The Stackable Glass Column

The

Stackable

Glass

Column

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Publication Date	June 2018

Aknowledgements

The last seven months, I have been doing this research with great joy. This joy was created by the variety of activities that had to be done and the people that helped me with these.

For this, I would like to express my great appreciation to my two mentors Faidra Oikonomopoulou and Marcel Bilow. Faidra, who knows everything about cast glass, provided the great enthusiasm that arose in me for cast glass. She was there to help me with the issues that I faced during research and gave me constructive feedback. And Marcel, who always has creative ideas when it comes to making and producing materials. His enthusiasm about the project, but also everything else, helped me a lot to stay positive in every step of the way.

Next to my mentors, I would like to offer my thanks to Telesilla Bristogianni and Tomasso Venturini, for their guidance, help and time into the production of the glass prototype. In particular, I would like to thank Telesilla for trying to make my program fit into her agenda, even when this does not seem to fit.

I would also like to thank Fred Veer who helped me in different ways. He always replies to my emails quickly and concisely, which made contact very direct and pleasant. He helped me with the experiments of the specimens and put me at ease during my P1 and P4 where he replaced Faidra.

The advice given by Peter Eigenraam have been a great help in the prediction of the breaking behaviour of the glass column. Next to this, he helped me constructing a FEM-calculation in Diana.

I would like to thank the examiners Marjolein Spaans and Jacob Jan Trip for listening to my presentations and providing me with new insights.

I wish to acknowledge the help provided by Bob de Boer of the 3D-printing lab, and Frank Krowinkel, Doortje Berghahn at the vacuum forming in the Marquette Hall at the faculty of architecture.

I am particularly thankful for the former-students that have uploaded their report on repository.tudelft.nl; this gave me a good view on what has already has been done, and which parts needed further research.

Lastly, I would like to thank my boyfriend, friends and family for the support and help they gave me during this research.

Abstract

Keywords: cast glass, dry connection, interlayer, interlocking geometry, glass column, multifunctionality

In 1942 cast glass columns were designed in the Danteum by Giuseppe Terragni. But due to the annealing time of large glass pieces, these have never been produced. Now, more than 75 years later, a new type of cast glass column will be designed. This time, the design is made out of interlocking dry stacked cast glass components.

Glass is a strong yet brittle material that is used in many different industries. In this research, we are looking at the glass type borosilicate. This glass type is used in practices where temperature differences could occur. When designing a load-bearing column, fire resistance is a significant part of the overall safety of the column.
Columns that are made out of glass can be separated in five types by Nijsse, R. & Ten Brincke (2014); profiled, layered tubular, stacked sheets, bundled and cast. As far as we know, the profiled glass column is thy only type that is used in the structure in a building so far. When wanting to produce a cast glass column, this column should be split up into smaller pieces. This is because it would result in an annealing time that is much shorter due to the smaller dimensions and volume of the different parts of the column.

When the column is split up into pieces, thoughts should be about how to connect those separated pieces. Previously in cast glass structures in the Atocha Memorial in Madrid and the Crystal Houses in Amsterdam, an adhesive glue was used to bond the bricks. In these structures it is not possible to remove the glue easily; which will eventually result in more residual waste with no recycled glass.

When a dry connection would be chosen, the column could be re-stackable and recyclable. Because the column should also be able to hold shear forces, this dry connection should be substantiated with a shear connection. This connection could be constructed by an interlocking surface or element. In this design, this connection is made with a dry interlayer of TPU and an interlocking sphere between the surfaces.

This interlocking sphere only had to bear the shear forces that will be applied on the column. These forces will be much lower than the compressive forces that will be transferred through the flat surface of the components. This is why there will be great freedom in the materials and the interlayers that may, or may not be used.

A list of design principles and challenges has been made during the literature research that has been done. From this different designs have been made for the component design. An elegant bone-like shape has been chosen to develop further, to find the limitations of glass as a material and the loads it has to carry.

In this design, ten subcolumns of constructed of the same component and its interlocking sphere will be the structure of the total column. Due to the forces that are applied in the case study the glasspalace, a building of multiple stories on the ground floor that has a height of 6 meter, the component and therefore the column grew very big and robust.

Different mock-ups on scale 1:3 are made with the silicone moulds that are produced; ice, sugar glass, glass and epoxy. Some were experimentally tested on strength and cracking behaviour in comparison to real glass.
This thesis aims to find out how we can design and produce a safe, engineering sound, re-stackable, free-standing column made of multifunctional cast glass interlocking components.

Content

Introduction

Problem Statement

Glass is a material that shows an unusual combination of characteristics; it is transparent but also has a very high compressive strength. Because of this strength, it is possible to use glass in structures.

The use of glass in structures started this century and is developing fast, but still has a lot of unknown and unresearched fields. Glass is most of the time used in structures by laminating multiple sheets of glass, which would be redundant therefore safe. But because the lamination of sheets will create a two-dimensional structure, it will be susceptible to buckling. When using glass in three-dimensional geometry, like cast glass, this could be prevented. Using cast glass in structures is still very rare, although very complex shapes with good buckling resistance could be created.

When redundancy is applied in a structure made of cast glass, the structural element should be made out of multiple components that can distribute the forces equally in case one of them fails. It would be possible to create this composition by connection the components by interlocking

When making a structural element of glass, a material with high compressive strength, it would be logical to use it in compression. A column is a compressive member who will carry only axial compressive forces, which make it valid to design a column as a structural element made of cast glass elements.

Next to this, there seems to be a disagreement between architects and structural engineers; architects would like to have an open space without any interruption in light and view, and the structural engineers would like to have enough loadbearing elements (walls and columns) to transfer the loads safely to the foundation. Columns usually give an option to keep the open space with some interruptions in view and light. When these columns would be made out of glass, these elements would be translucent to transparent. When doing this, a good compromise between an architect and a structural engineer could be created.

For these matters, research will be done in designing and testing a column made of cast glass interlocking components.

Research Objectives

The goal of this research is to contribute to the innovation of glass structures in general. In this case, this will be done by using interlocking structures of cast glass elements to create a column. Next to this, this research can help the architect and the engineer to a design which will suit both parties in any desired construction. The main research question in this thesis will be:

How can we design and produce a safe, engineering sound, re-stackable, free-standing column made of multifunctional cast glass interlocking components?

This main research question could be divided into these subquestions:

•What size should the components be in respect to the limitations of the casting process?

•What are the possibilities in the shape of the column and its components?

•How will the components be connected to each other?

•How can redundancy be included in the design of this column?

•How can we make this column fire resistant?

•How will this column be connected to the levels underneath and above (end-connection)?

Relevance

The data found to create a cast glass column made of interlocking elements can be used as a database for technologies in the structural glass field, interlocking cast glass elements and column design.

The directions that will be chosen in the design could help other designers in cast glass interlocking structures to make their own decisions based on the results of the design.

Furthermore, the design of the column that will be made can be applied not only in the Glasspalace but any other building. When applying this column physically in a building, significant steps will be made towards the realisation of a more transparent structure. The application of this column can set an example for other architects and designers who desire a building wholly constructed out of glass. With this, a glass building could become a reality.

Next to this, applying structural glass more and more, the regulations of structural glass should become easier applicable and therefore cheaper and more common.

Methodology

This research will be divided into different phases. The first phase is literature research in different subjects that will be met to come to a design of a cast glass interlocking column: glass as a material, glass columns, cast glass structures and interlocking geometries. After which conceptual sketches will be made considering design principles and challenges of this literature research and the context of the Glaspalace in Heerlen (case study).

In the second phase, the design phase, the options of the design will be further explored. Together with the design principles and challenges, different designs will be made with a hands-on approach. This phase will be ended when a final design of the column and its components is made.

In the testing phase, this design will be tested with analytical analysis and numerical analysis. Later, the adjusted design will be manufactured and examined physically. This experimental analysis will be about how the elements will break. This could be done either with sugar glass and/or real glass. After this, conclusions will be drawn from the research and the design.

Outline &Structure

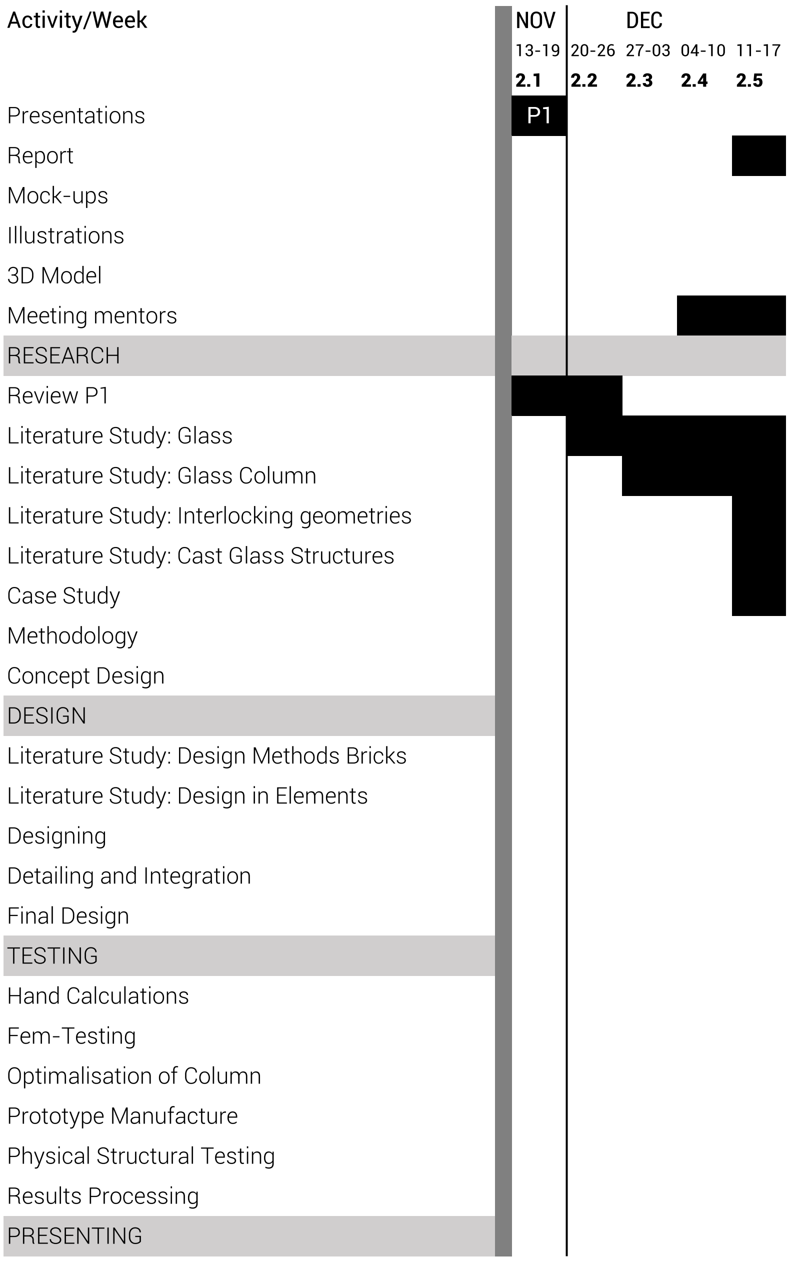
In the phases between the presentations, there will be a focus on different parts of the research. To end up with an optimal glass column design for the location, the force-flows and the aesthetics.

P1 – P2: Research
In this phase, literature research was done in the elements that would have anything to do with the subject glass column made of interlocking elements in the Glaspaleis (glass, glass columns, cast glass structures, interlocking geometries, case study). With this information the design principles and challenges were formed, the concept-sketches of the design was made, and the research questions are asked.

P2-P3: Design
Specified research is done in different comparable designs of elements and structures. Different designs will be made, keeping in mind the design principles. This design method will be a hands-on approach of designing. When a final design is made, this phase is ended. The final design is the best combination of the answers on the research question(s).

P3-P4: Testing
This phase will consist of calculating and testing the final design. This will be done by analytical, numerical and experimental analysis. The analytical analysis will consist of hand-calculations that will evaluate hand in hand with the design. The numerical analysis will be there mainly to test if the hand-calculations were done the right way. The experimental analysis or physical testing consists of testing how the elements will break, rather than on which force they will break. It will be done either with glass prototypes or prototypes made of ice or sugar glass. These tests will, either way, be done at the faculty of civil engineering at the TU Delft. After the testing, evaluations will be made, and the design will be visualised.

P4-P5: Presenting
During this phase the focus will be on the report, the scale model and the presentation. In the report, possible future continuation research topics will be suggested.



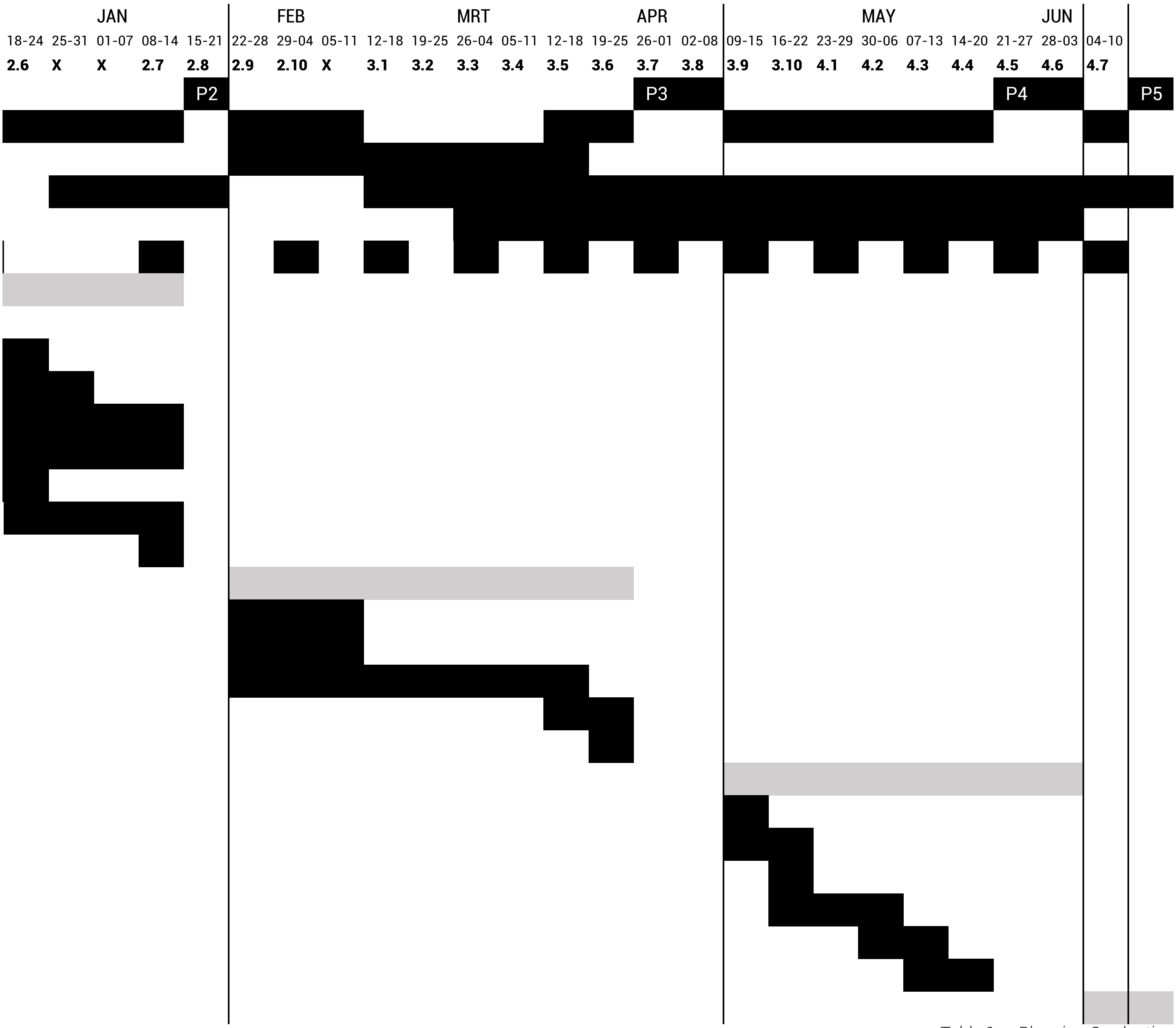


Table 1. Planning Graduation

The Material Glass

The Material Glass

Glass is used in many applications, some of which we don't even know that glass is involved. Glass surrounds us: we drink and eat from it, use it in our furniture and cars, apply it in machines, fibre network and building insulation and even use it as reinforcement in other materials.

This material has many contradicting properties. You can look through but not pass through; this is very useful when wanting something to stay on the other side while looking at it, think about for example the snow outside or an aquarium with fishes. Also, glass is very strong in compression, solid and durable, but when it is scratched, it can easily and suddenly break and lose all its strength. Besides that, glass is a transparent material, but when the surrounding environment is darker, it will be a reflective material instead of a transparent one. The combination all of these contradicting characteristics makes it an interesting material to research.

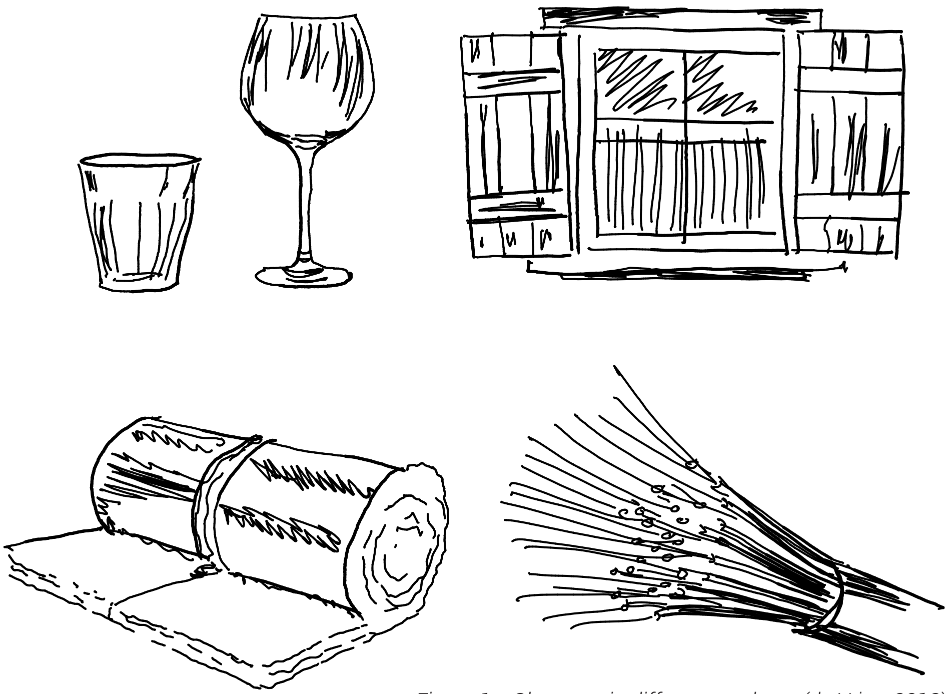


Figure 1. Glass use in different products (de Vries, 2018)

History

By nature, glass is made as long as the globe exists. When lightning strikes or meteor impacts in the sand in the desert, rapid cooling of lava or rock crystals in mountain caves glass arises from the raw materials. ('Glass in Nature | Corning Museum of Glass', n.d.)

From 2000 B.C. people in Mesopotamia (now Iraq and northern Syria) are making glass themselves, which means it is one of the first known materials made by humans. The first method to make glass was cast glass; the glass is molten in the mould that it will solidify in later. Since then, many other ways of making glass have appeared. (Pender & Godfraind, 2011)

After the casting of glass, a new method of making glass discovered at 1st century B.C.: blowing glass. This was done by blowing on a hollow pipe with at the end of the pipe, molten glass which will inflate into a bubble.

In the 14th-century crown glass was made, which made it able to create flat glass to use for example in windows. Circular plates were formed with a blowpipe, which was flattened and rotated. This manufacturing of glass

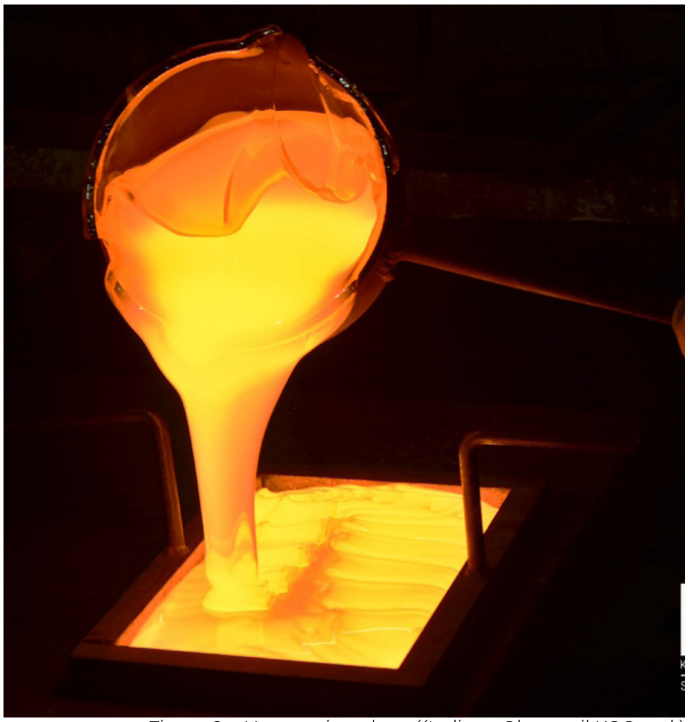


Figure 2. Hot pouring glass ((Indiana Glasstrail KOG, n.d.)

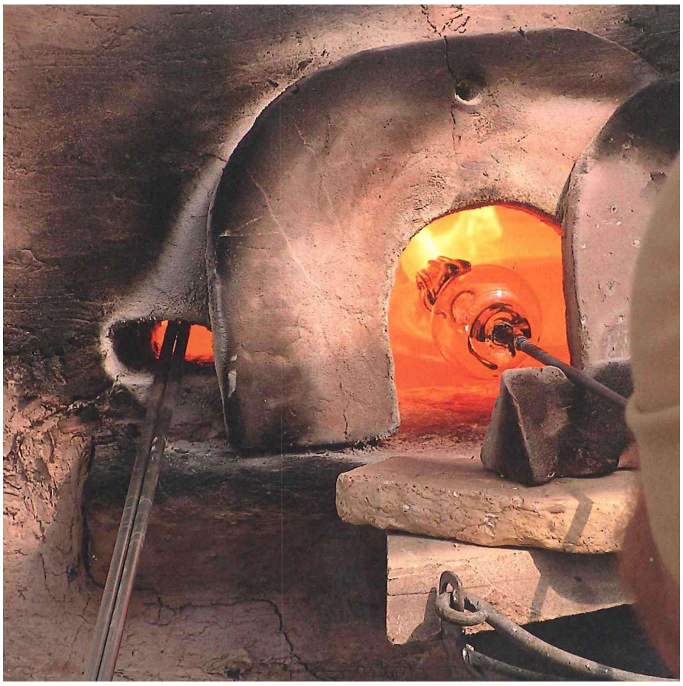


Figure 3. Blowing glass (Pender & Godfraind, 2011)

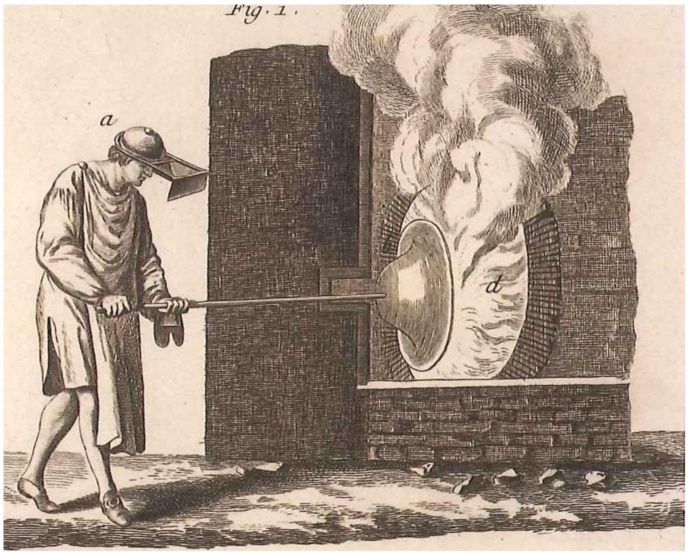


Figure 4. Crown Glass (Pender & Godfraind, 2011)

could make glass panels of 30x40cm maximum. In the middle of the glass, there always was a bulge; they call it the bullseye of the glass.

In the 17th century, the blowpipe was used to inflate a big cylinder pipe which could be cut and made flat, called broadsheet glass. This way surfaces of 100 to 80 cm could be reached.

In the 19th century in Belgium, another method of creating glass was found: pulling glass with a steel bar. With this method (Fourcault process) the dimensions of the glass could be unlimited.

Float glass, which is used nowadays for modern glazing is first created in the 20th century in England. This glass is produced with the "Pilkington process" by melting glass on a bed of molten tin (or other low melting point alloys), which will give the glass a uniform thickness. (Weller, 2009)

Nowadays glass is used in many fields: architecture, sculpture craft and design. ('Timeline of Glass History | Corning Museum of Glass', n.d.)
As Ulrich Knaack told in his hearing, there are three generations of structural glass. Starting with the first around 1940; with an example the Palm House in the Kew Gardens. The second generation will be around 1980, with the example the construction of Parc de la Villette. The third generation has just started about 2017. An example of this generation is Casa Musica in Porto.

This century glass is also used as a structural element in buildings.
Glass could be the material of a beam, column, floor or a brick. (Knaack, 2018)

From the steps in structural glass that have been done the last years, it will be possible to imagine an entire building made of glass in some decades. To make this happen a lot more research on the material, and how to design and create structural glass elements best has to be done.


Figure 6. Kew Gardens Glasshouse ('Royal Botanic Gardens, Kew', n.d.)


Figure 7. Parc de la Vilette ('La Villette Facades | Ian Ritchie Architects', n.d.)


Figure 8. Casa Musica Porto ('Trip to Portugal/1 - Porto - Ma Che Davvero?', n.d.)

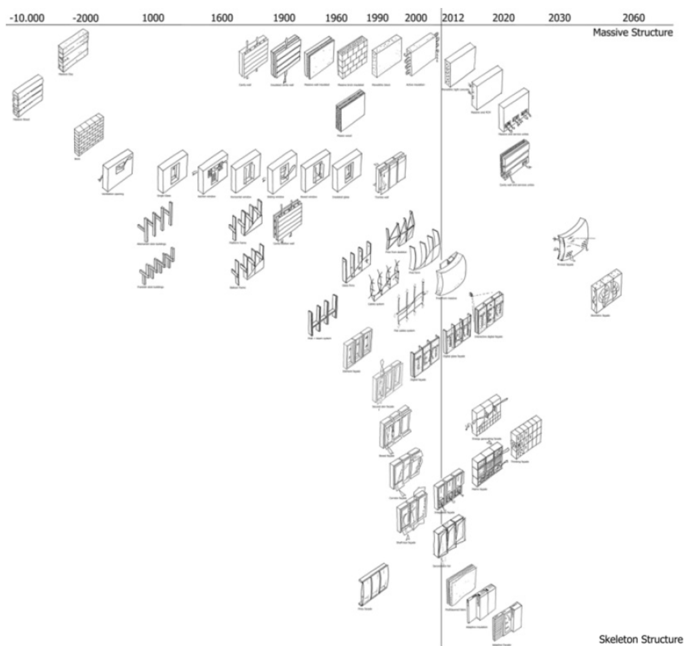


Figure 5. Next generation facades (Knaack, 2018)

Figure 10. Production hall of float glass (Float glass production', n.d.)

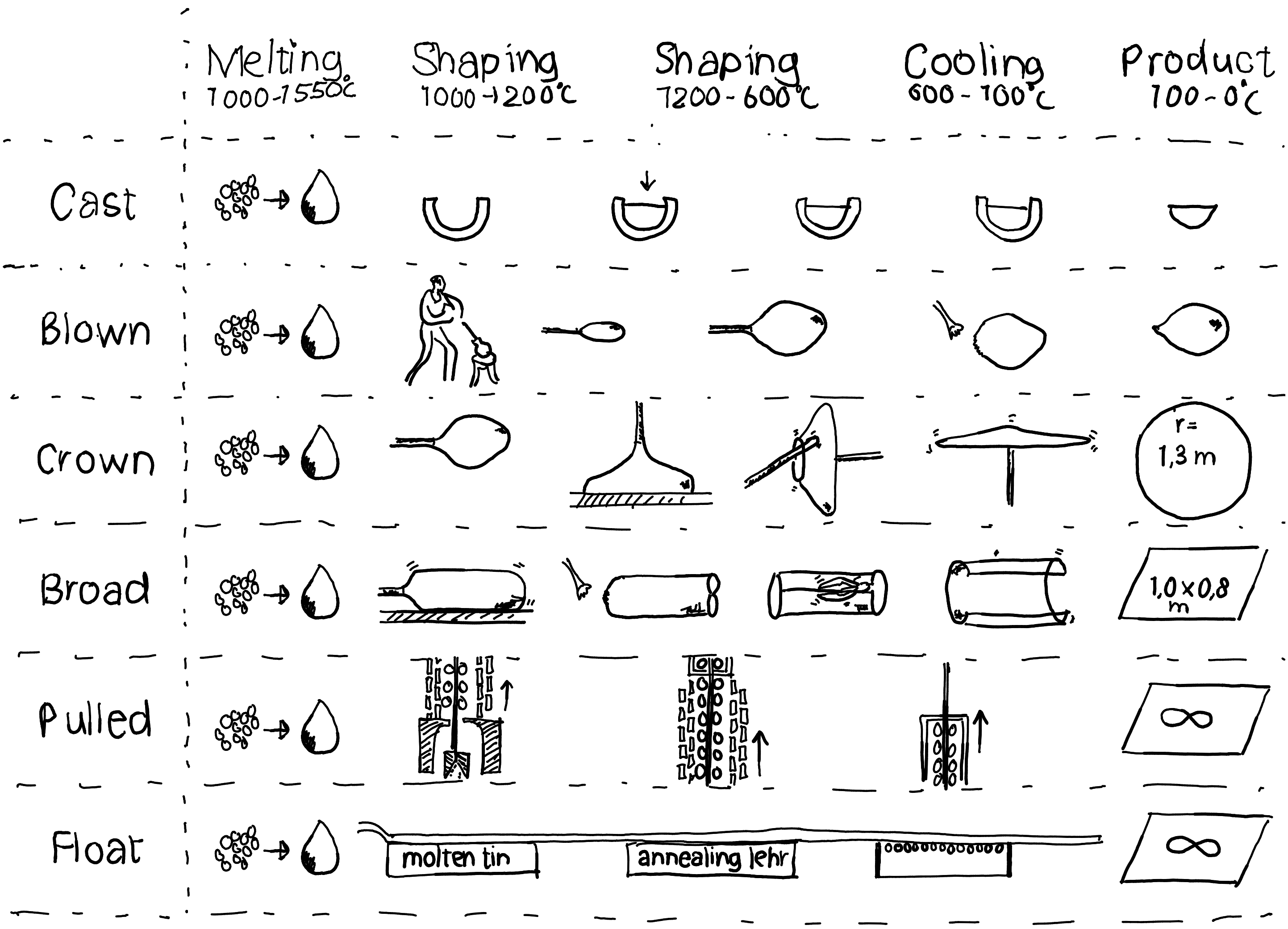


Figure 9. Manufacturing methods of glass in History (de Vries, 2018)

Figure 11. Crumbed glass (retrieved from: http://boisestatepublicradio.org/post/idaho-artist-finds-niche-business-glass-recycling#stream/0)

Composition

We know that glass is used in many industries; chemistry, electronics, construction and many more. Because of these different uses, there are a lot of types of glass. For example Quartz glass, soda lime glass, borosilicate glass, alumina silicate glass and lead glass. To create the necessary chemical and physical properties, they all have ingredients in different proportions.

The building industry mainly uses soda-lime-silica glass and sometimes borosilicate glass. Soda Lime glass is the first glass that was made in history and also the cheapest. Borosilicate has better thermal properties, which makes this type used in specific industries. Their composition and differences will be explained briefly. Soda lime glass is the glass type that is used 90% of the time; glazing of buildings, drinking glasses etc. Borosilicate glass is due to its excellent resistance to heat, used in the kitchen and laboratory.

	Density	Price	Young's Modulus	Hardness	Tensile Strength	Compressive Strength	Thermal Expansion Coefficient	Poisson's Ratio	Working Temperature	Melting Temperature
Glass Type	*kg/m3*	*€/kg*	*GPa*	*kg/mm2*	*MPa*	*MPa*	*10-6/K*	*-*	*℃*	*℃*
Quartz	2170-2200	5,140-8,580	68-74	450-950	41-155	1100-1600	0,55-0,75	0,15-0,19	1600	1700
Soda Lime	2440-2490	1,160-1,370	68-72	440-485	30-35	360-420	9,1-9,5	0,21-0,22	700	1200–1400
Borosilicate	2200-2300	3,430-5,150	61-64	84-92	22-32	264-348	3,2-4	0,19-0,21	830	1400–1600
Alumino Silicate	3950-3990	3,300-5,100	53-55	472-525	23-24	232-244	8,82-9,18	0,23-0,24	830	1700
Lead	2490-2300	1,170-1,370	85-89	68-75	40-44	400-440	4,11-4,28	0,23-0,24	620	1000

Table 2. Glastypes with characteristics (Granta's CES EduPack 2017, n.d.)

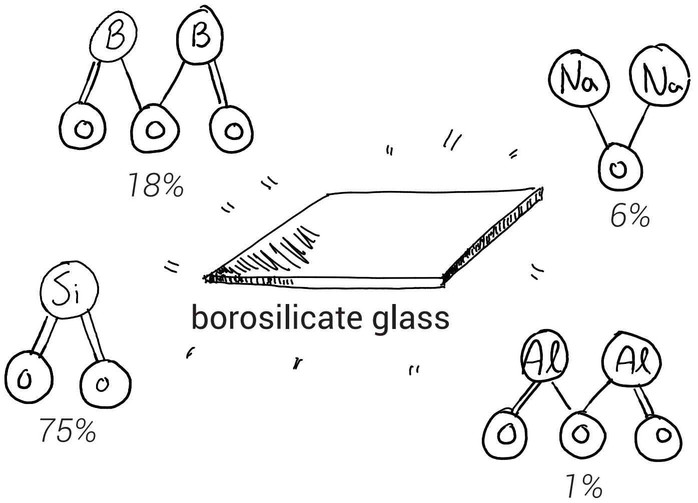


Figure 12. Borosilicate glass composition (de Vries, 2018)

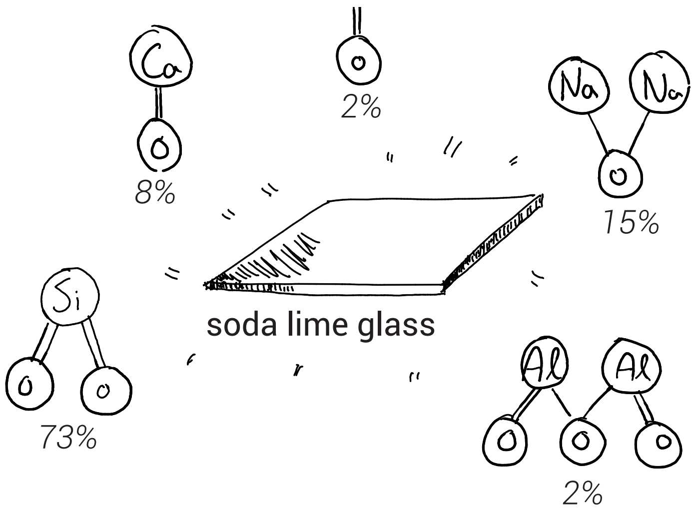


Figure 13. Soda -lime glass composition (de Vries, 2018)

Soda-Lime glass

This type of glass was the first type of glass known (3500 BC) and still very popular. Soda-lime glass is the most used glass in the world, 90% of the glass is this type of glass. It is used very widely: Windows, bottles, containers, tubing, lamp bulbs, lenses and mirrors, bells, glazes on pottery and tiles. Because of its high production volumes and relatively low working temperature compared to other glass types, it is very cheap. But it is not as durable as other types of glass, because it is prone to thermal shock failure and it degrades in chemically corrosive environments. ('Granta's CES EduPack 2017', n.d.)

Borosilicate glass

Borosilicate glass, also known as Borosilicate glass, also known as Pyrex, was first produced by Corning Glass Works in 1915. ('Technical information -glassware', n.d.)It has a good thermal shock resistance and can withstand extreme thermal cycling with minimal effect. Because of its low thermal expansion coefficient, it has fewer internal stresses, which is why it would crack less easily. Also, it has excellent chemical durability and transmits UV at higher wavelengths. But it is 2 to 4 times more expensive than Soda-lime-silica glass. Also, it has poor resistance to strong alkalis, hydrofluoric acid, hot concentrated phosphoric acid and is harder to work with than soda-lime glass.

Due to its excellent thermal properties; this type of glass is still very useful as kitchen and laboratory ware, high-intensity lighting applications, as glass fibres for textile and plastic reinforcement, piping, lenses and mirrors, sealed beam headlights, tungsten sealing and sunlight lamps.('Granta's CES EduPack 2017', n.d.)

Differences

The thermal expansion coefficient of borosilicate glass is much lower than the one of soda lime glass. A low thermal expansion results in more resistance to different temperatures in the glass. Because of the low thermal expansion coefficient, the glass will have a shorter annealing time. (Oikonomopoulou, Bristogianni, Veer, & Nijsse, 2017). Next to this, borosilicate glass is better resistant to strong acids and therefore more durable.
Choosing between the two different types of glass would be on the grounds of temperature difference, annealing time and costs. Due to the required fire resistance, borosilicate seems to be the better choice for a construction in a building.

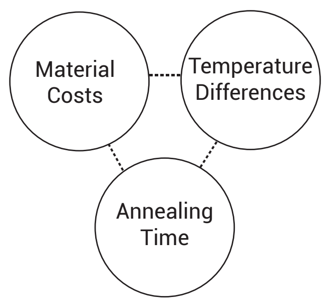


Figure 14. Choice between soda-lime Glass and borosilicate Glass (de Vries, 2018)

Properties

Psychology

Before the 20st-century glass was a very labour intensive and therefore expensive material to make. Accordingly, it was seen as very valuable for people, and there was a genuine high tax on the windows. It was a symbol of wealth to the society. (Weller, 2009)

Later, when float glass was introduced, it was much cheaper, and the image of glass as a sign of wealth disappeared. It became more the image of modernism. The new buildings had more and more glass on its facades. People liked it because it gave more open and transparent view on the society.

Next to its transparent features, it is a naturally shiny material. We seem to like shiny materials; as we can see in our cars, bathrooms and jewellery.
On the contrary of this transparent and open character of the material, it also is a very non-private material.

When glass is used in homes, it always must have a second removable layer (blinds or curtains) in the most private rooms. When a building is of glass only, thoughts while designing have to be about how to bring this private and secure feeling back in the building. (Deplazes & Eidgenössische Technische Hochschule Zürich. Departement Architektur., 2013)

People seem to be afraid of structures made out of glass, as they know how easy a drinking glass in their hands can break. Therefore glass as a structural material is not yet trusted entirely by people. Thus some people will not cross bridges, or walk over a floor made out of glass. Next to the anxiety over transparent glass floors, it could intrude women's privacy when wearing a dress or skirt. Therefore glass floors are mostly made translucent when people will be able to walk underneath.

Figure 15. Worlds longest glass bridge Shiniuzhai geopark China (Dainius, 2016)

Transparency & Reflectivity

In the English dictionary of Oxford, transparency is stated as: ‘allowing light to pass through so that objects behind can be distinctly seen.’ (‘transparent | Definition of transparent in English by Oxford Dictionaries’, n.d.)

Glass is transparent because it is an amorphous solid, the molecules of this material are not locked in its place, but instead, they are having idiosyncrasies of the bonds within the glass itself in neat but also random arrangements.

When the glass is crystallising during heating, it becomes opaque due to the different molecule structures. Resulting in a mechanically solid material but with distorted molecules like a liquid has. These kinds of solids occur when a material is melted at a high temperature and cooled rapidly, we call this process quenching. (Weller, 2009)

The amount of light that will be passed through will be determined by the shape of the component, the surface of the element and the type of glass. The light can also be passed through an object, without the possibility to see through an object. This would mean that the light is scattered or altered its path.

Transparent is not the same as invisible for the human eye. When looking at this glass column, it is evident that the column is there, due to the way it reflects and scatters the light. This interaction between the object and the light could be by reflection (specular and diffuse), refraction and absorption.

When we are designing with glass in architecture, we should not only look at the transparency of the material but also its reflectiveness. Glass seems to be very reflective with dark surroundings, so less reflective in open and light surroundings. It is reflective in darkness and very transparent on the other brighter sight of the glass.

But this transparency is also created by other factors like the glass itself, the nature of the façade constructions and the sunshades. We can conclude that glass is only transparent under certain conditions. (Deplazes & Eidgenössische Technische Hochschule Zürich. Departement Architektur., 2013)

Different types of glazing give different reflectivity's. This depends on the texture in and on the glass. For example, mat glass is not reflective and translucent. The degree of reflectivity and transparency could be determined by the pattern that is applied to the glass and the shape that is made from the glass.

When designing the glass bricks of the crystal house, the bricks should be as light transmitting as possible. This is why its surface is flat, and the interlayer (and therefore tolerance) is as small as possible, which resulted in a visible transmittance of about 0,8. (Janssens, 2018)

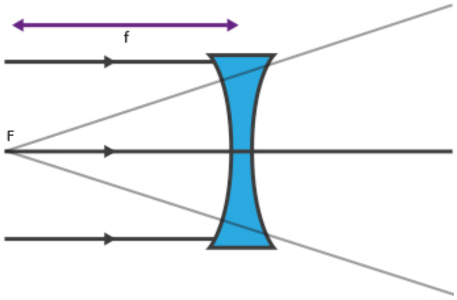


Figure 18. Hollow Lens (‘H2 Licht | De natuurkunde fabriek’, n.d.)

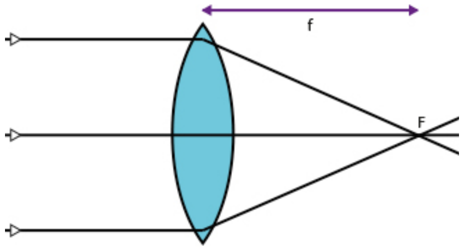


Figure 17. Convex Lens (‘H2 Licht | De natuurkunde fabriek’, n.d.)

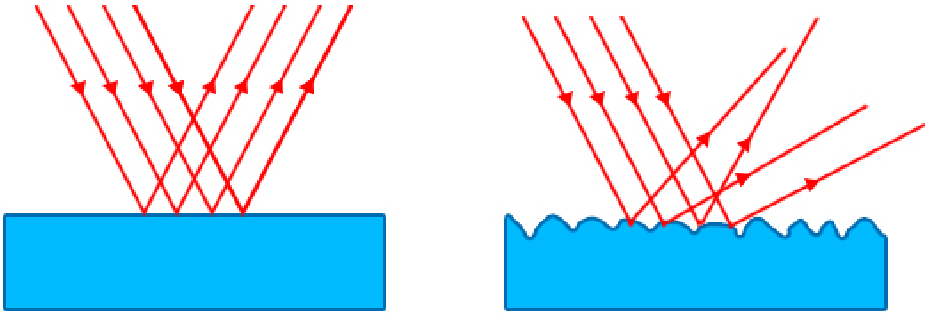


Figure 19. Reflection; specular and diffuse (‘H2 Licht | De natuurkunde fabriek’, n.d.)

Figure 16. Translucent reflective display in Short Hills mall in Millburn, New Jersey (Tomwsulcer, 2014)

Figure 22. Broken glass

Brittleness

The material glass does not yield plastically; therefore it is impossible to predict its failure. Other materials like steel do yield, so it is visible to see when a structure is going to collapse, this way the material is warning you before it is going to fracture.

In the figure you can see the stress to strain of different kind of materials; brittle, not ductile, ductile and plastic. The applied pressure on the brittle material can be very high, but when it breaks the material is not able to hold up any force.
This brittleness of glass does occur due to the ingredient Silicate; which gives glass the hardness and strength as well. (Weller, 2009)

Tension and Compression strength

During the production process of glass many flaws, notches and cracks appear on the surface which is invisible to the human eye. Because of this glass has a much higher theoretical strength than the actual strength we measure from glass physically. Therefore, we can talk about the theoretical strength of glass and the physical strength of glass.
When talking about the strength of glass, we have to differentiate two types of strength with very different values: tensional strength and compression strength.

The compressive strength of glass can hold up to 1000 N/mm2 ('Physical Properties of Glass - Saint-Gobain Glass UK', n.d.) exceeding that of wood, concrete and even steel ('Granta's CES EduPack 2017', n.d.) Compared to its compressive strength, glass has a lower load-bearing capacity when loaded in tension.
The load-bearing capacity of glass is also influenced by the time-span the force is applied to the structure, as well as the size of the surface area. (Weller, 2009)

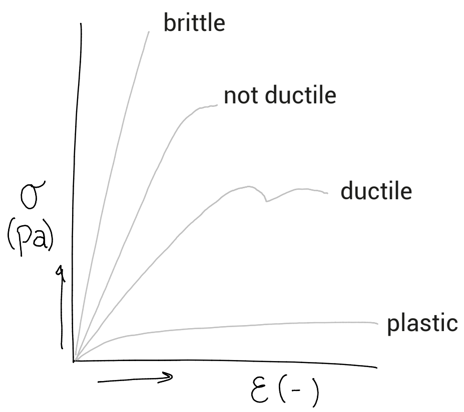


Figure 20. Brittleness (de Vries, 2018)

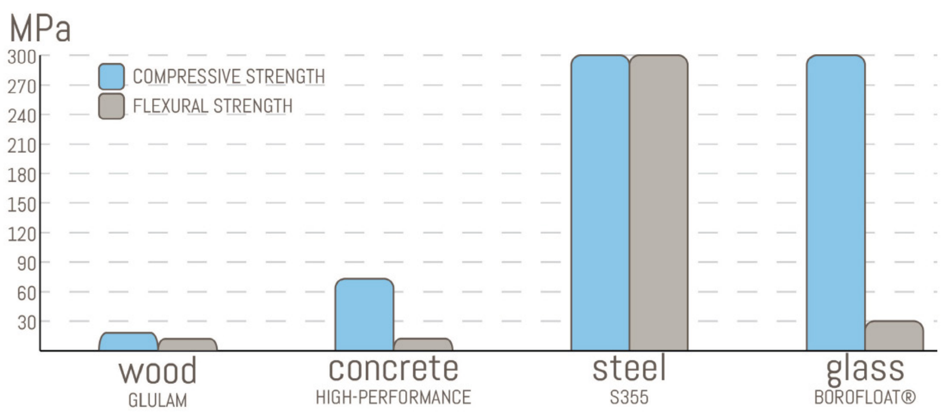


Figure 21. Mechanical strengths of common materials (van den Broek, 2017, P17)

Mouldability

Glass is a material that is formed by heating it until it is liquid. In this state, it is possible to mould it into any wanted shape. Crystals suddenly become liquid when they reach their certain melting point. But because glass is a non-crystalline, it happens more gradually. When the temperature rises to 520 to 550 degrees Celsius, the glass will slowly change from a brittle material to a plastic-vicious one. If the temperature increases more (up to 1200 degrees Celsius), the material becomes more like a liquid, which could be cast. (Weller, 2009)

For every type of glass this mouldability will be possible at a different temperature, the working temperature.

