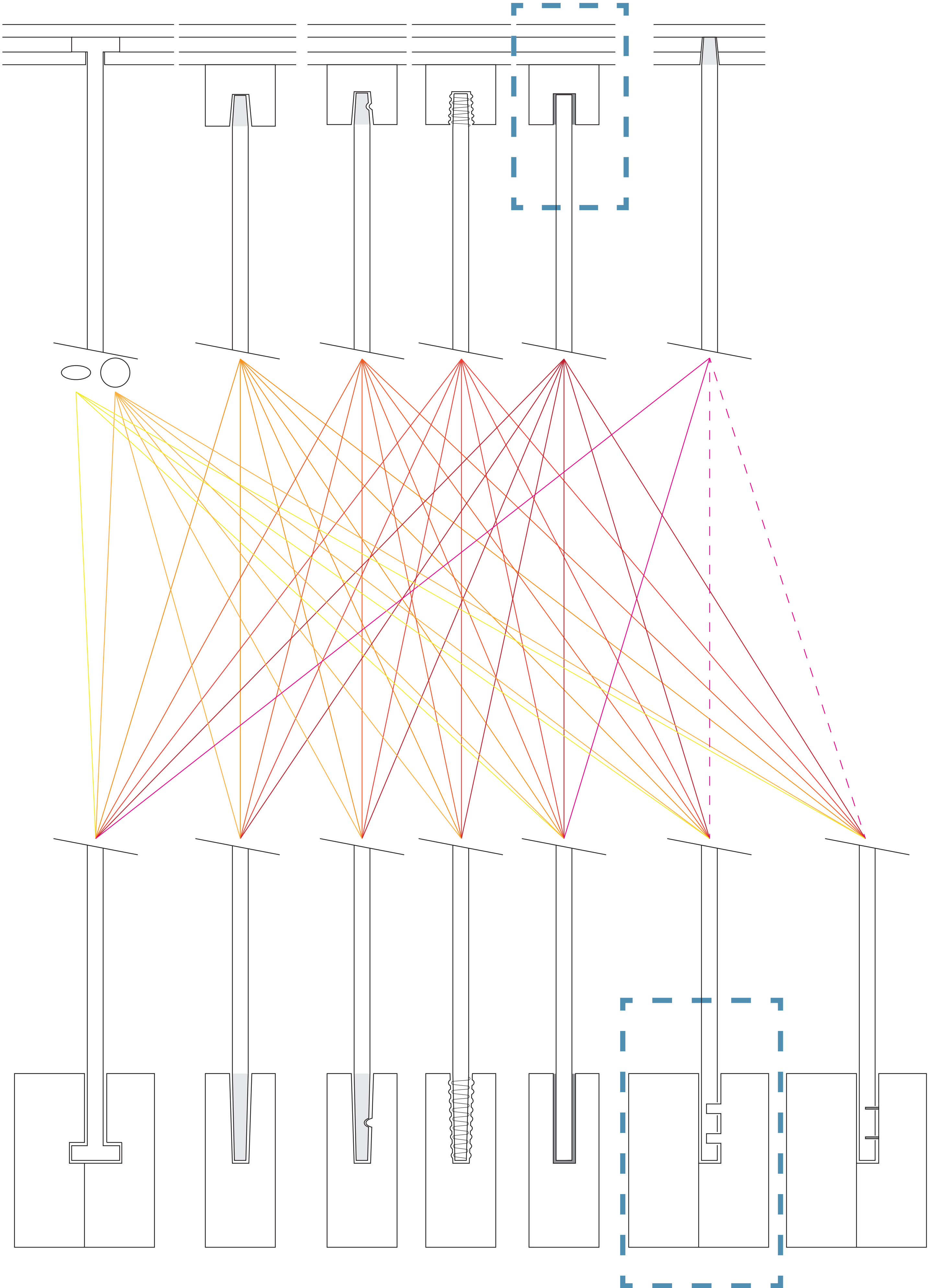


Figure 6.8 choosing connection on the other side

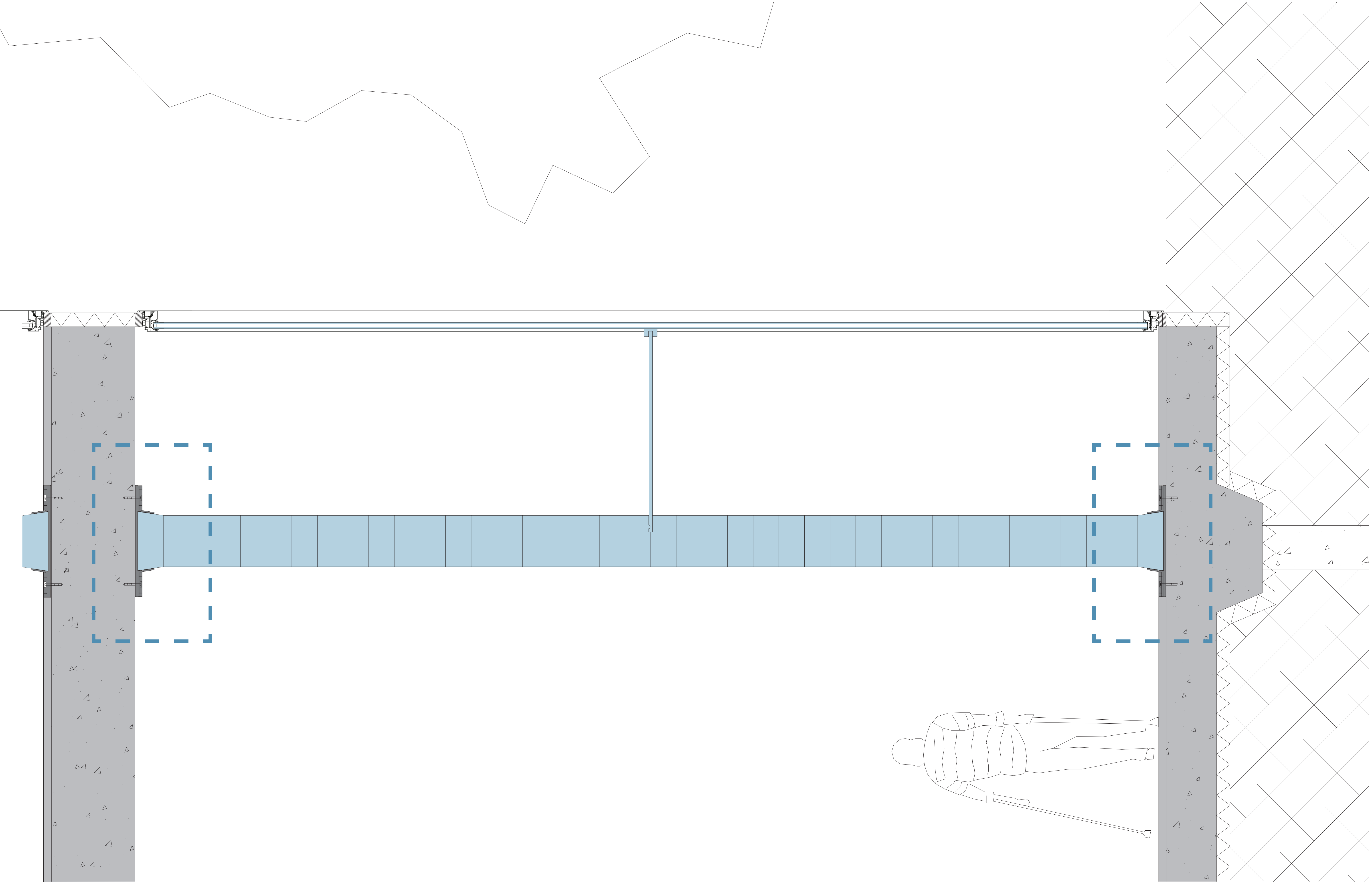


Figure 6.9 Detail 1:50