Thermal Expansion

Fracture can occur by a changing temperature and temperature differences on both sides of a glass object. When the thermal expansion coefficient is lower, glass will be less vulnerable to fracture by thermal loads. There are different types of glass which can withstand thermal loads better than others like borosilicate glass and fused silica. This is because of the boric-oxide which is inside the mixture of this glass type. In the chapter with the glass types, this difference is visible. ('Granta's CES EduPack 2017', n.d.)

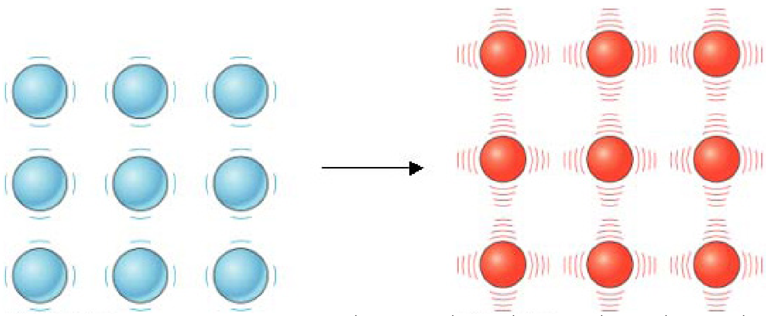


Figure 25. Thermal contraction and expansion (jacknapo93, n.d.)

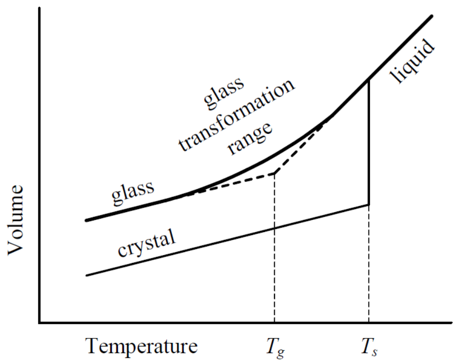


Figure 23. Schematic representation of volume's dependence on temperature for a glass and crystalline material ;Tg=glass transition temperature; Ts=melting temperature (Louter, 2011, P 46)

Figure 24. Production of glass at working temperature (Novosibirsk, 2013)

Manufacturing

Figure 26. When producing float glass, temperatures exceeding 1,750 degrees Celsius are required - a challenge for both man and material. (Schott AG, 2014).jpg

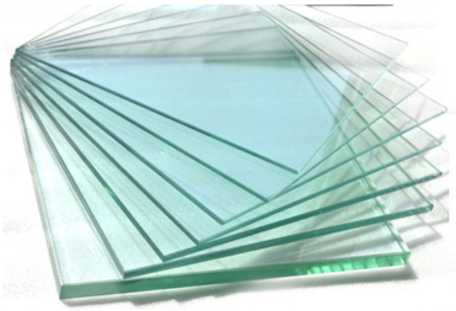


Figure 27. Float glass sheets ('clear-float-glass-homepage', n.d.)

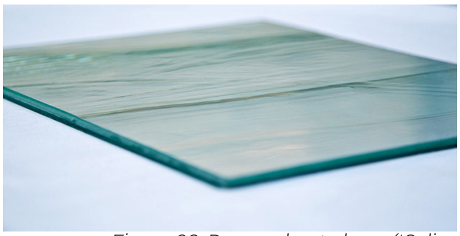


Figure 28. Drawn sheet glass ('Cylinder-Glass-MONO', n.d.)

Melting tank

The manufacturing of glass starts in most methods with melting the mixture of raw materials in a melting tank. This melting mostly happens at a temperature of 1550 degrees Celsius. At this temperature, the remaining bubbles and gas will be removed. After this, the molten substance will be cooled down to 1000-1200 degrees Celsius. Then it will be transferred to one of the manufacturing methods. Sheet glass could nowadays be created by floating, rolling and drawing. (Weller, 2009)

Float glass

Floating glass is the production method to create most windows and other flat objects from glass. Therefore is made in massive quantities all over the world. 35% of all the glass products are made with the floating glass process. The glass is made in the least acceptable quality, but because it is such a low-cost method to make glass, it is easier to replace the glass than to adjust the production process. The sizes of the glass are regularly limited to a maximum of 3,2 x 6,0 meters due to the transport of the glass. For higher prices, glass could even come in more significant surfaces up to 8,0 m. Because of the typical thickness of the glass, the machines are limited to make thicknesses from 2 to 19 mm thick, but when changing the settings of the machines, the thickness of 0,5 to 25 mm could be produced. The glass ingredients will melt and spread to a bath of tin where it is distributed evenly due to gravity force. When the glass is leaving the bath of molten tin, the cooling process will start from 600 degrees Celsius to 100 degrees Celsius. (Weller, 2009)

Rolled glass

Rolled glass is created by rolling molten glass through two water-cooled contra-rotation rollers. The thickness of the glass can be adjusted by putting the rollers more and less close to each other. These rollers can have a flat surface, this way they will create clear glass. But this surface will never be as transparent as float glass or drawn sheet glass. This method could also create patterned glass by using a textured lower roller; this could make the glass translucent or opaque. Polished wired glass is formed by polishing and grinding the glass surface. It is also possible to create profiled glass by this production method; the glass can be turned up to 90 degrees by the rollers. (Patterson, 2008)

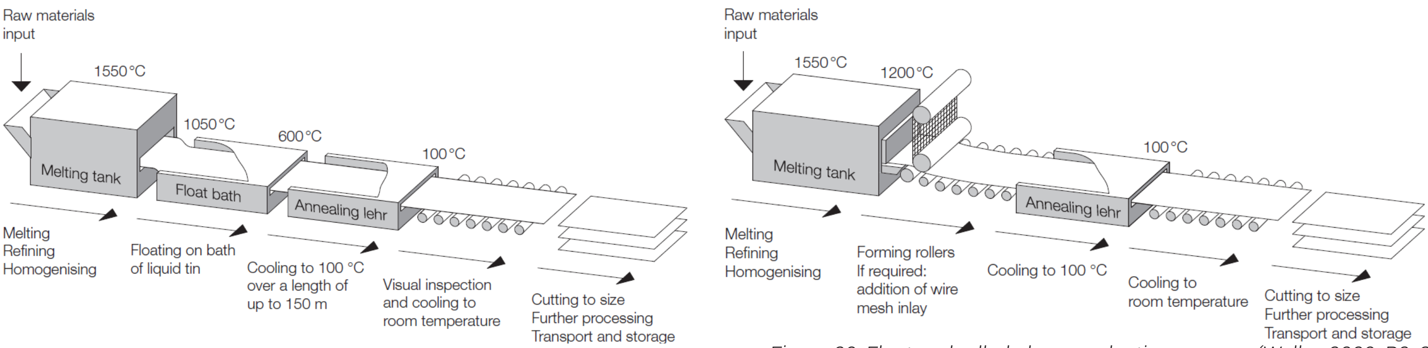


Figure 29. Float and rolled glass production process (Weller, 2009, P2-3)

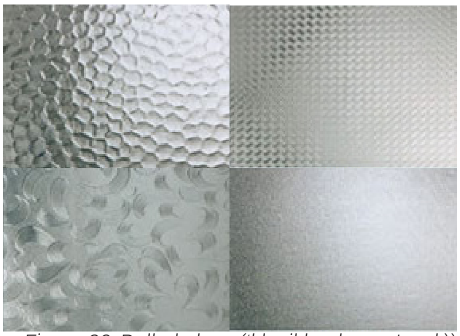


Figure 30. Rolled glass ('klasikbuzlucam', n.d.))

Figure 31. Extruded glass tubes rods and profiles (SCHOTT, n.d.)

Figure 34. Picture of cast glass elements at glass lab Civil Engineering of TU Delft

Drawn glass

From drawn sheet glass, which is first made in 1905, it is possible to create flat sheet glass. But this production method is not able to compete with float glass regarding productivity and optical quality. With this production method, you can see a distorted reflection due to slight waves and batter on the surface perpendicular to the direction of the drawing. This distorted reflection is often wanted in old buildings, and therefore this 'antique' glass could be used for renovations of these buildings.

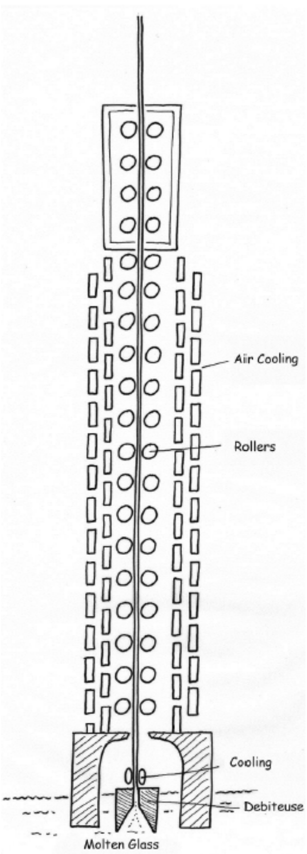


Figure 32. Drawn Glass (davinciglas, n.d.)

Extruded glass

Glass that is made with hot extrusion is called extruded glass. This method mostly produces profiled glass which is used in different industries. This process will be done at working temperature in which it will be viscose. Borosilicate is the most used glass type for extrusion. Extruded glass profiles have tight geometrical tolerances, high thermal shock resistance and high optical quality. Next to this, they have an extensive range in geometry and size. ('Tubing – DURAN® borosilicate glass 3.3 tubes, rods and capillaries | SCHOTT North America', n.d.)

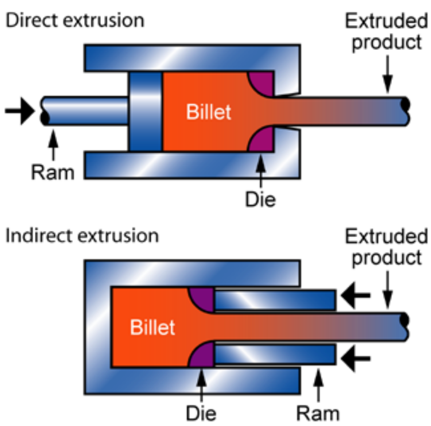


Figure 33. Extrusion process ('Granta's CES EduPack 2017', n.d.)

Cast glass

By the cast glass method, the glass can be transferred into almost every shape and size. Therefore it is possible to produce very complex shapes. It could give clear optical results and does not have to be cut into the right shape anymore. When creating a geometric shape with cast glass, the element will not be limited to a certain thickness. The drawbacks of this manufacturing method are that it takes a long time to cool the cast glass when the element is thick.

Before manufacturing the cast glass, a mould will be made of the preferred shape. This mould could be made of different materials like sand, plaster, graphite and steel. Plaster is mainly used to produce only one component (disposable mould), while steel is used for multiple copies of the same element (permanent mould).

The labour of the cast glass is mainly caused by the cooling process of the glass. Because there are no restrictions on the size of the glass, it could take months or even years to cool down a big piece of glass. This is the reason why in building industry this way of producing glass is not applicable (yet).

In other industries casting glass is used to create a clear view or an optical effect. This is visible in the sculptures by Roni Horn and the giant telescope mirrors(Johns, 2006)(Roni Horn, 2006).

Two methods can make cast glass; hot pour and kiln casting. (Oikonomopoulou, Veer, Bristogianni, & Nijsse, 2016)

Figure 37. Hot pouring (retrieved from: http://www.sinacastudios.org/wp-content/uploads/2016/08/glassblowing2-copy.jpg)

<u>Hot pour</u>

Hot pour is the production method that uses permanent moulds. The glass with a temperature of 1200 degrees Celsius is poured in a mould that is pre-heated to 850 degrees. After this, the mould is put in the oven (kiln). This production method is mainly used to create massive productions of cast glass products. The steel moulds can be reused many times and can, therefore, produce many similar shaped objects. The elements of the Crystal houses, the Atocha monument, the Crown Fountain and the optical house were all produced with this method.

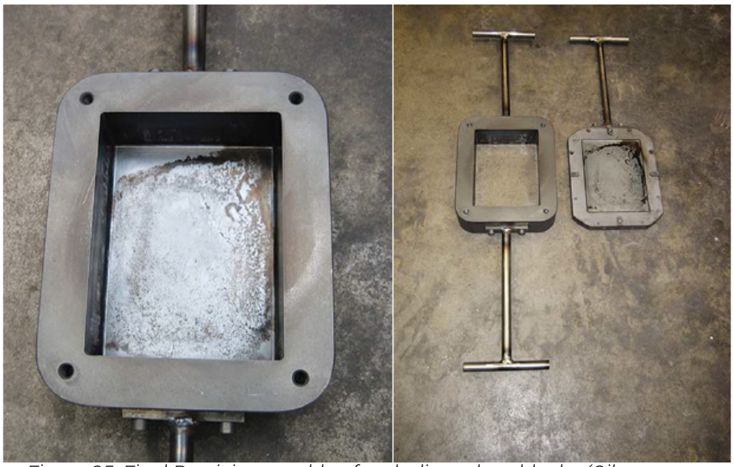


Figure 35. Final Precision moulds of soda-lime glass blocks (Oikonomopoulou et al, 2014, P 209)

Figure 36. Casting of the soda-lime glass blocks by Poesia Company, using preliminary moulds. (Oikonomopoulou et al, 2014, P 209))

Figure 41. Kiln with flowerpots and crystal cast moulds (Bristogianni, 2018)

Kiln casting

When kiln casting, one or more disposable moulds have to be made. To make these oven-resistant moulds, different mould have to be made first. Starting with an element that has the desired shape. This element could be made by 3D-printing, CNC-milling, lasering or anything else that would be able to produce the desired shape. After this, the negative of the shape will be made with silicone. From this silicone mould, a wax mould will be made. Around the wax element, a disposable gypsum mould will be made. Lastly, the wax will be molten out of the gypsum mould.

In this method, the disposable mould is in the kiln the whole time. The dry ingredients for the glass are placed in a bucket with a hole in the bottom. The temperature of the oven will rise to 1200 degrees Celsius. The ingredients of the glass will slowly melt and drip down in the mould which is placed underneath the bucket. When the mould is filled with the molten glass, the kiln will cool down slowly, until room temperature is reached. (Bristogianni, Oikonomopoulou, Veer, Snijder, & Nijsse, 2017)

Figure 39. Kiln-casting method (Bristogianni et al,2017, P27)

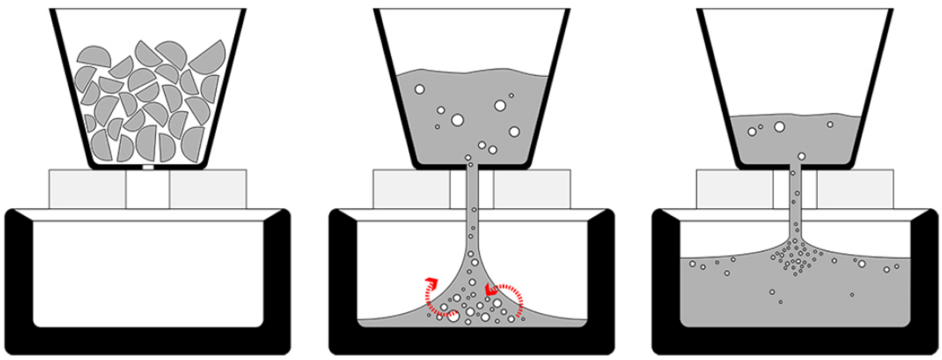


Figure 40. Air-entrapment during kiln-casting (Bristogianni et al, 2017, P27)

Figure 38. Production steps from MDF mould to final glass model of glass bridge components (Bristogianni et al, 2017 P1)

Figure 43. Temple in Thailand made of Heineken bottles(http://www.pattayatrader.com/images/32478jOn.jpg)

Recyclability

Nowadays sustainability is a big topic because of the scarcity of food and water, deforestation, global warming and too much waste. We all want to be very eco-friendly, but sometimes we don't even know how.

In the building industry, a good start is to reduce the use of toxic materials, make recycling easier and use less energy while producing materials.

Glass could offer some advantages; you could recycle 100% of the material, and it is not toxic. Also, it can provide natural lighting and heating to a building, which could save energy. ('Granta's CES EduPack 2017', n.d.) Next to this, it has excellent resistance to salt water, strong acids, organic solvents, ultraviolet radiation and common chemical elements that glass could get in touch with. From this, we can conclude that glass is a durable material.

When it breaks, it is possible to recycle the glass again and make something else of it. For the environment, it is even better to use already produced glass, because the producing temperature (embedded energy) is much lower than from raw materials. This will help the environment regarding energy and material.

Glass can also be recycled even without melting it. An example of this type of recycling is visible in a temple in Thailand that is made out of 1,5 million empty bottles of Heineken. (Firrone, Bustinto, & Montalbano, 2016) Or in concrete, glass charts can be added to create a higher strength material and interesting optical features. (Shao, Lefort, Moras, & Rodriguez, 2000)

When making a loadbearing glass column of different interlocking elements, it is useful to make sure that the different parts could be replaced. Replacing is much easier when there is no glue on the elements. Better is to use dry stacking of elements with an interlayer that is not adhesive. This way the column itself is replaceable, which makes it a very durable structural element as well.

Figure 44. Glass Recycling ('Glass-Recycling', n.d.)

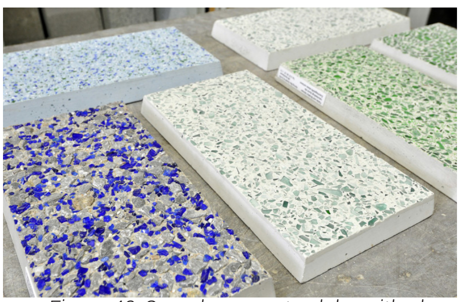


Figure 42. Sample concrete slabs with glass aggregates and different surface finishes (heringinternational, n.d.)

Increasing strength

Glass is a material that is hard, transparent, thermally stable and is resistant to radiation and chemicals. (Weller, 2009)

Standard float glass, also known as annealed glass, is slowly cooled, this makes the glass more resistant to temperature changes. But when it breaks, it will break into large sharp pieces with fatal loss of coherence, which can cause significant accidents. This means that it is a ductile material, it is slowly reaching the limits to its carrying capacity, and it breaks or collapses suddenly. It has no warning in the form of visible deformation (yielding) or cracking. Therefore, it is good to use in harmless products, like furniture and drinking glasses. But when creating a structure of glass in a building, it is not sufficient.

Structural glass has to be redundant, capable of carrying after the failure of a major part. There are different methods to make the glass suitable for structure, those are explained in this chapter.

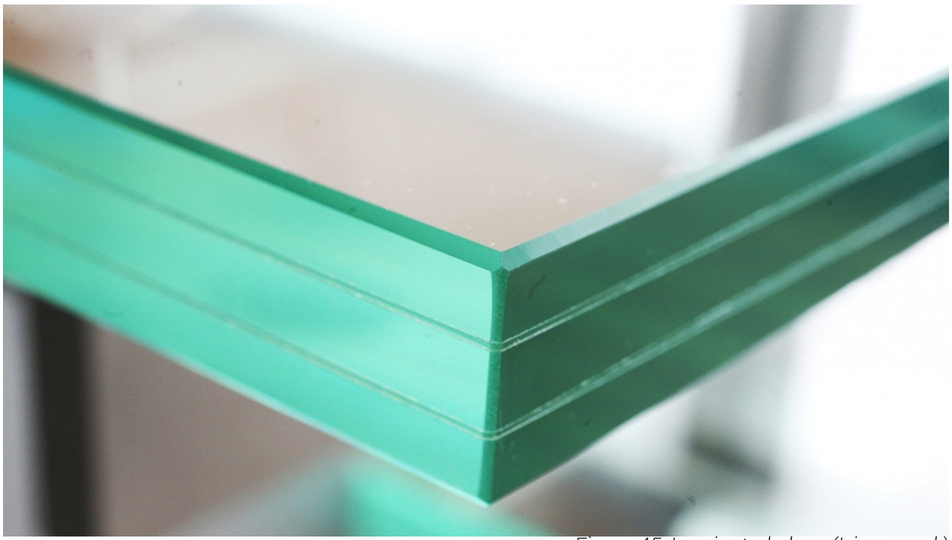


Figure 45. Laminated glass (I-icom, n.d.)

Lamination and sacrificial layers

Lamination or layering is done with invisible glue or foil layer between two separate glass panels. This layer will keep the structure together, even when one of the glass panels breaks; it takes care of the safety of the element. It prevents broken glass pieces flying around injuring people because the interlayer will stick the broken glass pieces to the element. The element can still bear some of the load, depending on the number of whole and broken layers. Because of this capacity, laminated glass is also called safety glass.

Lamination is usually done with 2 to 5 layers of glass. When using three glass panels, the middle one will always be covered while the panels on the sides. When those outer glass panels have about the same thickness as the middle one, they will normally be structural as well, and when they are thin, they will only be sacrificial.

One could calculate the element strength due to the strength of the middle panel when the outer panels are only sacrificial. When there are structural, 2 out of the three panels should be able to hold up the structure.

Most of the time PVB (polyvinyl butyral), SentryGlas® foil or a two-component mix is used as a thin interlayer. PVB is a resin which is mostly used when an optically transparent, strong binding is required. ('SentryGlas®-IONOPLAST INTERLAYER', n.d.)

When calculating the strength of the laminated element, different factors are relevant: number of glass layers, the thickness of each glass layer and the type of the glass. It has to be assumed that one or more layers break, to calculate the strength of the element.

The lamination process starts with cleaning the glass planes. After which the glass planes and interlayer are put on each other. The planes and interlayer will be de-aired with pressure rolls. Lastly, the glass sandwich panel will be heated, and with pressure, the glass and interlayer will be bonded together. This way of strengthening the glass is completely transparent in one direction and translucent in the other direction (depending on the type of float glass). With its strength and transparency, it is used in many different fields as for example bulletproof glass, drop and fall resistant glass, automobile windscreens.

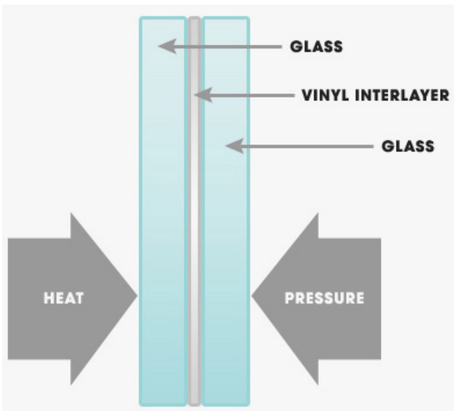


Figure 46. Laminating glass (Verrage, n.d.)

Reinforcements in glass

Reinforced concrete is a lot used in construction because it can take compression (concrete) and tension (steel reinforcement). Glass, can't take tension forces, just like concrete. Reinforcement in glass will make sure the structure is safe because it can still hold the applied forces after breaking and increase the tensile strength. When using lamination

By lamination, tension force could be applied to glass when inserting metal or GFRP (Glass Fibre Reinforced polymers). When placing these reinforcements on the edges of the glass, transparency hardly has to be compromised, because the edges are already translucent. When using steel-reinforced glass, there will still be load bearing after breakage. (Louter, 2011)The level of the load-bearing capacity of the reinforcement is subjected to the shape type and percentage of the reinforcement and the degree of contribution of the interlayer.

When putting a metal wired grid into the glass, it makes the glass less strong. Glass is very susceptive to cracks and with a metal grid into the glass it only has multiple cracks which make it less strong. But, when applying this grid, the glass is safer because the grid will hold the broken pieces of glass together.

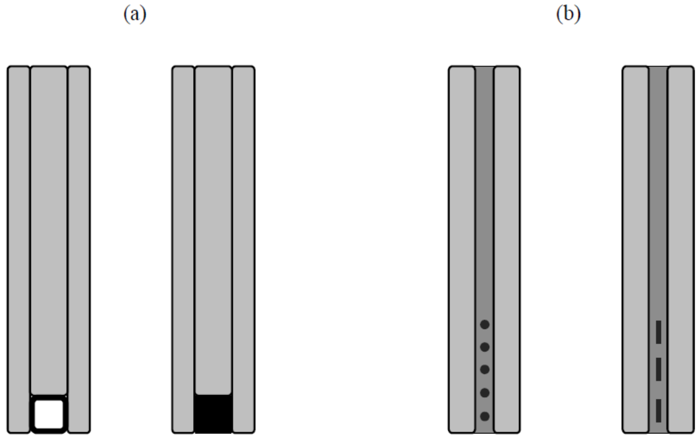


Figure 48. Cross-section of triple-layer annealed float glass beams with a stainless steel reinforcement section bonded at the inner recessed edge; (b) Cross-section of double-layer annealed float glass beams with GFRP reinforcement rods embedded in the interlayer. (Louter, 2011, P 253)

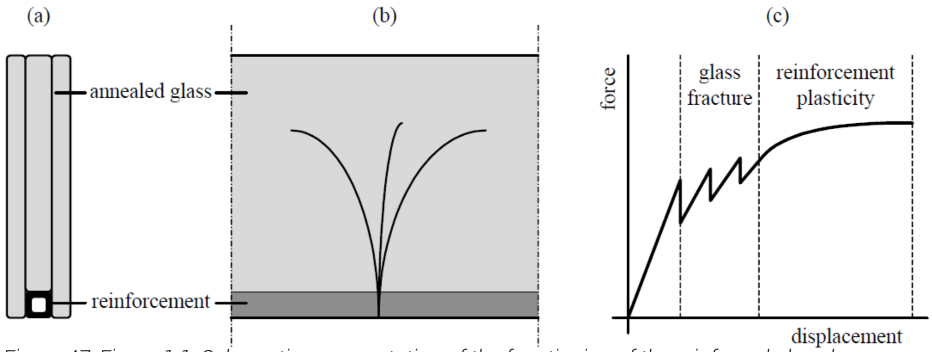


Figure 47. Figure 1.1: Schematic representation of the functioning of the reinforced glass beam concept; (a) cross-section of a reinforced glass beam; (b) side-view of a cracked reinforced glass beam; (c) intended force-displacement diagram, which shows a significant post-breakage strength. (Louter, 2011, P 39)

Figure 49. Optical House in Japan with steel rods connecting the cast glass bricks (https://i.ytimg.com/vi/1H0Cd_Hwxks/maxresdefault.jpg)

Strengthening glass

Thermal treatments on glass will increase impact resistance and thermal fatigue. But it will also give minor distortions to the glass in optical view. There are two ways to ways of thermal treatments on annealed glass; tempering or heat strengthening. Toughening is also called tempering, which will create fully tempered glass (FT) or toughened glass.
Next to that, it is also possible to strengthen glass chemically.

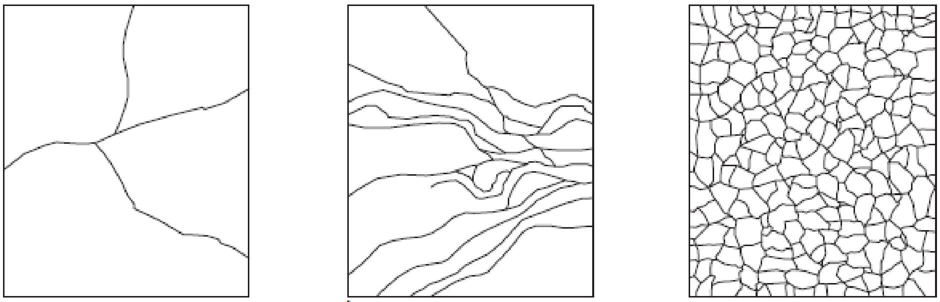


Figure 50. Schematic presentations (not to scale) of the fracture patterns of untreated and thermally, toughened glasses (Weller, 2009)

<u>Tempering</u>
Toughening or tempering glass is done by heating the glass to 620–650°C, after which the outside of the panel is rapidly cooled with ventilated air with room temperature. By doing this, the inside cools slowly and shrinks: this pulls to the outside which will make the scratches smaller on the outside of the panel. The middle will be under tension of the compressed glass on the outside. The toughening will make the glass much harder and stronger than annealed glass. Also, the glass could be heated up to 240 degrees Celsius. But the stress inside the glass causes that when the glass breaks, it will break in small, harmless pieces. Toughened glass is very strong in general but very weak in the edges. Next to this, it is not possible to cut toughened glass; this will break the bond of the outer glass layers which will break the entire glass plane immediately. (Weller, 2009)

<u>Heat strengthening</u>
Heat strengthening the glass (HS) is a similar process to toughening, but less extreme. The results in strength, hardness and breakage are in between toughened and annealed glass. It can only be applied to planes with thicknesses of maximum 12mm. As you can see in table 2 (Kington Group Co. Limited, n.d.)". But because it's reliability regarding breakage, it is more suitable for structural glazing. (Weller, 2009)

<u>Chemical strengthening</u>
This way of strengthening plays a small role in the building industry. It is used for very thin planes of glass and curved geometries. This is because the chemical treatment is only extending in a very thin layer of the glass. The chemical strengthening is usually done with potassium nitrate at 450 degrees Celsius. When chemically strengthening the glass, the surface will generate a compressive strength because the ions on the surface of the glass will grow their atomic radius (potassium ions will replace sodium ions) and get closer to each other. The ions in the core will be in tension. This way of strengthening is mainly used in optical applications and the car industry. (Weller, 2009)

When chemically strengthened, the glass will be 6 to 8 times stronger, but it will still break into large and sharp pieces, like annealed glass. When comparing chemically strengthened glass to thermally strengthened glass, we can say that chemically treated glass has a better optical view. Next to this, it is possible to cut chemically treated glass without breakage, but it will lose it additional strength around 20mm from the cut. (Haldimann, Luible, Overend, & International Association for Bridge and Structural Engineering., 2008)

	Tempered glass	**Heat-strengthened glass**
Safety	good	common
Mechanical strength	12 0MPa	70 Mpa
Thermal shocking	200 °C	100 °C
Surface compression	≥ 90 Mpa	24-69 Mpa
Fragmentation	obtuse - angle grain	Radical crack
Spontaneous breakage	Yes	No
Thermal stress breakage	No	No

Table 3. Glass treatments and its characteristics (Kington Group Co. Limited, n.d.)

Surface treatments

To modify glass different surface different treatments can be done. These treatments can influence the properties of the glass, create artistic effects or create new functions.

Subtractive treatments

Substantive treatments of the glass will take place in the glass itself, instead of an addition to the glass like coating or enamelling. It will remove a surface of the glass. It can be applied to only a part of the surface or the total surface.

Etching

When etching glass, hydrofluoric acid is used. This way of treating the glass can deliver a very homogenous surface with a mat finish. If parts are masked during the treatment, patterned can be created on the surface. (Deplazes & Eidgenössische Technische Hochschule Zürich. Departement Architektur., 2013)

Sand-blasting

The result of sand-blasted glass is very comparable to the acid etching result. But the effect of acid etching offers more finishes and a smoother result. (Weller, 2009)

Edge finishing

If the edge of a material is exposed, it is useful to finish the edges. This can be done by grinding or polishing. When glass is water jet cut, it does not need further edge finishing.

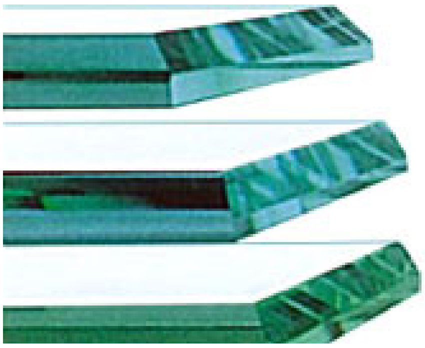


Figure 53. Edge Finishing (PinsDaddy, n.d.)

Figure 51. Etched glass (Lightcutters, n.d.)

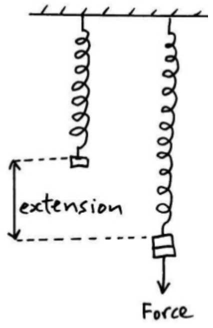
Figure 52. Sand blasting (DANH MỤC DỊCH VỤ, n.d.)

Figure 54. Frosted_etched_glass('High Strength Tempered Frosted Glass , Flat Acid Etched Glass Sheet Product', n.d.)

Increasing stiffness

Stiffness is described as 'the quality of being severe or strong' by the dictionary of Oxford. In a formula, this will be described as the force divided by the deformation of the structure (Hooke's Law).

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



When talking about the deflection in a column, we have to calculate it the same way as we would calculate a beam's deflection. The deflection of the column will depend on the way it is fixed with the rest of the structure. There will be different options to connect the beam on top and bottom: fixed, pinned (rolled, hinged) or free. This will give different options to calculate the deflection, and therefore the stiffness.

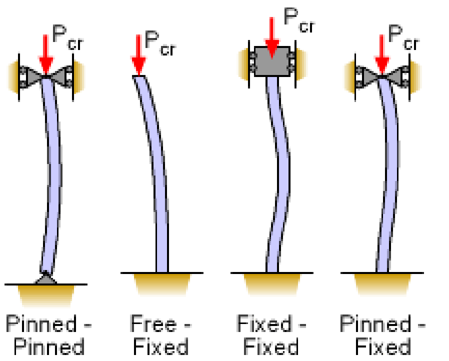


Figure 57. Column endconnections ('Mechanics eBook: Fixed Columns', n.d.)

The deflection will always be constructed with the Young's modulus, the second moment of area, the force applied on the column and the length of the column. The Young's modulus is dependent on the type of the glass and the second moment of area on its section properties.

This means that when the cross-section of the element changes, in addition to that the second moment of area, the stiffness will change.
Changing the cross-section could be done in different ways; by bending, or creating 3D elements.

Bending

When bending the glass of the column in vertical direction, the cross section will change and therefore the second moment of area could increase.
Bending glass can be done with cold or hot bending.

Cold bending is done by room temperature fixing the glass either in a frame on site or a laminating them in a formwork. The glass will be permanently deformed due to the bending stresses, during a particular time and load. Cold bending is restricted to a limited radius.

On the contrary hot bending, can create any wanted curvature radius. Also, it free of internal stresses, which makes it stronger and therefore very usable for structural glass. However, it is much more expensive and energy and time-consuming. The process will start with preheating the mould after which the glass will put in. The temperature in the oven will rise, and the glass will gradually by the force of gravity deform to the wanted curvature. The radius of the curvature will determine the stiffness of the glass. (Weller, 2009)

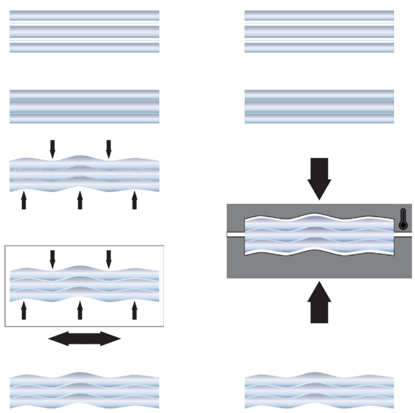


Figure 55. Cold and hot bending (de Vries & van Es, 2017)

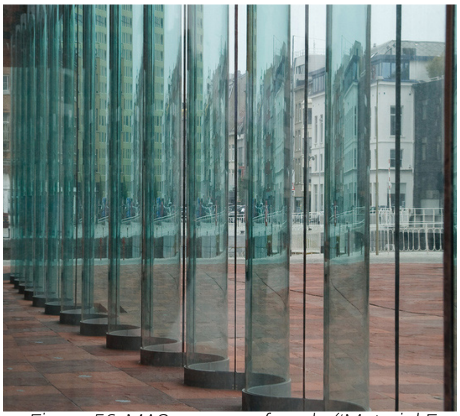


Figure 56. MAS museum facade ('Material Focus: MAS Museum | Material Strategies', n.d.)

3D cast glass

With cast glass, it is possible to create any wanted cross-section. This makes it possible to develop stiff geometries. When a structure is built of multiple-jointed elements, the load will be divided among the rigid elements. The elements will carry the load due to their stiffness rate. This means that the deflection between the elements remains the same.

Conclusions of the Material Glass

Glass is a transparent but reflective, strong but brittle and modern yet ancient material.

Two types of glass are mainly used in the building industry; soda-lime glass and borosilicate glass. Soda-lime glass is in raw materials much cheaper then borosilicate glass. But because the thermal expansion coefficient of borosilicate glass is much lower, this type of glass can withstand much higher temperature differences then soda lime glass. Due to this property, borosilicate glass could be annealed much faster then soda-lime glass. Choosing between those two types of glass will have to do with the following factors: material costs, temperature difference and annealing time.

Glass is very strong in compression but only has about 1/10th of his strength in tension. This is why tensional stress should be avoided as much as possible.

There are two types to produce cast glass: hot pour and kiln casting. Hot pour is the most efficient method to create multiple identical components for commercial purposes. Kiln casting is mostly used for research, in which much less of the same type of components are needed.

Glass could be recycled 100% when it could be separated from other materials. When this separation is wanted, the glass should not be glued to each other or something else. This makes safety a hard topic; float safety glass is mostly laminated by adhesives in between the glass so that if one element breaks the others can carry the rest of the load and will hold the broken pieces together.

When wanting to increase the stiffness without using adhesives, 3D geometries could be cast in glass. Due to the transparent, diverting, converting, absorbing and reflective effects of glass to light, very interesting play of lights could occur when using these geometries.

Glass Column

Glass Column

Figure 59. Danteum (Danteum Foundation, n.d.)

General Column

In the Encyclopaedia, a column in architecture is defined as: "A vertical element, usually a rounded shaft with a capital and a base, which in most cases serves as a support. A column may also be nonstructural, used for a decorative purpose or as a freestanding monument. ('Column | architecture | Britannica.com', n.d.)

In history, we know the Egyptian columns (2639 BC) which has a lot of similarities to the ancient Greek columns. In the classical architecture from the ancient Greece (1200BC), we know three types of columns; Ionic, Doric and Corinthian. In all the traditional column types, the section of the middle part of the column is rather small compared to the top and base elements of the column. These elements will distribute the loads evenly from the roof to the column. In the centre of the middle part, the section is a bit wider than the rest, which will prevent the column from buckling. (Akerboom, 2016)

Glass is not the usual material to create a column, mostly stone, concrete, timber or steel are used. The column will transfer the compressive load to the underlying structural member like a beam, floor or foundation. As we saw in the previous chapter, glass is very strong in compression. This is why it is logical to apply glass in a compressive member, like a column.

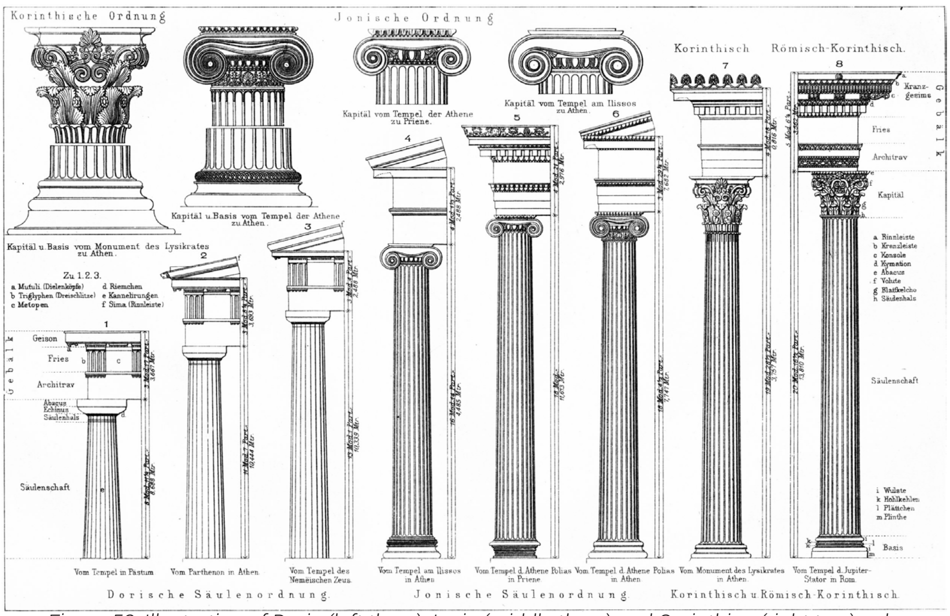


Figure 58. Illustration of Doric (left three), Ionic (middle three) and Corinthian (right two) columns. (Sanseverino, 1983)

Slenderness

The dictionary of Oxford describes something that is slender as something 'of small girth or breadth'. In this sense the small girth (cross-section thickness) will only be in comparison to the length of the object. The opposite of slender will be an object with a wide or big girth in comparison to its length.

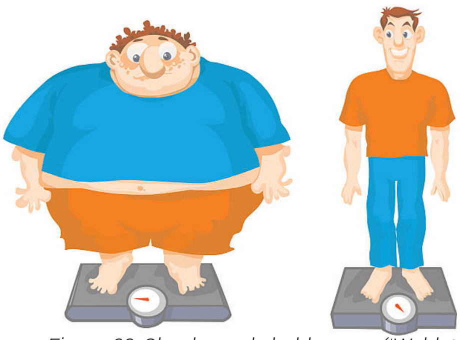


Figure 62. Slender and chubby man ('Weblet Importer', n.d.)

When describing the girth of a column, we mostly talk about the cross-section of the column. To compare the thickness of this cross section we have to look at its distributed radius. This radius is called the radius of gyration and can be calculated by:

$$R_g = \sqrt{\frac{I}{A}}$$

In which I is the second moment of area and A is the surface of the cross-section.

When the column is long or slender (or the radius of gyration is high), buckling can occur. The column will buckle due to its elasticity modulus. When the slenderness is short, the column would fail due to its shear force. In between the short and the long, the column will be dominated by the strength of the material. (Hognestad, 1951)

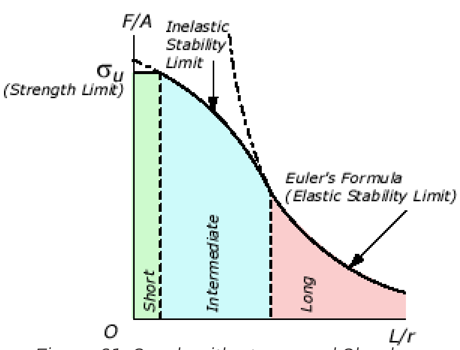


Figure 61. Graph with stress and Slenderness Ratio (eFunda, n.d.)

Buckling

The definition of the verb buckle is described as 'bend and give way under pressure or strain' by the dictionary of Oxford. Because columns are slender elements, they will be exposed to buckling.

Columns can buckle or bend under extreme loading. The buckling strength can be calculated by the Euler buckling formula:

$$F = \frac{\pi^2 EI}{(Kl)^2}$$

With different factors involved; material properties (E-modulus), cross-section (second moment of area), the method of fixing (effective length factor), length of the column.

Since the length of the column (l) is known by the case study, the only variable factors will be the cross section (I), conditions of end supports (K) and the type of glass (E).

Because of the imperfections in the surface of the glass, the glass will generally break before it reaches its buckling strength. Therefore it is insecure under how much load the glass will break; we do know that it is influenced by (Luible & Crisinel, 2004):

- Glass thickness
- The initial deformation
- The load eccentricity
- The degree of damage to the surfa ce of the glass

Stability

When an object is stable, it is not likely to give way or overturn.

Stability can be explained in the relationship between deformation and load. When no ambiguous state of equilibrium can be found when a particular load is applied, a stability problem occurs. (Luible & Crisinel, 2004)

There are three types of load situation in no unambiguous state of equilibrium to distinguish: (Pflüger, 1964)

- Stable
- Unstable
- indifferent equilibrium.

There must be said that the indifferent equilibrium is very rare. This is because there will always we imperfections in the element or material, like; initial inaccuracies in the dimensions of an element, residual stresses or lack of homogeneity and eccentrically applied loads. (Luible & Crisinel, 2004)

In a structure, a stable state of equilibrium is required. The stable state of equilibrium is defined as the ability of the structure to remain in position and support the given load, even if it is forced slightly out of its position by a disturbance. (Gambhir, 2004)

The structure can be called unstable when the load exceeds the critical value. With only a slight disturbance the structure will fail.

If a stability problem occurs, it can be solved analytically and/or numerically.

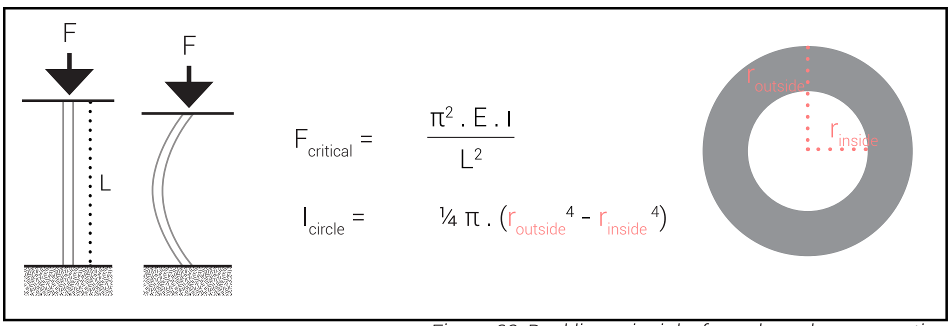


Figure 63. Buckling principle, formula and cross-section

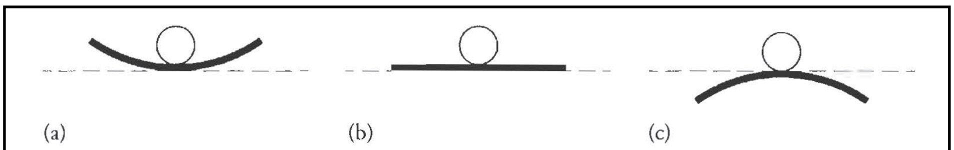


Figure 60. A stabie state of equilibrium is represenred by (a),whereas an unsrable state of equilibrium is represenred by (c). The ball analogy for anindifferent state of equilibrium is shown in (b). (Roebroek, Snijder, Van Herwijnen, & Huveners, 2010)

Torsional buckling

When the torsional rigidity is smaller than the bending stiffness of a cross-section of a column torsional buckling may occur. (Man & Eldik, 2001)

Torsion happens when a moment is available which tends to twist the column, and the strut axis remains straight. The horizontal planes will rotate around the centre point of the cross-section. (Hartsuijker & Welleman, 2013)(Timoshenko & Gere, 2009)

Stiffness can be created by making the cross-section solid. When the cross-section has the shape of a circle, it has maximum torsional rigidity. In contrary, cruciform or round sections have a much lower torsional rigidity.

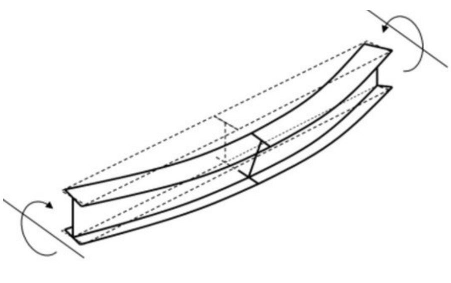


Figure 64. Torsional buckling schematicly ((Quora- Matmatch, n.d.)

Thermal stresses

Thermal stress could lead to a failure of a material. It will occur when thermal differences appear on two locations of the same element, which will cause internal forces. These differences could be in the glass itself or at two surfaces of the glass. When the critical stresses are exceeded, the glass will crack and fail.

These thermal stresses are influenced by external and internal factors. The external factors could be the location of the building, the orientation or the environment. The internal factors could be the type of glass, the edge quality, the framing material, the window size and the internal heating system.

The strengthening of the glass has a significant influence on the critical thermal stress values. Annealed glass could resist around 30 degrees Celsius, whereas this is 200 degrees Celsius for toughened glass. ('AGC Yourglass', n.d.)

When the temperature rises, the air pressure will increase as well. The pressure divided by the temperature will result in the same constant. This is explained by the law of Boyle and Gay-Lussac:

$$\frac{P}{T} = k, \qquad \frac{P_1}{T_1} = \frac{P_2}{T_2}$$

This means that a high air pressure difference, just like a high difference in temperature, will result in failure.

Figure 65. Thermal shock on ceramics ('The porcelain is harder, but the terra cotta has it beat for thermal shock!', n.d.)