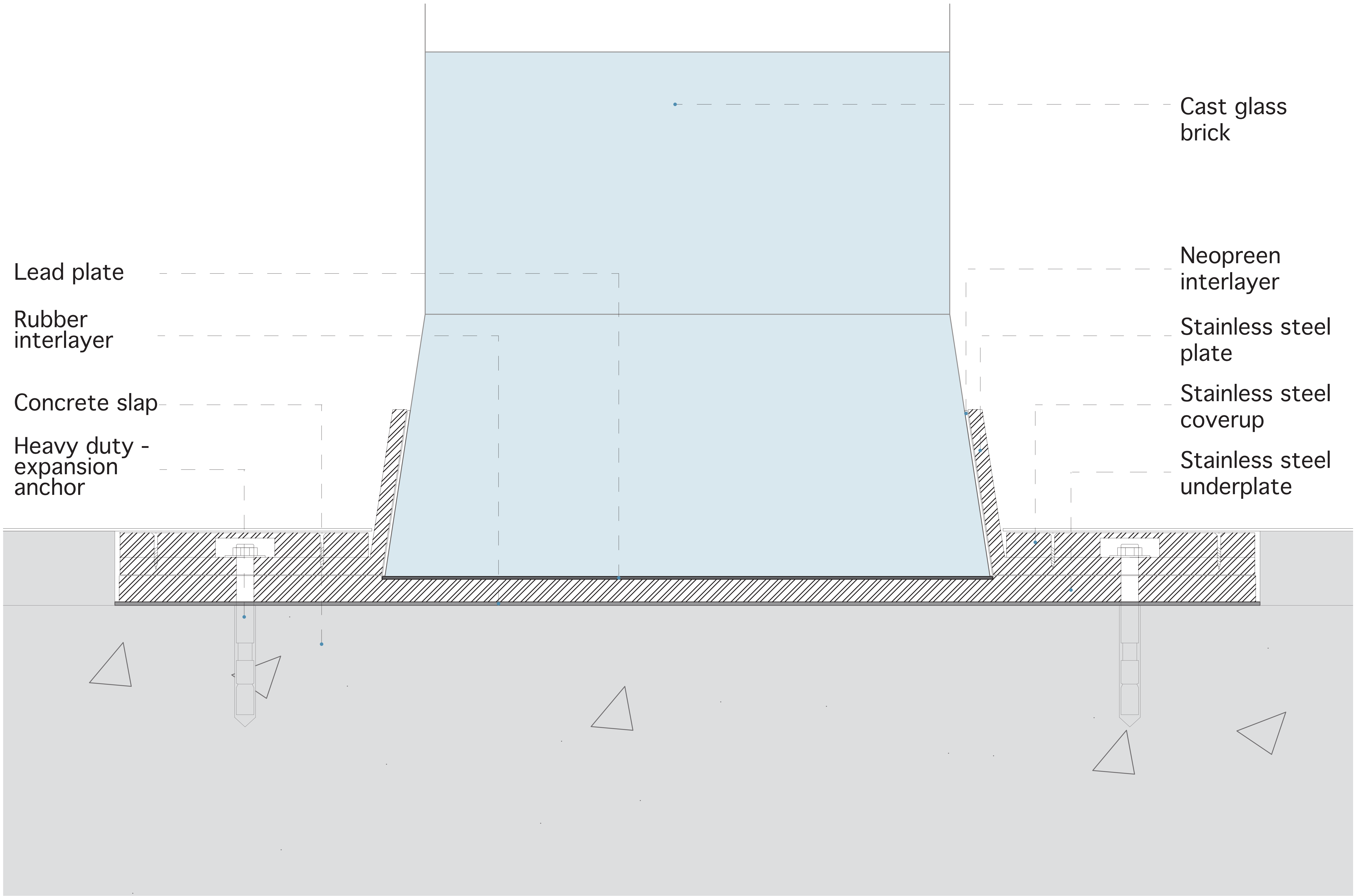


Figure 6.10 Detail 1:5 bottom

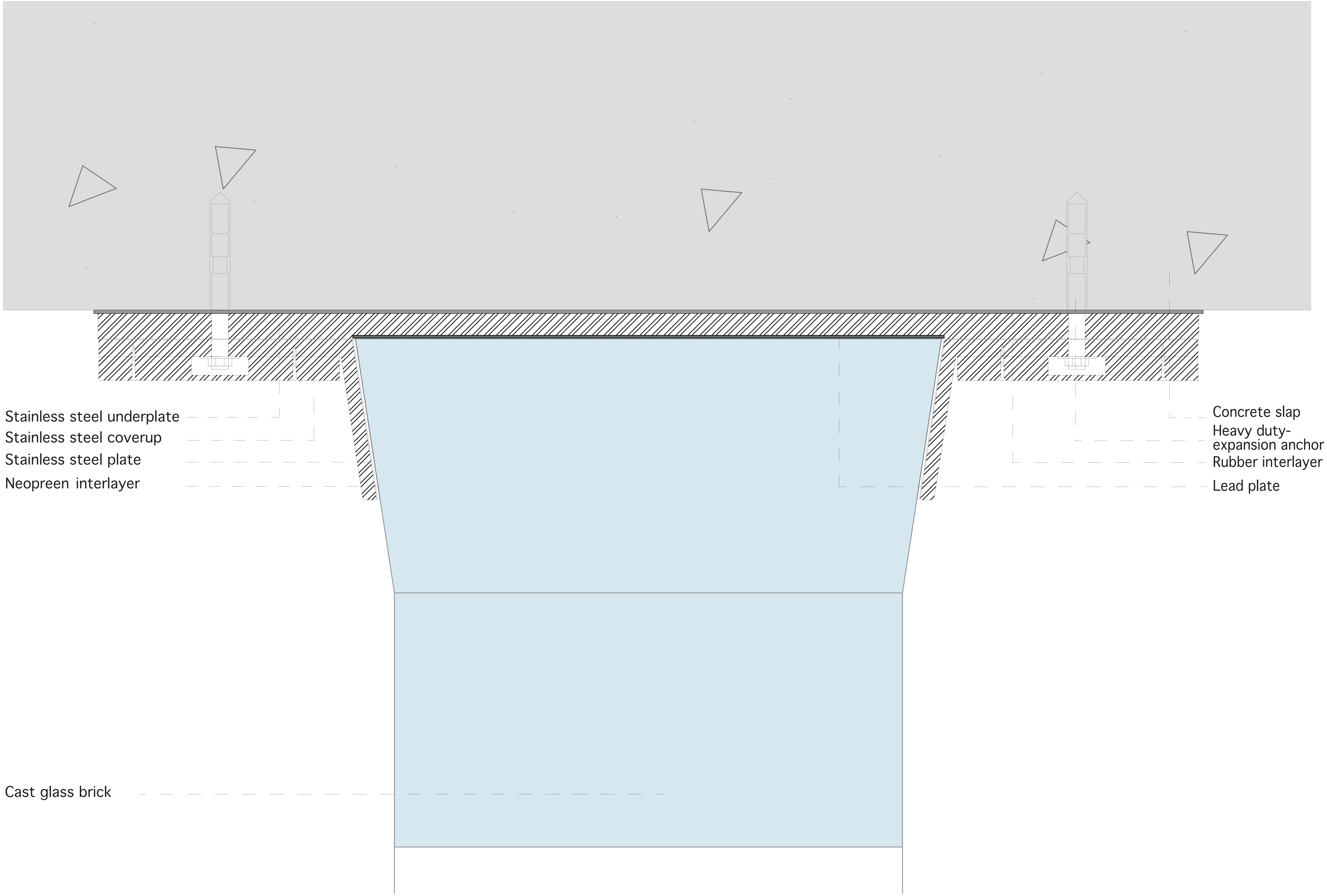


Figure 6.11 Detail 1:5 Roof