Fire resistance

Fire resistance is the ability of an element to keep its design function during exposure to fire. For glass, it is mostly connected to the thermal stresses inside the glass due to the temperature differences, the elasticity modulus and coefficient of the glass. (Weller, 2009)

When glass can withhold the thermal stresses 10 minutes, the glass can be loaded until 520 degrees Celsius. (Ouwerkerk, 2011) From this temperature on the element will start to become more soft and viscose. But when the temperature is increasing too fast, the glass will fail before this stage already. Annealed glass with a 40 degrees Celsius difference will give failure in 1 minute. (CUR B&I, n.d.)Toughened glass will be resistant to the fire longer, but after a specific time, the glass will break as well. (Veer, Van Der Voorden, Rijgersberg, & Zuidema+, 2001)

It is also possible to give the glass other fire-resistant treatments like; an intumescent coating, an organic interlayer or a foaming interlayer. Borosilicate has, compared to soda lime glass, a much higher thermal resistance. This is why it can stand the heat of the glass for a longer time. And is, therefore, more applied in elements that need fire resistance.

In the Bouwbesluit, the building regulations of the Netherlands, there is told that the construction of a building should resist 30 minutes of fire before it collapses. This will give the people inside the building a chance to leave the building in safety. These 30 minutes could even be exceeded when the building is bigger, and the people would need more time to evaluate. For glass as a construction material, the regulations are not very clear. ('Bouwbesluit 2003', 2003)

Figure 66. Melted glass after fire in building (Team WFM, 2011)

Section properties

Second moment of area

The second moment of area, also known as moment of inertia, is a planar surface of the cross-section that is characterised because it can predict deflection, bending and stress in structural members. When it increases, the structure becomes more resistant to buckling in y- and z-direction directions.
This property can be calculated by three formulas that can be applied to three different cross-sections. The moment of inertia is one of the critical variables while designing a column.

Open or closed profile

Thermal stresses could be decreasing or increasing in open and closed profiles, due to the use and placement of the column. When cold air would be blown inside the open profile, and the column is heated up by the sun meanwhile, the temperature differences could become very large. Next to this, with a closed profile, the stresses would enlarge because the solid has less external surface and therefore have a bigger distance to the centre of the element. This could create big temperature differences due to the slowly changing temperatures in the glass element and fast-changing on the surface of the glass.

Next to this, cleaning would be a factor too thick about while designing a column with an open or closet profile. When the openings are large enough, cleaning should not be a problem. But with small openings, insects or dust could go in and not be taken out. This would leave a non-transparent and dirty column in the end.

Connections

Like all connections, glass connections are meant to transfer forces from one element to another. When they are used in a load-bearing structure, there is even more focus on the strength, stiffness and reliability of the structure. This puts a high pressure on the end connections of the elements to work sufficiently. Connecting glass and glass or other materials can be done with mechanical connections, glued connections and physical connections.

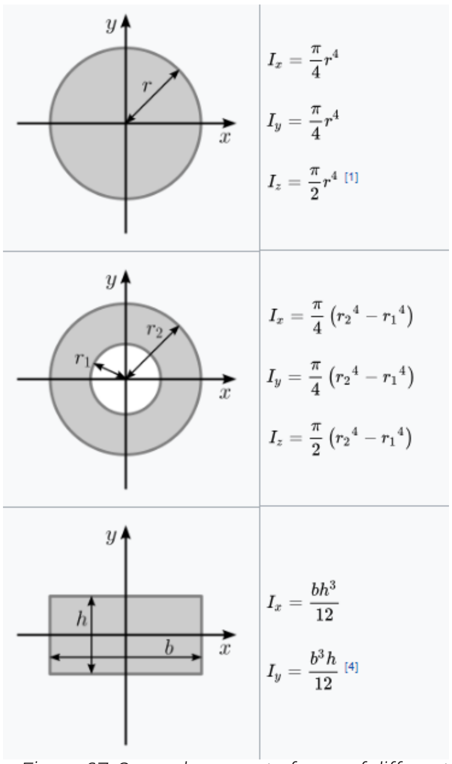


Figure 67. Second moment of area of different cross-sections (Circle, n.d., Rectangular area, n.d.)

Types of glass columns

Glass columns have not been applied widely in the world although it could be very interesting to use glass in a compressive element like a column.

When making a structural element of glass, a material with high compressive strength, it would be logical to use it in compression. A column is a compressive member who will carry only axial compressive forces, which make it sensible to design a column as a structural element made of cast glass elements.

Next to this, there seems to be a disagreement between architects and structural engineers; architects would like to have an open space without any interruption in light and view, and the structural engineers would like to have enough loadbearing elements (walls and columns) to transfer the loads safely to the foundation. Columns usually give an option to keep the open space with some interruptions in view and light. When these columns would be made out of glass, these elements would be translucent to transparent. This will be a good compromise between architect and structural engineer.

Because of the insufficient knowledge in load-bearing capacity and structural behaviour under exceptional loading conditions of the glass column, there is still a lot to explore in the field of glass columns. (Oikonomopoulou, van den Broek, Bristogianni, Veer, & Nijsse, 2017)

As we know all about the material glass and about designing a column, in this chapter both of the literature topic will be combined into different types of glass columns.

As far as we know, there are five possibilities to create glass columns: (Nijsse, R. & Ten Brincke, 2014)

1. Profiled
2. Layered Tubular
3. Stacked Sheets
4. Bundled
5. Cast

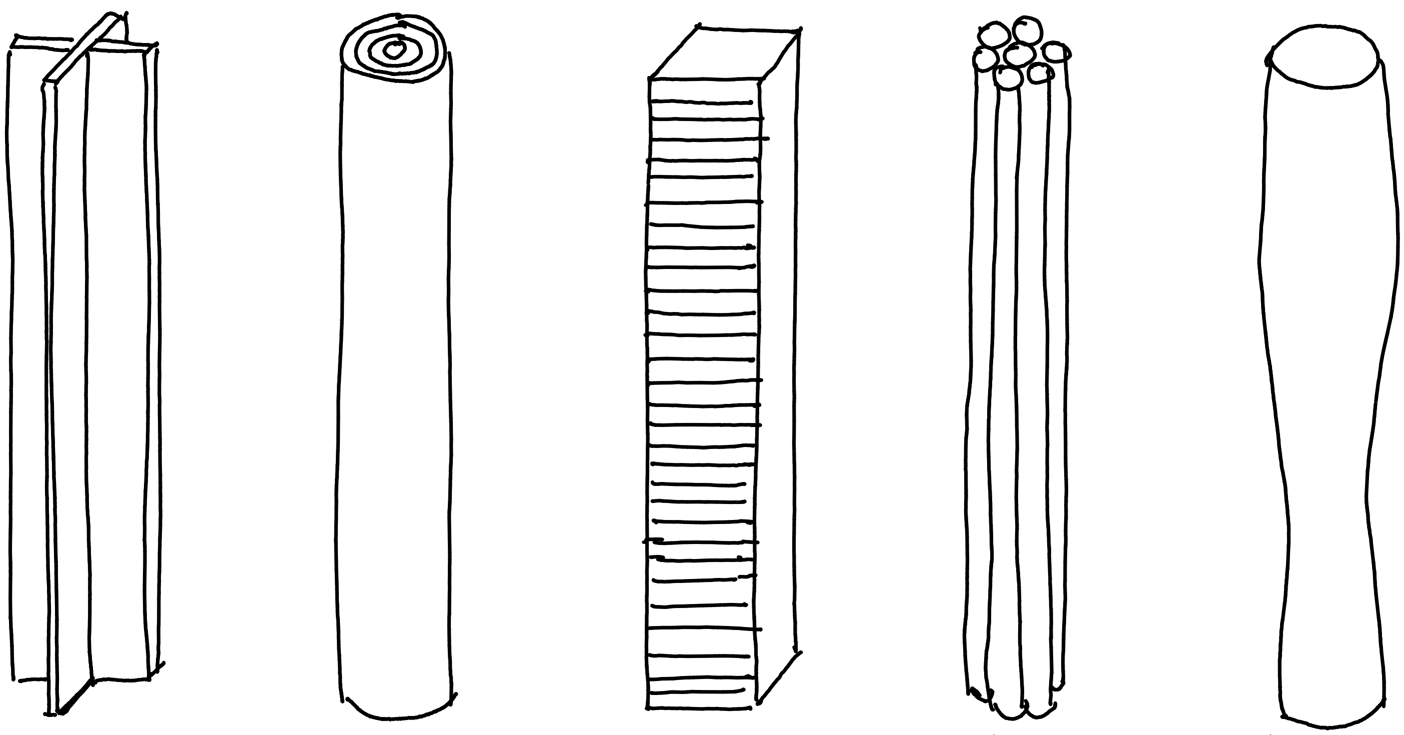


Figure 68. Types of glass columns : stacked , profiled, layered tubular, bundled, cast (Based on (Nijsse, R. & Ten Brincke, 2014)*, de Vries, 2018)*

Profiled

The profiled column is made of flat sheets of glass that are combined to a profile. This profile could vary from I-, X-, H-, to rectangular- or square-profiled.

The only free-standing load-bearing glass column that is realised is the X-profiled column, due to its good cross-section and easy production method. This column is first applied in the Town Hall in St-Germain-en-Lave (2000) and later in Danfoss Headquarters in Nordborg (2010). Both columns include two safety systems. One is that it has a safety factor of more than 2. The second is that the roof is designed with sufficient redundancy that it could distribute the forces of the glass again, after failure of one of the columns. ((Petersen & Bagger, 2009) (Nijsse, 2003)

In 2011 E. Ouwekerk researched the failure strength of different glass profiled columns. From her research, we could see that the profiles have a major and minor direction, which makes them weaker when the load is placed in the minor direction. (Ouwerkerk, 2011)

Figure 69. Danfoss Headquarters in Nordborg ('Danfoss Fernwärme', n.d.)

Figure 70. Civic center in St Germain en Laye (Taylor-Foster & Brittain-Catlin, 2017)

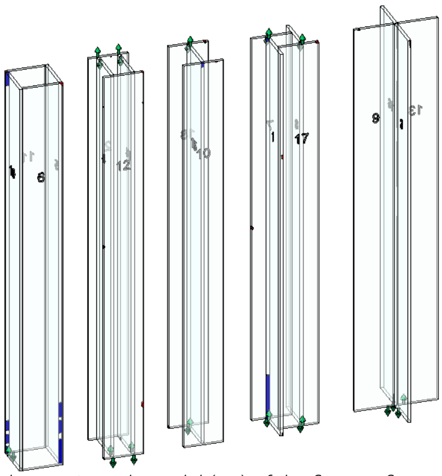


Figure 71. Revit model (3D) of the five configurations which shows the observed imperfections. The green arrows correspond to adifference in vertical position, the blue lines to an imperfection in the glue line and the small red figures to holes in the glass.(Ouwekerk, 2011)

Layered Tubular

In 1999 first test has been done with the layered tubular column by Pastunink and Veer. They concluded that the curing process is very time consuming and therefore expensive due to the lamination of two stiff glass tubes and the clear temperature-dependent resin. (Veer & Pastunink, 1999)

Before, tubular systems had only be used in art like visible in the Glassbaum in Aachen constructed by U. Knaack (1998).

Later tubular structures have been applied, not in columns but in a facade in the Tower place in London, engineered by ARUP (2002). ('Structural Glass Tubes - Tower Place in London - DETAIL - Magazine of Architecture + Construction Details', n.d.)

After research by E. van Nieuwhuijzen in 2005 in the layered tubular column nobody, as far as we know, dared to make a loadbearing column made of layered tubes. (van Nieuwenhuijzen, Bos, & Veer, 2005)

Zak Timan did remind us of how beautiful a glass column could be, in his artwork that he made in 2009, Prakashakaya (Cutler, 2012)

Figure 73. Prakashakaya Zak Tilman (Retrieved from: http://www.zaktiman.com/Prakashakaya)

Figure 75. Tower Place London Arup (Retrieved from: https://www.mimoa.eu/projects/United%20Kingdom/London/Tower%20Place/ 2002)

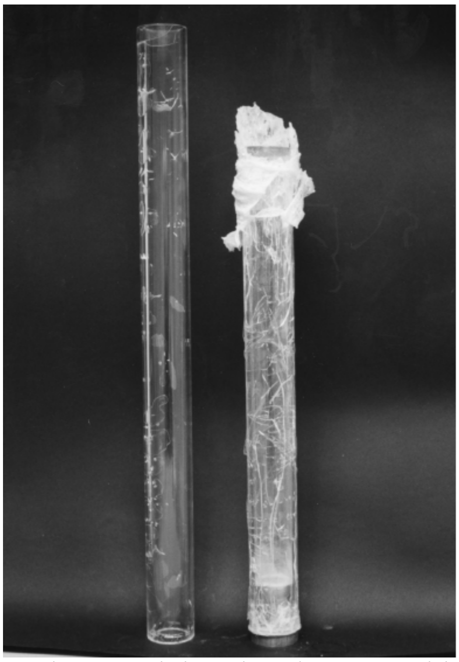


Figure 74. Tubular_Column (Veer &Pastunink, 1999)

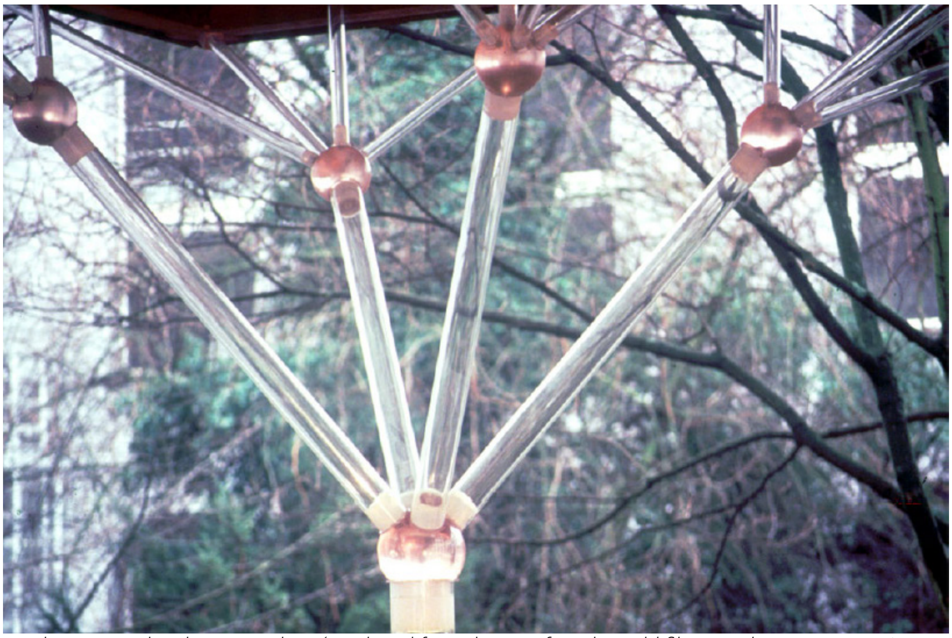


Figure 72. Glassbaum Aachen (Retrieved from: https://facadeworld.files.wordpress.com/2013/09/glasbaum-07.jpg)

Stacked Sheets

Stacked sheets columns have a great freedom in shape and could be almost unlimited in its size. Therefore, this type of column is much used in artwork. An example of this is the Pompano Park made by C. Jones and M. Wilson in Florida. ('Pompano Park, Florida, USA - Malishev Engineers', n.d.)
Other examples of art pieces with stacked glass sheets are the Glass Angel(s) in Zwolle and the glass Sphinx in Venlo. The Sphinx is demolished within a couple of months after the built because of cracks in the glass. ('Glazen Sfinx Venlo wordt afgebroken - L1', 2014)(Harry Plantinga, 2010)

The sheets can be stacked horizontally or vertically. When the sheets are stacked horizontally the vie through the column will be translucent due to the cuts in the glass sheets, which are the visible part of the column. If the sheets are stacked vertically, one side of the column will be transparent, and the other will be translucent, again due to the cut of the sheets. This lamination process is very time consuming and does not have the optical desired effect.
This translucency does not seem to be a problem when using it as a boundary between a private house and the environment, like in the laminate house in Leerdam designed by R. Nijsse (2001). ('Laminata House - Data, Photos & Plans - WikiArquitectura', n.d.)

A glass column made of glass sheets is only be tested by its loadbearing capacity by R. van Heugten in 2013. (Van Heugten, 2013)
Zak Timan did remind us of how beautiful a glass column could be, in his artwork that he made in 2009, Prakashakaya (Cutler, 2012)

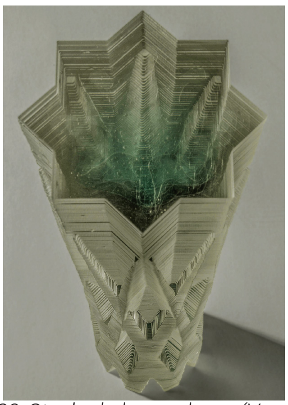


Figure 80. Stacked glass column (Van Heugten, 2013)

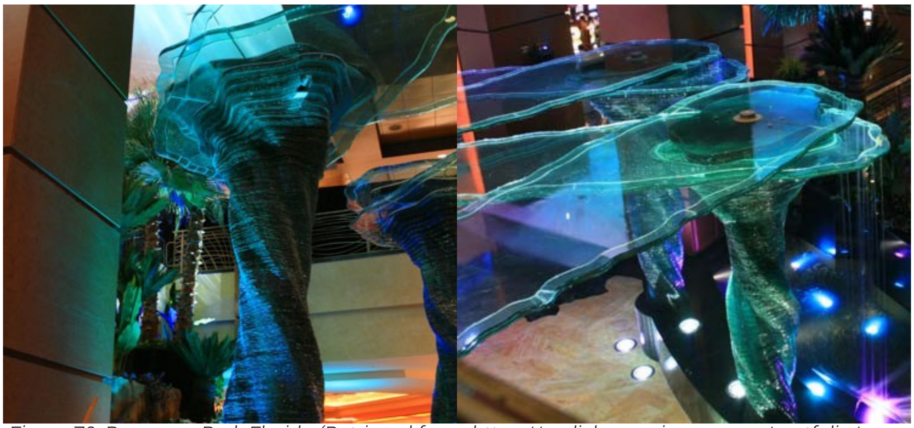


Figure 79. Pompano Park Florida (Retrieved from: https://malishevengineers.com/portfolio/pompano-park-florida-usa

Figure 78. Glass Angles Zwolle (Retrieved from: http://www.twinsholland.nl/glas-en-spiegels/)

Figure 77. Sfinx Venlo (Retrieved from: https://www.glasinbeeld.nl/8600/onthuld-glazen-kunstwerk-sfinx-6-meter-hoog/)

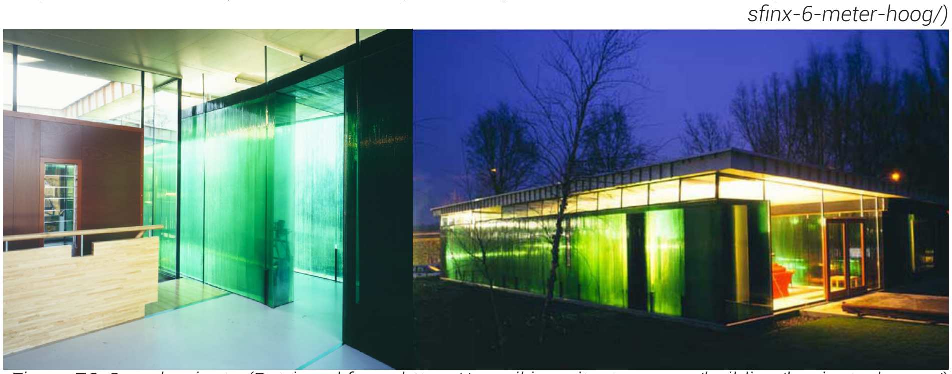


Figure 76. Casa laminata (Retrieved from: https://en.wikiarquitectura.com/building/laminata-house/)

Bundled

The Bundled glass column consists of multiple glass rods that are combined to one element. In 1993 R. Nijsse constructed a design with bundled glass columns to put in a house in Holten but the residents hold off the columns eventually. Later, in 2003 Nijsse made a design with bundled glass columns again for his office of ABT in Arnhem, which was not realised.(Nijsse, 2003)

More than ten years later other research about the bundled column was done. They all concluded that bundling multiple rods of glass is a safe way to conduct a load bearing column. When one of the rods snaps, the other will still hold the force that is applied, and therefore the structure will still be load bearing after failure. (Kamarudin, Disney, & Parke, 2016)(F. Oikonomopoulou, van den Broek, et al., 2017)

In 2017, a 14-meter long glass bridge was built at the TU Delft campus as a gateway to the green village. This bridge was constructed with glass rods from SCHOTT that are bundled. (Faidra; Oikonomopoulou, van den Broek, Bristogianni, Veer, & Nijsse, 2017)

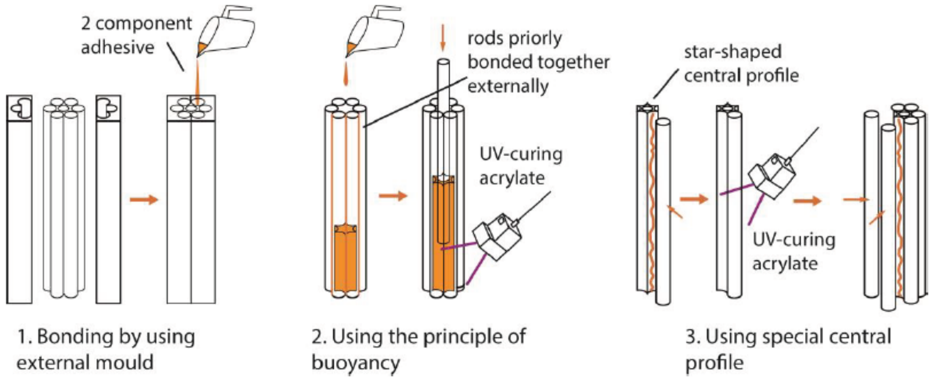


Figure 82. Illustration of the explored bonding techniques. Left: Bonding via the use of an external mould. Centre: Production technique using the principle of buoyancy. Right: Bundle with special central profile (Oikonomopoulou, 2016)

Figure 83. Rod configuration of the final bundled column design. (Oikonomopoulou, 2017)

Figure 84. The 500 mm long specimen series tested in compression (Oikonomopoulou, 2017)

Figure 81. Glass Bridge Green Village (Retrieved from: http://www.schott.com/innovation/en/technology-meets-aesthetics/)

Cast

Cast glass is the oldest way of creating glass, but therefore not the most applied one in structures. This way of creating glass gives a very transparent view on all sides of the glass, but it takes a lot of time, and therefore money to produce. The cooling time of the element (annealing time) increases related to the size and shape of the element. Consequently, the element sizes should be related to the amount of time and money there is available. Also, lamination of the cast elements can cause irregularities and therefore unpredictable failure.

As we know, the first person to conceive a design with glass columns were G. Terragni and P. Lineri in their design of the Danteum in Rome in 1942. These columns would take months or even years to cool down, and therefore were not produced. ('Danteum - Wikipedia', n.d.)

In 2010 R. Horn made art pieces of cast glass, called opposites of white of about 1,1 m in diameter and 0,4m in height, which took four months to cool. When cutting the manufacturing of the cast glass column in smaller elements, the cooling down time could be much shorter. In 2016 R.

Akerboom and Felekou researched different glass columns made of cast glass elements connected with an interlayer. (Akerboom, 2016)(Felekou, 2016)

Felekou made glass bricks that were stacked on each other and bonded together with adhesive bonding. Akerboom connected the different components together with dry assembly and interlocking, this way the elements could be replaced and therefore it is a more sustainable concept.

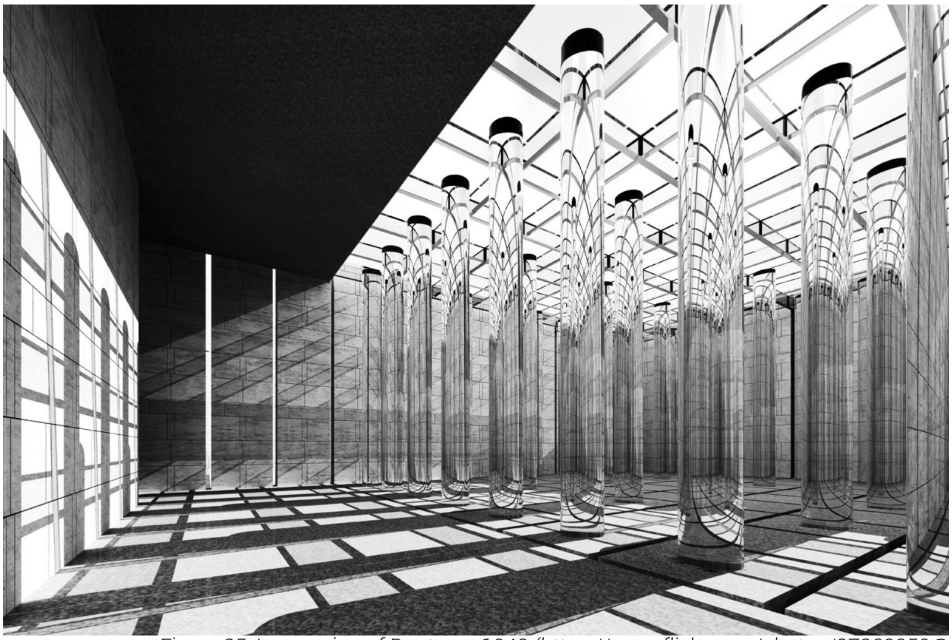


Figure 85. Impression of Danteum 1942 (https://www.flickr.com/photos/27862259@N02/6766795145)

Figure 86. Opposites of white by Roni Horn (Retrieved from: https://krollermuller.nl/roni-horn-opposites-of-white)

Figure 87. Left: Interlocking column of Akerboom (Akerboom, 2016). Right: Stacked float & cast glass column specimens (Felekou, 2016)

Conclusions glass column types

As we saw in the previous chapters, the glass column still has a lot to explore. The only realised load-bearing glass column is the X-profiled columns in St-Germain-en-Larve and in Nordborg. The Profiled already proved to work. Other types of glass configurations proved to work in other constructions but still need more research to get their trust in the building industry. The column made out of cast glass components has a lot of potential by designing different interlocking components.

In short, glass columns are not widely used in buildings yet. This is because of three different reasons, that are all connected to each other which;

- Costs
- Regulations
- Uncertain Variables

__Uncertain variables__

Because of the unpredictable failure of glass, the design process with structural glazing has little room for mistakes. The tolerances are very small because of the high peak stresses and the low strengths on the edges of the glass. This makes the glass an unsafe material in certain conditions. Next to this, when testing glass, this will be done manually, which will give unpredictable results.

__Regulations__

Due to the lack of knowledge about the glass column, there is hardly any regulation about it. This leads to very high safety factors in glass. The safety factor of steel is 1,5, and reinforced concrete has a safety factor of 1,7. Safety factors that are demanded for glass are 5-7. After a couple of decades working with glass, we can see that the material has good values in strength, safe connections and probabilistic design methods. Veer explains that a safety factor of 2 should be sufficient for glass. With more research and testing, a reasonable regulation on structural glazing should be possible. (Felekou, 2016)

__Costs__

Like any new technology, the design and manufacturing of a glass column is costly. Apple, a company that can spend a huge amount of money on their stores, caused a big boost into the world of structural glazing. Still, there are no standard designs or production lines, which makes it a very time and cost consuming process as well.

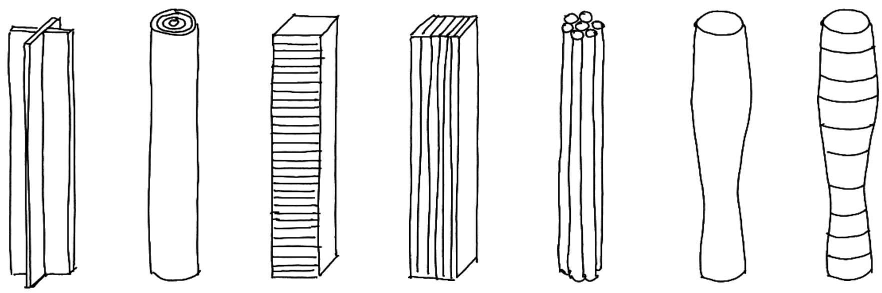
Because of the unknown regulations, the elements will be oversized, which will increase the costs as well. Until now a glass column is only applied when a secondary safety structure is integrated, which is more expensive.

__Type of glass column__

Looking at the general knowledge we have about designing a column, made of any material; we know that the cross-section should be the strong enough for a column not to buckle. This strongest cross-section could be reached by a wide round shape, preferably filled. This shape is evenly strong in any direction the forces would be applied. Next to the cross-section, the glass thickness, the initial deformation, the load eccentricity and the degree of damage to the surface of the glass are important factors for failure of the column.

Next to the strength of the column, the heat resistance of the column is very important. When the column has high heat resistance, it will take longer for the column to fail, in a fire.

The table underneath is showing the different characters of each type of column. In the third column is shown how important these aspects are to the desired design. Due to this column, it is visible that the glass column made of cast glass elements is the most suitable for this design.



		Profiled	Layered Tubular	Stacked Horizontal	Stacked Vertical	Bundled	Cast	Cast Elements
Architectural	*Transparency*	-	+	-	±	±	+	+
	Size Freedom	+	-	+	+	-	+	+
	Shape Freedom	-	-	+	±	-	+	+
Mechanical	*Buckling resistance*	-	+	+	±	±	+	+
	Torsional Resistance	±	+	+	±	±	+	+
	Safety	+	+	+	+	+	-	+
Financial	*Manufacturing time*	±	-	-	-	±	-	±
	Manufacturing Costs	+	±	+	+	±	-	-
Sustainability	*Replaceability*	-	-	-	-	-	+	+
	Recyclability	-	-	-	-	-	+	+
Total		±	±	**+**	±	±	**+**	**+**

Table 4. Comparing types of glass columns (de Vries, 2018)

Conclusions of the Glass Column

A column is a structural compressive element that supports other parts of the construction vertically. When designing this structural member, different aspects have to be considered. When the column is slender, buckling could occur. This could be prevented by a wide and even distributed cross-section. The cross-section could be determined by the second moment of area. The optimal shape for a cross-section would be a circle. Torsional buckling could be prevented by making a column solid instead of hollow. Thermal stresses could occur when there is a temperature difference in the glass. This could lead to a thermal shock, which would break the glass. When there is fire surrounding the column, a significant temperature difference will occur. It is essential when designing a column that this column can bear a fire for 30 minutes or more.
Connections will create peak stresses around the connection; this is why these should be avoided as much as possible.
Types of glass columns are: profiled, layered tubular, stacked sheets, bundled and cast. Profiled is the only column so far that has been built. This is because of uncertain variables of the glass, regulations on building with glass and costs that come with building a glass column.
Due to different criteria, we concluded that a column made of cast glass elements is interesting to research.

Cast Glass Structures

Cast Glass Structures

In this chapter, different examples of realised cast glass structures will be examined. After this, conclusions will be drawn about the design principles and challenges of cast glass structu-res.

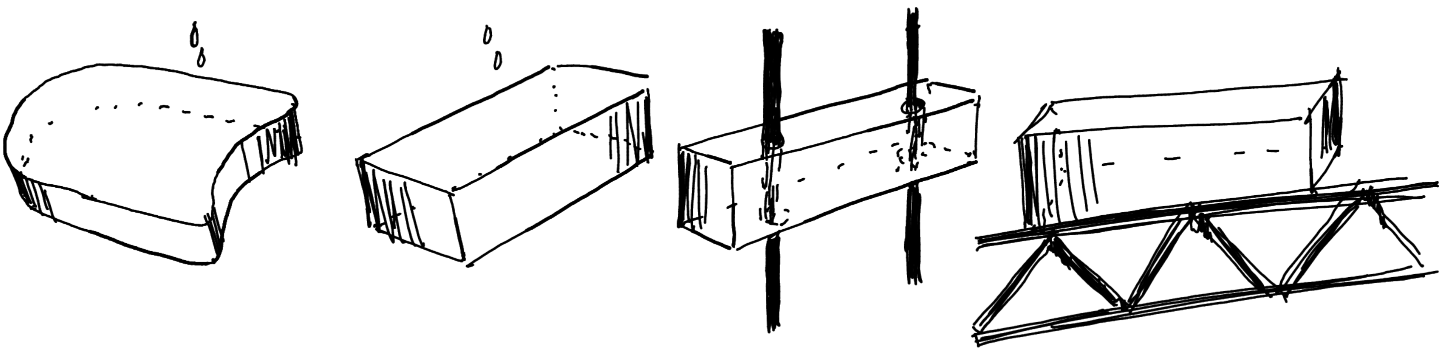


Figure 88. Interlocking structure components. Left to right: Atocha Monument, Crystal Houses, Optical House, Crown Fountain

Figure 90. Children playing at the Crown Fountain (Retrieved from: http://jaumeplensa.com/works-and-projects/public-space/the-crown-fountain-2004)

Crown Fountain

The Crown Fountain is located in Chicago's Millennium Park. It is an interactive work of public art and video sculpture. The entire Fountain consists of a granite reflecting pool of 15 x 71 x 0,0064 m and two towers of 15,2 x 7 x 4,9 m. The towers display faces on their LED screens that spew water into the pool.
The fundament of the structure consists of a special stainless-steel T-frame. Rods with a diameter of 13mm are connected to the structure to prevent lateral stresses.
22500 glass blocks of 127 x 254 x 51 mm were produced in cast iron open moulds. Five sides of the blocks were textured, and one is polished.
The secondary structure of the towers was made by 44 grates that are stacked welded together. The reflection and the thickness of the glass made the grid virtually invisible. ('Crown Fountain', 2005)

Figure 91. The two fountains facing each other (Retrieved from: http://jaumeplensa.com/works-and-projects/public-space/the-crown-fountain-2004)

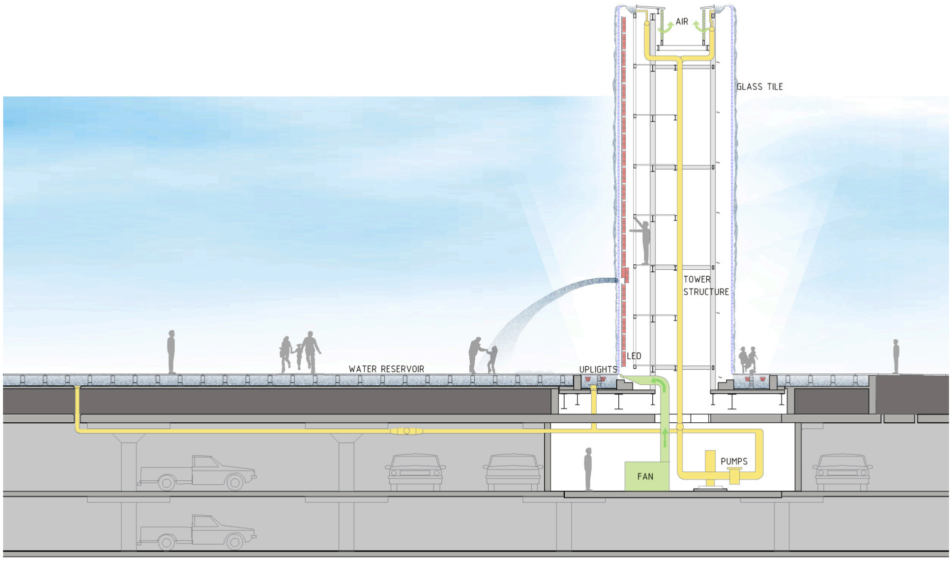


Figure 92. Sectional Diagram of Crown Fountain (Retrieved from: https://www.archdaily.com/109201/the-crown-fountain-krueck-sexton-architects/60872-011-001)

Figure 93. Construction of the Crown Fountain (Retrieved from: https://www.archdaily.com/109201/the-crown-fountain-krueck-sexton-architects/60872-011-001)

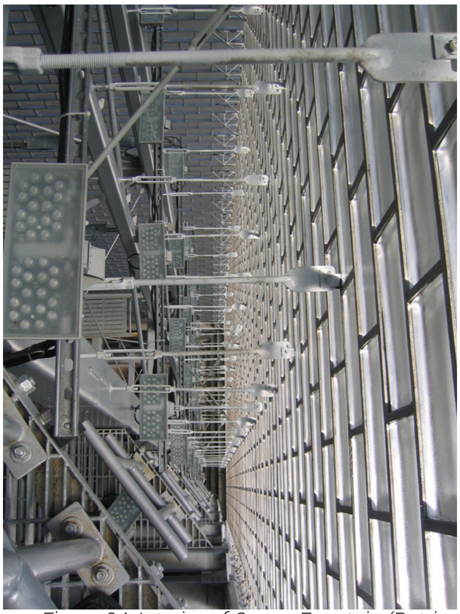


Figure 94. Interior of Crown Fountain (Retrieved from: https://www.archdaily.com/109201/the-crown-fountain-krueck-sexton-architects/60872-011-001)

Figure 96. Atocha Monument (Retrieved from: https://thelede.blogs.nytimes.com/2007/03/12/311-memorial-opens-in-madrid/)

Atocha Station Memorial

This memorial is made to honour the 191 victims who died and the 1824 people that were injured during the 11 March 2004 bombings in the train and the seven special forces agents who died on 3 April 2004 by bombers on rain on an apartment. The Memorial is placed at a site across the railway station where the bombing attack took place. It is an oval-shaped glass cylinder of 11,2 m high with an underground presentation room. With transparent ETFE foil expressions of condolence are printed on the inside of the memorial.

The cylinder is made out of 15100 massive, 8,4 kg curved glass blocks that are convex on one side and concave on the other. This shape of the only glass element that is used for the façade allows the shape to be irregular. The curvature of the cylinder gives the façade rigidity which creates a shell structure made out of structural glass. They are connected with a liquid-acrylic transparent adhesive hardened by UV light. The glass blocks are produced under pressure in specially produced moulds. The glass blocks have a tolerance of ±1 mm, which gave the adhesive a chance to be applied in even thickness of around 2 mm. This 2 mm thickness was controlled by weighing the glue cartridge after applying each block.
This is the first time that a structure is only made out of glass blocks and an adhesive without a substructure. The roof is made out of 5 beams with on top 12 glass plates, which stiffen up the open edges on the top of the glass wall to prevent reshaping of the section.

A massive glass element is experiencing high-temperature differences due to rain and sun-heating which will result in high surface tensions. Because borosilicate glass has a better thermal coefficient (4,3 x 10-6 1/K), it was preferred over soda lime glass.
During the construction of the monument, the glass blocks were glued together by a specially fabricated UV-curing acrylic adhesive. It took 4 minutes of exposition to a UVA radiation (wavelength of 320÷380 nm, intensity between 15 and 30 mW/cm2)
To reduce the high shear forces in the glue joints and the temperature strains between the glass and substructure, the glass blocks were placed on 200 elastomer pads (160 mm x 100 mm x 45 mm). The elastomers were positioned between the U-shaped steel ring (S355) and the first row of glass blocks. After this, a low-modulus silicone sealed the glass blocks and the steel ring to protect the elastomer pads from water and pollution. The concrete flooring was post-tensioned by applying a preload before the glass structure was build.

The structure was constructed inside a tent that protected the site from rainwater, radiation of the sun and pollution and in which the humidity and temperature were controlled. (Göppert & Paech, 2004)

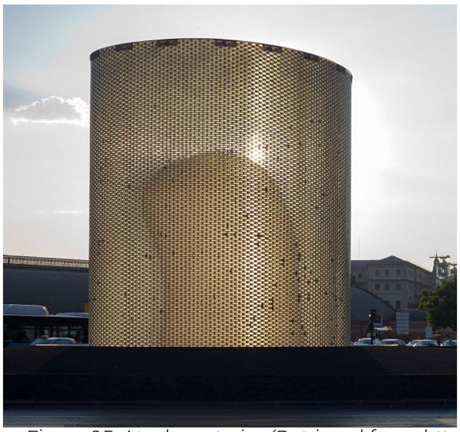


Figure 95. Atocha exterior (Retrieved from: https://www.gettyimages.nl)

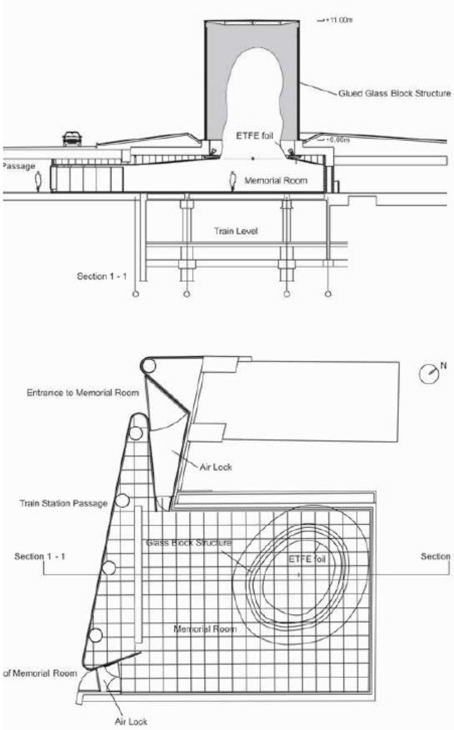


Figure 101. Sectionalandplanviewsofthemo-nument (Göppert & Paech, 2004)

Figure 97. Atocha interior (Retrieved from: http://www.buffalo.edu/news/releases/2007/10/8925.html)

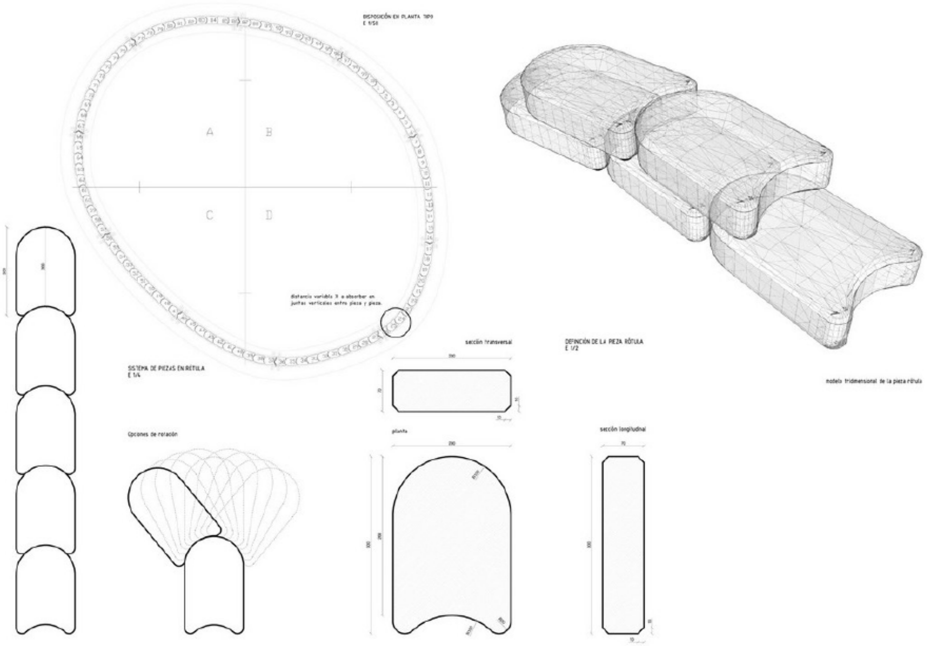


Figure 98. Technical drawing (Retrieved from: https://folio.brighton.ac.uk/user/ps160/exem-

Figure 99. Glass bricks Atocha Monument (Retrieved from: https://www.e-architect.co.uk/madrid/atocha-monument-madrid-fam181207_7.jpg)

Figure 100. Distributionofadhesiveontheglass blocks(Göppert & Paech, 2004)

Figure 102. Glass wall during construction (Göppert & Paech, 2004)

Figure 103. Glassgirderonsite(Göppert& Paech, 2004)

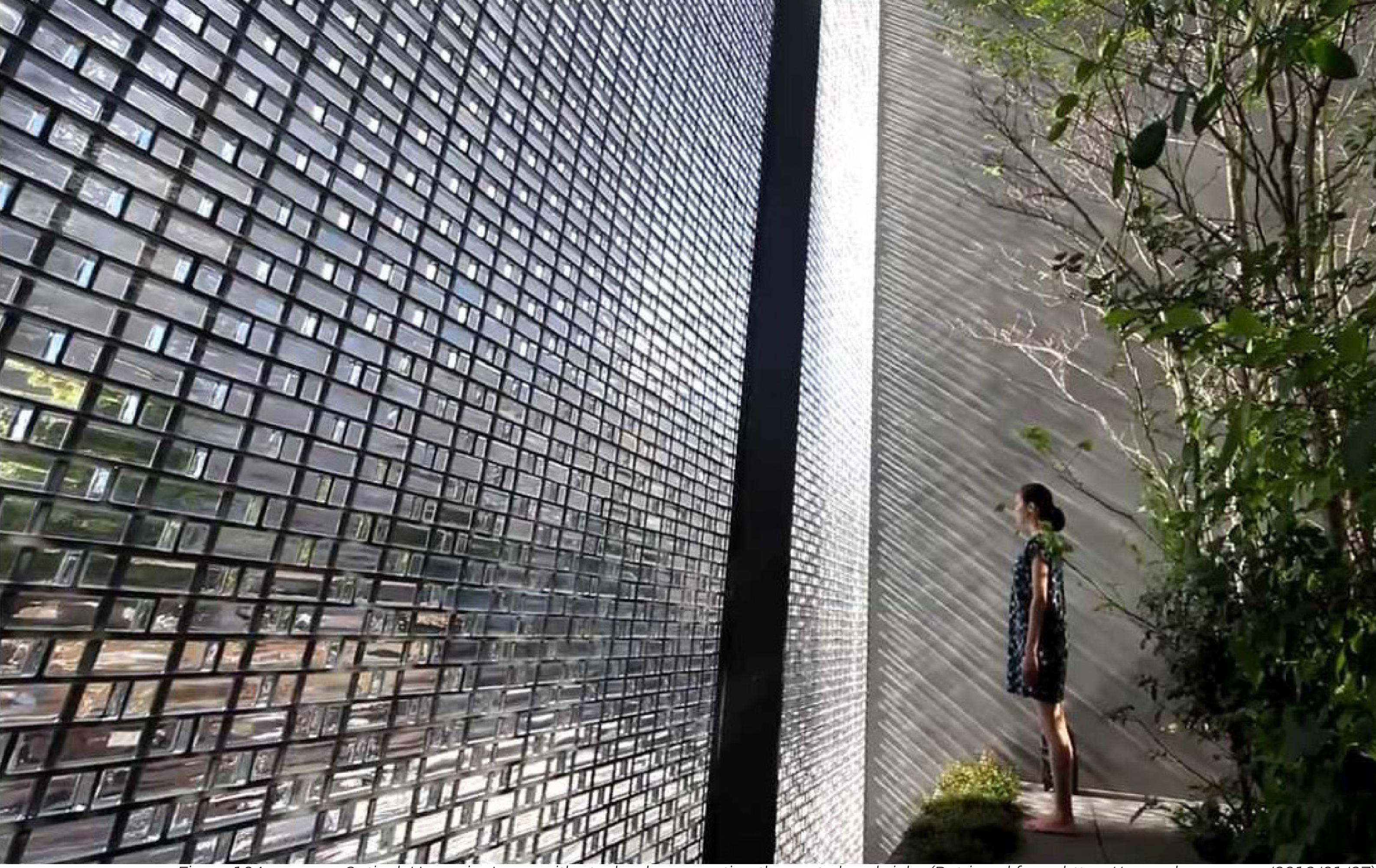


Figure 104. Optical House in Japan with steel rods connecting the cast glass bricks (Retrieved from: https://www.dezeen.com/2013/01/27)

Optical House

The optical house is a private house that is constructed beside a busy road. It shows the difference between the busy road with many people and a lot of traffic and the private oasis in a house.
It is a two-story high building made of glass blocks of 50mm x 235mm x 50mm that are bolted to each other to guaranty safety of the construction. The cast glass blocks are made of borosilicate glass with high accuracy. The glass surface showed some imperfections, but they were welcomed due to their optical illusion.
The glass blocks were penetrated with holes that made place for the stainless-steel bolts that suspended from the beam above the façade. Next to the 75 stainless steel bolts, every 10cm stainless steel flat bars of 40mm x 4mm were installed to overcome the lateral stresses. These bars were placed in a 50mm thick glass block, which made them look invisible. The fundament of the structure is made out of concrete with a pre-tensioned beam. ('Optical Glass House by Hiroshi Nakamura & NAP', n.d.)