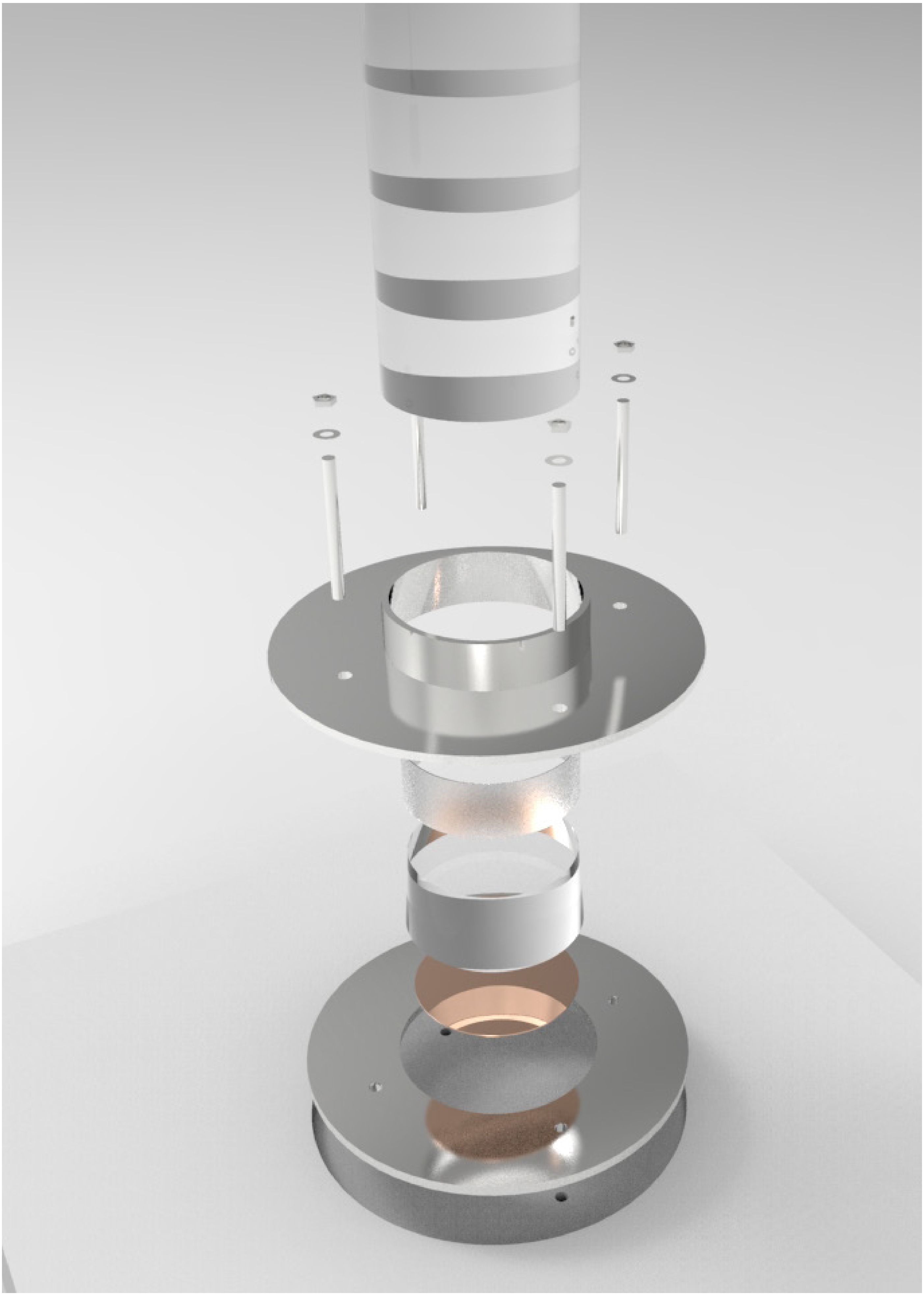


Figure 6.12 Bottom detail exploded vieuw

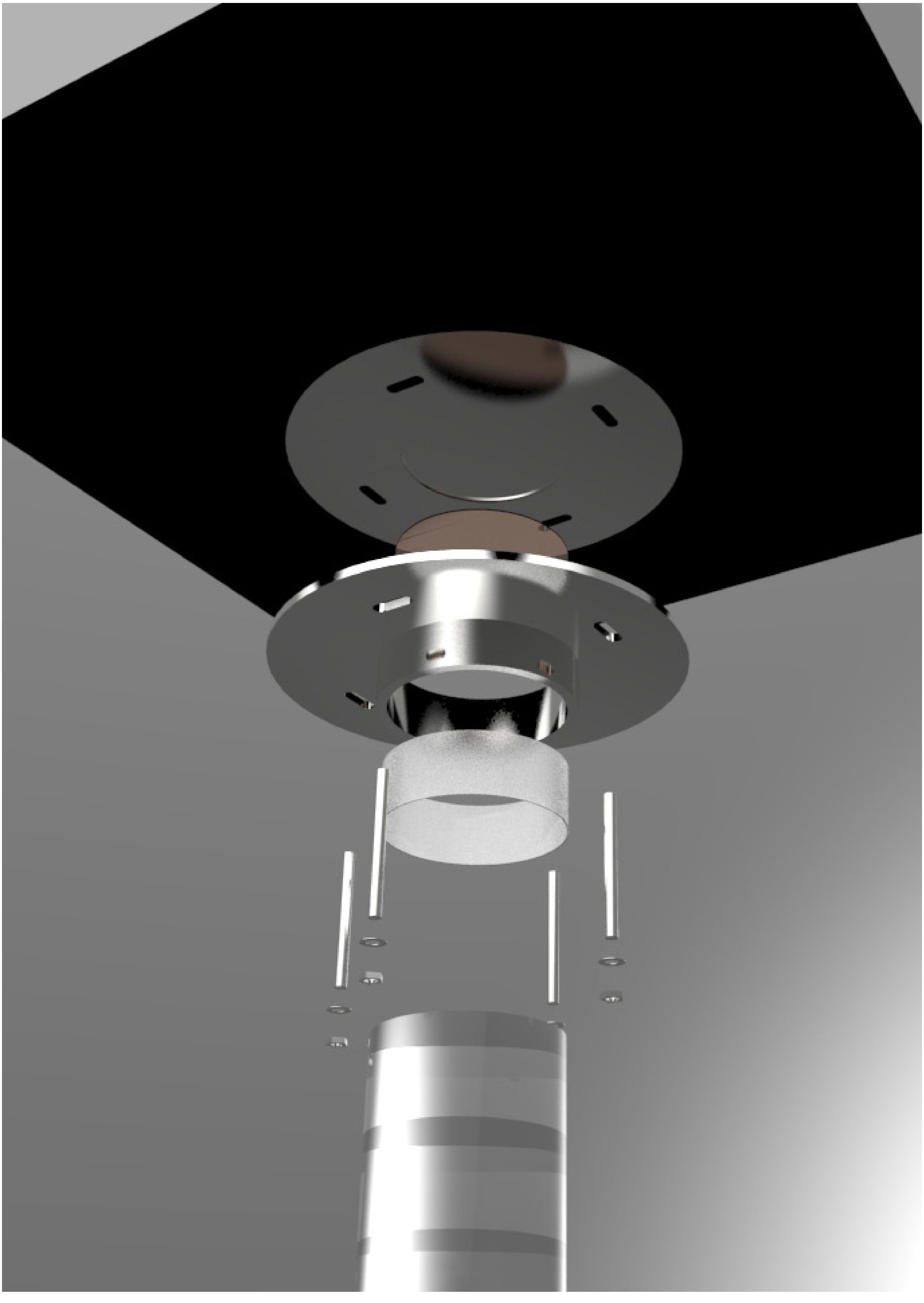


Figure 6.13 Roof detail exploded vieuw

Detail explanation
The details at the top and the bottom are similar. This is because the connection is mostly to keep the collumn in place. There are multiple interlayers implied that take care of transfering the forces. Glass is also very sensitive for scratches. This is also a pospose of the interlayers.
The end bricks have a slope. This so the bricks stay in place without the use of an adhesive. They are this way stuck between the stainless steel plates.