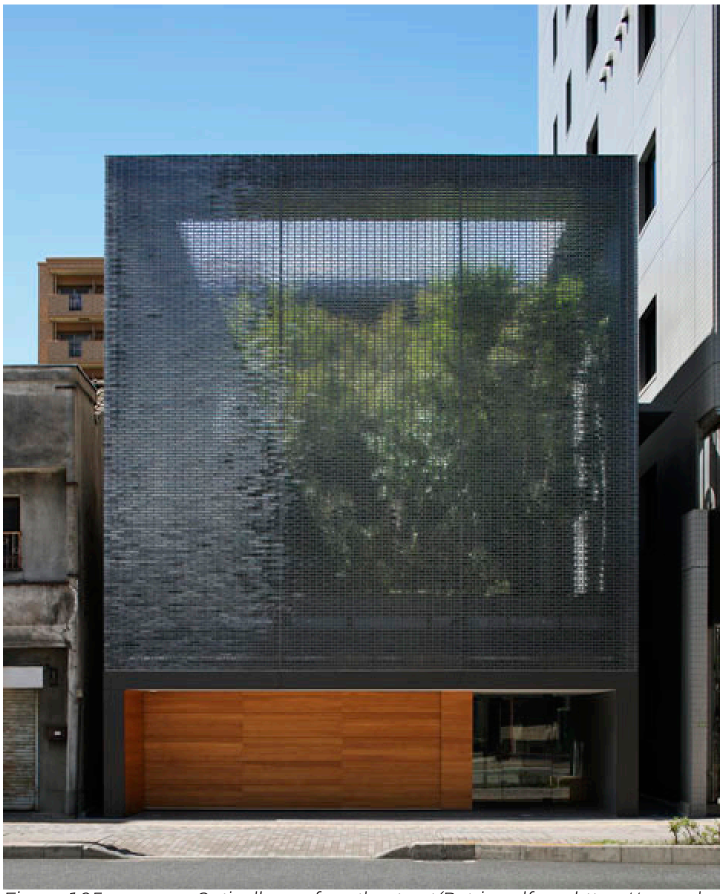


Figure 105. Opticalhousefromthestreet(Retrievedfrom:https://www.dezeen.com/2013/01/27/optical-glass-house-by-hiroshi-nakamura-nap/)

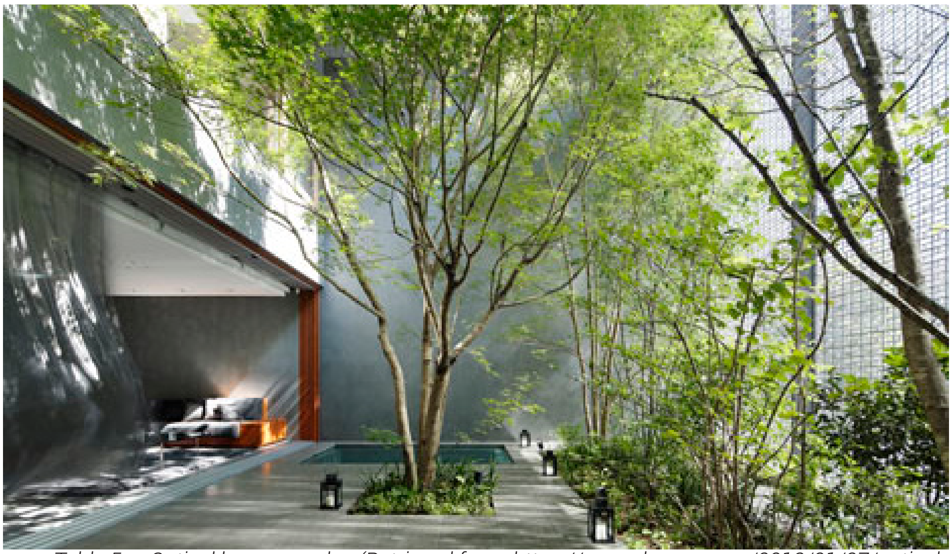


Table 5. Optical house garden (Retrieved from: https://www.dezeen.com/2013/01/27/optical-glass-house-by-hiroshi-nakamura-nap/)

Figure 106. Construction of optical house (https://inhabitat.com/gorgeous-optical-glass-house-in-hiroshima-is-made-from-6000-glass-bricks/exif_jpeg_picture-12/)

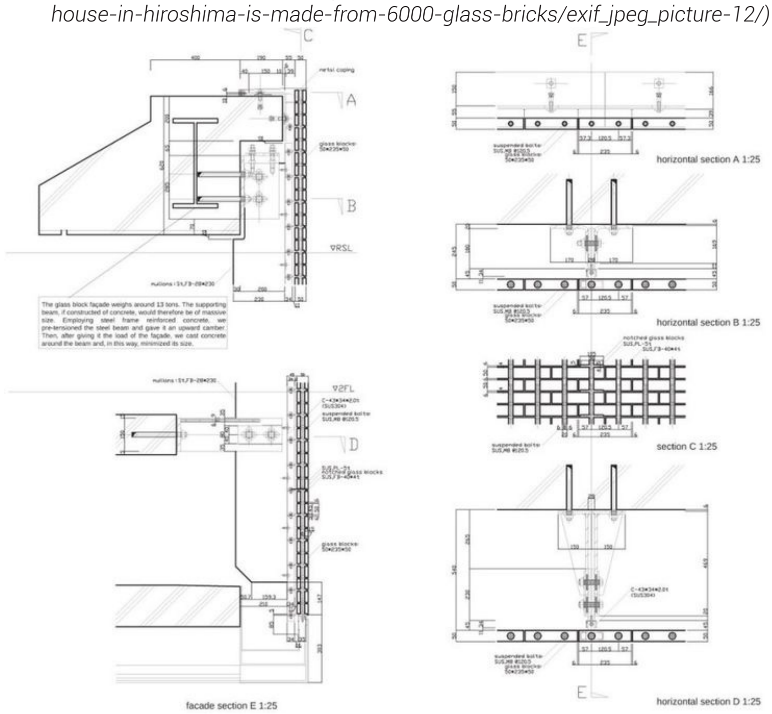


Table 6. Tehcnical drawings optical house ('DOMESTIC CURRENT: Pam Jinapa 's case study: Optical glass house', n.d.)

Figure 107. Crystal houses facade (Retrieved from: https://www.arcam.nl/crystal-houses/)

Crystal Houses

The crystal houses, just like the Atocha monument was only supported with glass blocks and adhesive, without a substructure. The 10 x 12 m façade is constructed by 6500 solid glass bricks which can carry its own load and withstand the wind load. The adhesive Delo Photobond 4468, a one-component, UV-curing acrylate is used to maintain a monolithic structural performance and a high transparency level. Experiments by Oikonomopoulou showed that a uniform layer of 0.2–0.3 mm thickness gave the best results. (Oikonomopoulou, Veer, Nijsse, & Baardolf, 2014)
The adhesive if colourless and has the same reflective index to glass (1,5). It is only applied in horizontal direction; vertical direction is left dry.

The glass blocks are made of low-iron soda lime glass in an open, and high precision moulds were preferred to reduce the manufacturing costs of the bricks. High accuracy is attained by CNC-cutting and polishing the horizontal faces to the desired height. Next to this, homogeneous application of the adhesive is determinative for the structural performance of the building.

Just like the construction of Atocha houses, the construction of the crystal houses was conducted in a tent that was protected against solar radiation, dust and other weather conditions. The temperature and humidity were controlled by equipment inside the tent.

To protect the building from hard body impact, a 0,6 m x 0,2 m side concrete plinth was placed on the bottom of the glass structure. It was sealed with laminate of a stainless-steel sheet and annealed patterned glass, laminated together by SentryGlas® foil.

At an upper level of the structure, the glass bricks will be mixed with the terracotta bricks. The terracotta bricks have a much bigger tolerance, and the bonding between the two types of bricks is very different. Therefore, the glass bricks were first bonded into place after which the ceramic strips will be put in. A brown coloured silane polymer with a thickness of 3mm is applied to bond the two types of bricks to each other. (F. Oikonomopoulou, Bristogianni, et al., 2017)

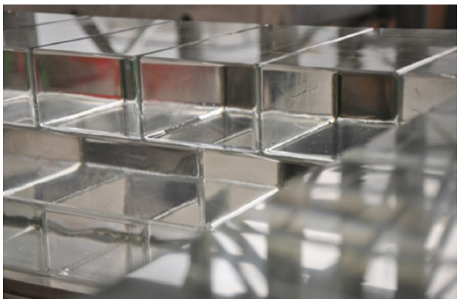


Figure 108. Glass bricks of crystal houses (Oikonomopoulou et al., 2017)

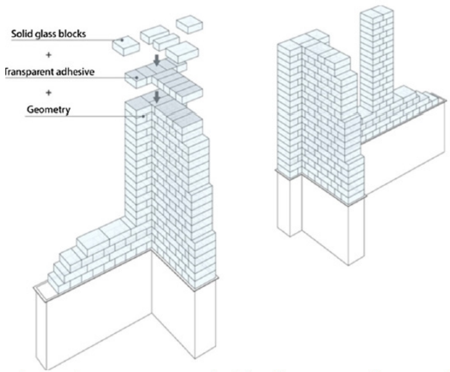


Figure 109. Principle of the proposed structural glass system (Oikonomopoulou et al., 2017)

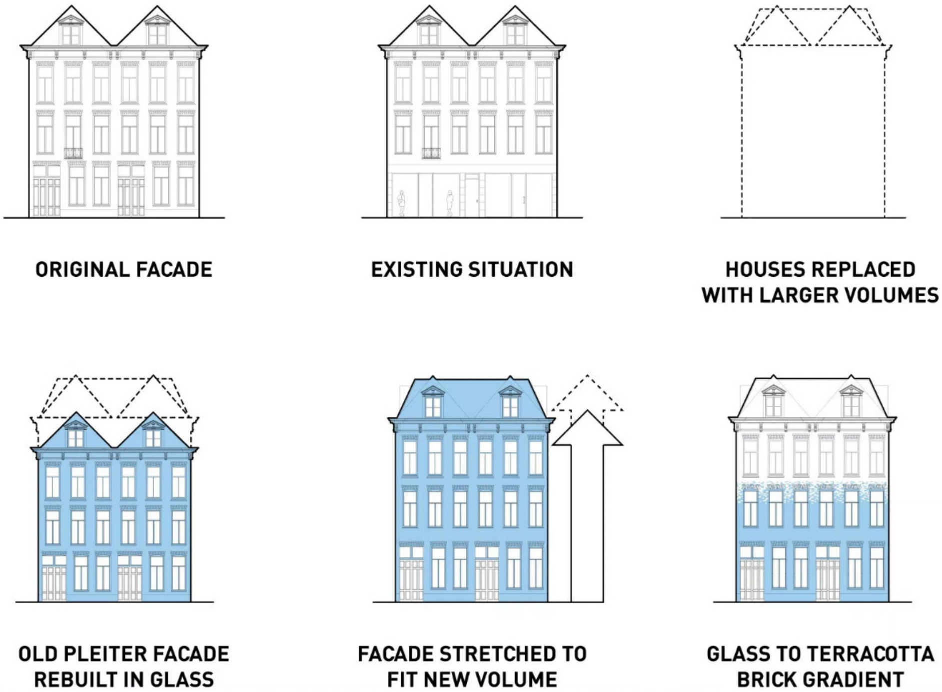


Figure 114. Illustration by MVRDV of the concept behind the Crystal Houses façade (Oikonomopoulou et al., 2017)

Figure 110. Molten glass bricks during the rapid cooling phase from 1200 to 700 degrees Celsius (Oikonomopoulou et al., 2017)

Figure 113. Visualization of the façade by MVRDV. Right The realized façade (Oikonomopoulou et al., 2017)

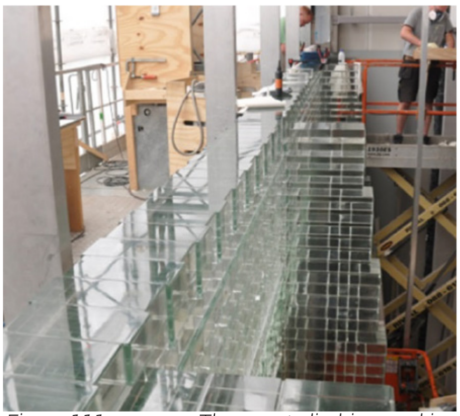


Figure 111. The mast climbing working platform and one of the three mobile elevated platforms (Oikonomopoulou et al., 2017)

Figure 112. Bonding of adhesive in crystal house (Oikonomopoulou et al., 2017)

General

Element size

From other chapters, it is visible to see that the downside of cast glass is that the cooling time takes very long when making big geometries. When looking at the research that is done, it is clear to see that the thicker and more volume the glass has, the longer it takes for the glass to anneal. For costs and time efficiency, the annealing time should be limited to 50 hours. The limit has to be set either on the weight, the glass type and/or the thickness of the element; they will both be connected to the annealing time.

The only research that is found about the annealing time was done with the soda lime glass. For this weight, it would have to be about 10 kg for soda lime glass. In the tests, the smallest section was in every block the same (65 mm). When using borosilicate glass, the annealing time could be much shorter for the same weight of a block. For example, the block used in the Atocha monument was 8,4kg and annealed for 20 hours only with a wider cross-section (0,7). (F. Oikonomopoulou, Bristogianni, et al., 2017) Because time and money are limited in this research project, the annealing time should be not too long. This is why the element weight is limited to 15 kg. According to the shape of the element and the type of glass that is used, the annealing time will still differ.

Element Shape

When a glass element is gradually annealing the element would create less internal forces which could cause more strength in the element. The graduate cooling of an element would lead the design of separate elements to a sphere of glass. This way all the sides of the ball would be evenly cooled down, until the whole sphere, including the centre, is cooled down. Also, very slender protrusions can result in weak locking constraints and risk the integrity of the structure. (Barou, 2016) This notion would lead to a design that is more rounded and organic shapes.

In all four glass constructions, we could see that the element size was block-shaped, the shape terracotta bricks usually have. The fact is that bricks made of terracotta or concrete have a different tolerance which is much higher than the tolerance in which the glass will produced (±1 mm). These small tolerances would make much room for different shapes of the elements. Next to this, The production of terracotta bricks and glass bricks is rather different. Glass will be made in high temperatures, and terracotta is not. To design components in glass that suit the material, the design should be based on the material properties, rather then what has already been made with other materials.

To create extra cohesion in the structure, it would help to apply interlocking systems in the elements-shapes. This cohesion could lead to extra strength, more safety, recyclability and less material use.

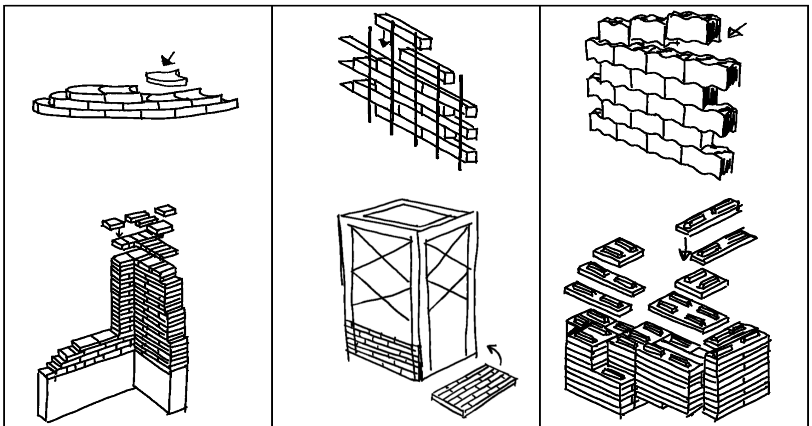
Adhesive, substructure or interlocking

When designing a cast glass structure, different connection-possibilities will appear adhesive, substructure and interlocking.

The adhesive has the advantage of being completely transparent and therefore the most coherent to the concept of a transparent glass façade. But when using an adhesive, it is essential to be very accurate in the total structure; the dimensions of the blocks and the thickness of the interlayer only have a minimal tolerance. When the tolerances are too big, peek stresses will appear, and the structure will fail. When using an adhesive, it is tough to use the glass (blocks) again. The adhesive will be hard to remove from the glass which will make it less hard to recycle.

When using a substructure, the tolerances can be much bigger. Next to this, the glass structure could be much smaller in contrary to the oversized blocks of the loadbearing blocks with the adhesive. A big downside of using a substructure is that you will give in on the transparency of the structure. Interlocking connections will be explored in the next chapter.

In the table underneath the three different structures are compared with each other. It is visible that a glass structure can be put together with an adhesive, a substructure or it can be interlocking. By comparing the three systems, it is visible that interlocking could be a good solution to for this design proposal.



	Adhesive	Substructure	Interlocking
Transparency	+	±	+
Ease of assembly	-	+	+
Reversibility	-	+	+
Redundancy	±	+	+
Multifunctionality	-	±	+
Sustainability	-	±	+
Total	-	±	+

Table 7. Interlocking geometries with different structures (de Vries, 2018)

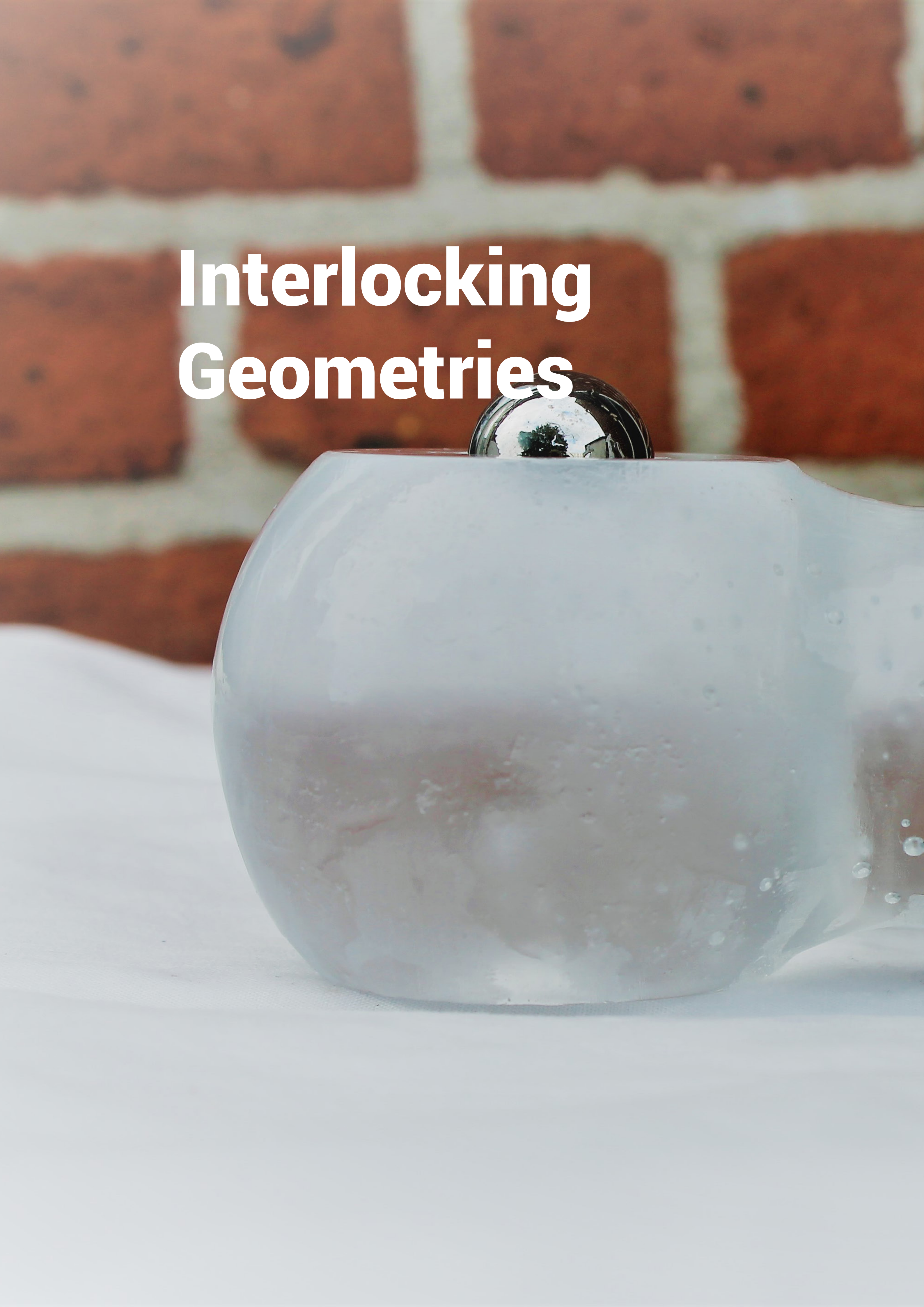
Conclusions of Cast Glass Structures

Different examples of cast glass structures have been investigated; Atocha monument, Crystal Houses, Optical House, Crown Fountain.

From these examples, we found that the element size should be limited to as small as possible. Next to this, we found that the shape should be able to cool gradually, to prevent stresses inside the element.

These example constructions are made in two different types of constructions adhesive (Atocha monument & Crystal Houses), or they have a substructure (Optical House & Crown Fountain). Recent research has shown that creating a structure that is made out of interlocking dry stacked cast glass elements could be a good solution regarding; transparency, ease of assembly, reversibility, redundancy, multifunctionality and sustainability.

Interlocking Geometries



Interlocking Geometries

Interlocking geometries are based on the concept of different solids forming a solid structure without using glue or mortal. The geometry has to restrain lateral movement in the construction. The construction itself is stabilised by the compressive force of the self-weight and load-bearing weight of the structure. (Faidra Oikonomopoulou et al., 2018)

The Ancient Greeks already made columns that were bonded by interlocking. Examples of these are visible in the Parthenon where the very precise marble blocks are self-aligned with wooden pins. (Korres, 1995). The Incans were also using interlocking systems with their walls. These walls consisted of blocks that were cut in irregular polygons that made the wall very stable. Roman arches could but don't have to, be made by dry assembly. Japanese joinery is also a good example of interlocking systems. Japanese wood joinery is also is made by dry assembly of elements that only can be taken out when certain other elements are moved before. (Faidra Oikonomopoulou et al., 2018)

In interlocking structures, keys or connectors will be avoided in a structure.

Figure 115. Incan wall in Sacsayhuamán, Cusco, Perú, (Retrieved from: https://en.wikipedia.org/wiki/Sacsayhuam%C3%A1n)

Figure 116. Dry stacked arch in Ireland (Retrieved from: https://thinking-stoneman.blogspot.nl/2011/12/)

These keys will generally reduce the overall strength of a structure because they will take on a large part of the stress of the structure. Interlocking structures do not have these keys. This is why interlocking structures are seen as strong systems of structures.

Topological interlocking is described by Estrin, Dyskin and Paternak as a design principle by which elements (blocks) of particular shape are arranged in such a way that the whole structure can be held together by a global peripheral constraint, while locally the elements are kept in place by kinematic constraints imposed through the shape and mutual arrangement of the elements.

Only in 2003, we saw the benefits of fragmentation or segmentation. With this, an engineering design principle of interlocking structures gained popularity. (Ashby & Bréchet, 2003) The different elements could be held together without the use of binders, keys or connectors. This is a way to combine tolerance and flexibility to failures that are offered by fragmentation of a material with overall structural integrity. (Estrin, Dyskin, & Pasternak, 2011)
An excellent example of an interlocking structure is the orthomorphic interlocking blocks were twice designed without the knowledge of each other. First by Glickman (Glickman, 1984)and later by Dyskin et al. (Arcady V. Dyskin, Yuri Estrin & and Elena Pasternak, 2001). They are based on kinematic constraint in two directions; one normal to the assembly plane and its transverse.

Topological interlocking is the way to connect flexibility and tolerances to local failures, due to fragmenting a surface together with keeping the structural integrity. This way of connecting pieces has different advantages. It is possible to combine different materials in one structure with various components. Interlocking gives higher strength and better structural stability. Another advantage is that this structure has an emergency system because it can withstand breakage of 25% of the structure. After breakage, the structure can re-divide the load between the intact elements. Next to this, interlocking structures have a high resistance to crack propagation. It also has good resistance to earthquakes when they can undergo small movements between the elements. Lastly, it is also easy to assemble and disassemble when it has a dry connection. The interlocking could help with aligning the elements. This way the construction of the system is much easier and more precise. (Estrin et al., 2011)

With the assembly and reassembly, replacing and reusing an element of a dry stacked interlocking structure is possible. Glass is a material that is 100% recyclable and still is the second largest waste material in the EU. By using a dry interlocking structure, this waste material could be recycled material. ('Packaging waste statistics - Statistics Explained', n.d.)

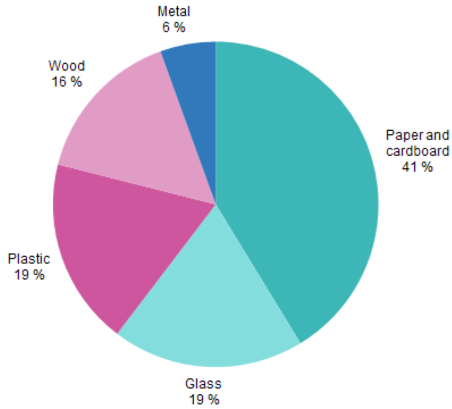


Figure 119. Shares of packaging waste generated by weight in the EU (Retrieved from: http://ec.europa.eu/eurostat/statistics-explained/index.php/Packaging_waste_statistics)

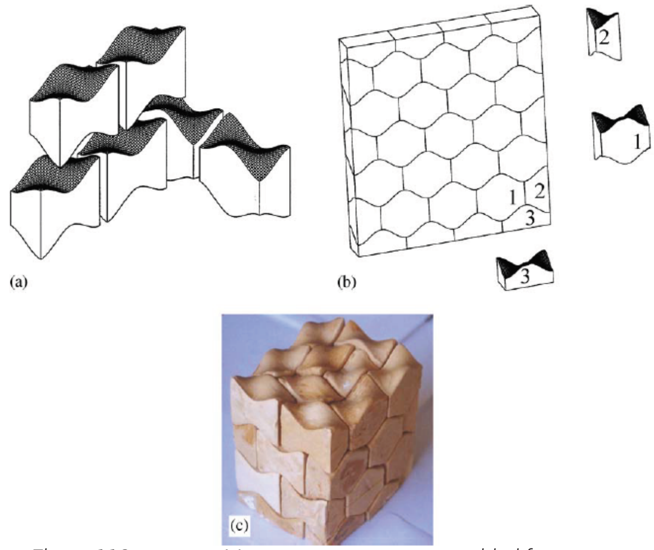


Figure 118. Masonry structures assembled from osteomorphic bricks (a) principle of assembly of layer and corner structures, (b) layer of osteomorphic blocks (1) completed with half-blocks (2) and (3), (c) a column structure. (Dyskin, Estrin, Pasternak, Khor, & Kanel-Belov, 2005)

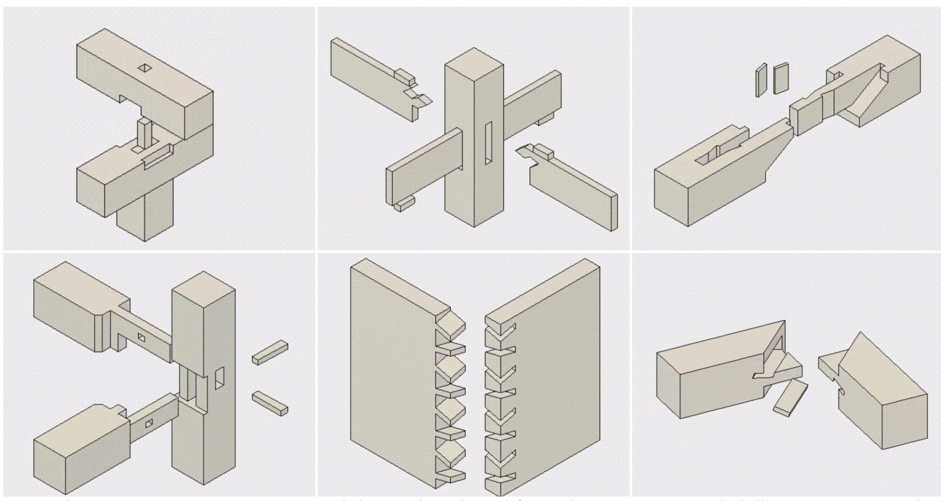


Figure 117. Japanese joinery (Retrieved from: https://www.archdaily.com/796918/these-mesmerizing-gifs-illustrate-the-art-of-traditional-japanese-wood-joinery)

Types of interlocking systems

As far as we know there are four types of interlocking methods (Barou, 2016):
- Tongue and groove
- Protrusions and depressions
- Topological non-planar contact (Kintingu, 2009)
- Recursive Puzzle Interlocking. (Song & Fu, 2012)

The tongue and groove and protrusions and depressions are the most common types. (Kintingu, 2009)

The elements of the interlocking systems will be held in its place by the kinematic pressure of their neighbour elements. The structural integrity will be dependent on the force of the self or dead weight or constraining frames, pre-tensioned tendons or cables.

The recursive interlocking is derived from interlockings puzzles. That only can be assembled and disassembled by one sequence. This way, all the elements are locked when only one specific element stays in place. (Arcady V. Dyskin, Yuri Estrin & and Elena Pasternak, 2001) These sort of systems are very complicated, due to its elimination of multiple joining options and all different elements.

Figure 121. Toungue & groove (Retrieved from: http://www.woodworkersjournal.com/cutting-tongue-groove-joints-table-saw/)

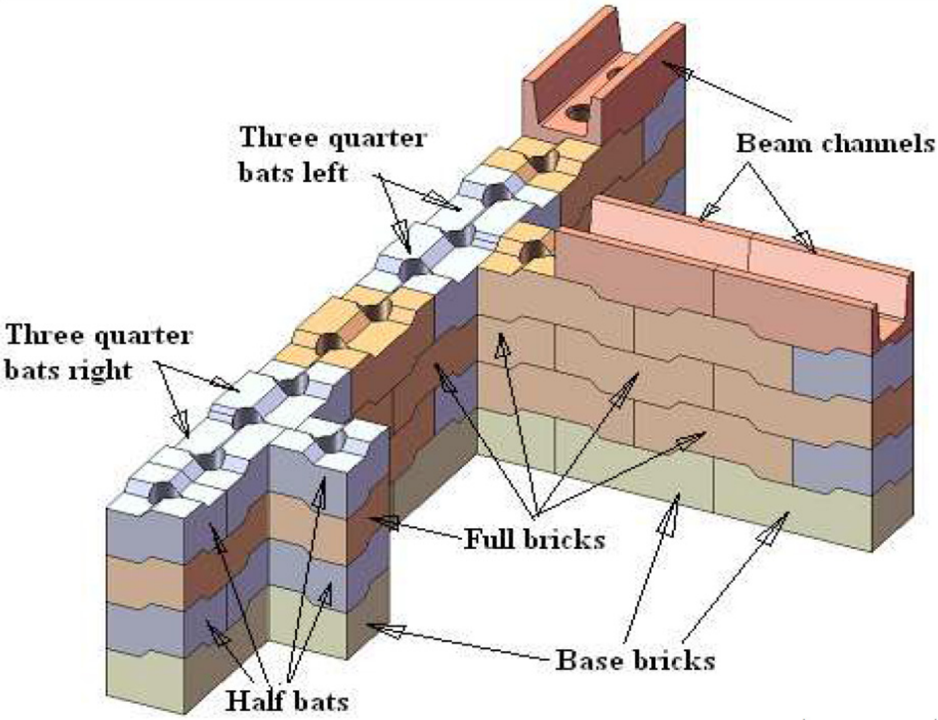


Figure 122. Bamba interlocking Brick wall (Kintingu,2009)

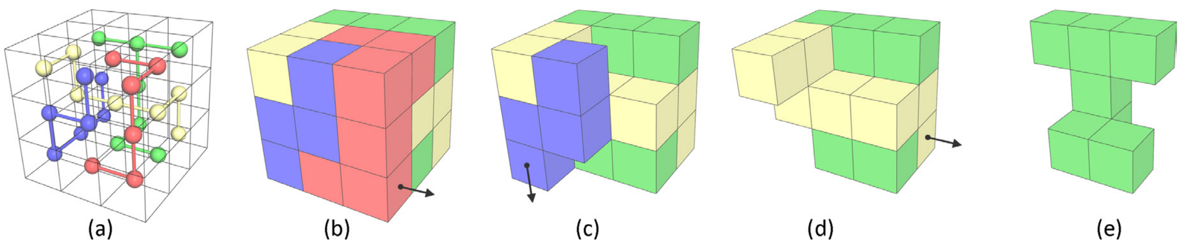


Figure 120. : A 4-piece 3^3 recursive interlocking CUBE generated by our method: (a) the puzzle piece anatomy; and (b-e) its disassembly (Song & Fu, 2012)

Improving stability

The stability of an interlocking structure is better because it allows the structure to undergo small movements within the structure which would avoid failure under dissipating vibrational energy and high amplitude vibrations in the process. A good example of this is the Temple of Zeus erected circa 330 BC (Konstantinidis & Makris, 2005).

With these small displacements in the structure of any material some unusual mechanical responses could occur like: negative stiffness in indentation loading. (Estrin et al., 2004),(S. Schaare et al., 2008)

Figure 123. Temple of Zeus (Flickr, 2018)

Negative Stiffness

In the chapter about glass columns, we talked about stiffness. In an interlocking system, negative stiffness could occur.
The negative stiffness in point loading manifests itself as a post-peak descending branch of the loading curve (as in classical brittle and quasi-brittle materials) under positive displacement of an indenter (loading) as well as in unloading (negative indenter displacement). Negative-stiffness is not associated with a result of failure or buckling. (Estrin et al., 2011)
The occurrence of a negative stiffness in unloading, and post-peak softening not associated with any damage of the material. (Estrin et al., 2004)(S. Schaare et al., 2008)In the only tested example, the negative stiffness does not exhibit. (Estrin et al., 2011)

Just like other structures, the stiffness of the structure is in relation to the stiffness of the material and the elements. But research found out that the

$$dF = k_{+}(1-\lambda)du, \quad \lambda = k_{-} / k_{+}.$$

material and element stiffness were independent from each other. (Stephan. Schaare, 2008)

k Stiffness (_ negative, + positive)
F Force
u producing a displacement

The equations which determent the negative stiffness of the element does not include the tolerances of the elements and the possible interlayers. Which could be why the measurements could be inaccurate to the physical elements properties. (Estrin et al., 2011)

Manufacturing elements

Next to all the advantages of making a structure out of interlocking elements, it also has its downsides, the manufacturing. The manufacturing of these elements could be done by machining, casting, injection moulding or sintering techniques. It has to be done in small tolerances (of about a millimetre); otherwise, the element will not be able to interlock with each other. (Estrin et al., 2011)

Interlayer

Glass is a very stiff material, and next to this the surface is never perfectly flat. This means that when glass is loaded in compression and placed directly on other glass, at the points of contact, stress concentrations will occur. This will give peak stresses in the material, and tension stresses will occur. Glass is not able to take as much tensile stresses as compressive stress so that these peak stresses could lead to failure.

When glass is directly in contact with other glass, it will break when it hits the tensile stress limit of glass (20-30MPa). (Oikonomopoulou et al., 2014)

This is why it is needed to place a softer interlayer between 2 compressive members of glass. This interlayer should be able to divide the peak stresses over a bigger surface, which would overcome failure in the glass. In the thesis of M. Aurik he "designed" the ratio between the stiffness/thickness of the adhesive interlayer. By the following formula: (Aurik, 2017)

$$t_{int} \geq \frac{2\Delta}{1 - \frac{\sigma_{avg}}{E_{int}}}$$

In this formula, it is visible that the young's modulus of the interlayer and the maximum deviation are the variables for the interlayer thickness.

R. van Heugten explains that for the adhesive interlayer we have to look at the following characteristics of the material (Van Heugten, 2013):
- Transparency
- Young's modulus (min of 2 GPa)
- Glass temperature (min 80°C)
- Durability against water (salt)
- Radiation (acceptable, excellent)
- Possible forming methods (thermoforming, injection moulding).

Akerboom adds the characteristic of small thicknesses to the list. (Akerboom, 2016)

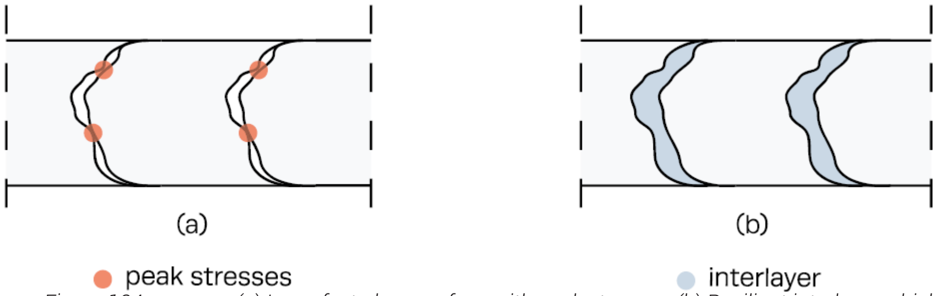


Figure 124. (a) Imperfect glass surface with peak stresses, (b) Resilient interlayer which accommodates the peak stresses based on (Aurik, 2017) drawn by (Janssens, 2018)

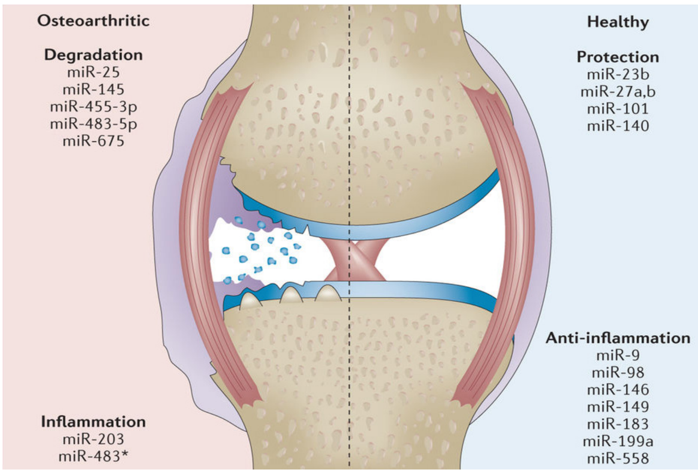


Figure 125. Differnce between a joint with and without osteoarthritic (Healthy wealth, 2017)

Dry connection interlayer

When talking about a dry connection of an interlayer between two surfaces, an interlayer that is not permanently sticking to the surfaces is meant.

The elements are a good option, because of its reversibility (replacing and restacking). When connecting two glass elements, there should always be a layer in between because of the flaws in the surface of glass and the brittleness of a material. If a dry connection is wanted, an intermediate foil between the structural glass members should be placed. This foil will tribute the shear and compression forces evenly over the next element. The glass should be connected to each other, as well as connected to the end connections or surfaces of the element.

Next to the dry assembly of interlocking structures, it is also possible to combine the hard materials of the elements with a more soft material. A good example in nature of this is the soft structure between the bone segments and the cartilage. When somebody has Osteoarthritic, the cartilage is broken, and the rough and hard surface of the bones will touch each other; this hurts and ruins the bones. In this case, the geometrical interlocking may be actuated to increasing stiffness. (Estrin et al., 2011)

Polyurethane

E. Jacobs researched the material Polyurethane (PU) as an interlayer for dry stacking interlocking compressive components. This material is transparent, rigid, durable and UV-resistant. Polyurethane is a wide material with many different sub-materials in it, which he researched to find the best option. They can vary from soft to semi-rigid elastomers. There are two categories in the PU; thermoset pU and thermoplastic PU. (Jacobs, 2017)

Thermosets will react directly when the components are mixed and form chemical cross-links which are irreversible and will happen faster when heated. (Huntsman, 2010)
Shaping thermosets is possible with rotational moulding, compression moulding, polymer casting or composite forming (CUED, 2003)

Thermoplastic PU's are recyclable because they can be melted and used again. This is also why the shaping of the thermoplastics has more options: extrusion, injection-, blow-, compression-, or rotational moulding or when solid, with machining (CUED, 2003)
But thermoplastics has the downside of being weaker and having a lower thermal resistance.

With both, the overall rigidity is determined by the larger or smaller quantities of rigid elements. Next to this, the amount of cross-links has a high influence on the rigidity and hardness of the PU. (Jacobs, 2017)

The properties depend on the mixture of the PU-type. To see if the material reacts as a plastic or as a rubber, Shore durometers can be used to look at the hardness of the material. Haarhuis and Aurik looked at the deformation of PU in compression. From these thesis's we can conclude that the assumed young's modules of PU in compression will deform linearly. (Aurik, 2017; Haarhuis, 2010; Jacobs, 2017). In smaller shape factors the linear prediction was more adequate, than the larger shape factors. It must be said that using PU in a project should always be tested in the laboratory before applying in practice, with the applied mixture and thickness of the material PU.

The frictional coefficient is the resistance ratio of two elements surfaces that are sliding on each other. In this case, we are talking about glass the interlayer (PU).

Because PU is considered to be an in compressive elastomer, it is assumed that it will behave like a rubber. (Jacobs, 2017)
The tests of Tuononen in 2016 shows that μ = 2.0 is a valid input for the friction coefficient for rubbers. (Tuononen, 2016) Still, when applying in practice, this should be tested in a laboratory.

The Poisson's ratio is the transverse of the lateral strain to the axial strain for a uniaxial stress state. In a column, the elements will mostly be subjected to compression force and some shear force. When compressing an element of a column, the material can only be deforming while at the same time it should be retaining its volume. When the shape is changing, material will be bulging out where it can.

Polyurethane has higher values for hardness than normal elastomers. Which makes PU a material that could work with a wide range of applications. (Wright & Cumming, 1969)

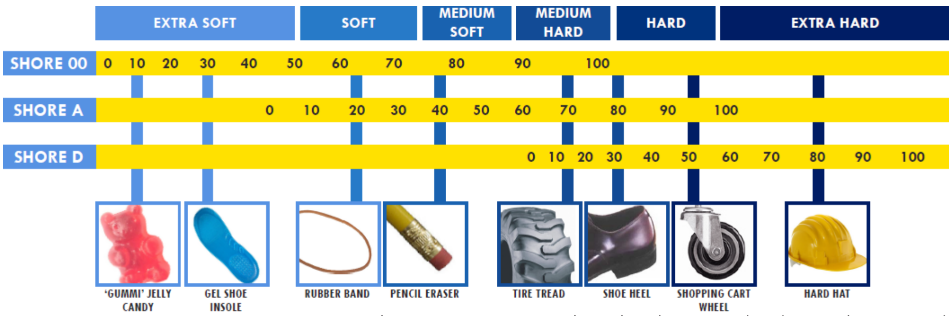


Figure 128. Shore hardness scales (Smooth on, 2008)

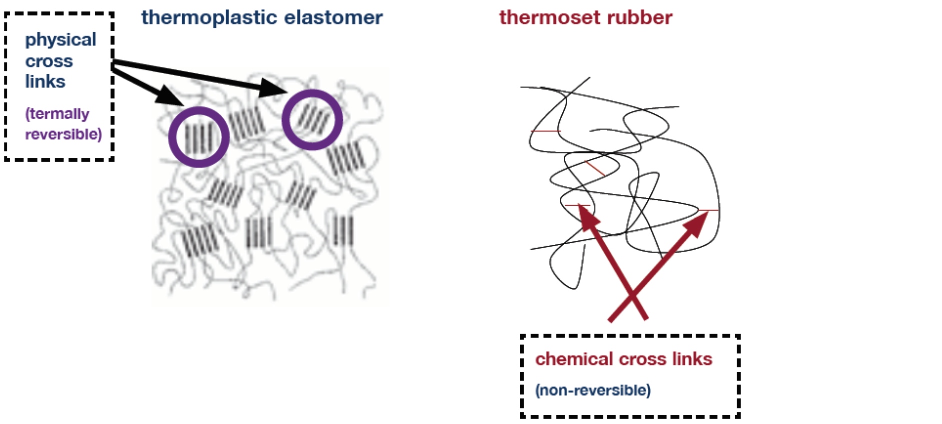


Figure 126. the cross-linking structure of a thermoplastic elastomer versus a thermoset rubber. It shows that there are no chemical cross-links in TPUs unlike thermoset rubbers or casted polyurethane systems. (Huntsman, 2010)

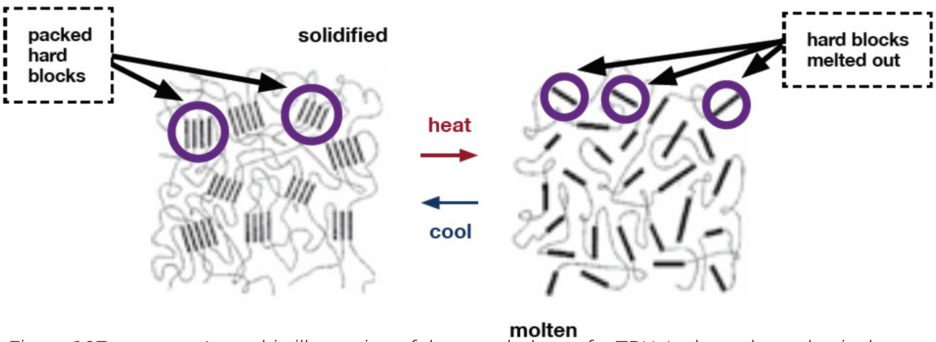


Figure 127. A graphic illustration of the morphology of a TPU. It shows how physical cross-links melt out under heat and repack when the material is cooled.(Huntsman 2010)

Examples Interlocking Cast Glass Structures

In 2016, 2017 and 2018 thesis design reports and research have been written about interlocking loadbearing cast glass structures by Barou, Akerboom, Aurik, Jacobs, Janssens and Oikonomopoulou & Bristogianni. Barou, Aurik, Jacobs and Oikonomopoulou & Bristogianni focused on a wall structure and Janssens on a dome; although the design of Aurik and Oikonomopoulou & Bristogianni could also be applied in a column.

Jacobs
Jacobs designed a brick parametric input that was optimised with DIANA FEA. His design was a rectangular brick that has waves in top and bottom part of the brick. These parts could be interlocking in different configurations (Jacobs, 2017)

Sombroek/Aurik
Sombroek made a design of the brick for a bridge made of cast glass components. These bricks are dry-interlocking. Aurik has researched the interlayer between the bridge and the stability of the bridge. These bricks cannot be used in other structures.
(Sombroek, 2016 & Aurik, 2016)

Akerboom
Akerboom designed a column made of cast glass elements. His design was based on the fact that the column should not interrupt the view of the room and should, therefore, be as thin as possible. This resulted in a design with a minimal cross-section.
The column-design is made out of many different rings with curvature on its planar surfaces. These rings were all different, which resulted in many different moulds. (Akerboom, 2016)

Barou
Barou designed a brick, which is interlocking and is used in a restoration of a facade located right next to the sea. This interlocking brick is rectangular and has rectangular interlockings. These make it impossible to create other structures then a wall. Due to the extra pieces that are designed, this type of component could be used in different configurations as well.
The bricks have a dry interlayer and are restackable. (Barou, 2016)

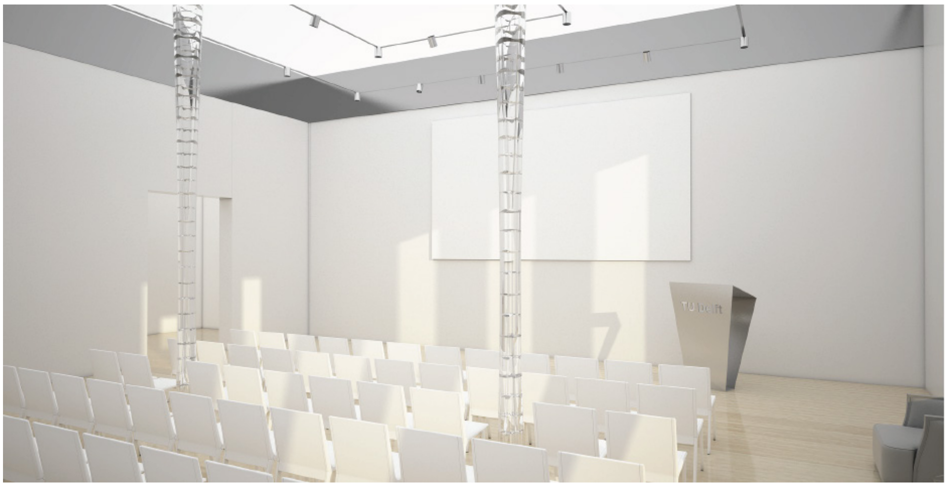


Figure 130. Visual impression of the proposed Akerboom's column in its context (Akerboom, 2016)

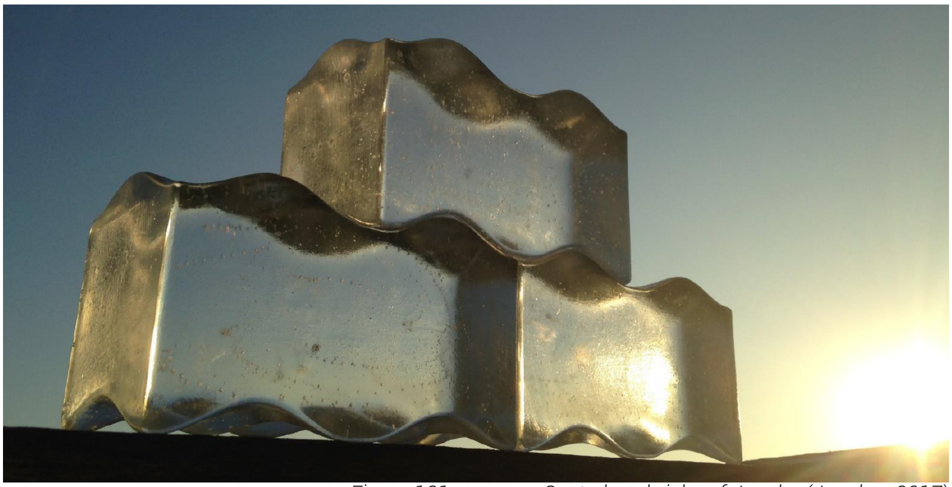
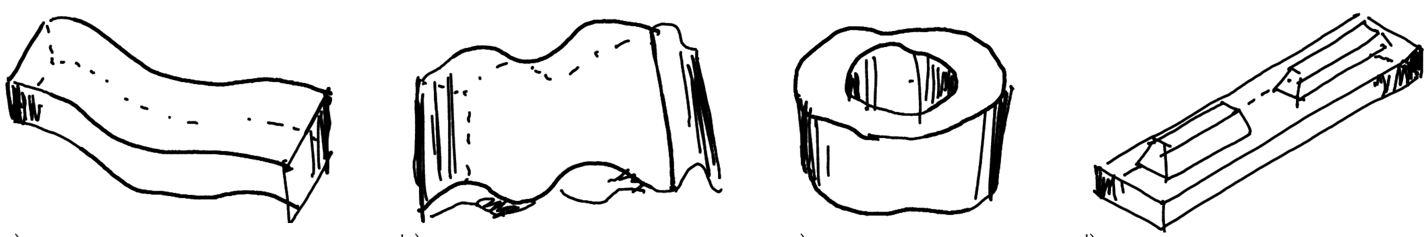


Figure 131. Cast glass bricks of Jacobs (Jacobs, 2017)



a) b) c) d)

Figure 129. Examples of interlocking structures by Aurik (a, 2017), Jacobs (b, 2017), Akerboom (c, 2016) , Barou(d, 2016) (de Vries, 2018)

Janssens

Janssens designed a bone-shaped component that is used in a dome shape. As well as the structure, she researched the thermal performance of the dome. The component that was used is only suitable for a dome structure. (Janssens, 2018)

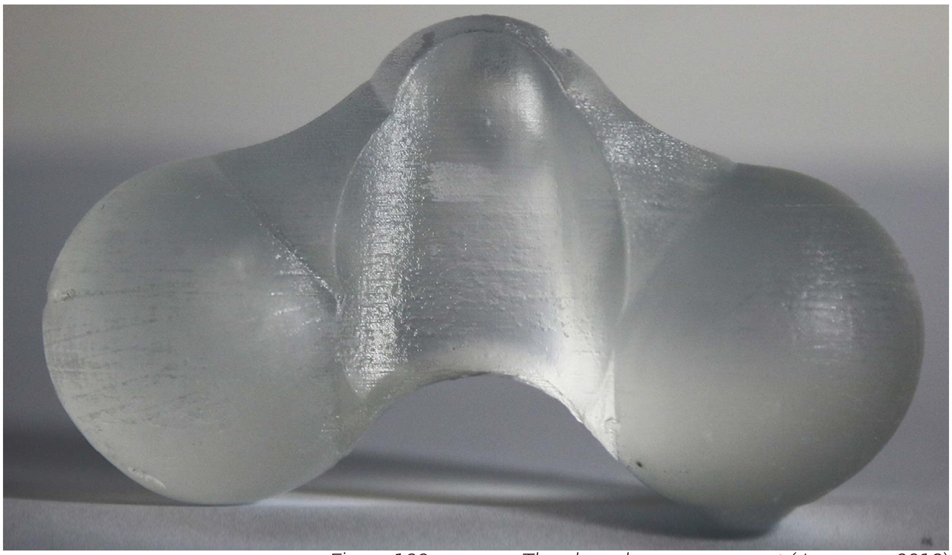


Figure 132. The glass dome component (Janssens, 2018)

Oikonomopoulou & Bristogianni

In 2017 the project "Re3 Glass" was executed. This is a new generation of recyclable, reducible and reusable cast glass components. This project is proposing an innovative and sustainable way of building with diaphanous structural components.
Five types of components have been designed.

(F. Oikonomopoulou et al., 2018)

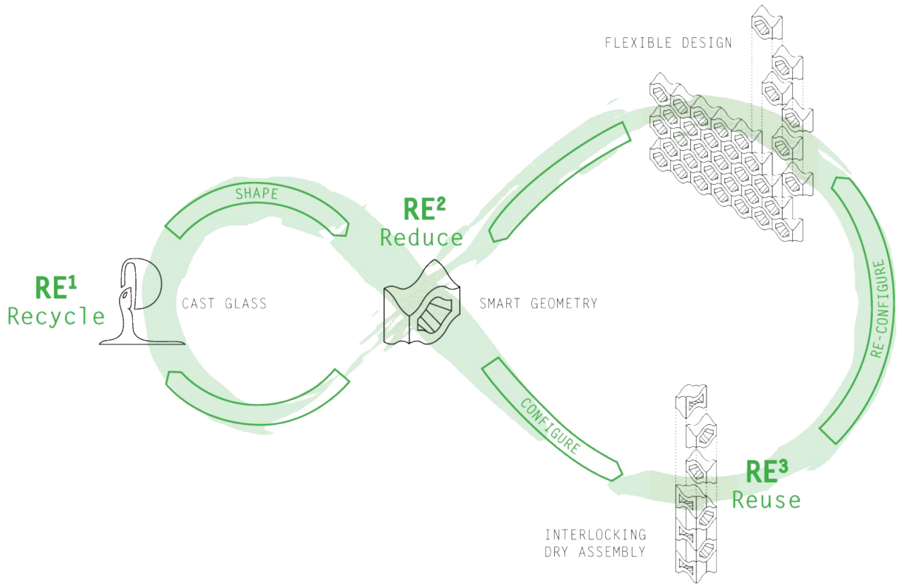


Figure 133. Re3 Glass can tackle the challenges generated by the aforementioned system and enable the circular use of the glass components (F. Oikonomopoulou et al,. 2018)

Figure 134. Re3 Glass types (F. Oikonomopoulou et al,. 2018)

Conclusions of Cast Glass Interlocking Structures

Types of interlocking: tongue and groove, protrusions and depressions, topological non-planar contact, recursive puzzle interlocking. To create interlocking compressive components, it seems necessary to have planar contact between the component, which results in the option of interlocking with either tongue and groove or protrusions and depressions. Because the element will have to be stable, also when a shear force from any horizontal direction would be applied, the component has to be able to stay in his place. With a tongue and groove, the elements would be able to slide from one side to the other. This is why protrusions and depressions seem the most suitable way to interlock the components.

When interlocking glass it is necessary to provide an interlayer between the two glass surfaces. Due to irregularities in a glass surface, when placed onto another glass surface, peak stresses will occur that will quickly make the glass break, due to its brittleness. This interlayer could be adhesive or dry. The choice for dry connection is made due to its recyclability and re-stackability.

Examples of Interlocking cast glass structures have been investigated; those are made by Akerboom Barou, Jacobs, Sombroek & Aurik, Janssens and Oikonomopoulou & Bristogianni. From these different designs, we can see that it is valuable to create components that are multifunctional, easy to assemblable and redundant in composition.

Design

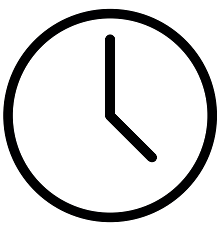
Design

Design Principles & Challenges

From the literature study in the previous chapter, certain design principles and challenges became clear. These will be explained in this section.

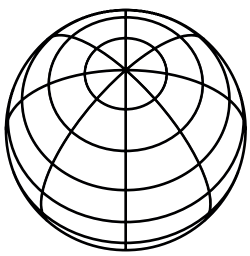
Limited Annealing Time

The annealing time should not expire 50 hours. This annealing time will be influenced by different factors: the volume and thickness of the element and the thermal expansion coefficient of the glass type. In this design, the material will be borosilicate glass. Borosilicate glass has a much lower thermal expansion coefficient compared to soda lime glass. This is why the annealing time will be much lower when an element is made of borosilicate glass instead of the more common soda lime glass. A (brick shape) element of 8,4kg will take 20 hours to cool. To limit the annealing time, a maximum weight of 15kg has been set to the base of the component.



Cast Glass Elements

The geometry of the design will be made out of cast glass elements that are interlocking in each other. The elements will be connected to each other so that the forces will flow through the different elements directly to the fundament.
Because the elements will be made out of glass, a glass-like shape would reduce the internal stresses. The optimal glass shape is a sphere. In this shape, there will be no corners or angels that can be chopped off. Also, the cooling process will happen more gradually from the outside to the inside.

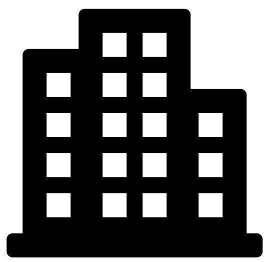


Limited moulds

Producing moulds takes a lot of time, money and effort. This is why the moulds should be as limited as possible. The number of moulds has been set to two for this design.

Even mass distribution

The mass that is placed on the structure should be evenly distributed over the incorporating elements. This is possible when no point loads will appear. To prevent this, the elements should be connected closely with each other with small tolerances between the elements. When the mass is distributed on a flat surface, the distribution will be easier to make precise, regarding tolerance of the element and the interlayer.



Interlocking in planar directions

When a structure is interlocking, it will have a bigger strength due to the better shear distribution along the elements. The number of access keys to this interlocking system should be avoided because it reduces the strength of the total column. The elements will be connected to each other in planar direction because the main force on a column is a compressive force. This constraint makes the component interlocking and easy to align when building the column

Multifunctionality

In a successful element design, the elements should be able to be placed in different ways. This way the elements could be used in a column of different sizes, but also as a wall or other structures.

Wide round Cross-Section

To prevent a column from buckling it is important that the cross-section is optimised. This will happen with a wide and possibly round cross-section. The original column that is placed in the building has a cross-section of 550mm. This will be the minimum. The maximum size of the diameter will be 1000mm, so that it will still be a column, instead of a small room.

Redundancy

One of the big problems with the material glass is that it will not give a warning before it breaks regarding deflection or cracking noises. This is why, when one element breaks, the other elements should take over the load-bearing capacity of the broken element, so people have time to escape from the failing structure. When using 3 or more elements on one layer, the structure can still be stable when one of the elements breaks.

Recyclability & Restackability

By connecting the different elements with a dry connection, the various elements could be used somewhere else, or in another configuration later. Or the glass could be molten into some other glass elements without having to take off an adhesive material.

Constrictions of Case Study

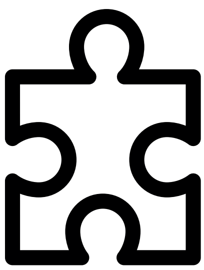
On the ground floor of the case study, the Glasspalace has a height of 5,65 meters. It has two basement levels, and on top of the ground floor, six other levels are placed. From this building, the loads on the columns on different levels are calculated. This load is taken with a safety factor of 4, to prevent buckling.

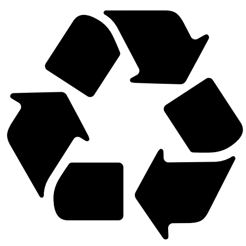
Strong connections on top and bottom

To create a column that is stable and takes up all the forces, a good connection to the building is crucial. This connection should be as much fixed and tightened as possible, to decrease the buckling length.

Fire safe

Creating a fire safe, glass column is a thesis topic on itself. To create a safe column, it also has to be fire safe. The choice of glass could help; borosilicate glass would not crack as easy as soda lime glass at high-temperature differences. Next to this, sprinklers should be applied in and around the column.





Context

General

The "Glaspaleis" (meaning the Glasspalace in Dutch), is a historical building in Heerlen, in the South of the Netherlands. It was initially designed as a big department store by the architect Frits Peutz. It is one of the important examples of 'Het Nieuwe Bouwen', a modern building style in the Netherlands. It was built from 1934 to 1935. Twice a renovation was done, one in 1973 and 1999-2003.
This department store was made as a covered marketplace for the fabric trader Peter Schunck. Some old buildings were bought and demolished to make place for the Glasspalace.
The construction consists of 20 columns on each floor which carry the next levels. The higher in the building the column stands, the smaller the column is. Because of the non-bearing façade, the façade is made entirely out of glass.
The design was inspired by the department store of Henri Sauvage in Nantes from 1931.

Figure 135. Location of Heerlen in the Netherlands

Figure 136. Location of Glasspalace in the city center of Heerlen (Stefan Koopmans, 2017)

Building Physics
With the curtain wall that is physically separated from the floors, natural ventilation between the floors can take place with ventilation hatches at the roof of the building.

Construction
The construction consists of Mushroom-columns; just like the ones that are used by Brinkman and van der Vugt in the Van Nelle-fabriek in Rotterdam.
The building is placed on a hilling terrain between the market square and the church square. Columns, floors and fundament are made of reinforced concrete. Two basement floors of reinforced concrete as a fundament of the building. The floors are made of concrete floors without beams. The curtain wall is 50cm deep.
The floors are 17cm thick. There are about 30 columns per floor. The floor is approximately 30 x 30 m. The total floor area is 10.000m2. The full height of the building is 26,5 m.

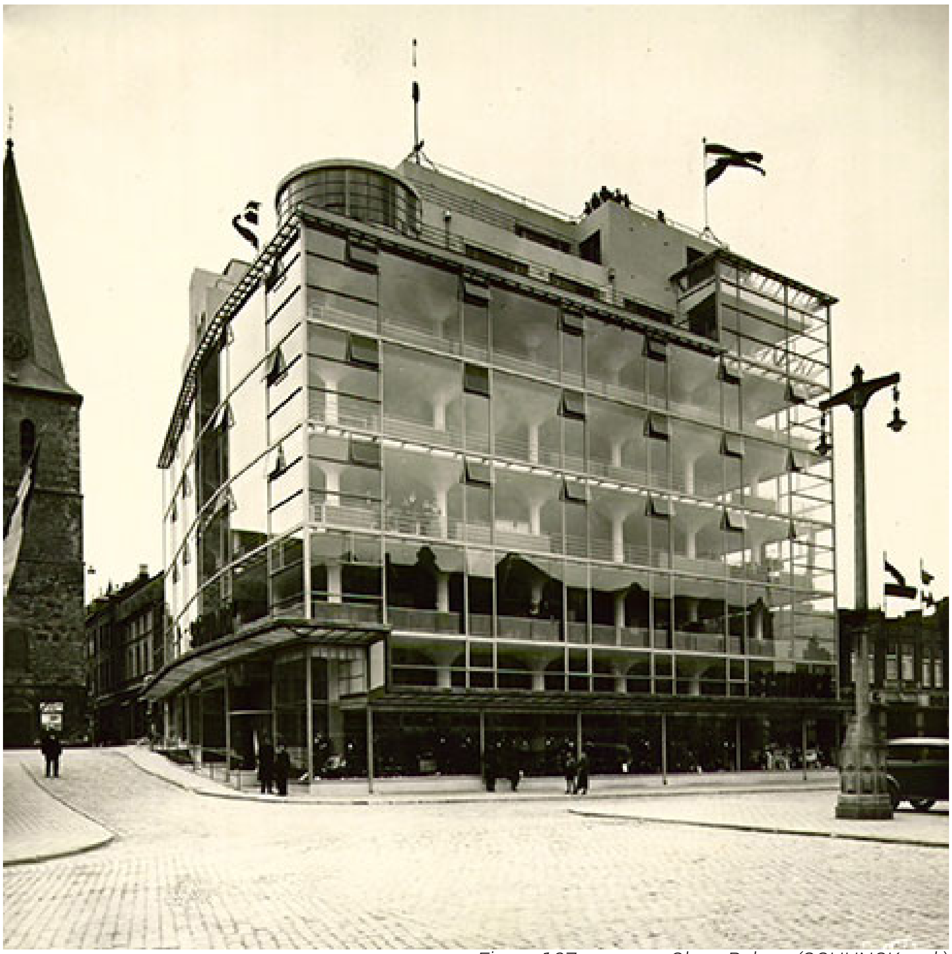


Figure 137. Glass Palace (SCHUNCK, n.d.)

Figure 138. 3rd floor Glass Palace(SCHUNCK, n.d.)

Figure 139. Ground floor Glass Palace(SCHUNCK, n.d.)

Timeline

1973: Beb Groenendijk bought and renovated the building with smoked glass. It was used as an office, a restau rant, a supermarket and an open market.

1995: The building became a "Rijksmonument", a national monumental building.

1999: Jo Coenen and Wiel Arets made renovation plan

1999: The Glaspaleis was stated at the list of 1000 most important buildings of the 20th century by The Interna tional Union of Architects.

2001-2004: Second renovation, after which it was named with the original SCHUNCK* design on the façade. Since then the use was as a multidisciplinary cultural institution, " specialising in Modernity and Urban-Culture in international contemporary art and culture."

2009: New uses in the building: the museum for modern and contemporary art ("Stadsgalerij Heerlen"), the centre for architecture and urban planning (Vitruvianum), the public library of Heerlen and the music school. Also located in the building are "Filmhuis De Spiegel" (cinema)and "Brasserie Mijn Streek"

(restaurant). ('SCHUNCK* | SCHUNCK* Ons verhaal - Geschiedenis Glaspaleis', n.d.)

Figure 140. Glass Palace at nigth (SCHUNCK, nd)

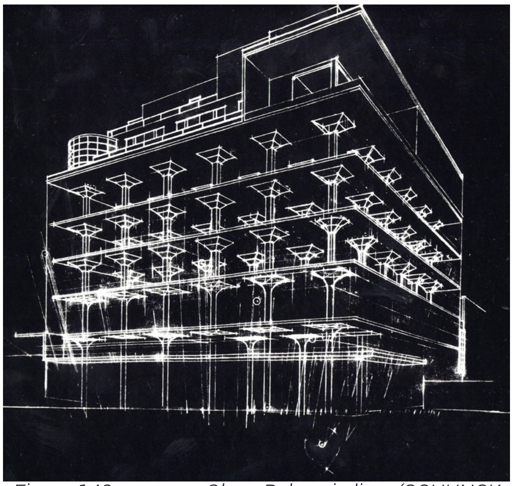


Figure 142. Glass Palace in lines(SCHUNCK, nd)

Figure 141. Glass Palace at nigth 2 (SCHUNCK, nd)

Figure 143. Glasspalace column (retrieved from: https://hiveminer.com/Tags/glaspaleis)

Column Design

The column will be placed in the glass palace in Heerlen at the ground floor, which has a height of 5,65 meter. The ground floor is an open space that is used as an entrance with a bookshop, space for cultural activities and a reading area. When replacing one of the concrete mushroom columns by a column made out of glass components, this would attract the attention. It will be an eyecatcher in the middle of this open space. The diameter of the existing column is 56cm. A maximum of 1m has been set for the new diameter of the column.

In "Glass Column Design Principles & Challenges" we could see that the shape and width are determinative for the buckling of the column. The bigger the cross-section of the column, the less likely it is that the column is going to buckle.

The buckling will always start at the weakest point in the cross-section. When the column is round, all the directions are even in weakness or strength.

Concept Designs

The concept designs were created by looking at what has already been done in the past; by nature, the building industry, but mostly in research in cast glass. The elements that were created in the glass research were evaluated on points in the design principles and challenges:

- Glass and annealing shape
- Column Shape
- Interlocking
- Redundancy
- Multifunctionality
- Planar compressive strength

After judging the components that have already been made, six types of concept design were created for this design process. They were judged by these points as well. By judging them on this list, we saw that some components were not multifunctional or could not be used in a round column. Next to this, the 3rd component has too many similarities to the component created by Akerboom. This is why three types were chosen to investigate further. These types are later on combined into two types.

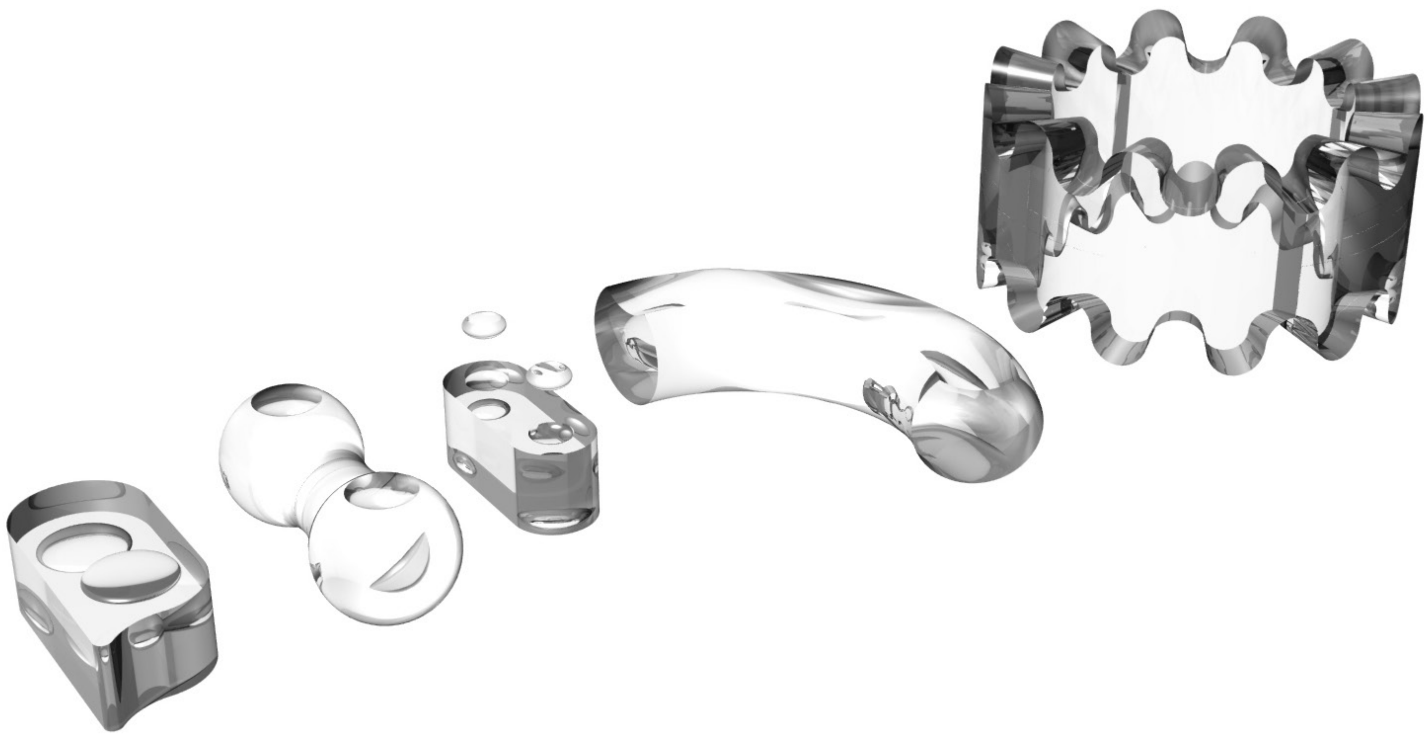
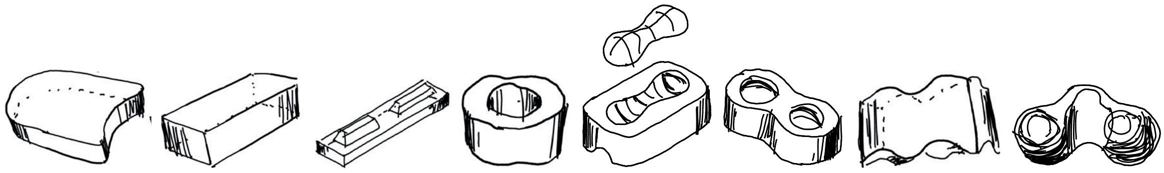
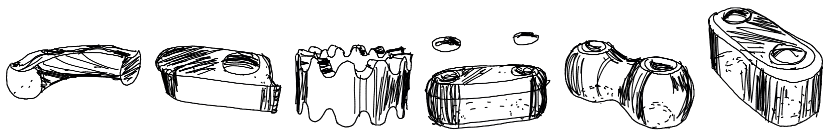


Figure 144. Render of concept designs



	Atocha monument	Crystal Houses	Barou Thesis	Akerboom Thesis	Type C blocks Oikonom-opoulou& Bristogianni	Type E blocks Oikonom-opoulou& Bristogianni	Jacobs Thesis	Janssens Thesis
Glass and annealing shape	bad	very bad	bad	good	good	good	medium	good
Round column of about 60cm diameter	only very small angles	only 90° angle	not possible	possible	not possible	possible	only 90° angle	not possible
Interlocking	no	no	yes	yes	yes	yes	yes	yes
Redundancy	yes, multiple emenents	yes, multiple emenents	yes, multiple emenents	no	yes, multiple emenents	yes, multiple emenents	yes, multiple emenents	no
Multifunctionality	medium	yes	no	no	no	yes	medium	no
Planar compressive strenth	yes	yes	yes	yes	yes	medium	yes	no

Table 8. Table of reference shapes



	Type 1: Curved Chain	Type 2: Costomized Atocha Brick	Type 3: Circular interlocking	Type 4: Smarties	Type 5: Bone	Type 6: Lego
Glass and annealing shape	medium	very bad	bad	medium	good	medium
Redundancy	yes, multiple emenents	no	no (one element), yes (will not crumble)	yes, multiple emenents	yes, multiple emenents	yes, multiple emenents
Multifunctionality	no	yes	no	yes	yes	yes
Planar compressive strenth	yes	medium	yes	medium	no	yes

Table 9. Table of concept designs

Elegant & Robust Components

Before creating the concept designs, three designs were chosen to develop further:

- bone
- lego
- smarties

Of these elements, a silicone mould was created, and sugar glass was made inside them. These sugar glass elements taught a lot how to make the elements and where to watch out for when making silicone moulds and sugar glass elements.

The bone has an unusual shape that has not been used in a column before. The smarties-design has potential because it could open possibilities to use other materials between the glass elements. The lego-design is the most predictable, but also the most solid choice. When applying the smarties in a spherical shape to the interlock of the bone-design and the lego-design, two new designs were constructed: the elegant design and the robust design.

Two elements that are quite the opposites of each other have been created.

One makes the column robust, stately and as one evenly flat outer surface. It would disappear in its background and be as transparent as possible.

The elegant element would be interesting to look at and search for the limits of the glass in cooperation with the loads it should carry. Therefore the elegant one would be more interesting to look at in research. This way testing the limits of glass would be possible.

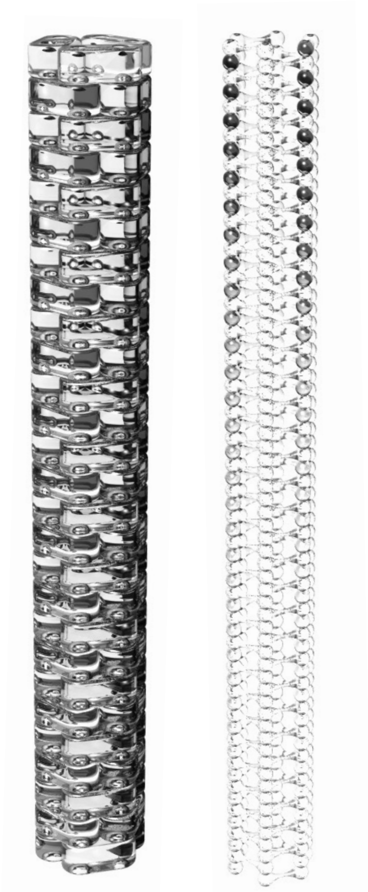


Figure 147. Robust and elegant column designs

Figure 145. 3 concept element designs

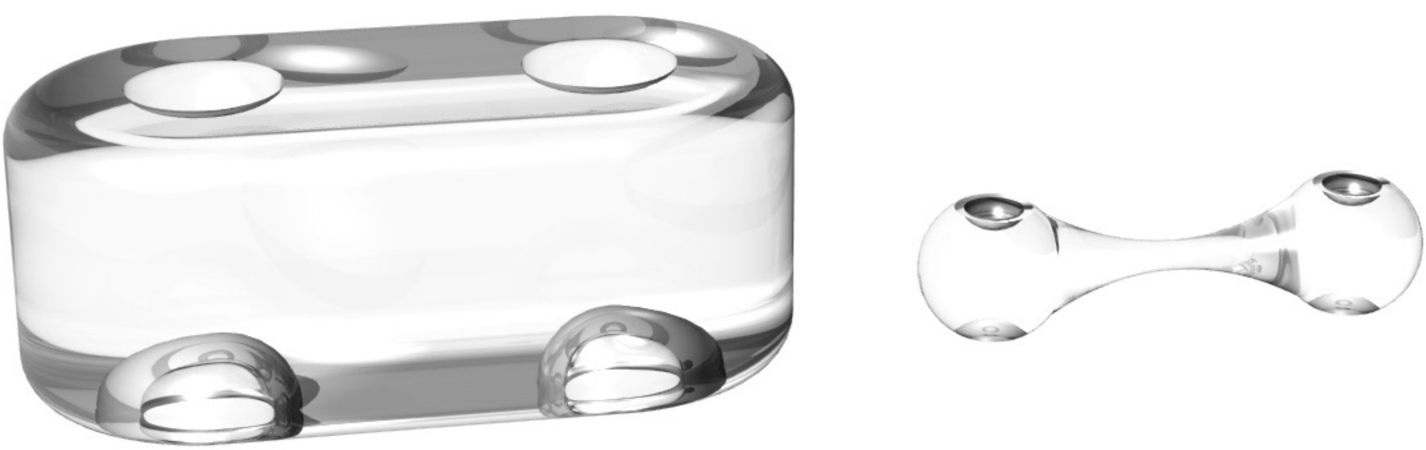


Figure 146. Robust and elegant component designs

Final Component

Dimensions

The final component has been created by combining different calculation for all the specifications of the column and its components. This mainly has to do with buckling and redundancy.

d_{column}=	800	mm
r_{column}=	400	mm
l_{interl}=	247	mm
l_{total}=	477	mm
d_{middle}=	142	mm
r_{middle}=	71	mm
$d_{bigsphere}$=	230	mm
$r_{bigsphere}$=	115	mm
d_{interl}=	66	mm max.
r_{interl}=	33	mm max
d_{flat}=	154	mm min
r_{flat}=	77	mm min
h=	170	mm
$m_{bigshere}$=	14,4	kg
$m_{component}$=	30,9	kg

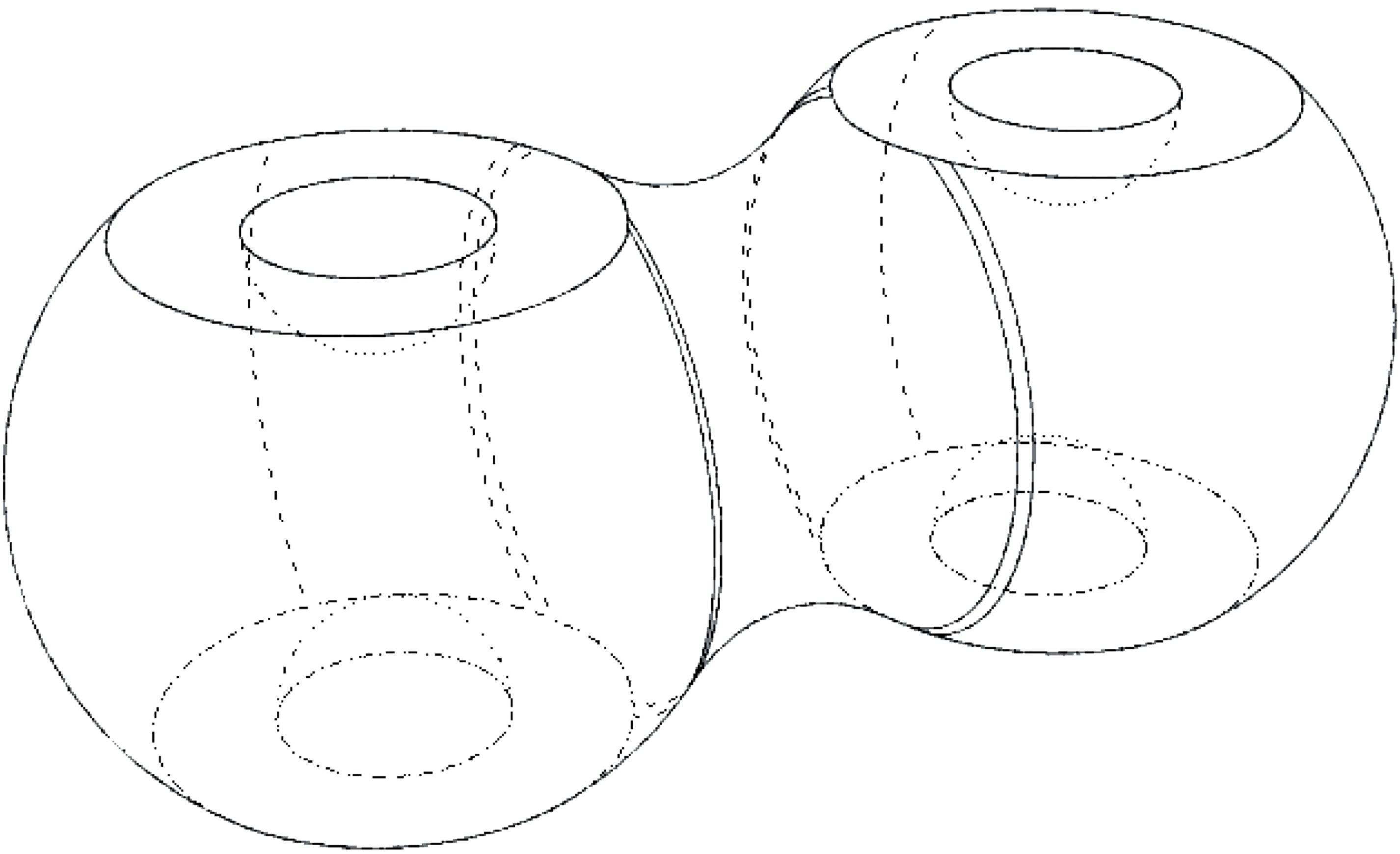


Figure 148. Schematic image of the component design

Transparency

In the design of this interlocking column, the desire is not to create a column in which the glass is as transparent as possible. But the column itself should be as open as possible. These open spaces should be lead to the feeling of transparency and openness. To create this, the shape of the elements have a smaller "neck", compared to the force transmitting part of the component. Next to this, the component is made out of spherical shapes, which is the natural shape of glass.

These spherical shapes that are visible in the design will work as lenses to the light. They will work as converting lenses, as well as divertive lenses.

As E Janssens described in her thesis of a dome made of 'bone' like elements, the colour scheme close to the component will be similar to the real colour scheme. But when the focus point is more distant from the component, the colour scheme will be inverted. (Janssens, 2018)

When the glass would be completely transparent, the glass would be reflected as shown in the images on the next page. But due to the glass itself, the view will be more blurred, and mainly transmit the colours behind the element, instead of the total view.

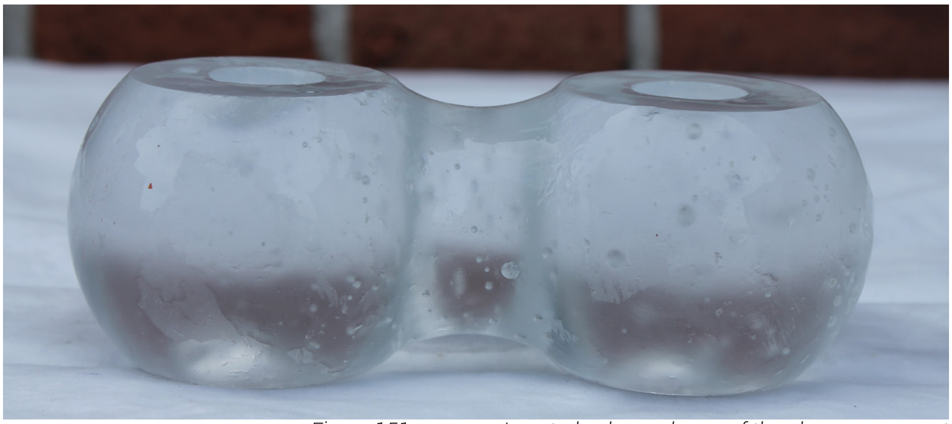


Figure 151. Inverted colour scheme of the glass component

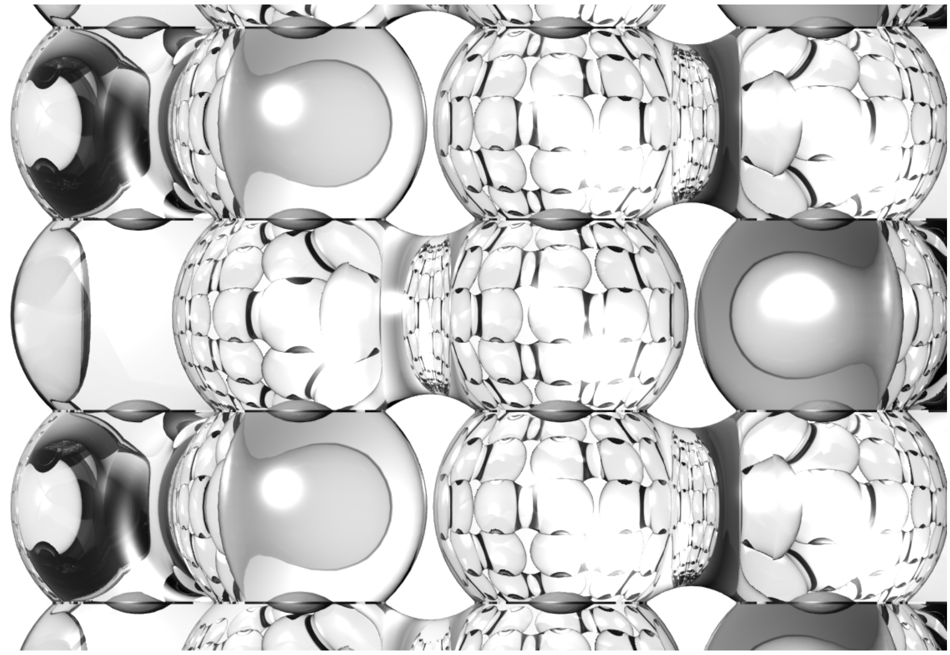


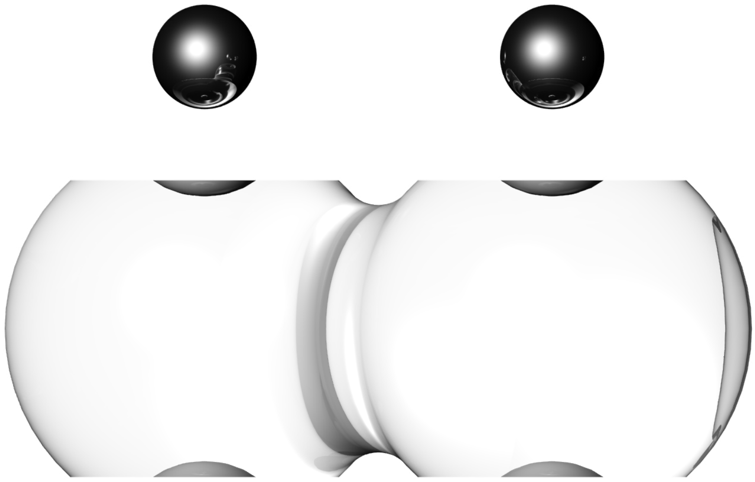
Figure 150. Render of column, of the glass components would be cmpletely transparent

Figure 149. Side view of the column design

Aesthetics

As been said in the last chapter, the component is not entirely transparent but transluscent. Next to this, the interlocking becomes very small due to the convection and diverging effect f the spheres. This makes the interlocking components almost invisible to the human eye.

Steel will reflect everything around and glass will create a more transparent look. Marble will introduce a matt white surface which makes the column and therefore the building lighter.



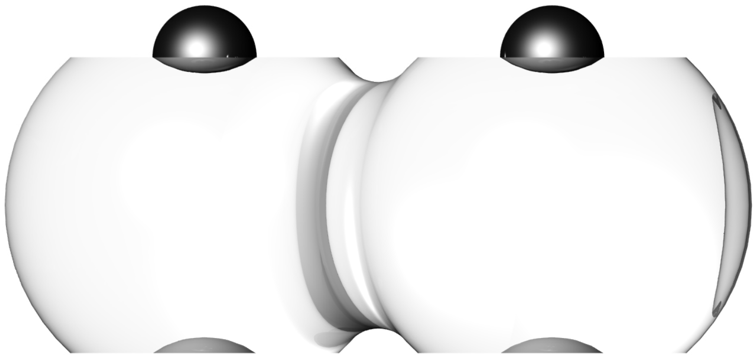


Figure 152. Effect of interlocking sphere on view of the component

Other optional components

The components with the column are optimised for the case study that it will be applied in, the Glasspalace.
But because this component is very multifunctional, it could be used in other configurations as well. Also, it could interlock with components that have the same interlocking mechanism. Examples of these optional other components are visible in the figure below.

Other configurations

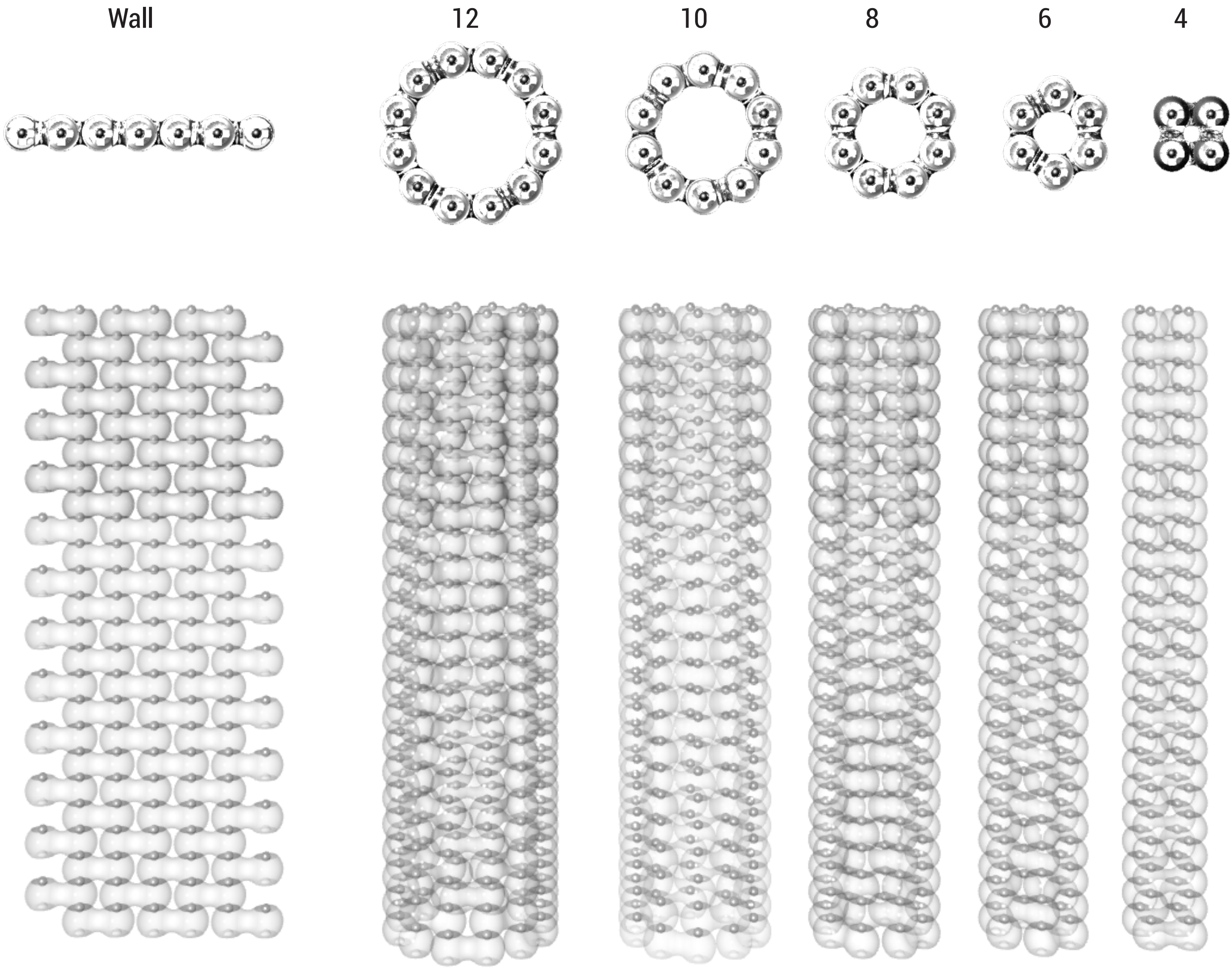


Figure 154. Other optional configurations of the elements

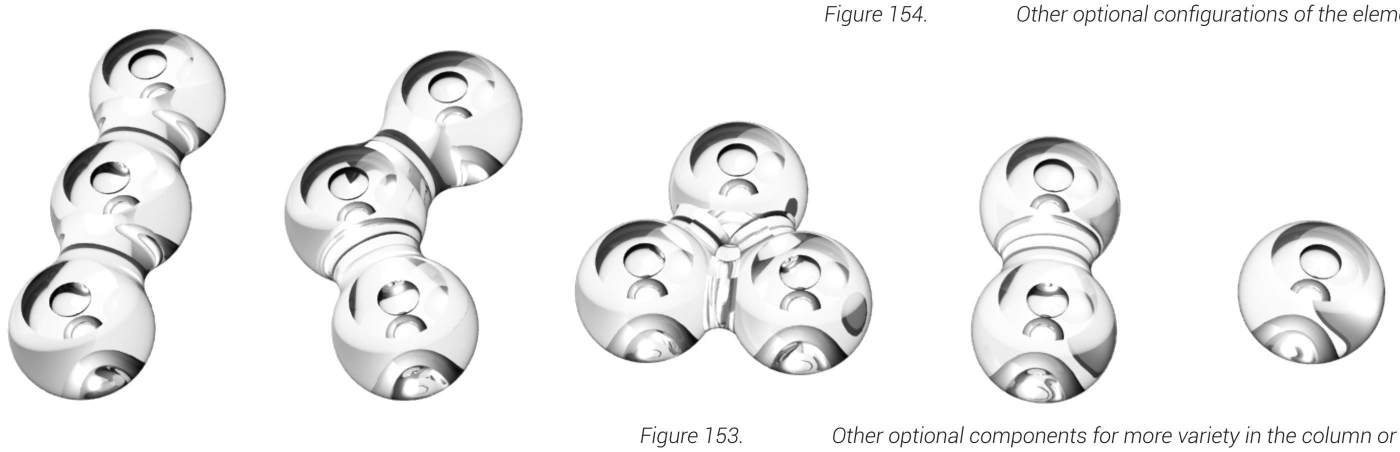


Figure 153. Other optional components for more variety in the column or wall

Figure 156. Other optional components for more variety in the column or wall

Figure 155. Column configurations of different components

Interlocking Sphere

Why a sphere?