The top detail has slots in the plates. This is done so there won't be a problem when the holes aren't exactly above the ones on the bottom. This will help the tolerances.

Figure 6.14 Impression connection

Figure 6.15 Impression

list of figures

7 Conclusions

In this chapter all the conclusions are once again viewed and set against each other.

In the first chapter of this report there is a problem visualized. This problem is a result of a fascination of the differences between the architect and constructor. The research question that rose out of this problem is:

“Is it possible to make a glass column that is connected to a glass wall, with a glass rod?”

The second chapter is a literature study after glass. This study reveals what glass is, how it is made and what the possibilities are with this material. At the end of this study there is looked at the reference projects. Here became visible that the connections between glass and glass are mostly made from steel. To make a challenging design this research will be done after a glass connection. Shear and tensile stresses are an important aspect for this. To make the best use of glass the conclusion was made that cast glass and extruded glass will give the best results for this design.
To make a good working connection, the following criteria are composed.

Stress concentrations
Glass is not great with stresses; therefore, the connections need to be so that there are not many places where this can occur.

Manufacturing ease/costs

This research is done so that it could be a used connection. If it is to expansive to make, it is too hard to test it and won't be a mainstream connection.

Tolerances
Cast glass has a specific manufacturing. This causes that it is hard to make very specific tolerances. To make the manufacturing possible, it is necessary that the needed tolerances are brought to a minimum.

Challenging
A graduation project needs to be challenging and innovative.

In the next chapter the connections are designed. There is looked at different connections that rose into seven designs. These connections are tested with the previous said criteria.

There was no design that scored a 100 percent on all the criteria so there were two designs chosen. The first one is a profiled design and the second one a sanded design. The profiled makes use of is shape and ability to cast glass in every shape you desire. The second one, the sanded design, is based on a friction principle.

The fifth chapter is the experiment chapter. Because there were two very different designs chosen it was needed that both these designs were tested. To test them, simplified versions are made. The profiled designed is tested with a smaller part of the design and the sanded one

with Erlenmeyers and their stops.
The compression of the column is something that is tested before, so the main goal of these tests was to mimic pulling forces. These were done with the use of a pulling machine.

The results of the sanded design showed that it is possible to get to forces of around 150 N. 350 N was reached, but it was not a standard. The tests were done with multiple Erlenmeyers with different stops, tubes and girth.
150 N is not enough force to use for a façade. This concludes that the connection can be used for, for instance a coffee table, but not for this propose.

As said is there a smaller part of the profiled design made. This was made with multiple moulds and models. Because it was a very open gypsum mould there was not made use of a flower pot. This did cause for some extra crystallization and stresses in the bricks.

For this design is again the pulling machine. There are multiple tests done. The first with a steel end connection to connect to the machine. This gave potential results, around 1700 N. This connection broke in the wrong place what made that there were new rods produced, that had aluminum end connections. These broke in the right place, but gave a lower result than the previous test. This made that there was one more rod made. This one completely made out of aluminum to look at the behavior of the glass component. None of these tests gave the results that was searched for. They did give a higher result of around 2000 N. This is enough to build a façade. To build this façade, it is probably needed to place 9 rods per column instead of 2.

Recommendations

For the sanded design are still many options to test, like the usage of sparkling water. Up until now the results for the sanded connection were not high enough to make a façade. For further research to this construction this design can be illuminated.

The profiled design has more potential, but further researches are necessary. The profile can for instance be extended to two holes and bulges. This might give a problem with the rod. This means that it might be needed to use a bigger rod, to make sure there is enough glass left to handle the forces.
Another research that can be done is the one after a combination between this design and an interlocking column. This is an interesting research because the main problem for interlocking glass columns is the shear stresses. This is extra emphasized by the use of the rods.