As we could see in the literature research about interlocking, interlocking could be created in many different ways. Due to the design principle of creating a multifunctional component, the most obvious solution is to create something round. This way the component would be placed in every single angle that is wanted.

A counterargument for not creating something round could be that it wouldn't be as easy to align with the rest when as it would be with something that has angles. The solution for this would be easy when creating a "round" column with a different number of components on one layer.

A round interlocking part could be made in many different configurations. But only one shape has no corners at all, and that would be a sphere. A sphere is, therefore, a very strong shape, for any material.

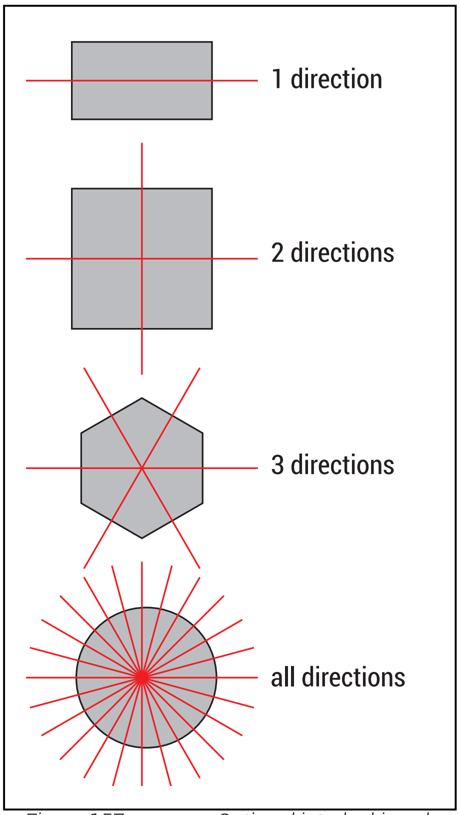


Figure 157. Optional interlocking shapes with their number of directions they could interlock

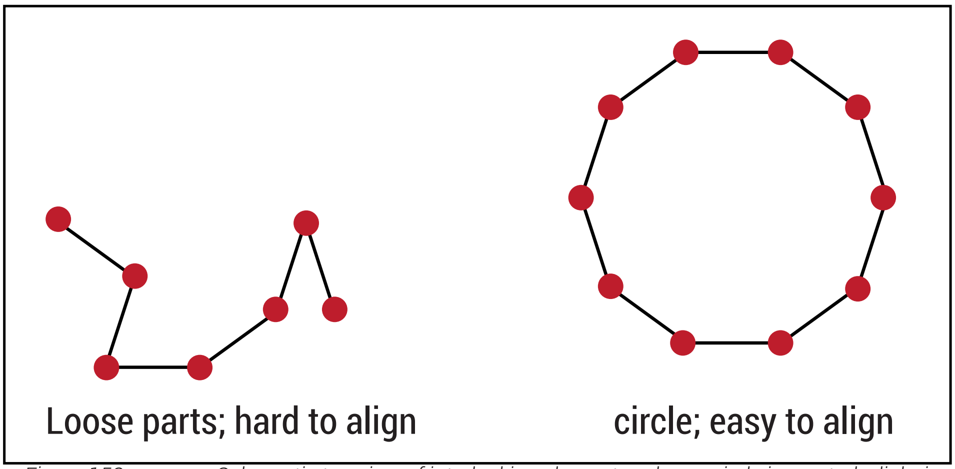


Figure 158. Schematic top view of interlocking elements: when a circle is created, alighning is easier.

Load on the interlock

Unlike the flat surface of the component, the load of the building will not be resting on the spheres. The forces will be translated through the flat surface of the component. Therefore there will be none of these compression forces on the sphere. The sphere will be laying "loose" between the other components.

When selecting materials of the interlocking sphere, it is essential to explain what the applied forces are. The interlocking sphere is meant only to transfer shear forces to the components. By doing this, the components will stay aligned when a force from the side would push the component. These interlocking spheres should be able to hold the maximum shear force that will be applied to one component of the column.

When looking at the risk analysis, we can see that the maximum force that could occur, created by four people would be 2400 N.

600 N x 4 = 2400 N per element

This is why 2400 N is taken as a maximum shear force that would be applied to one component. One component has four interlocking spheres, two on the top and two on the bottom. This is why, when calculating the force on one component, this force should be divided by four.

2400 N / 4 = 600 N per interlocking sphere.

This gives us a maximum shear force of 600 N per interlocking sphere. When wanting to know the stress this would deliver on the sphere (and inside the component), the surface of the interlocking has to be identified.

When the interlocking sphere has a diameter of 62 mm, there will be a space of 1 mm between the interlayer and the sphere. The sphere will have a total surface of $4\pi r^2$. When the radius is 31mm the total surface will be:

$A_{spheretotal} = 4\pi r^{2} = 12.076 \text{ mm}^2$

Because the load will only be applied on one side of the top or bottom part of the sphere, the surface has to be split into 4 to get the applied stress. The surface on which the stress will be applied is:

$A_{sphere} = 12.076 / 4 = 3.019 \text{ mm}^2$

But the actual working surface will only be the half circle (1/8th of the surface of the total sphere). This would result in a surface of 1509mm2.

$A_{circle} = 12.076 / 8 = 1.509 \text{ mm}^2$

As told before, the applied load will be 600 N per interlocking sphere. This would result in stress of:

$\sigma_{sphere} = F_{sphere} / A_{sphere}$
$\sigma_{sphere} = 600/1.509$
$\sigma_{sphere} = 0,40 \text{ MPa}$

This is much less then the glass can hold due to its tensile strength of 28 MPa. This means that when the element is made out of glass and in direct contact with the glass of the component, the glass can be loaded with a maximal force of maximal 2,85 kg/mm2. Because the effective surface of one sphere is 1509 mm^2, this could be up to 4307 kg per interlocking sphere.

In the table, the forces that are applied on the column are put together, so it is visible that the shear force on the column is very small compared to the compression forces that are applied.

Comparing this to the design, prototype and shear force test of Barou. It is interesting to see that this interlocking looks over-dimensioned as well. The element could withstand a force of:

17,3 kN = 17300 N

The force that it needs to withstand was only 1 kN/m2 which meant in her component of :

40 x 500 mm = 25000 mm^2

F= 1 kN $*$ 25000 mm^2 = 25 N

This 25 N would be split over an interlocking of:

Interlocking surface of one interlock= 152,79 x 27 mm = 4125,33 mm^2

Interlocking surface of one component = 4125,33 mm^2 x 4 = 16501,32 mm^2

This would result in a stress of:

25 / 16501,32 = 0,0015 MPa

Because in her case the interlocking surface was aswell transmitting the compression forces, the interlayer was necessary. (Barou, 2017)

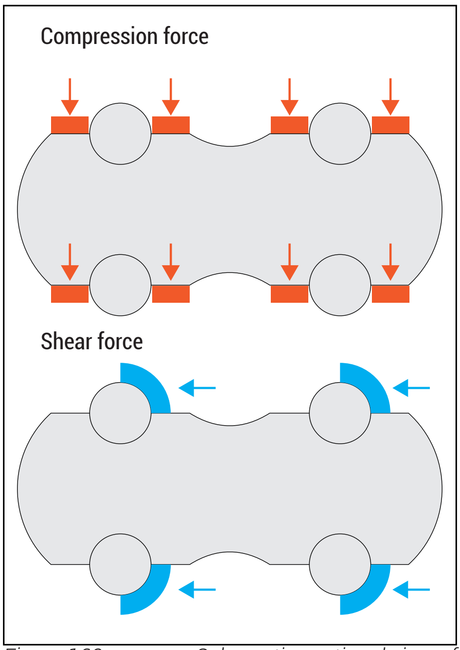


Figure 160. Schematic sectional view of elements with applied forces.

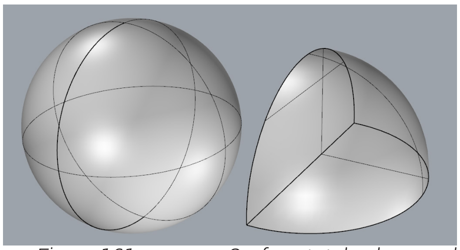


Figure 161. Surface total sphere and only contact surface

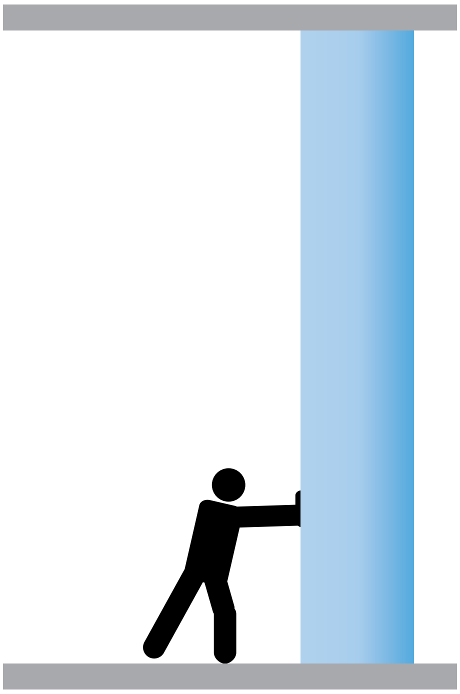


Figure 159. Creating shear force by pushing to the column

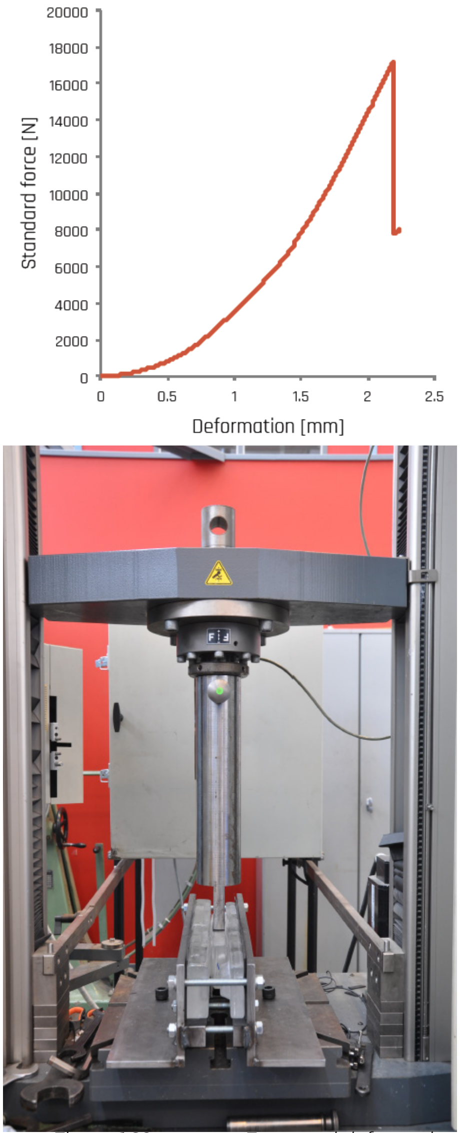


Figure 162. Force and deformation diagram and a picture of the test set-up of the shear force test on the component of Lida Barou (Barou 2016)

Forces applied on the column	***N***
compression force total column minimal	126.100
compression force subcolumn minimal	126.000
shear force on compoonent maximal	42.252
applied shear force	2.400

Table 10. Forces applied on the column

Material selection

The material of the interlocking sphere does not need an interlayer when it comes to shear force only.

When wanting to create safety against trucks that would drive into the building, the glass could have an interlayer between the sphere and the component; this could increase its shear strength a lot from a maximum of the tensile strength of the glass (28 MPa) towards its maximal compressional strength (280 MPa). This does not seem logical because the glass would break since in the Glasspalace the risk it too small for scooters or other vehicles to drive in at high speed.

Because the sphere design is not limited to the hardness of the material, the choice between materials is very wide. But the material does have some limitations:

-Compressive and tensional strength need to be at least 0,66 MPa

-Young's modulus of at least 5

-Durability against UV radiation

-Flammability

-Maximum service temp 50 °C

-Fracture toughness of at least the one of glass 0,54

-Durability against water (salt and sweet)

From these limits, many materials appeared to be a suitable material for this geometry. From this list, some interesting materials have been selected that could be interesting aesthetically these are compared in a table.

All of these materials are suitable for the interlocking sphere between the glass components.

The choice for me would be to select marble and stainless steel as interesting materials to use in this design. Marble has a chic appearance and would receive extra attention through the enclosure of glass. Stainless steel usually is not in direct contact with the glass, due to the peak stresses that will appear at high applied forces. But to use it inside the components would be very interesting; they reflect all the light entirely which would give an extra dimension to the intriguing light effect.

It would be valuable to test these materials in this composition, to see which ones will suit the design best.

		Marble (2.7)		Bric h
Price	*EUR/kg*	0,367	0,931	0
Price per unit volume	*EUR/m^3*	1,00E+03	2,65E+03	1,10E
Density	*kg/m^3*	2,72E+03	2,85E+03	1,98E
Young's modulus	*GPa*	50	70	
Tensile strength	*MPa*	6	10	
Compressive strength	*MPa*	55	105	
Poisson's ratio		0,14	0,22	
Shape factor		15		
Hardness - Vickers	*HV*	16	20	
Fracture toughness	*MPa.m^0.5*	0,6	1,2	
Melting point	*°C*	1,23E+03	1,34E+03	
Thermal expansion coefficient	*μstrain/°C*	3	5	
Color		White/Gray		
Transparency		Opaque		
Water (fresh)		Excellent		
Water (salt)		Excellent		
UV radiation (sunlight)		Excellent		
Flammability		Non-flammable		Non
Recycle		False		
Downcycle		True		

Figure 165. Optional materials for sphere: marble, steel and glass

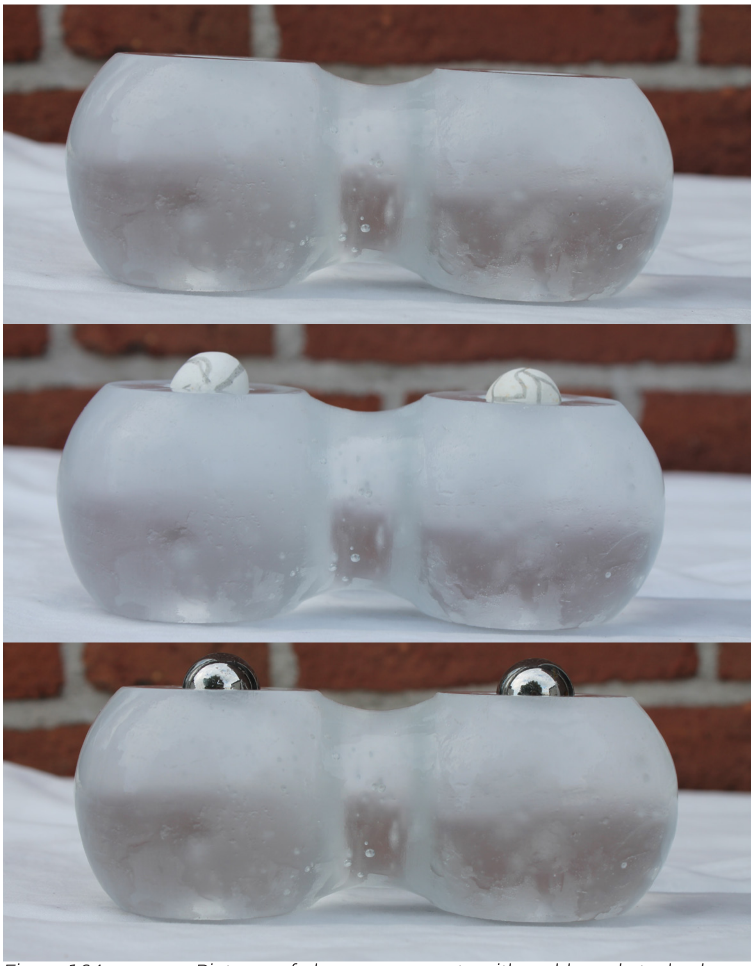


Figure 164. Pictures of glass components with meble and steel spheres

ck (common, ard)(2.03)		Cast iron, high silicon, BS grade Si 10		Borosilicate - N16B		Polyester SMC (25% glass fiber, V-0)		Stainless steel, martensitic, AISI 440A, tempered at 316°C	
,555	1,49	0,475	0,519	1,85	11,1	2,95	3,38	0,886	1,06
E+03	3,08E+03	3,28E+03	3,69E+03	4,54E+03	2,78E+04	4,73E+03	6,41E+03	6,82E+03	8,34E+03
E+03	2,07E+03	6,90E+03	7,10E+03	2,45E+03	2,50E+03	1,60E+03	1,90E+03	7,70E+03	7,90E+03
10	50	120	128	63,7	83,8	8,2	9,9	190	210
6,9	14	150	180	28,3	37,7	55	83	1,61E+03	1,97E+03
69	140	580	800	283	377	160	240	1,49E+03	1,82E+03
0,2	0,23	0,27	0,28	0,19	0,24	0,27	0,33	0,275	0,285
15		24,4		15		11		14	
28	31	480	520	93,1	103	17	37,2	500	600
1	2	9	15	0,61	0,7	15,3	37,4	17	34
930	1,20E+03	1,24E+03	1,44E+03		-			1,37E+03	1,48E+03
8	11	12,4	13,1	8,52	8,87	16,4	19,8	9	11
Red/Buff				Clear					
Opaque		Opaque		Transparent					
Excellent		Excellent		Excellent		Excellent		Excellent	
Excellent		Excellent		Excellent		Excellent		Excellent	
Excellent		Excellent		Excellent		Good		Excellent	
n-flammable		Non-flammable		Non-flammable		Self-extinguishing		Non-flammable	
False		True		True		False		True	
True		True		True		True		True	

Table 11. Material selection of interlocking sphere

Interlayer Design

Interlayer materials

From the literature study, we have seen that it is important to select an interlayer based on different factors. Limits are set for this design and will be explained in the following paragraphs:

Transparancy

The transparancy level has to be; translucent, transparent or optical quality. This means that light will at least be able to pass the interlayer. The more transparent the interlayer, the better.

Young's modulus

The Young's modulus of the interlayer could be based on the thickness of the interlayer and the stiffness of the total structure. (Aurik, 2017)
The stiffness of this structure is not calculated, this is why another, less precise determination has to be made. This method is based on the method Janssens did in her thesis (Janssens, 2018).

Research has been done in about which amount of stress glass breaks when it is in direct contact with other glass without an interlayer. The amount of stress it will be able to hold will be simular to the maximal tensile stress of the material. (Oikonomopoulou et al., 2014)

In this design, borosilicate glass is used, with a maximal tensile stress of 28 MPa. Therefore the stress at the surface of the glass should not expire 28MPa.

$\sigma_{contact} \leq 28$ MPa

With this been said another equation could be introduced:

$\sigma_{contact} = E_{int} * 2\Delta/t_{int}$

In which:

Δ = Deviation of the components (assumed to be 0,25 mm, same as Aurik)
E_{int} = Young's modulus of the interlayer
t_{int} = thickness of the interlayer

When combining those two equations this etuasion is formulated:

$E_{int}/t_{int} \leq 28 / 2\Delta$

When the interlayer thickness will be between 1 mm and 5 mm this equation will result in:

$E_{int}/1 \leq 28 / 2\Delta$
$E_{int} \leq 11{,}2$ MPa

to

$E_{int}/5 \leq 28 / 2\Delta$
$E_{int} \leq 56$ MPa

This would suggest a range of the youn'g modulus to be:

11,2 MPa $\leq E_{int} \leq$ 56 MPa

0,0112 GPa $\leq E_{int} \leq$ 0,056 MPa

Compressive strength

The interlayer should be able to hold the applied froce of at least 28 MPa, which is the tensile strength of glass.

		PEBA (Shore D25)		PVC (flexible, Shore A85)		TPU (Ester, aromatic, Shore A70)	
Price	EUR/kg	9,48	13,20	2,36	2,72	2,78	-
Young's modulus	GPa	0,012	0,021	0,030	0,035	0,014	0,014
Tensile strength	MPa	28,3	31,7	19,0	20,0	35,0	40,1
Compressive strength	MPa	34,0	38,1	25,0	30,0	42,0	48,1
Shear strength	MPa	22,6	31,7	0,0	0,0	28,0	40,1
Hardness - Vickers	HV	8	10	11	14	10	12
Thermal expansion coefficient	µstrain/°C	201	254	98	104	168	172
Transparency		Transparent		Translucent		Transparent	
UV radiation (sunlight)		Fair		Fair		Fair	
Flammability		Slow-burning		Slow-burning		Slow-burning	
Density	kg/m^3	999	1.010	1.330	1.340	1.150	1.190
Yield strength (elastic limit)	MPa	28,3	31,7	19,0	20,0	35,0	40,1
Poisson's ratio		0,48	0,50	0,47	0,48	0,48	0,50
Shape factor		1,60		2,20		1,60	
Hardness - Rockwell M		3,00	9,00	-	-	4,00	6,00
Hardness - Rockwell R		3,00	9,00	-	-	4,00	6,00
Hardness - Shore D		20,00	30,00	34,00	35,00	23,00	26,00
Maximum service temperature	°C	120	130	47	52	93	107
Refractive index		1,50	1,52	-	-	1,48	1,50
Polymer injection molding		Acceptable		Acceptable		Acceptable	
Polymer extrusion		Acceptable		Excellent		Excellent	
Polymer thermoforming		Unsuitable		Excellent		Unsuitable	
Water (fresh)		Acceptable		Excellent		Excellent	
Water (salt)		Acceptable		Excellent		Excellent	

Maximum service temperature
On a summer day, the heat in the building could build op, especially with a floor height of 5,6 m. The maximum temperature that will be reached in the building will be assumed to be 50°C. When the column is heated up to this temperature, the interlayer should not be starting to melt. This is why the maximum service temperature has to be 50°C.

Durability against UV radiation
The design will be placed in a building with a facade made entirely out of glass. This is why there will be UV-radiation due to the sunlight that will shine through the facade on the column. The interlayer has to be able to not fail or change colour due to the sunlight. This is why a limit on UV radiation has to set to fair, good or excellent.

Flamability
A column has to be fire-resistant. This is why fire safety is also a point of attention when selecting a suitable interlayer. The material should at least not be highly flammable; but optional slowly burning, self-extinguishing or non-flammable.

Selected interlayer materials
With these limits set in the program CES EduPack 2017 gives an output of seven materials:
- PEBA (Shore D25)
- PVC (flexible, Shore A85)
- TPU (Ester, aromatic, Shore A70)
- TPU (Ester, aromatic, Shore A85/D35) (1)
- TPU (Ester, aromatic, Shore A80)
- TPU (Ester, aromatic, Shore A85, flame retarded)
- TPU (Ester, aromatic, Shore A85/D35) (2)

These materials would all be suitable, in different thicknesses, to use in this design.

When the different materials are compared in the table underneath, it is visible that only one of the materials is self-extinguishing. This is why this material, TPU (Ester, aromatic, Shore A85, flame retarded) is chosen to be used in this design.

Thickness interlayer
The thickness of the interlayer could be determined using the theory of Aurik (2017):

$t_{int} \geq 2 . \Delta / (1-\sigma_{avg}/E_{int})$

with:

Δ = Deviation of the components (assumed to be 0,25 mm, same as Aurik)

σ_{avg} = Force on subcolumn/Area subcolumn = 126.000N / 15.000mm^2= 8,4 N/mm^2 = 0,0084 GPa

E_{int} = 0,028 GPa (TPU, Shore A85, flame retarded)

When filling in this formula this would result in:

$t_{int} \geq 0{,}77$

2 mm ≥ 0,77 mm

An interlayer of 2 mm , it is visible in this formula that this would be possible.

TPU (Ester, aromatic, Shore A85/D35) (1)		TPU (Ester, aromatic, Shore A80)		TPU (Ester, aromatic, Shore A85, flame retarded)		TPU (Ester, aromatic, Shore A85/D35) (2)	
2,78	4,21	9,04	12,40	3,46	5,20	2,78	4,21
0,029	0,040	0,033	0,033	0,020	0,028	0,020	0,021
38,0	49,4	36,9	42,9	29,5	37,5	31,9	38,9
45,6	59,3	44,2	51,4	35,4	45,0	38,3	46,7
30,4	49,4	29,5	42,9	23,6	37,5	25,5	38,9
11	15	11	13	9	11	10	12
151	169	264	278	160	170	162	172
Transparent		Optical quality		Transparent		Transparent	
Fair		Fair		Fair		Fair	
Slow-burning		Slow-burning		Self-extinguishing		Slow-burning	
1.180	1.210	1.070	1.100	1.120	1.220	1.110	1.130
38,0	49,4	36,9	42,9	29,5	37,5	31,9	38,9
0,48	0,50	0,48	0,50	0,48	0,50	0,48	0,50
1,60		1,60		1,60		1,60	
12,00	24,00	6,00	16,00	28,00	31,00	9,00	14,00
12,00	24,00	6,00	16,00	28,00	33,00	9,00	14,00
34,00	44,00	26,00	38,00	47,00	50,00	30,00	36,00
93	107	66	76	93	107	93	107
1,48	1,50	1,49	1,50	1,48	1,50	1,48	1,50
Acceptable		Acceptable		Acceptable		Acceptable	
Excellent		Excellent		Excellent		Excellent	
Unsuitable		Limited use		Limited use		Limited use	
Excellent		Excellent		Excellent		Excellent	
Excellent		Excellent		Excellent		Excellent	

Table 12. Optional interlayer materials (Granta's CES EduPack 2017, n.d.)

Interlayer types

In the final design of the column made out of identical components, there will be different interlayers that should and could be used. The interlayer should at least be between the flat surfaces of the two glass components and between the steel end-connections and the components. Next to this, the interlayer could also be formed inside the interlocking hollow sphere, but this is only necessary when the material of the sphere could not be in direct contact to the glass when there is a shear force applied. This is why there are two options available for the interlayer tween the glass components:

1. Two of the same bent surfaces with a flat and a round part. The flat part will have double the thickness of the spherical part.

2. A flat interlayer between the components with a hole in the middle for the interlocking sphere

When connecting the components to the top-floor and bottom-floor, the glass has to be connected to the steel end-connections. For this, another interlayer will be created (3). The interlayer will look like the second glass-to-glass interlayer, but it is thicker and made out of neoprene, which is a soft rubber. These interlayers will be thicker because of the thermal movements of the column, and the rest of the building. This interlayer has a thickness of 5 mm.

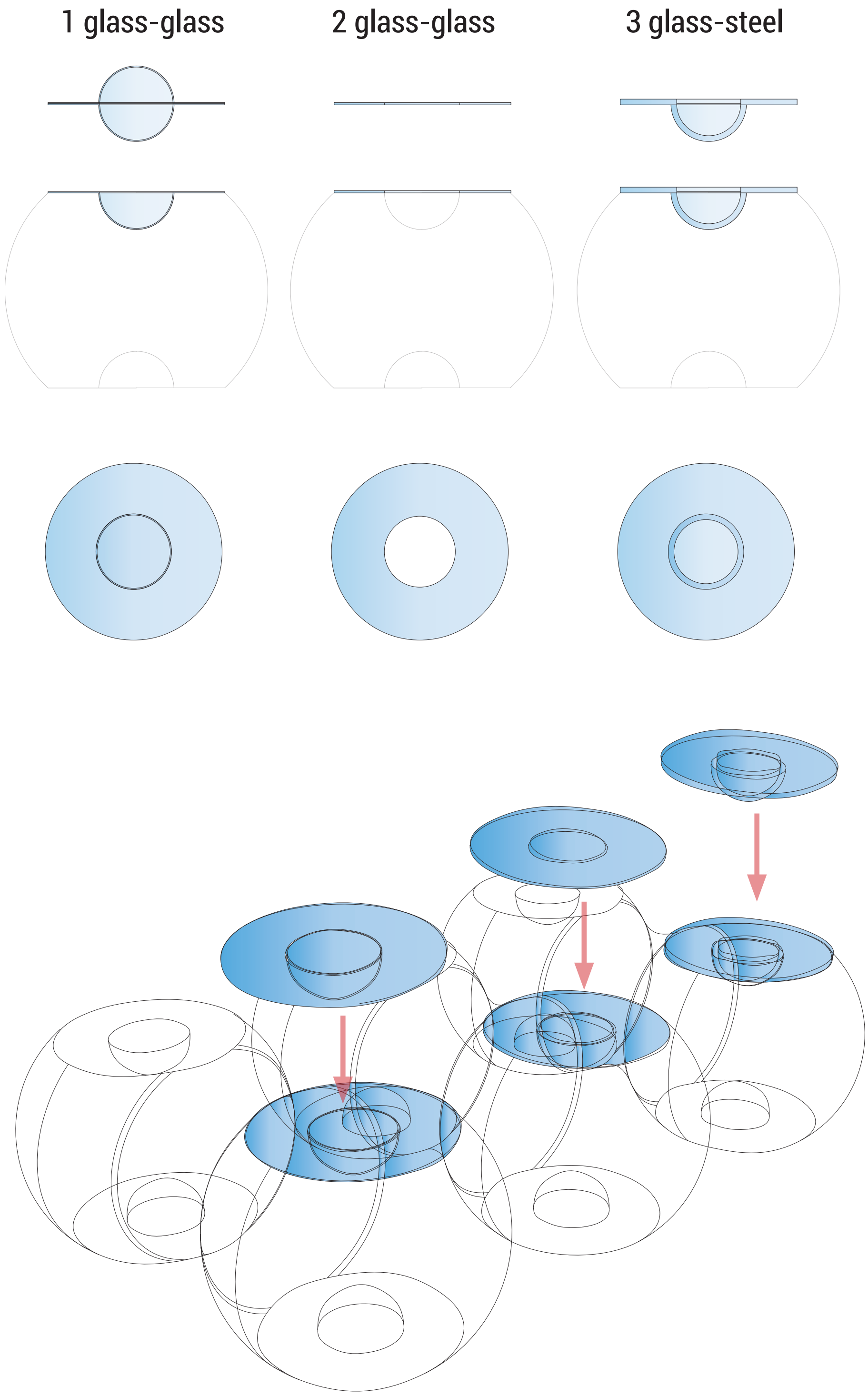


Figure 166. Different interlayer-types

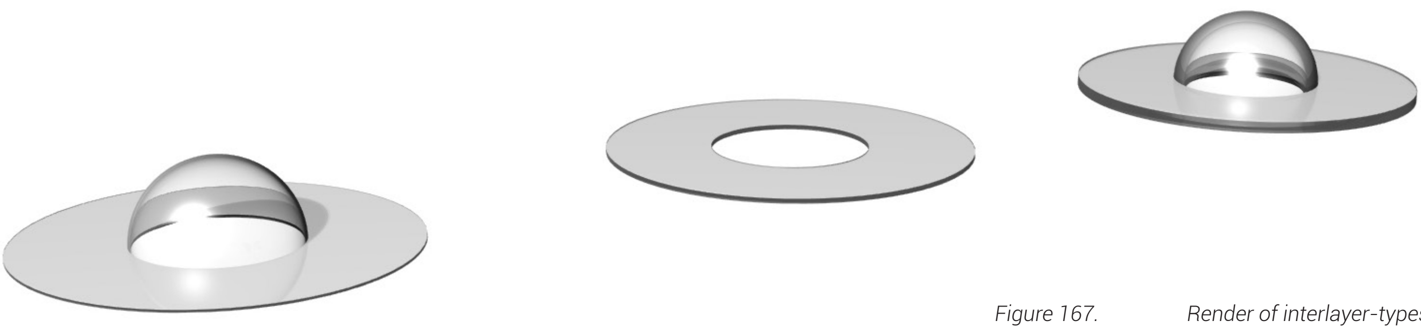


Figure 167. Render of interlayer-types

Processing interlayer

The chosen material TPU (Shore A85) has different ways of processing the material. Only some of them could shape the interlayers 1 and 3; compression moulding, injection moulding and thermoforming.

Next to this, interlayer 2, only has to be cut in the right shape, as well as interlayer 1 & 3. Therefore other methods will be used; stamping, press forming or laser cutting.

All of these will be explained in the next scheme.

From this, we could see that it is important to know how many of them would be made. From this column, we need about 400 pieces of the interlayer. This selects that stamping/press forming would be the cheapest option for the cutting method.

For the shaping process of interlayer 1 and 3, we need about 800 pieces, which would select compression moulding and thermoforming to be the cheapest options. The best option regarding tolerance would be compression moulding. This is why this processing method would be the most suitable for this design.

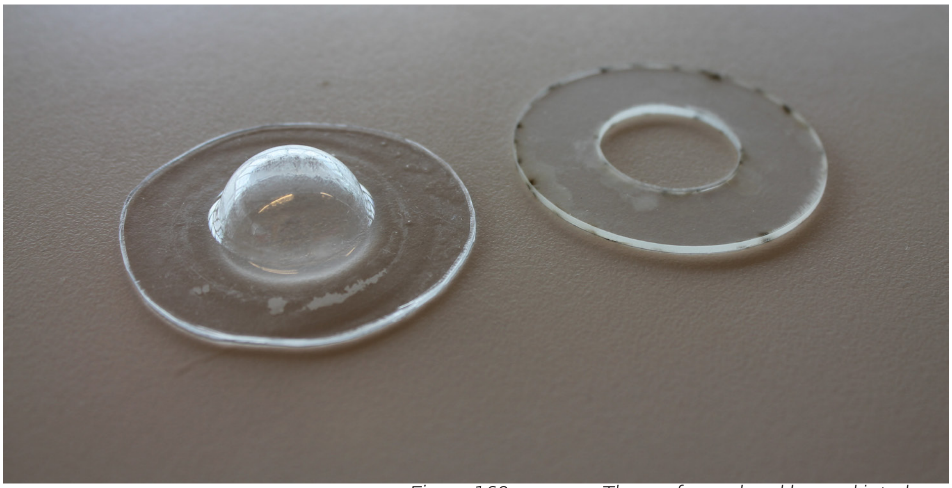


Figure 169. Thermoformed and lasered interlayer

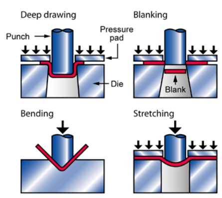
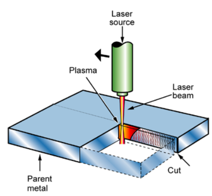
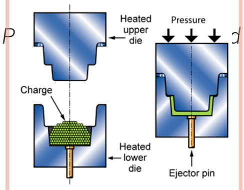
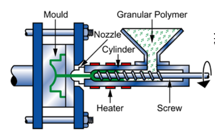
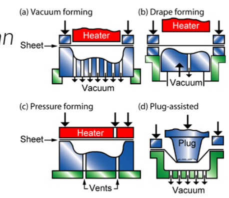
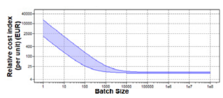
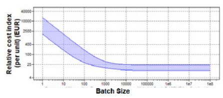
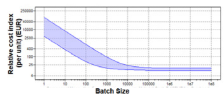
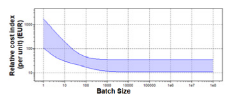
	Stamping & pressforming	Laser cutting	Compression molding	Injection molding	Thermoforming
					
Economic batch		no exonomic batch advantage			
Mass	0,001 - 100	0,001 - 50	0,1 - 20	0,01 - 25	0,003 - 10
Thickness	0,1 - 50	0,3 - 10	1,5 - 25	0,4 - 6,3	0,25 - 6
Tolerance	1 - 10	0,1 - 1	0,15 - 1	0,1 - 1	0,5 - 1
Shaping process	2nd	2nd	1st	1st	2nd

Table 13. Processes for interlayer production (Granta's CES EduPack 2017, n.d.)

Construction

End connections

To convert loads in a building from floor to column to floor, end connections have to be made. When building the column out of cast glass elements, these end connections need to be very precise and strong. This is why these connections will be made out of steel.

As we know, the column is placed in an existing building, the Glasspalace. This is why the end-connections need to be made out of different layers that could put the column under compression. Next to this, it is required when disassembling the column.

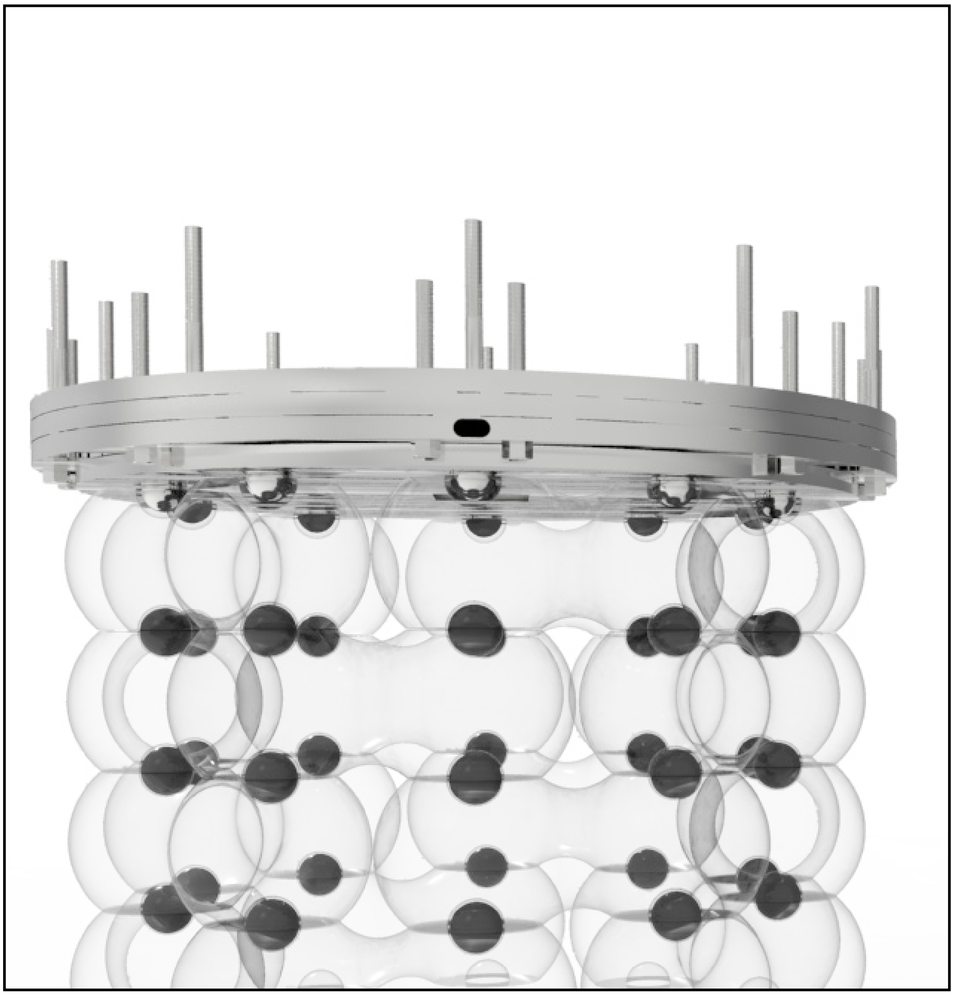


Figure 170. Detail of top part of the end-connection

Pre-stressing

Prestressing an element is usual when buckling is normative in a design, a (steel) cable in the middle of the column is not a problem and when the material is weak in tension. In the design, a cable in the middle of the column is not a problem, when it is not so thick that it becomes visible.
But because the big load of the building on the column the threat has to be very big to increase the compression on the column significantly. This is why the choice is made that the column will not be pre-stressed.

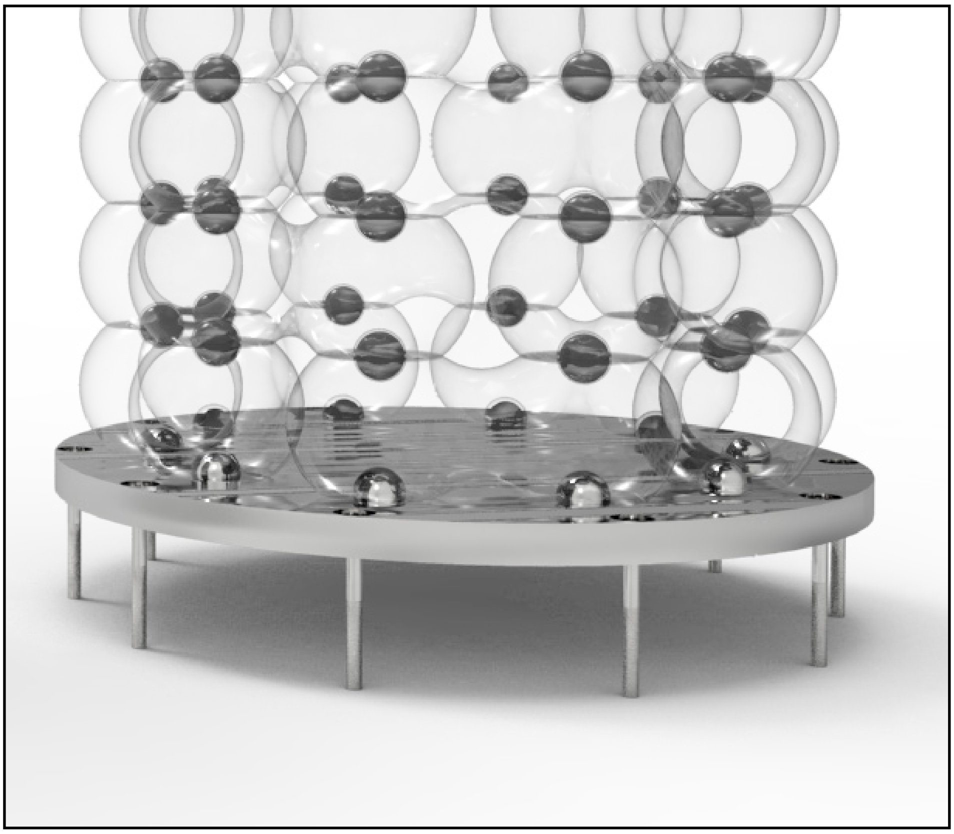


Figure 171. Detail of bottom part of the end-connection

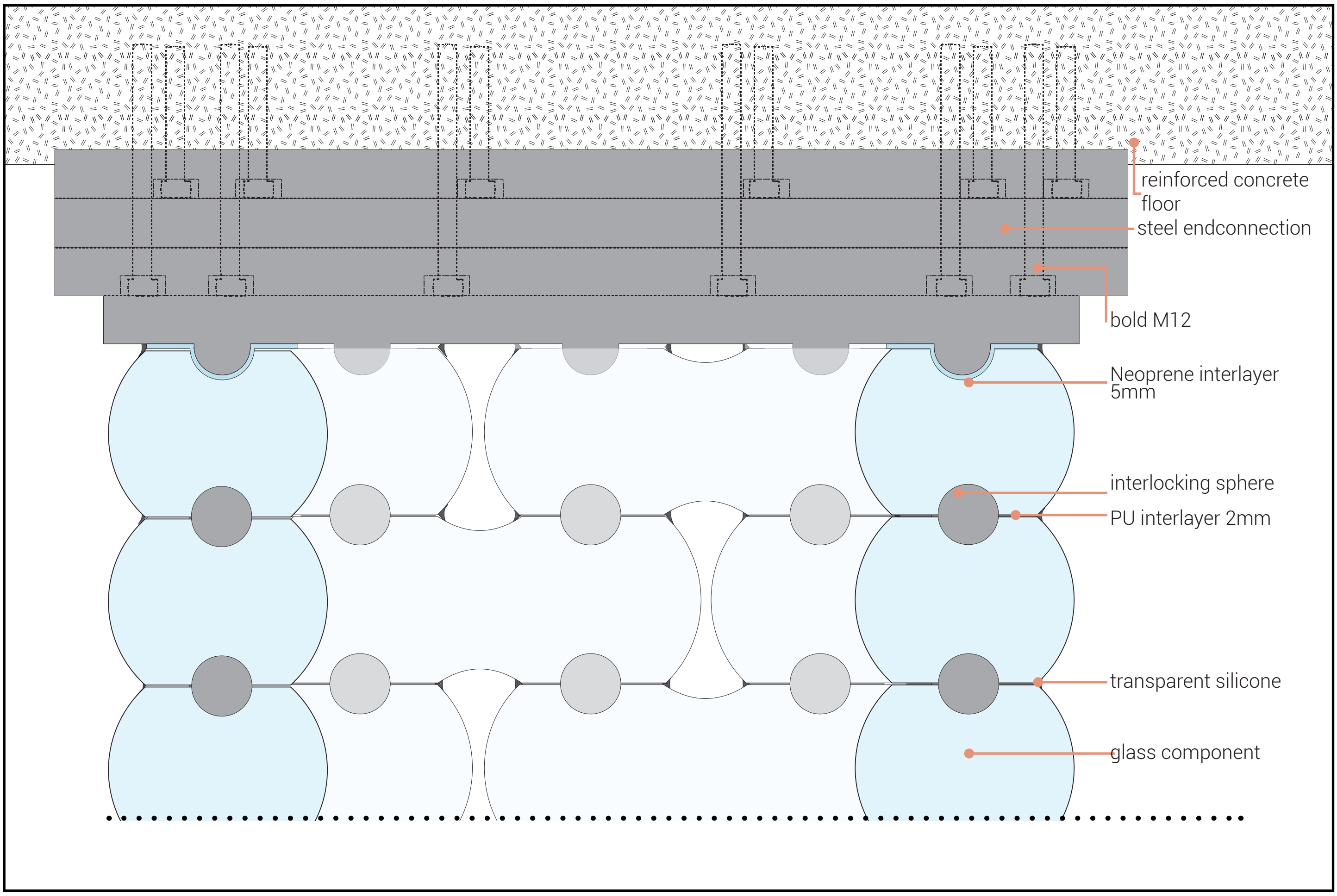


Figure 172. Detail of top part of the end-connection

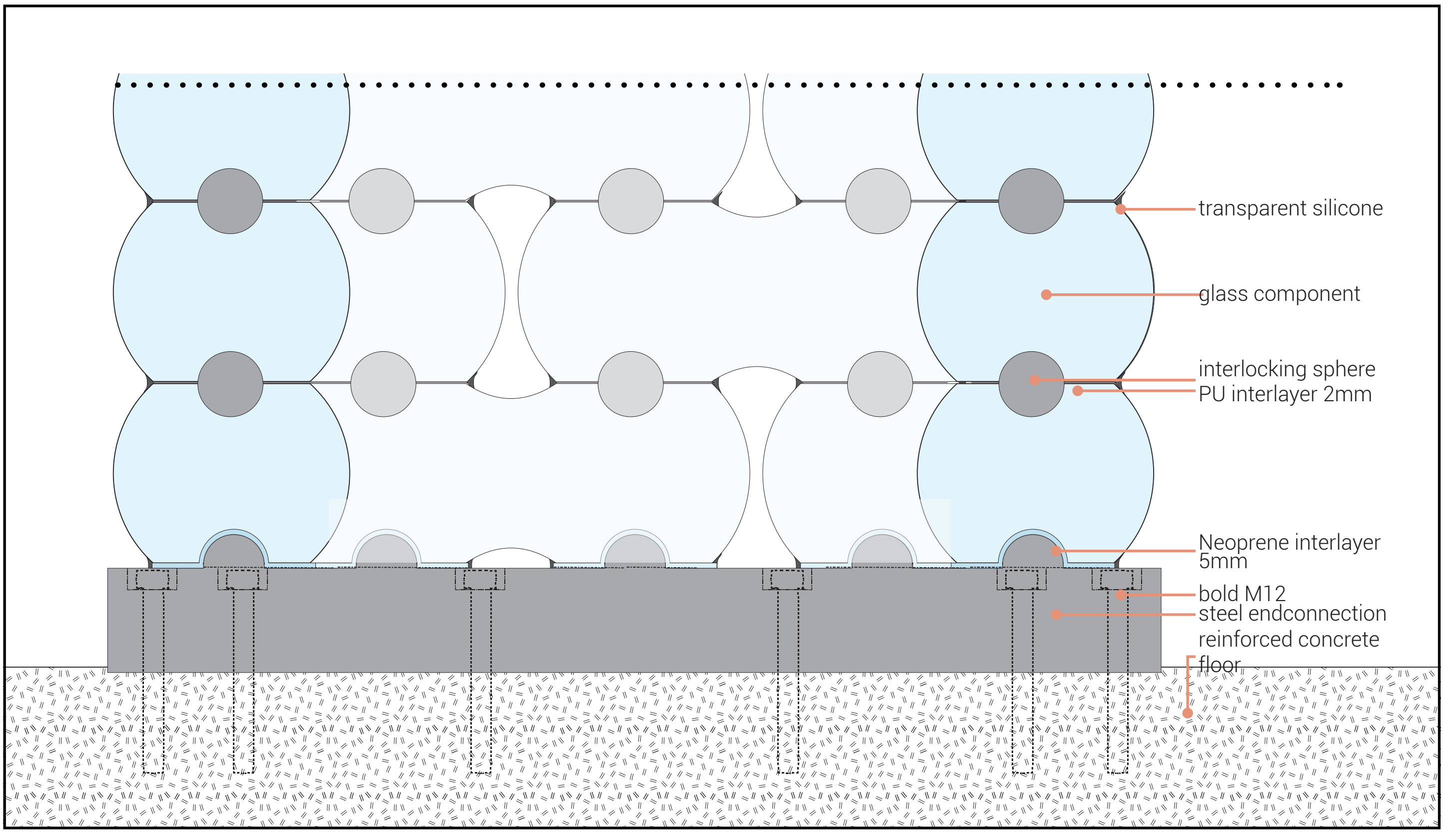


Figure 173. Detail of bottom part of the end-connection

Building sequence

The column design that is made will replace an existing mushroom column made out of reinforces concrete. This one first has to be removed, before the new column can be built up. This is done in a specific sequence:

1.Enclosing the area around the column for safety

2. Placing supporting ajustable jack posts around the existing column, which will take over the applied load on the column.

3.Demolition the existing column

4. The ceiling and floor have to be finished and cleaned

5. The top and bottom part must be fastened to floor and ceiling.

6. The interlayer of the end connection have to be placed

7.Building up the column: glass element + interlayer

8. When reaching the top of the column, an interlayer will be placed that connects the column to the bottom part of the end connection.

9. Another part of the end connection will be sided in between the top and bottom part.

10. This part of the end connection will be fastened to the rest of the column

11. The supporting poled have to be removed

12. The column is finished

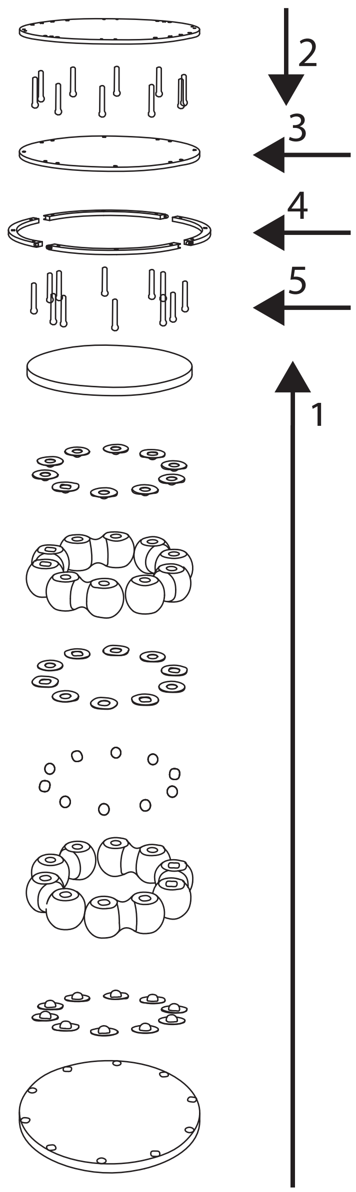


Figure 174. Building sequence

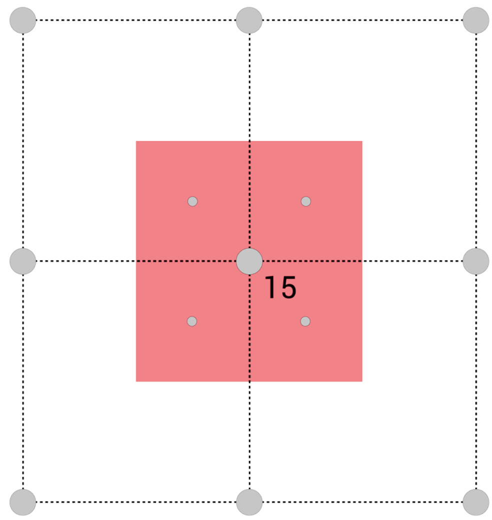


Figure 175. plan of the load bearing area (red) with the column that will be replaced in the middle

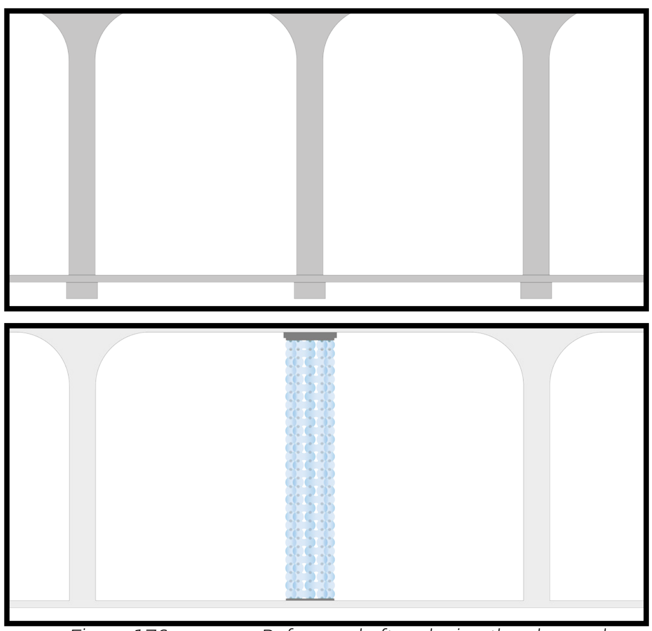


Figure 176. Before and after placing the glass column

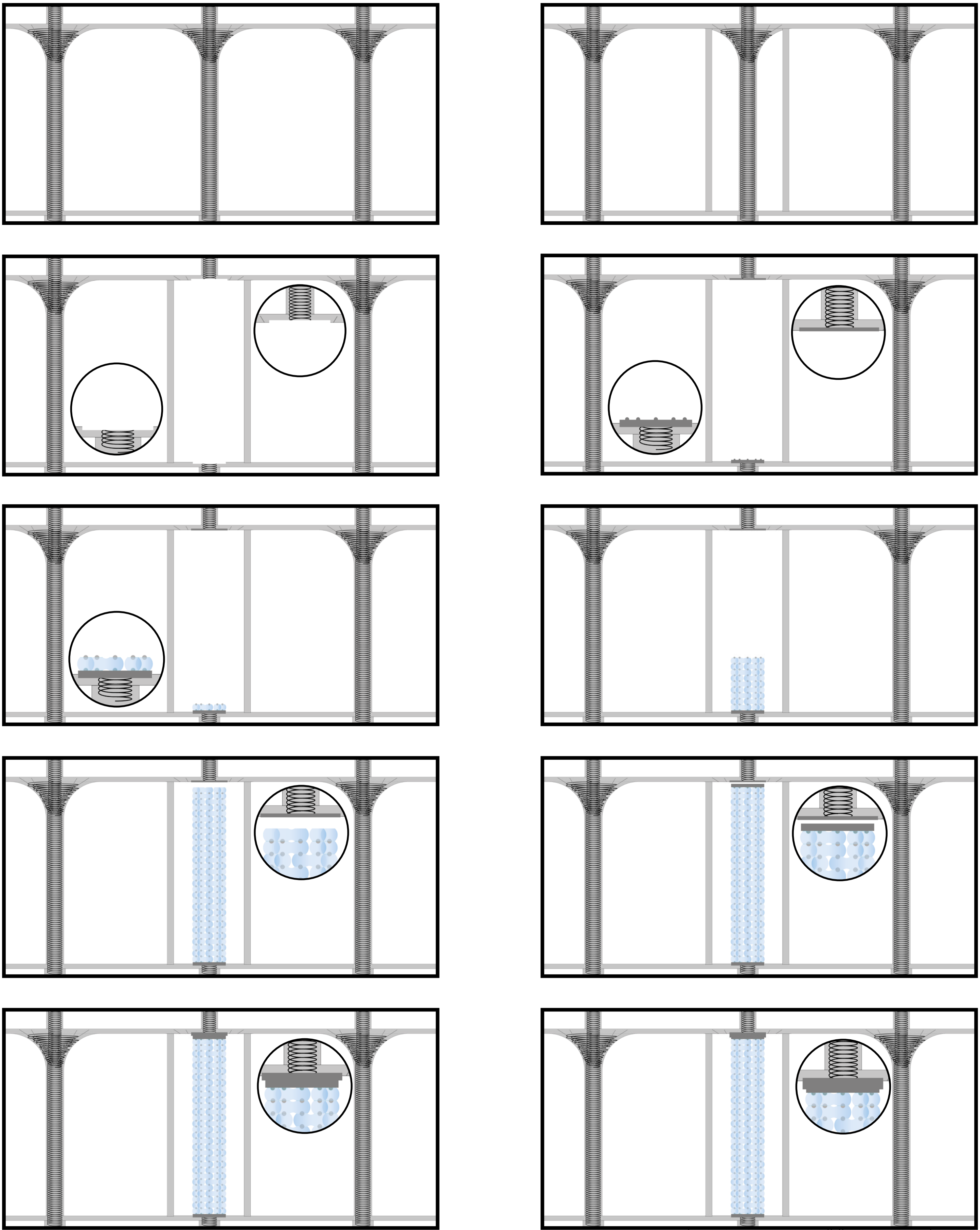


Figure 177. Building sequence in steps

Feasibility

Fabrication of components

As we could see in the chapter of glass production, cast glass elements can be made in different ways: by disposable moulds or permanent moulds.

When glass elements are made for research, disposable moulds are the most common. But when making a mould for commercial purposes where multiple identical parts are needed, permanent moulds made of steel or graphite could be more efficient. These moulds are much more expensive, and therefore a certain number of components need to be made, to break even with the costs of the mould. These moulds do ensure higher accuracy and a smoother finishing. This smooth finishing will only occur when the mould is pre-heated: when it is cold, the glass will immediately freeze to the surface of the mould, which will give a rough and wavy surface. (F. Oikonomopoulou, Bristogianni, et al., 2017)

A good example of the production process of cast glass elements is the way Poesia® makes the bricks of the Crystal House in Amsterdam.
To create a glass component, there are two steel moulds with a high precision: press mould and open mould. The open mould is more labour intensive because with this method, the funnel which was needed during the casting process have to be removed and the surface has to be polished.
When using an open mould, shrinkage will appear during the annealing process of the component. This is why post-processing the glass is necessary. Options for this are CNC cutting or polishing the surface, which increases the manufacturing process a lot. (F. Oikonomopoulou, Bristogianni, et al., 2017)

The bricks of the Crystal house were created with an open mould and were polished manually to create the highest tolerance possible of about 0,25 mm. The Atocha monument-bricks were made with a press mould that could produce approximately 1mm precision. (Göppert & Paech, 2004)

When using a press mould, the level of precision is less high, but the costs will be much lower since post-processing is not necessary. This production method is used to create high precision optical elements like lenses and decorative cast glass. (Barou, 2016)

Because the final shape of the component is made out of spheres with a limited flat surface, using a high precision press mould would be the most logical option. This pressure mould will consist of 2 or more pieces that push the glass together. This method could reach a precision of about 1 mm, which would be enough for this design.

In the column design that would suit the case study, only one component mould would be needed. But after a certain number of casts, also a steel mould would wear out. This number will not be reached when creating a column for the glass palace. But when the concept of these interlocking components would be used somewhere else, other components could be produced as well.

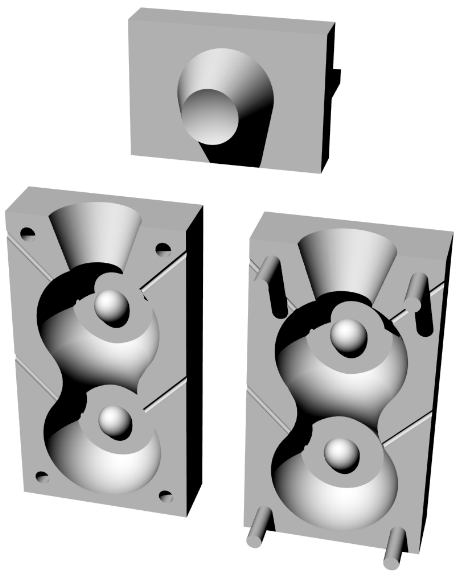


Figure 180. Final mould

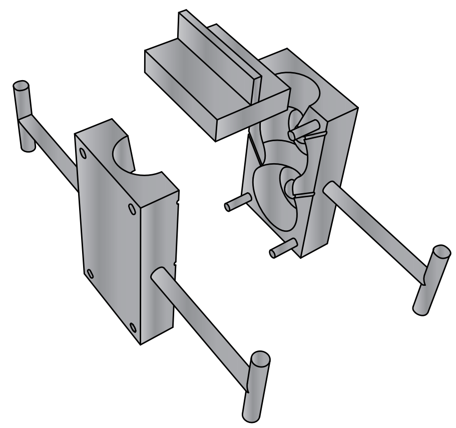


Figure 178. Final mould with handles

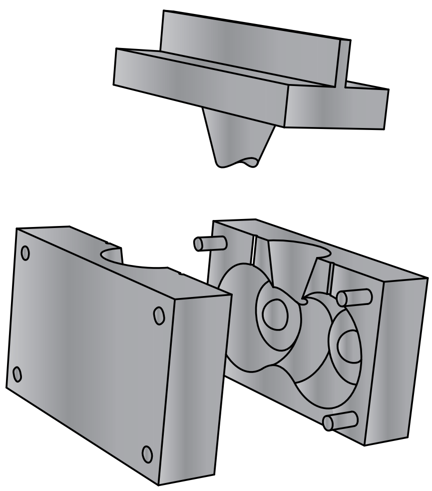


Figure 179. Optional mould

Mould Design

The mould design has been made based on a list of criteria:
- It has to be a press-mould made out of steel
- The interlocking surface has to be as flat and precise as possible
- The weakest part of the component, the neck, should be as strong as possible.

The surface that needs to be as precise as possible should not be interrupted by the seam of the mould. This is why this seam will be on the other side of the component. Considering only this criteria, two designs would be possible; one with the funnel on the top and one with the funnel in the middle.

Due to the last design criteria, the one with the funnel placed in the middle, the neck, of the component will not be possible. The location of the funnel will be the location from which the glass will be cast, which will be more critical.

When the funnel is placed on top of the element, all the molten glass will be able to take its place in the mould due to gravity. The air will be able to escape from the mould by going up into the air holes that are placed on top of both spheres.

Glass production steps

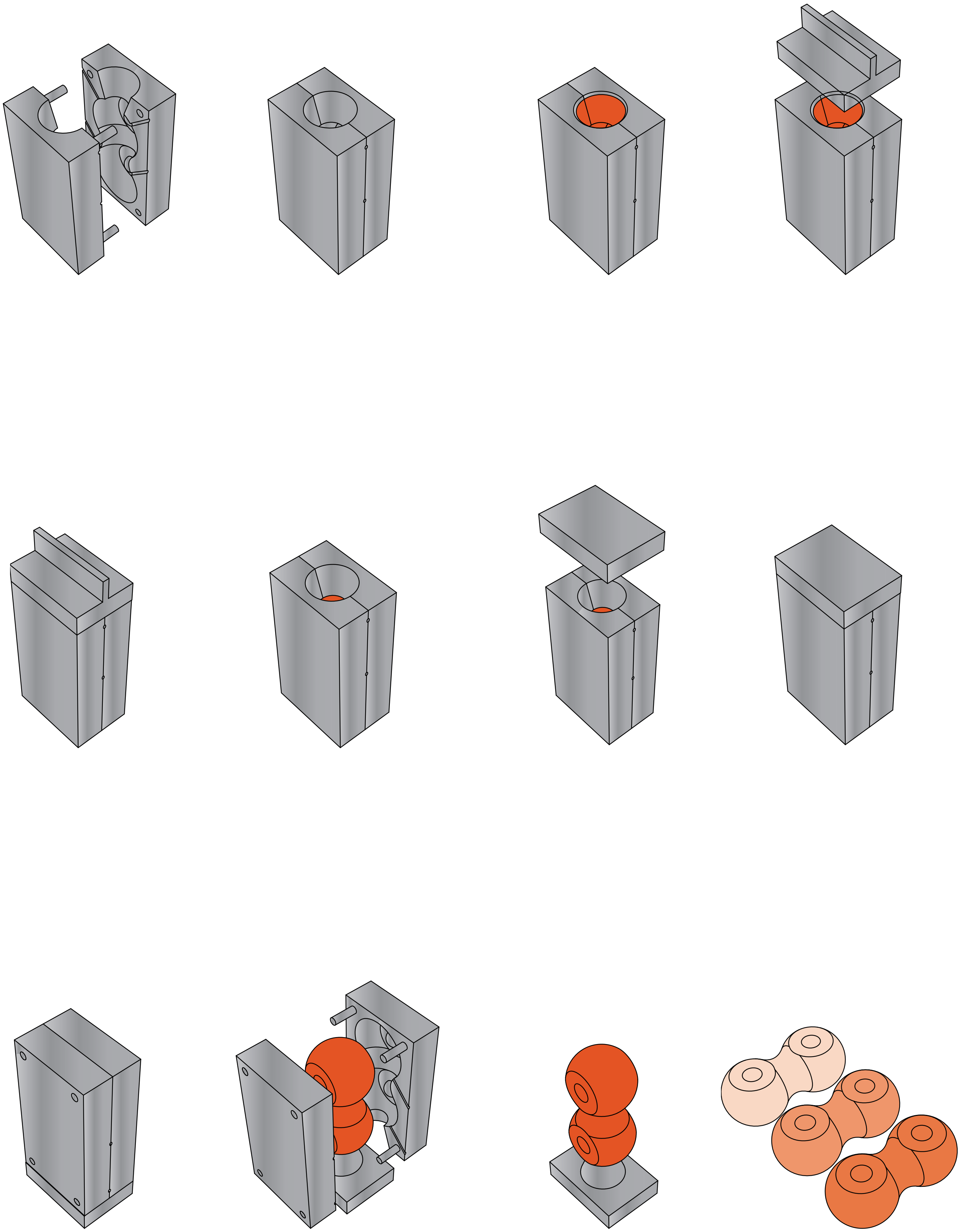


Figure 181. Steps in cast glass production with a pressuremould

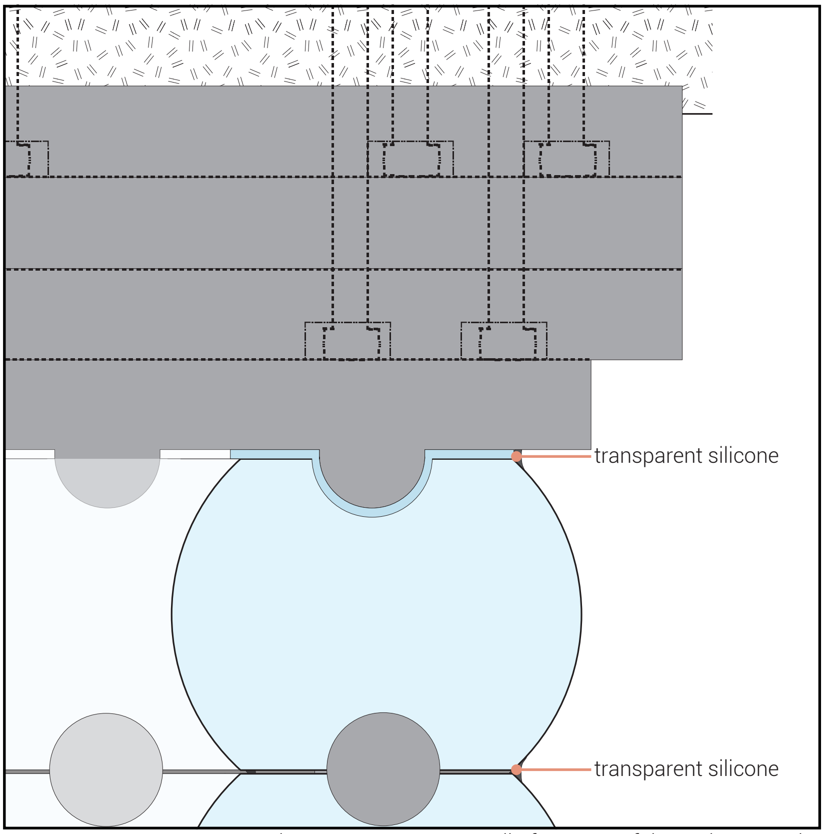


Figure 182. Detail of top part of the end-connection

Maintenance

Cleaning

Glass in an easy material to clean, especially when inside. Still, dust will be everywhere, and there will be grease stains from hands that touch the glass. Due to the shape and the ratio between open and closed, inside the column will be harder to clean. The surface that is lower than 2 meter should be cleaned on a regular basis, to wipe off the grease stains and the dust on the bottom of the column.

To prevent fungus, water and pollution from damaging the surface of the glass components, a hydrophobic coating (Nanoshell) is applied on all the entire surface of the component. At the locations where the interlayer is applied in the structure, a transparent silicone will be applied. When sealing these parts, the uncleanable corners are filled, which will keep the structure clean.

The most significant holes in the structure will have a radius of more than 5 cm, which is enough space for a feather cleaning brush to clean the dust inside the column. Every couple of months, when the windows are wiped, the total column has to be cleaned as well. A scissor lift is needed for this.

Restacking the column

The column is easy to build when all the essential elements are on site. When a glass component needs to be replaced by a new one, the column has to be disassembled and assembled again. Disassembly is a rewind of the assembly, which you could find in a previous chapter.

Quantities

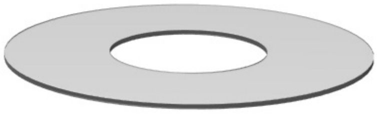
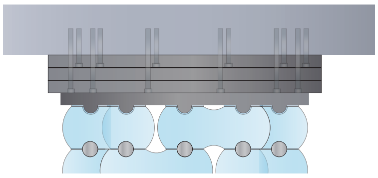
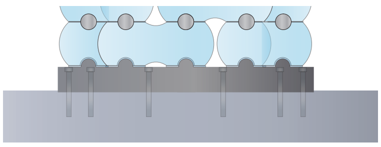
	Glass Column
	150
	280
	280
	20
	1
	1

Table 14. Table of quantities

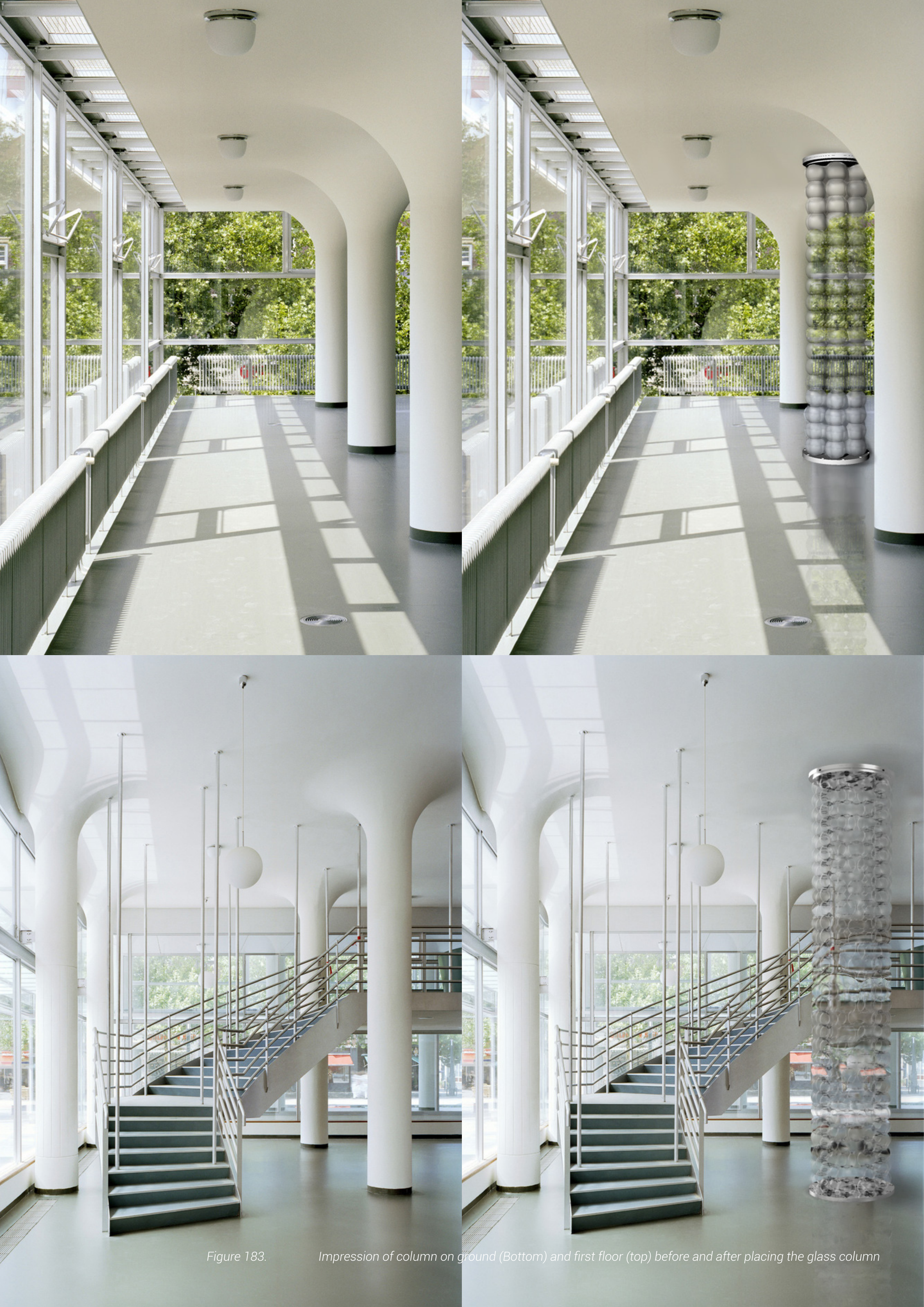


Figure 183. Impression of column on ground (Bottom) and first floor (top) before and after placing the glass column

Conclusions design

From the conclusions of the literature studies, a list of design principles and challenges is made. Due to the case study, the design has its limitations regarding load and dimensions. After looking at what has already been made in cast glass interlocking elements, concept designs were made. All the existing designs and concept designs have been evaluated by glass and annealing shape, redundancy, multifunctionality and planar compressive strength. From the concept-designs, three designs got chosen to research more. These designs were combined into two designs: the robust design and the elegant design. Both of them have a sphere-shaped geometry as the interlocking part of the structure. Because the elegant design would explore the limits of cast glass, this design is more interesting to be researched further. Due to calculations that have been done, considering buckling and redundancy, the design turned out less elegant than was initially imagined. Still, the element has a fascinating appearance. The light that falls on the column will be scattered through the spheres in the component and interlocking in all directions.

The component that is designed could be used in many different configurations. There is also an option to produce an element that is combined with three interlocking parts; these could create many more interesting structures.

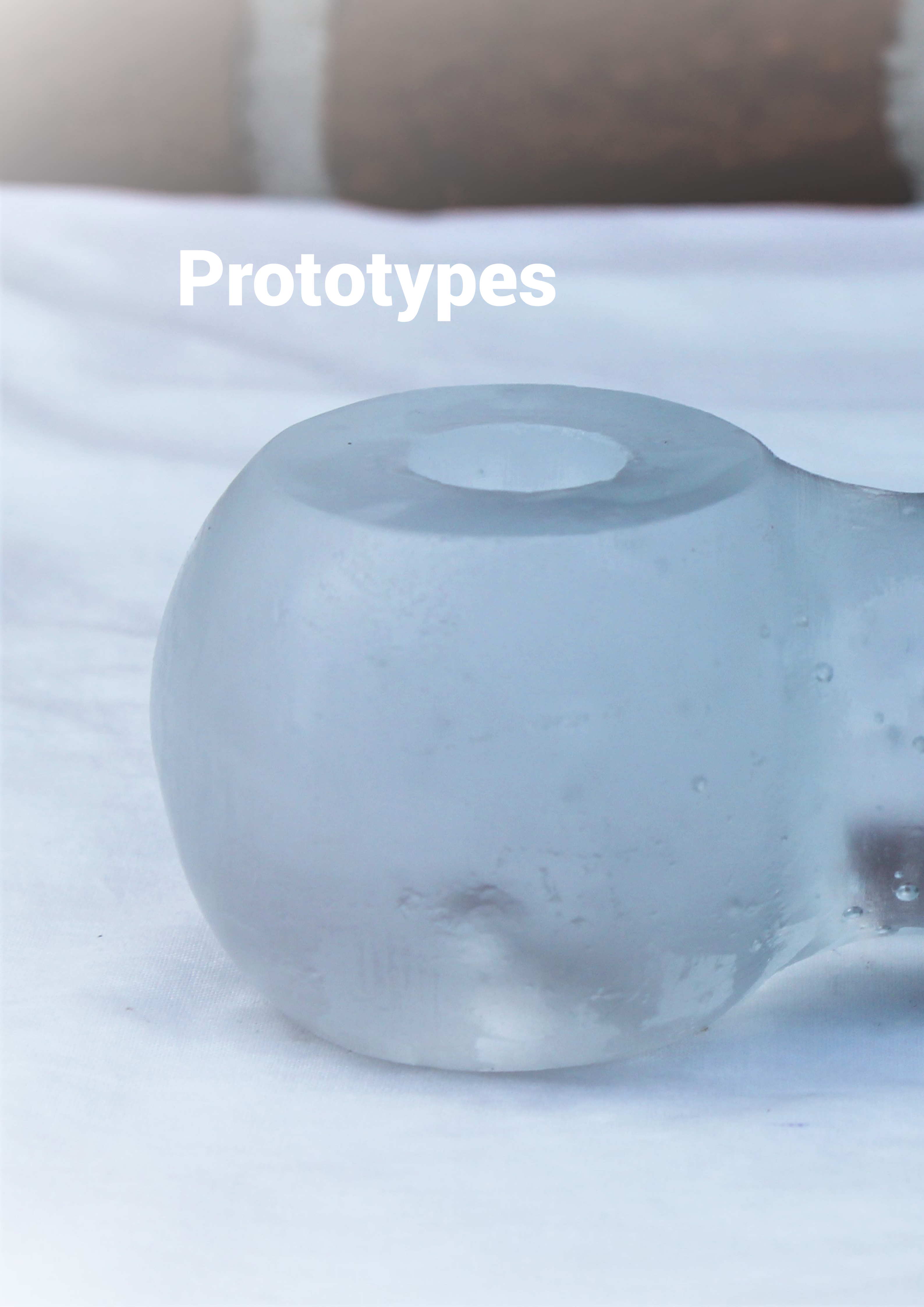
The sphere could be made of various materials. Glass could be used when the interlayer in between the components is also covering the surface of the sphere. Other materials that would not need an interlayer between its surface and the glass surface would also be an option when these are in addition to the aesthetics of the column and can hold the shear forces that could be applied to the component.

The interlayer that is chosen to be used between the components is TPU (ester, aromatic, shore 85, flame retarded). The interlayer is selected on different criteria: transparency, young's modulus, compressive strength, maximum service temperature, durability against UV radiation and flammability. The shape of the interlayer could vary due to the choice of the interlocking sphere. When the sphere is made out of glass an interlayer made by compression moulding is needed. When another material is used for the interlocking sphere, flat interlayer that is cut by pressforming could be used.

To install the column made of glass elements in a building, end-connections are necessary. The bottom end-connection will be attached directly to the floor. The one on the top consists of more pieces, which make it able to lock the column between the two floors. The column can be installed by a particular building sequence. Due to the shape of the components, the components are fabricated with a steel pressure mould. This mould-type makes components that need no post-processing in contrast to the open steel mould.

Cleaning the column will be harder for this column then for columns that are solid. But due to the openings in the surface, it is possible to clean the inside of the column as well. When replacing one of the elements of the column, the column will have to be disassembled and assembled again.

Prototypes



Prototypes

3D model

When the aim is to create a precise component in cast glass, making a 3D model is necessary.
If the design is determined by different variables that could still be modified it is efficient to use a model that is made in Grasshopper. Grasshopper is a visual programming input in the program Rhinoceros. The program could be used for 3D-art, but also parametric modelling, lighting performances and energy consumption. ('Grasshopper - algorithmic modeling for Rhino', n.d.)
When all the parameters are set right, the grasshopper model is finished. To convert the geometry to Rhinoceros, it has to be 'baked' and saved as a Rhinoceros-file.

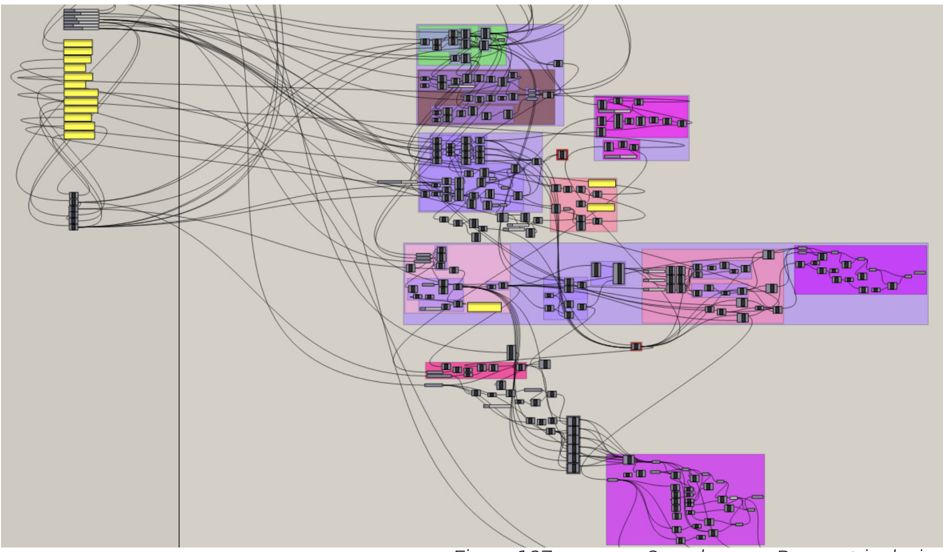


Figure 187. Grasshopper Parametric design

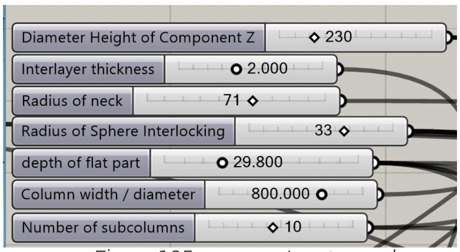


Figure 185. Input grasshopper

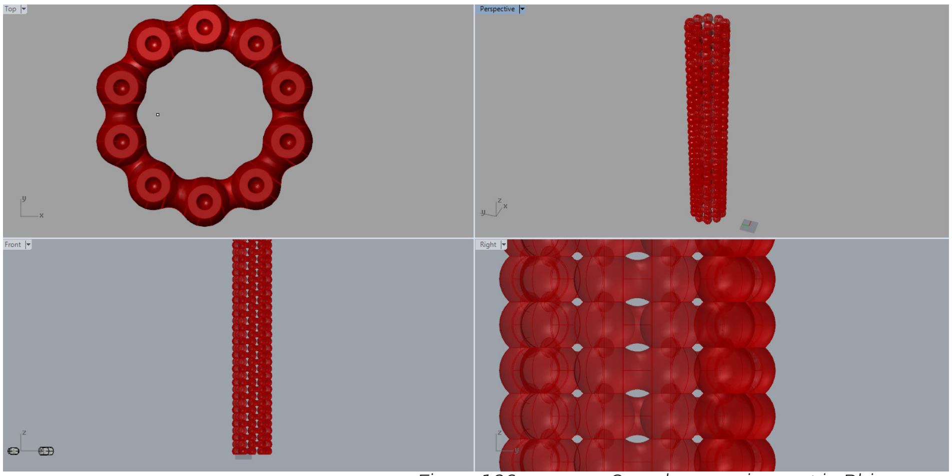


Figure 186. Grasshopper viewport in Rhinoceros

3D Printing

To be sure that the geometry is ready to print, it should be a closed boundary representation (brep). This will be visible in Rhinoceros when asking for the volume of the geometry.

When the material of the component will be poured into a mould, this should be taken into account when making the 3D printed geometry: a funnel should be included in the design. The funnel should be placed at a non-interlocking part of the design. The component and the funnel should be joined as one solid geometry.

The tolerance in the model should be adjusted to the 3D printer and the interlayer that will be in between the components. So when a component is interlocking, the outer interlock should be a bit bigger, and/or the inner layer a bit smaller. When the tolerance of the 3Dprinter is 0,1mm, 0,2mm would be taken into account as a minimum tolerance (without the interlayer).

Next to that, the placement of the component in the 3D printer is critical. The interlocking parts should be in the air and not on the base of the printing surface. This is because there is a chance that the 3D printing plastic is still hot when the next layer is printed, and the geometry will sag down. When the base is made out of the funnel, this is not a problem, but when the base would be the interlocking part, this could be a problem because it could ruin the interlocking effect.

To 3D print the model, the model has to be meshed into small polygons, after which it can be exported to the 3D printer.

The printing time is based on the tolerance of the 3Dprinting and the surface and the volume of the component. When the element has too little support, this support will be made with another type of plastic during the 3D printing. In this case, this support is made out of PVA, which is softer and water-soluble. To have your geometry visible, this PVA-support should be taken off with hot water file and pliers.

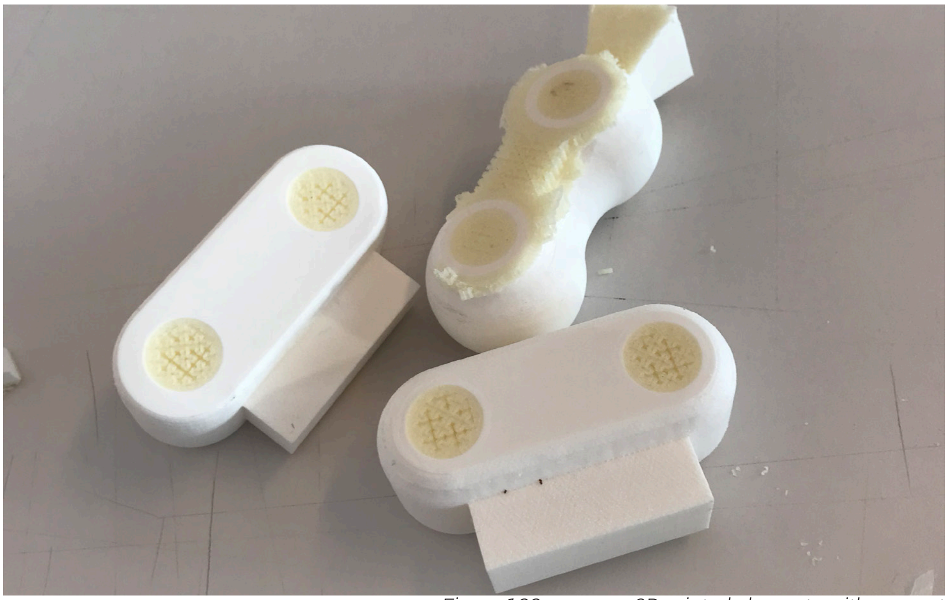


Figure 188. 3D printed elements with support

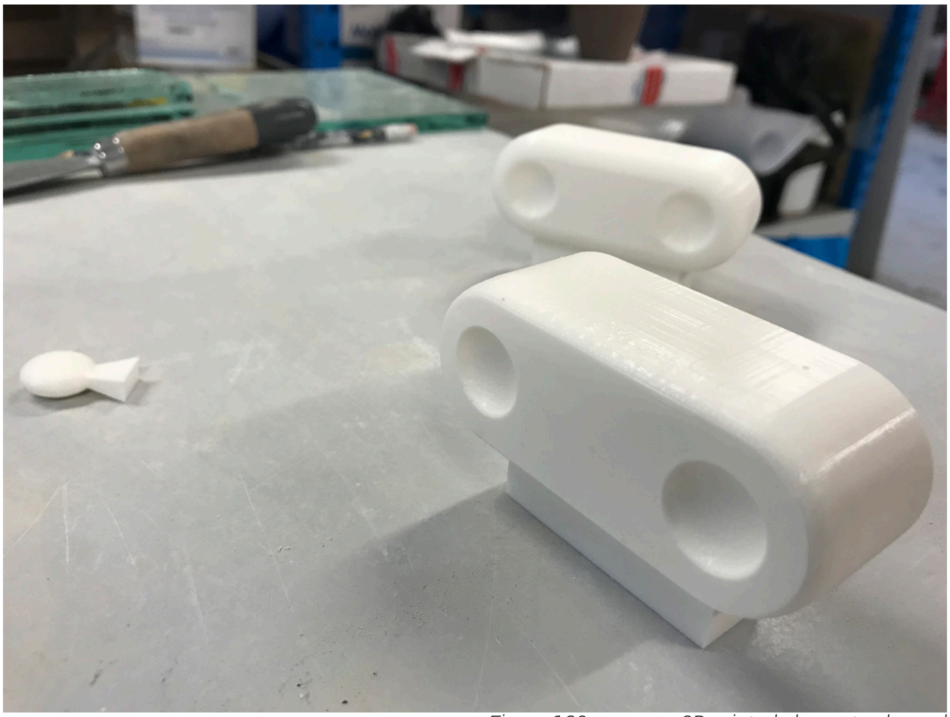


Figure 189. 3D printed elements cleaned

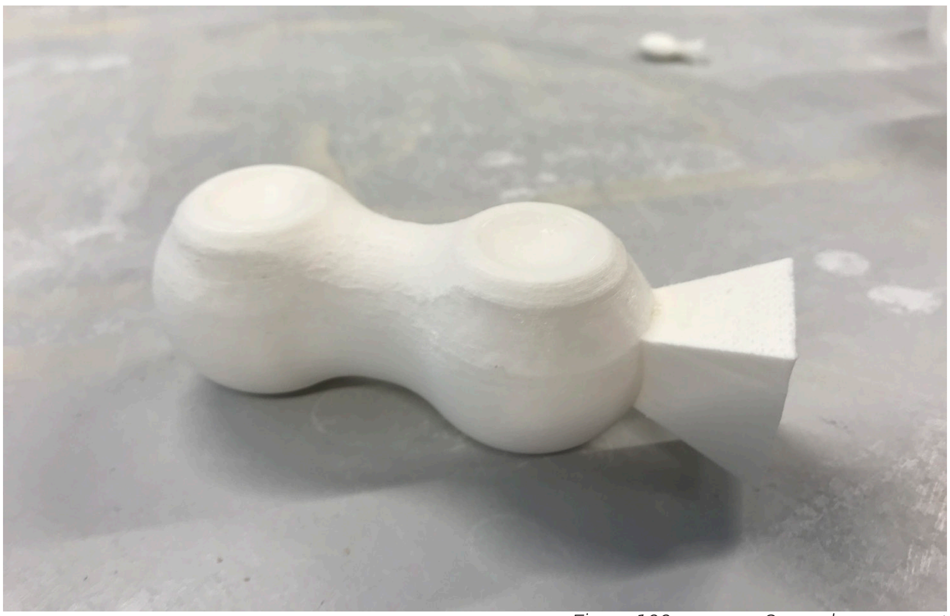


Figure 190. Sagged component

Silicone Mould

Silicone is a material that is heat-resistant and rubberlike. Therefore it is used for sealants, adhesives and as raw material for cooking equipment.

When making a silicone mould of a 3Dprinted component, different actions have to be done before the silicone will be made. First, the 3Dprinted component should be totally smooth. When this is not the case, it should be polished into a smooth surface.

After polishing it should be entirely dust free. Then the element should be placed on a working table, with its funnel in the base. The funnel should be fixed to the table with clay surrounding. The formwork should be made: this could be done with wooden planks that are kept in position with clamps. Make sure the box is placed at a distance of about 2 cm on each side of the component.

The planks and the 3D model should be sprayed with spray (Universal Mold Release) or greased with Vaseline so that it will come out quickly when the silicone is dry. The planks should be sealed with clay all around to prevent the silicone from flowing out.

To make the mixture of the silicone, two parts have to be put together. The pink part has to be 1:10th of the white part. (Mold Max™ Silicones) They have to be stirred together into a smooth mixture. When the mixture is mixed well, it can be poured into the wood around the 3D printed component. When pouring, pour only on one side and let the silicone flow to the other side to minimise the number of bubbles in the silicone. When the silicone is fully poured, bang on the table to help the remaining bubbles to come up. And meanwhile keep an eye on the clay edges, if the silicone is not pouring out. After 16 hours of sitting, the silicone could be taken out of its formwork. Take the casing off and cut the silicone that leaked out of the mould with a Stanley knife. Wash the silicone moulds and make them dirt free with the high-pressure air blower.

Figure 191. Multiple images of silicone moulds

Figure 192. Multiple images of silicone moulds

Ice

Why?

The design that has been made is based on the properties of glass. But testing glass is time-consuming and expensive. This is why it would be useful to find other ways to predict the behaviour of glass. This could be done by testing the same component in a material that breaks the same way as glass. Ice is this type of material. (van Ellen, 2018)

Issues

When predicting the behaviour of glass with ice, the ice has to be crystal clear. But creating clear ice components isn't as easy as it seems. When putting tap water in silicone moulds and putting them in the fridge will give very cloudy and cracked results. This is due to different problems that occur; the molecules of the water and the fast-changing temperature.

The tap water consists of air and other molecules than only water and. This is why the air is still inside the water when it freezes. These air bubbles will give an unclear view. The other molecules provide a white rash inside the ice. To solve the molecule and air problem, distilled or (double) boiled water could be used. Other sources tell that the difference will not be made with distilled water, because good filtered water should be below 30 parts per million total dissolved solids, and the effects of those impurities being squeezed out are very minimal. ('EPIA Mythbusters – water impurities don't give you cloudy ice | EPIA | European Packaged Ice Association', n.d.)

A bigger source of disturbance in the clarity of the ice will be the fast way it is frozen. When freezing a component very fast, the outside will freeze first, and after this, the inside will freeze. But because the water (ice) expands when it freezes, it will give cracks on the inside of the ice-component. This problem could be solved by either cooling the component down more gradually. This would be in a specific type of cooling system that would could down a certain number of degrees Celsius in a certain amount of time. Another way to mimic this would be to put the elements in a coolbox inside the freezer. This way the insulating layer will slow down the cooling of the element. Certain youtube videos also explain the idea of cooling down from top to bottom by leaving the coolbox open with an option of making a hole in the bottom of the silicone mould. This way the air bubbles will only be in the bottom (possibly outside) the component and the temperature would decrease more gradually.

Conclusion

My finding in testing this is that using boiled or distilled water makes no difference in the way the ice cubes turn out. The idea of using a coolbox to reduce the speed of the decreasing temperature did not help in my case; with a closed coolbox, it took over 24 hours to cool down a small element. And with an open coolbox, the element cooled down just as fast as it did without a coolbox. This also gave the same effect in cloudiness and cracks inside the component.
The option was not there to use a freezer that can decrease a certain number of degrees Celsius in a certain amount of time. This could be worked on for further research.

Due to the limitations that were faced, the crystal clear ice could not be produced. This is why another solution has to be searched for.

Figure 193. Rusult of an open silicone mould without ducktape

Figure 194. Multiple images of Ice components

Sugar Glass

Why?

As we saw in the previous chapter, it is useful to know how a glass component breaks by testing it in another material that breaks the same way.

Sugar glass, also known as breakaway glass, is a material that could simulate glass very well. It could break the same way and has a similar weight as real glass, but is less likely to cause injuries and has cheaper materials and production method than real glass. Therefore it is used in movies, photographs and plays. (Provost, Colabroy, Kelly, Wallert, & Wallert, 2016)

To know if sugar glass breaks the same way as real glass, it could be made and later tested.

Recipe

You need the right ingredients, cooking equipment and a cooking spit. The following ingredients should be put together:

- 3½ cups (790 grams) white, granulated sugar
- 2 cups (475 millilitres) water
- 1 cup (240 millilitres) light corn syrup
- ¼ teaspoon cream of tartar

All these ingredients should be stirred together in a pan. Then the mixture should be gradually heated on low fire. The mixture should be mixed in the pan until it becomes sticky at about 150 degrees Celsius, its 'hard crack' phase. When a thermometer is absent, this could be tested with a drinking glass that is filled with cold water. When a drop of the mixture solidifies directly in the water, it is ready; when it resolves in the water, it has to be heated for a bit longer.

If the sugar glass is ready, it can be poured into the silicone mould. Make sure the mould is hot before you pour in the sugar glass, this will prevent bubbles on the surface of the component. This could be done by preheating the mould with a hairdryer. Just like the making of the silicone mould, pour the sugar glass at one place inside the mould. This could also help to prevent air going into the component. Put the component in the freezer for 3-5 hours, or in the fridge for more than 8 hours. After this, you can take the component out of its element, and it is solid.


Figure 195. Left; testing method for the hard-crack temperature of sugar glass, richt: difference in length of cooking the sugar glass

Figure 196. *Boiling sugar glass and silicone moulds with sugar glass*

Issues
There are different problems with the sugar glass that could occur; these will be explained below. (Dries, 2000)

Wrong (quantity) of ingredients
The wrong ingredient or ingredients with wrong ratios to each other will lead to an incorrect mixture of ingredients; which could lead to a failing material. In the ingredients is written that cream of tartar is needed for the sugar glass, but this is very hard to find. Baking soda is used instead of cream of tartar.

Temperature too low or too high
Before heating, the mixture will be totally transparent. This mixture will later turn white, then yellow and then more and darker while boiling. There is an optimal temperature of the glass at 150 degrees Celcius. But if it heats up 5 degrees more, the mixture will become black. When boiling the mixture fast (about 1 hour), the mixture will always be a bit more caramelised then when the task is done in about 3 hours. It did become clear after making some components, that the darker the glass is, the less sticky it tends to become. When the mixture is put in the mould when the mixture has not reached the right temperature, the component will never fully harden.

Conserving too long
When a sugar glass components are conserved for too long, the humidity and temperature of the air could ruin the brittle quality of the sugar glass. This is why it should be consumed or broken not too long after the production of the sugar glass. When it has to be conserved, it has to be done at a cool but non-humid place; which is hard to find.

Cooling too short or too long
When the product is inside the mould, it should be cooled in the freezer or fridge. When this is not the case, they could turn out more sticky then they should. But when the component is in the freezer for too long, the component will experience a thermal shock, which makes it crack when it is taken out of the freezer. When the component is taken out of the silicone before it has hardened completely, the dry in another shape, then it should.

Conclusion
When the recipe is carefully followed, making sugar glass is possible. When only having one mould, and the sugar glass is made manually and tested at the same time, the different components will always differ a bit from each other in conserving-time, cooking time, the quantity of ingredients and cooling time.

Despite this, sugar glass has enough similarities to real glass which makes it valuable to test the behaviour of sugar glass with a pressure machine.

Figure 197. Pictures taken of component 1 at 10th (top) and the 14th of May (bottom). It is visible that the surface of the sugar glass has changed.

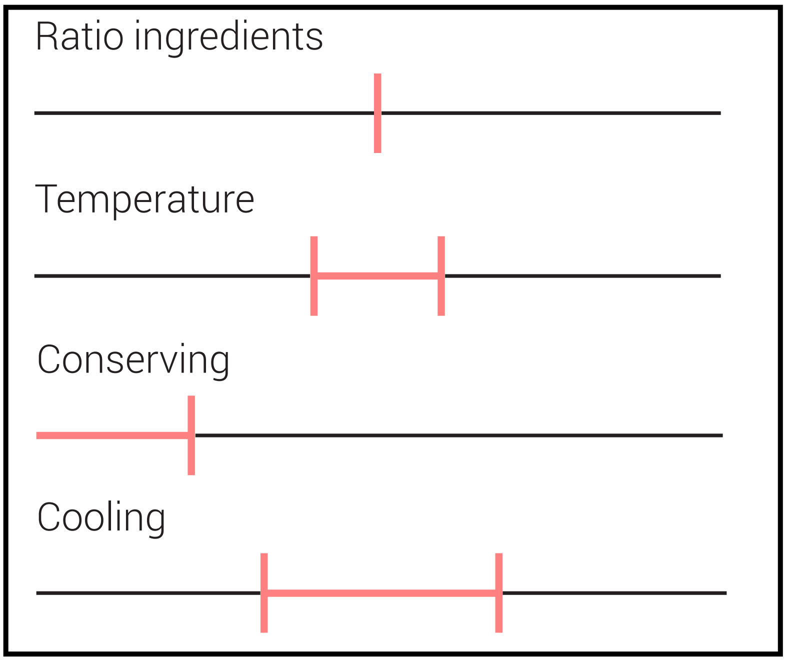


Figure 198. Variables that could lead to different breing behaviour of sugar glass

Figure 199. Top: all the components that will be used in the test, underneath; broken (thermal shock) en deformed components

Soda-lime glass

Wax models

From the silicone that has been made, three wax models were created. Was is a soft material that will become liquid when heated. This way, a hard mould can be cast around, and the wax will be removed by steaming. The wax will be heated to 70C after which the wax will be poured in the funnel of the silicone mould. After 5 hours, the mould can be removed from the wax model. The three wax models all showed bubbles on top of the spheres, where the air was trapped in the mould. These bubbles were covered with soft red wax that is used as a wrapping of Edam cheese of the brand Babybel. In the mould shrinkage was visible at the funnel, two of the wax models had to be filled up with extra wax, because of the hole that appeared in the middle of the funnel and top of the component.

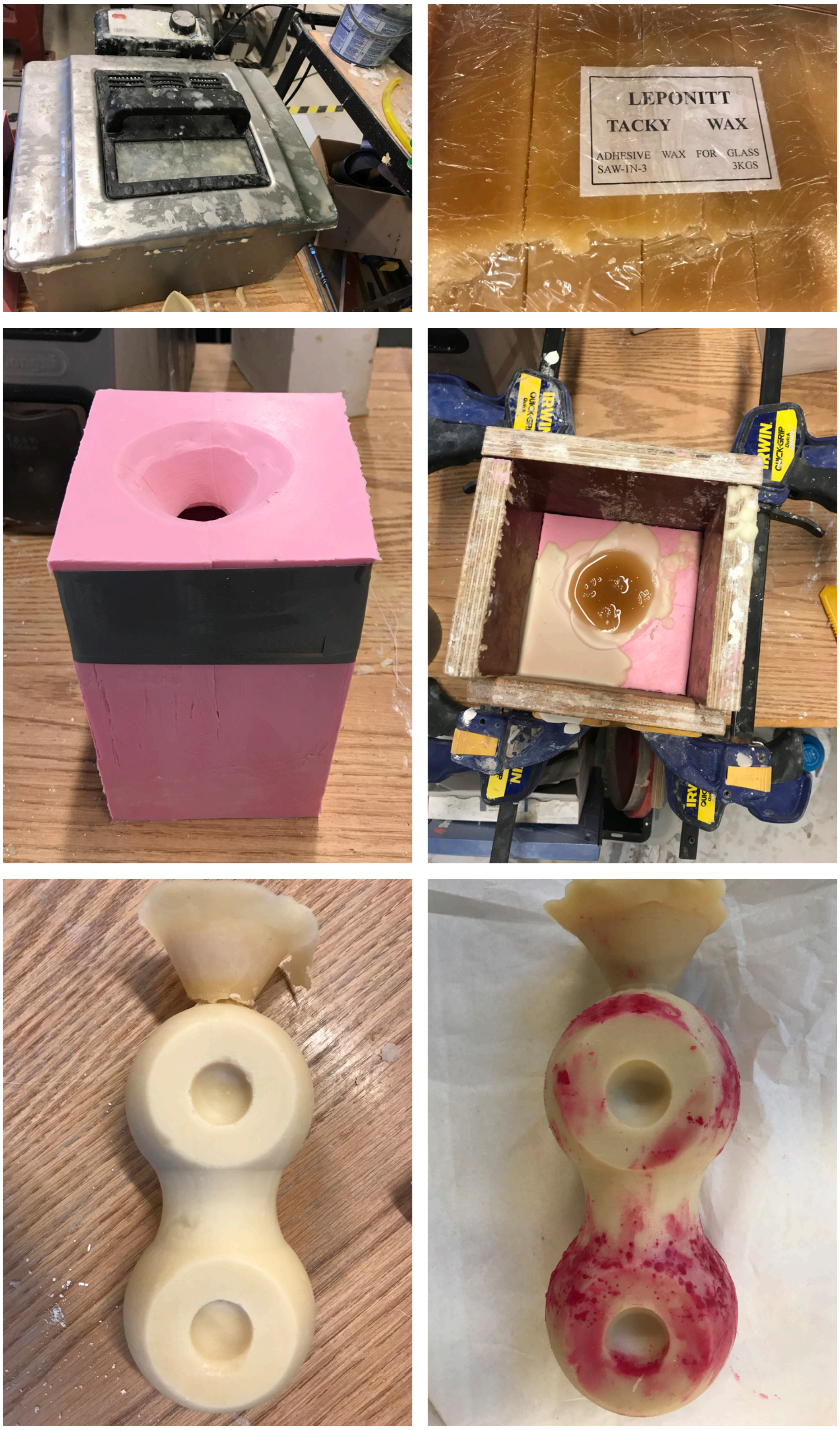


Figure 200. Production steps wax nodels

Crystal cast mould

When the wax model is ready and smooth, the production of the crystal cast mould can start. The three wax models will be the positives of the crystal cast moulds. Crystal cast is made out of the powder "Crystal Cast M248" which is bonded together with water. This soft material can withstand temperatures up to 900 degrees. For the crystal cast two different kinds of mould were made; one without air funnels (a) and one with air funnels(b).

Producing crystal cast mould is a similar process to producing the silicone moulds from the 3D printed model. The wax model with its funnel on the bottom has to be fixed to the table with clay. After this, if applicable, air funnels made out of wax rods will be attached with wax to the model and with clay to the table. Then, bounding boxes will be made at least 2cm around the model, after which the box is sealed with clay. After this, the crystal cast material will be made with 2,75 ml crystal cast powder to 1 ml water. After stirring the mixture, it will be poured from one side into the wooden box. After 1 hour, the crystal cast has set, and the bounding box can be removed.

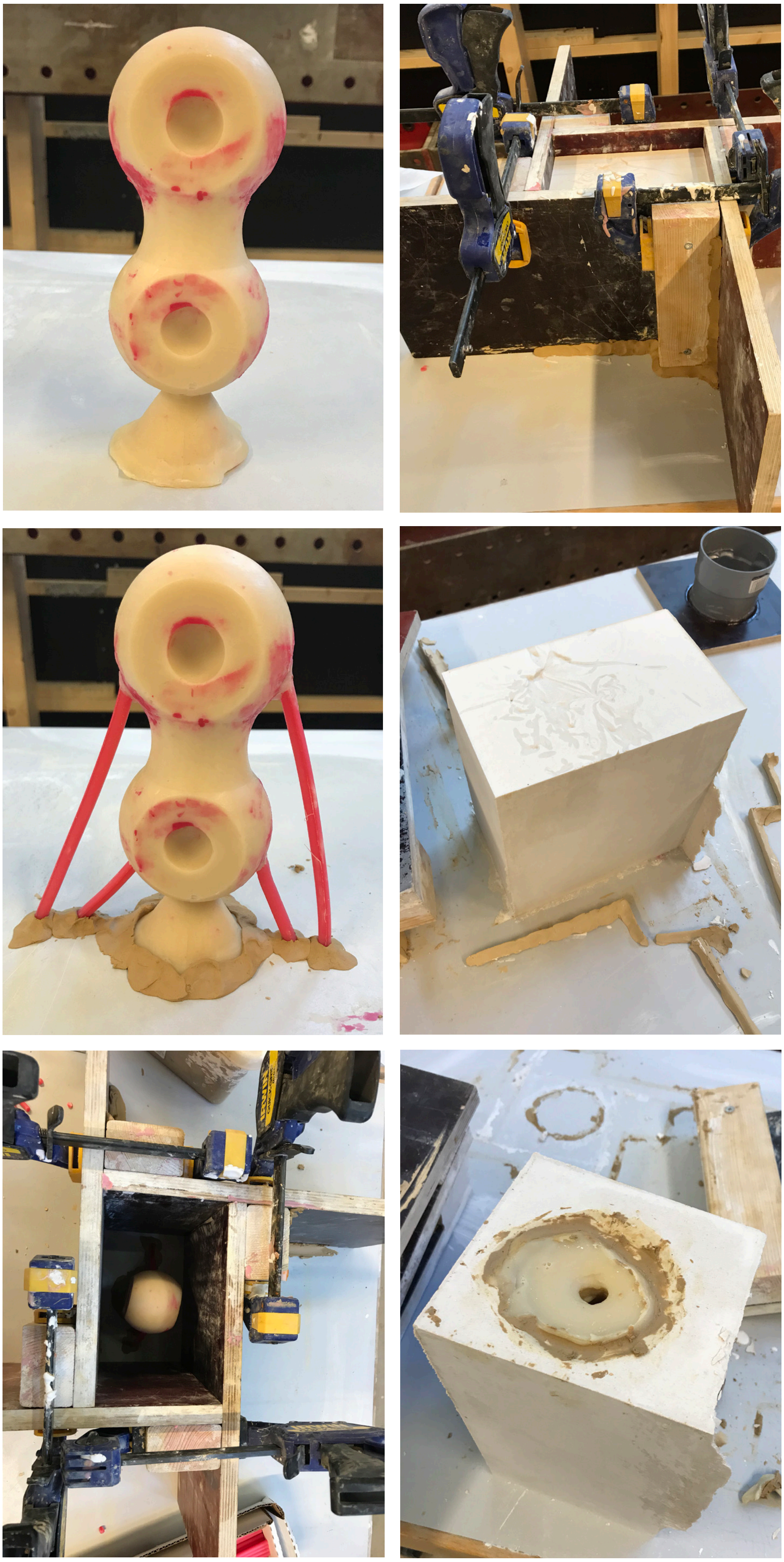


Figure 201. Production steps crystal cast

Steaming & Cleaning

When the crystal cast has solidified, the wax and clay should be removed from the crystal cast. First, the clay that is visible on top of the mould should be removed. After this, the mould should be put with the funnel down into a closed box filled with a layer of water with a steamer. This way, the wax can seep out, when the mould gets hot and humid. When the moulds were unwaxed, the moulds were taken out of the steaming-box. Finally, the last pieces of clay were taken off the mould, and the moulds were cleaned with water.

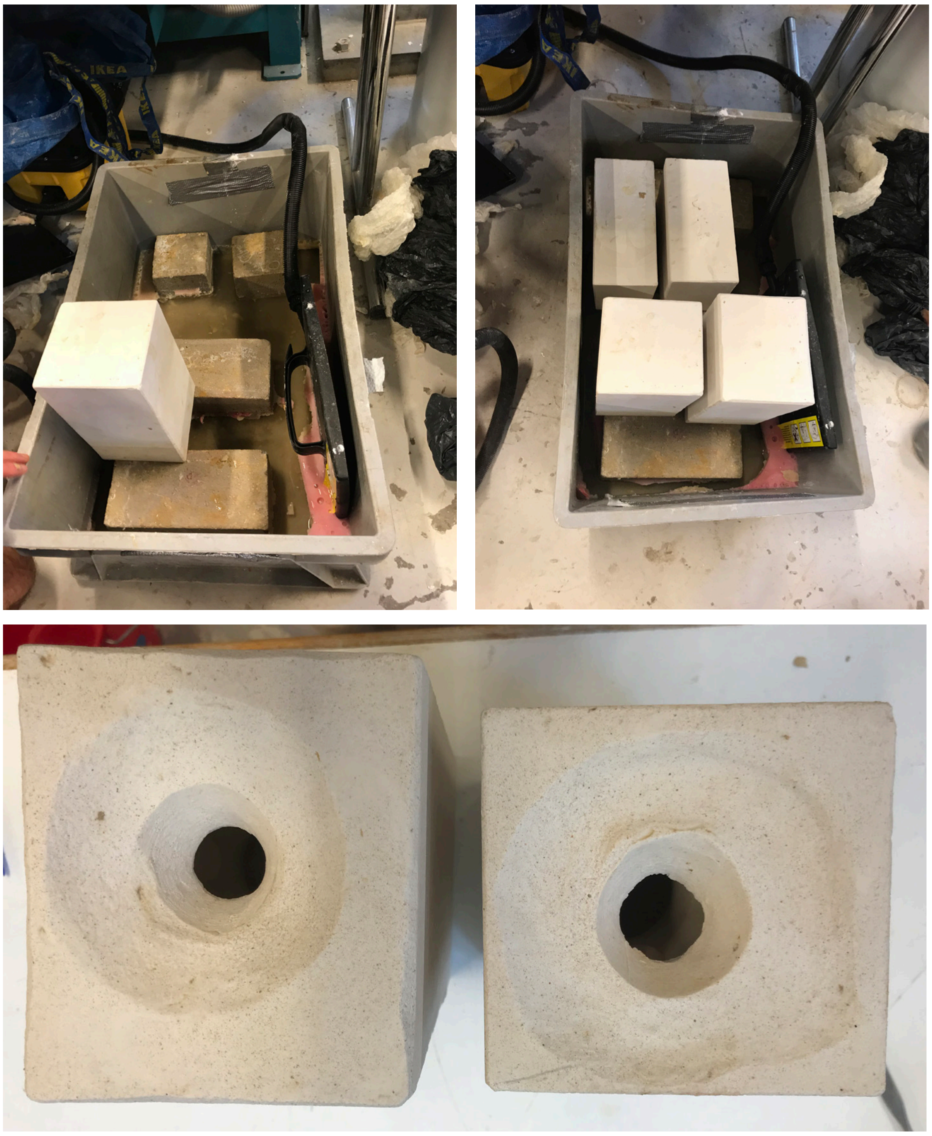


*Figure 202.		Steaming (top) and cleaned elements (bottom)*

*Figure 203.		Crystal cast after casting (left), crystal cast after steaming, crystal cast after cleaning (right)*

Flowerpot Treatment

Next to the mould, also the flowerpots, from which the glass will be dripped into the moulds have to be clean. These flowerpots are made of terracotta and have to big enough to fit in all the glass that is needed to fill the crystal cast moulds. To clean flowerpots, first, the uneven parts have to be sand off to prevent broken part going into the molten glass. After this, the flower pots are cleaned with water and dried with paper.

Figure 204. Cleaning and drying flowerpots

Glass Volume

When using the flower pot method, the exact volume of the glass should be put into the flowerpot. This can be calculated in different ways: checking the volume of the 3D model, or, more precise, measuring the volume from the produced crystal cast mould. This measurement will be done by putting the dry crystal cast on the scale that is zeroed, after which water will be added until the mould is full. This weight is the amount of mL water that fits into the mould. This volume (including funnels) will be multiplied by the mass density of the glass that is used, which is 2,55gr/cm3. On this weight, 4% of the total weight should be added to take in account the residual glass in the flowerpot.

The glass-type that is used for the prototypes is the soda-lime glass B270, by SCHOTT. This glass comes into broken lenses of about 6 cm wide. The precise weight of the clean glass should be measured for each mould. After which these weights should be put into the three separate flowerpots.

Figure 205. Weighting the glass by addingthe volume of the water

	Weight *(g)*	Volume *(L)*	Weight glass *(L*2550 g/L)*	Weight +4% *(g)*	Weight component polished *(g)*
1	*446*	*0,446*	*1137,3*	*1182,792*	*992,04*
2	*443*	*0,443*	*1129,65*	*1174,836*	*993,08*
3	*445*	*0,445*	*1134,75*	*1180,14*	*935,39*

Firing

The glass was put in the oven at 13/06. The moulds are placed on the bottom of the oven with spacers and flower pots on top of them, right above the funnels of the crystal cast moulds. The three models have been produced during one firing.
Due to the other components that were placed in the oven that were made out of a different composition of glass, the oven had a longer annealing time then was needed for the components and glass. This is why the components only has little stresses when looking at it with a polorized sheet.

Figure 206. Putting the crystal cast into the oven

Figure 208. Picture of flowerport after firing

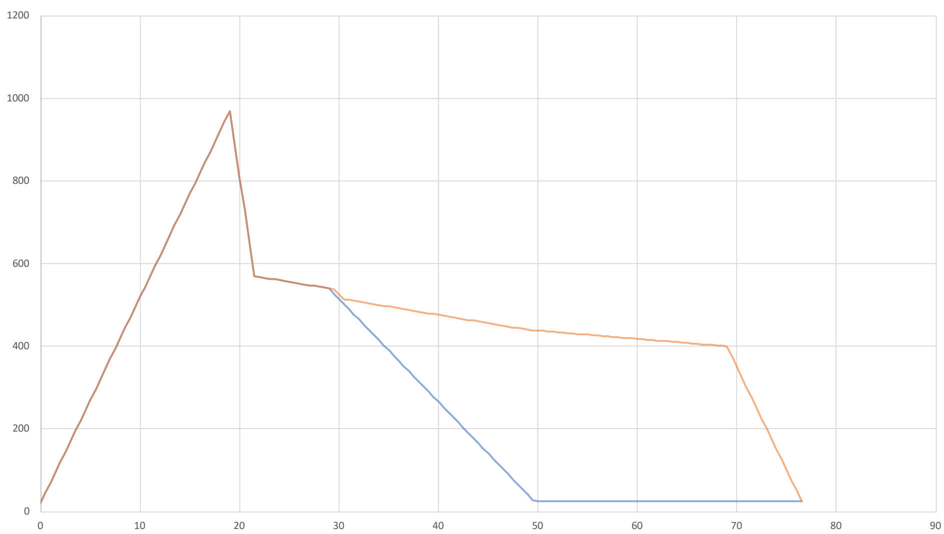


Figure 207. Diagram of firing schedule. Blue: the minimal annealing time for this glasstype and component. Orange: the annealing time the ove n took, for the other components that were inside the oven.

Post-Processing

When the kiln reached room temperature, the moulds were taken out. After this, the moulds should be released from the glass components. After which the post-processing of the glass starts.
The moulds will release when they are exposed to water for about 20 minutes.

The first part that needs to be post-processed is the funnel on the components. This will be removed with a saw and water. After this, the surface around will be polished in a spherical surface on top of the component.

Due to the manual production process, there are small imperfections in the components. This is visible regarding bubbles, stresses and the surface. These imperfections on the surface could be processed by sanding and polishing the surface by a dental tool. This dental tool has sex different polishing disks. Water was used to cool down the surface of the glass during the sanding and polishing, which prevented cracks from occurring during this process.

Figure 209. Sanding and polishing the components

Residual stresses

To see where the stress in the glass is located and spread, a polarised film can be used. When a polarised film is placed in front of the glass component with a white polarised light source in the back, the residual stresses in the component become visible. The pictures are shown in the next pages.
Due to the long annealing time of the glass, the glass only shows little stresses compared to other components, using the same palarized sheet.

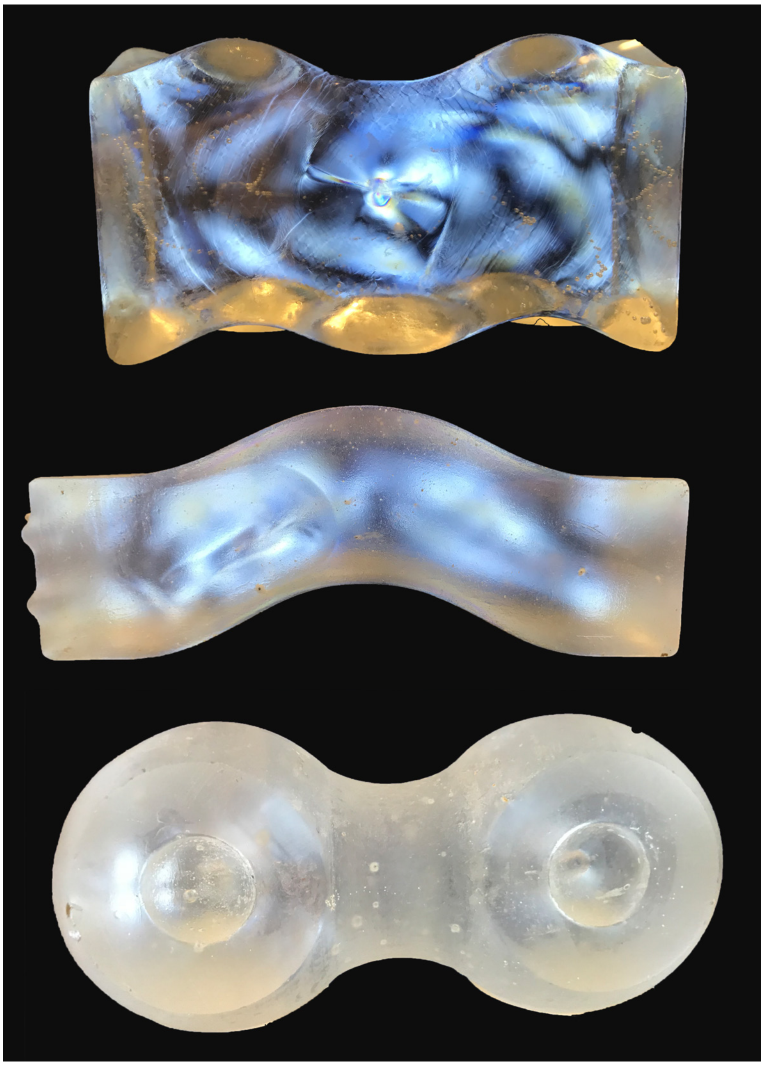


Figure 210. Stresses in the opper two components are much bigger then the lower one, due to the long annealing time and glass-like shape

Conclusions

From the pictures on the previous pages, different conclusions can be drawn.

firing
The components came out very well but did have some imperfections. Those differed per component. Component one showed shrinkage in the bottom of the element. Component had this shrinkage as well as some broken off flowerpot powder in the bottom and the funnel. The third component has no shrinkage at the bottom of the component. But does show shrinkage in the interlocking hollowed out spheres.
This means that the air funnels were not able to prevent the shrinkage of the element completely, it only shifted it to another part of the component.

There were only small air-bubbles inside the elements. There was no gradual difference in the number of bubbles between the different components.

The components were cooled down very slow, due to the other element that was made out of other glass types that needed this slow cooling. This resulted in components with only little residual stresses. The second component does show some lines inside the polarised sheets; it could be possible these occurred with the powder of the flower-pots.

The components were sanded and polished to a level at which the surface is matt, like milk glass. When the glass is wet, it is as transparent as it could be. Pictures show that the glass is translucent.

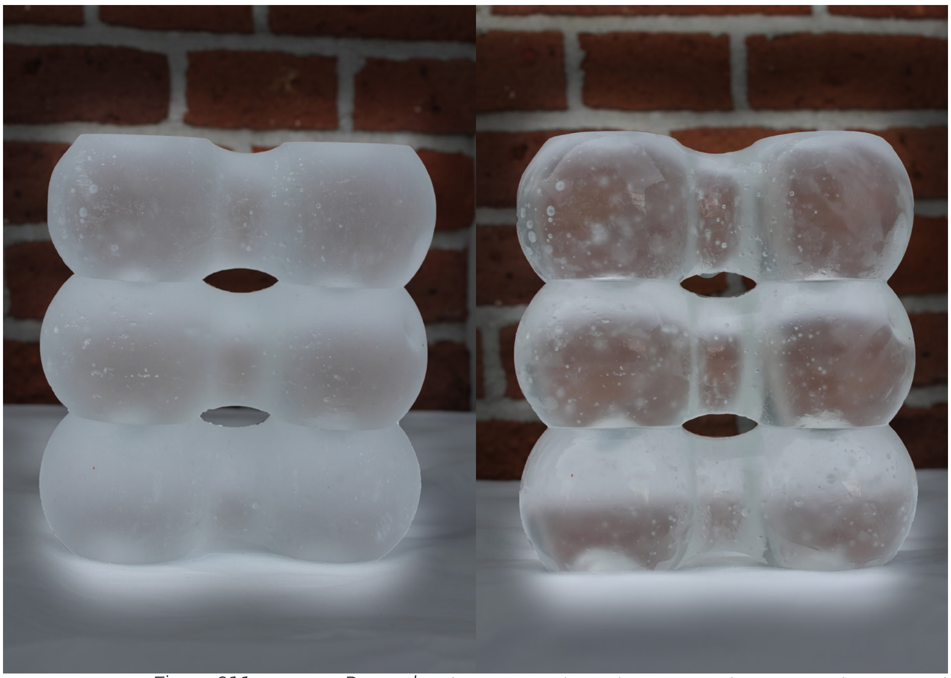


Figure 211. Dry and wet components, wet components are more transparent

Vivak Interlayer

To test the glass and have an overview of what the interlayer would look like, a prototype interlayer has been made.

As we saw in the previous chapter, there are two types of interlayers; one with a layer around the interlocking sphere (a) and one without (b).

Both of them could easily be made with VIVAK PETG; which is available at the faculty of architecture and is stiff enough (2,02 MPa). For both interlayers, a VIVAK sheet of 1mm is used.

For interlayer (a) thermal vacuum forming is needed. The sheet of VIVAK will surround the half spheres To produce these half balls, beads of wood must be split in half. These half balls will be put in the bottom of the machine. The vacuum thermoforming machine will heat the VIVAK to around 80°C, after which the sheet will take over the shape that is placed underneath when air is sucked from the bottom.

Because the sheet is thermally heated, inaccuracies in the thickness of the surface will occur. This could cause problems when a load is applied on a surface.

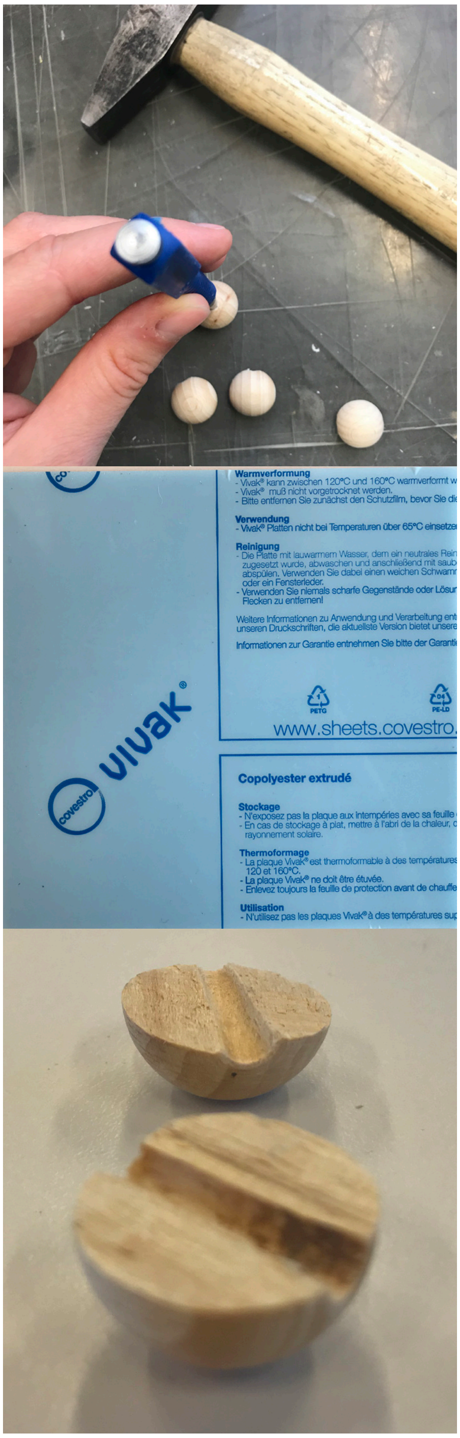


Figure 212. Splitting the wooden spheres and the VIVAK material sheet

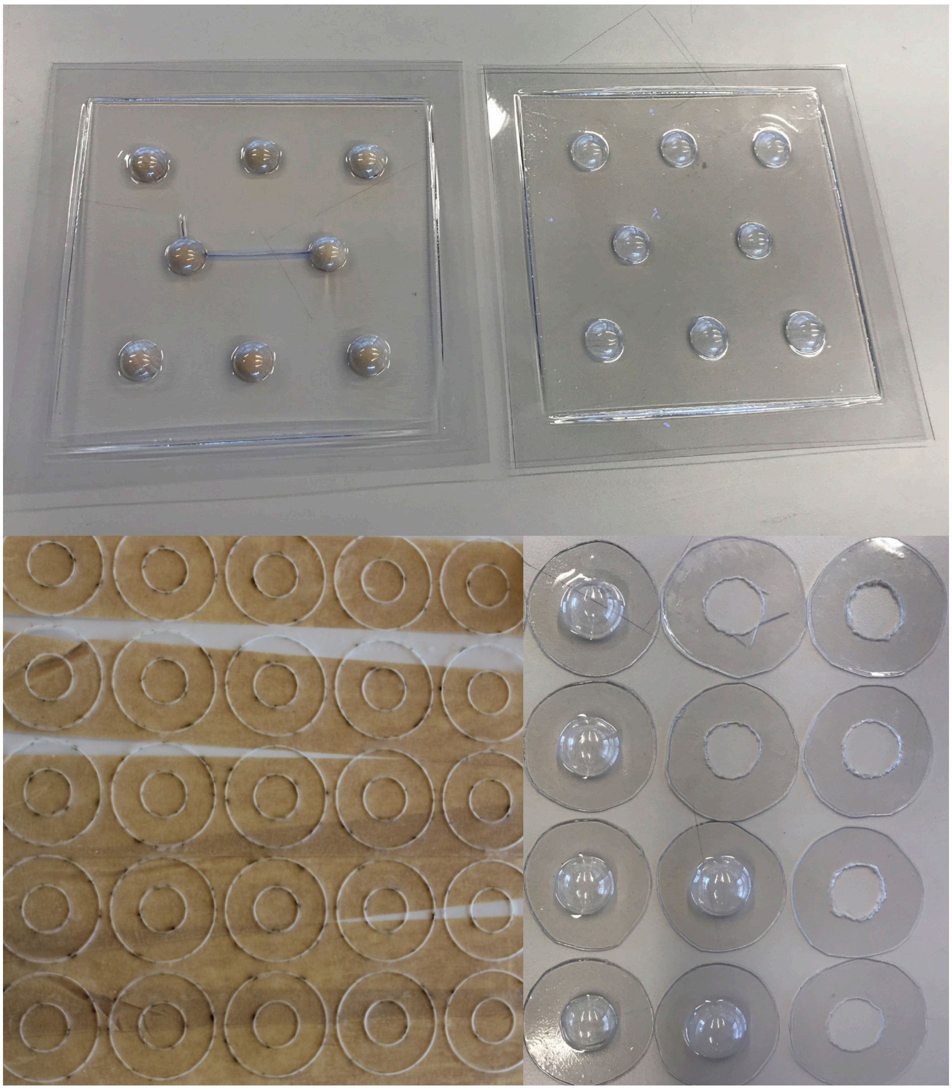


Figure 213. VIVAK vaccum forming and cutting

Epoxy models

Three epoxy models have been made to get an impression of what the glass models would look like. These epoxy mock-ups were made out of RESION Epoxy 2K GIET from polyestershop-pen.nl. This casting resin is transpa-rent and dries in one day. This resin will become active when two parts are stirred together in ratio 100: 60 (100 grams of resin, 60 grams of hardener).

Figure 214. Material used for the model

Figure 215. Epoxy model I, before and after cutting of funnel

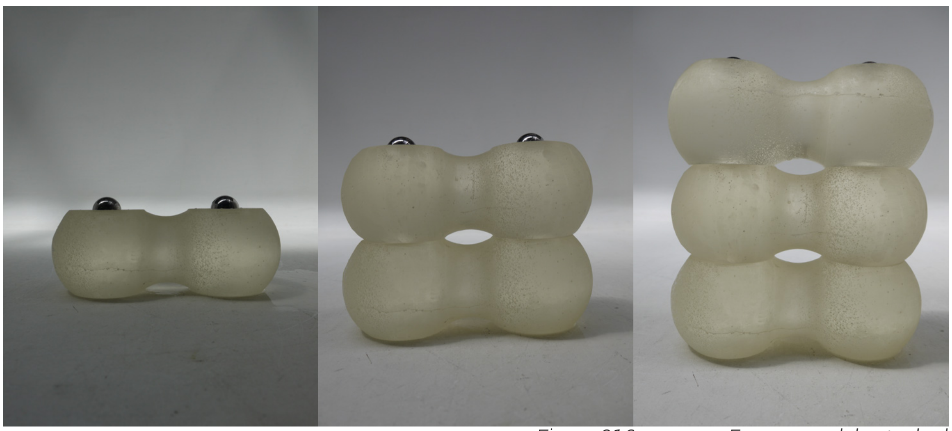


Figure 216. Expoxy models stacked

Foam model

The foam model is the only model that has been made in the actual scale (1:1), all the other models have been made on scale 1:3. This component is made to show the actual size of the component and therefore the column. The polystyrene foam that is used is available at the Faculty Architecture at the TU Delft.
This model is made by printing sections at different heights of the component on A3 paper. These prints are cut out, after which they are glued to the polystyrene foam. A hot wire foam cutter will be used to cut the foam in the approximate size. Later the layers will be glued together, after which the component will be sanded. The holes will be filled with a filler that is typically used to fill wood.

Figure 218. Production steps Foam model

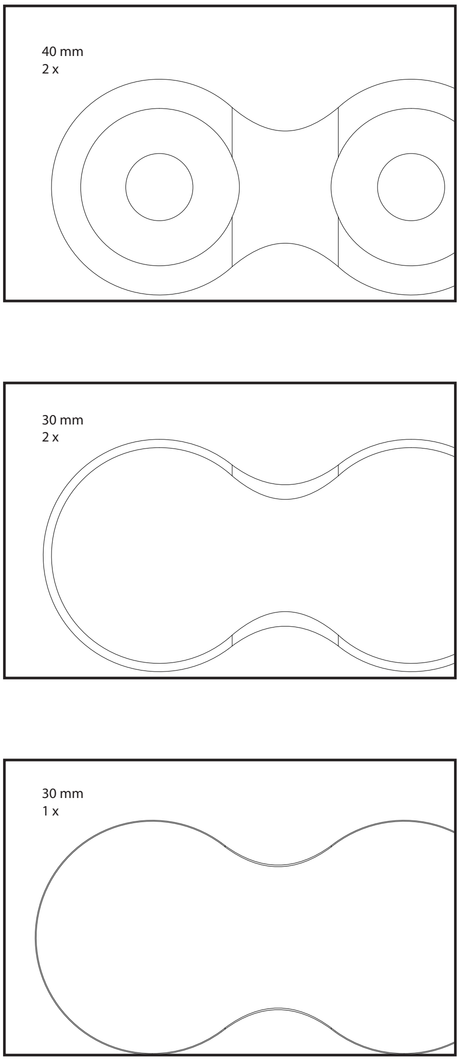


Figure 217. A3 sheets printed

Conclusions Prototype

When prototyping a complex 3D-geometry, it is efficient to make a 3D model of this shape. In this case, the 3Dmodel is made in Rhinoceros with the plugin Grasshopper. Different variables could be changed so that the perfect shape could be created with the calculated variables.
This 3Dmodel could become a reality when it is 3Dprinted. The geometry needs to have a certain tolerance in its shape and a funnel to pour in, in a later stage.

With this 3Dprinted geometry, a mould could be made. This would be a negative shape of the 3Dprinted geometry. In this case, the mould is made of silicone. The silicone mould could be used to create geometries from ice, sugar glass, wax and many more materials.

Making glass is an expensive and time and energy consuming process. During research of cast glass, a lot of different shapes have to be tested. When (cast) glass elements could be tested in a different material that predicts the breaking pattern of glass, this could prevent wasting a lot of time, money and energy. To be able to do so, we have to know if there is a cheap material, which is easy to produce, that breaks the same way as glass. Two options for this material, ice and sugar glass, were made manually and evaluated in this chapter.
The production of crystal clear ice is a hard task. Due to the fast cooling of ice in the freezer, the ice will create internal stresses which causes cracks in the middle of the elements. When a device would be available, that cools down the components more gradually; this could be a good option. But from this research is found that it is not feasible to do with a standard freezer.

The production of sugar glass takes more effort to make but does not need to cool down that gradually. A mixture of corn syrup, sugar and water should be heated up to 150°C, after which it could be poured in the mould and cooled down in room temperature, freezer or fridge. When they are cooled in the freezer for too long, the component will be in thermal shock when it is taken out of the freezer, which will break the element completely. Although the sugar glass stays more brittle when it is cooled, not conserved for too long and has to be kept out of a humid climate, it was stored at room temperature out of the sun for 1 to 7 days. This resulted in 8 solid but sticky components.

The three glass models that were made give a good view of what the actual components would look like. The shape seems to be very suitable to glass, due to the minimal internal stresses.

Notable is that the 3rd component has a 6% lower weight than the other two components. It is not clear where this weight loss comes from. Possibilities could be that the first two components lost less weight by the shrinkage of the glass then the 3rd one. Another option could be that the first two components have fewer air bubbles inside the glass. Lastly, it could be that from the 3rd one more material is sanded off by the post-processing.

In transparancy, the different moulds, one with and one without airvents did not give a different result.

Structural Validation

Structural Validation

When designing a structural member of a building, the strength of the member is the most important factor. Approaching the strength of a component could be done on three different levels: analytical, numerical and experimental.
When validating the structural strength of the component and its composition, different aspects need to be considered when designing:

1. The maximum compression stress of the material
2. The shear stress that could be created by people
3. The critical force of the buckling in the column and the sub-columns
4. The eccentricity that could be created by skew components or compression forces
5. The redundancy of the column. If one element fails, the rest of the column should still be able to be load-bearing.

Analytical analysis

Analytical analysing is a method to examine a status, problem or fact. It is a theoretical approach to the problem. In this case, it has to become visible if the designed components have the right strength to be applied in the case study. When approaching this theoretically, hand calculations have to be made.

The different aspects that need to be considered all have their way of calculating and validating. These aspects will be explained by the calculation of the dimensions of the different parts of the component design.
Before doing the calculations, there will be numbers or facts that have to be assumed, because this is a new type of column in different ways.

Buckling length

The buckling length is based on if the component is clamped and/or hinged. When a column is hinged on the top and the bottom, the actual length will be the same as the buckling length. When the column is clamped on top and bottom, only half of the actual length of the column is the buckling length. When the bottom is clamped, and the top is hinged, the actual length has to be multiplied by 0,7.

In this column design, it is not clear what the buckling length should be. Even if the top and bottom will be clamped, the column itself is not bending-resistant. The components are dry stacked on each other and applied with a great force (1200 kN). Therefore the column as total will react as if it is pre-tensioned.

But to prepare for the worst case scenario, two times hinged will be used. This means that the actual length is also the buckling length.

$L_{buckling} = L_{column} \cdot 1{,}0$

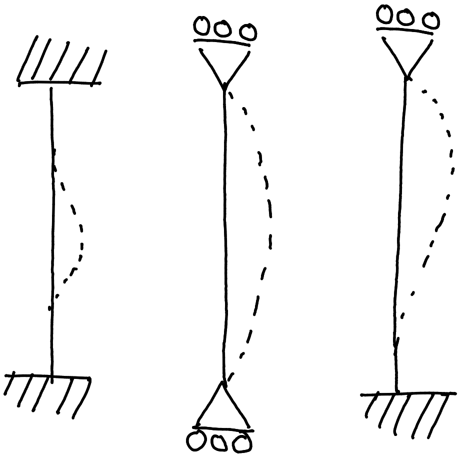


Figure 219. Buckling length

Buckling number

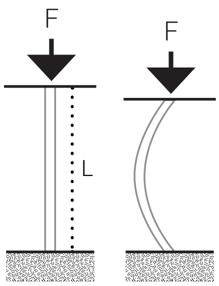
In the buckling formula of Euler, the critical force is the output, as you can see in the formula:

$F_{critical} = \pi^2 \cdot I \cdot E / L_{buckling}^{\;2}$

But because the design has to be made before the critical force in buckling is known, the critical force has to be assumed.

In the design at this stage, a safety factor of 4 is taken. This gives the formula:

$F_{critical}/F_{total} = 4$



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

$$I_{circle} = \tfrac{1}{4}\pi \cdot (r_{outside}^{\;4} - r_{inside}^{\;4})$$

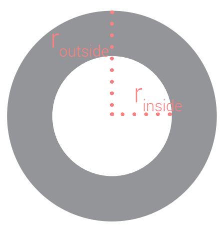


Figure 220. Calculation of the Isecond moment of area and the radius if the cross-section of column

Effect of a broken element

As we know an element will never actually go into thin air, but with the need for safety, this needs to be calculated.

When one element will break and not be load-bearing anymore, the other elements will take over the load.

At the start, you would think that the element above the broken element will take over all the load of the subcolumn.

But because the element will bend as much as possible, all the other elements on top of this element will take over some force. This way the force will distribute diagonally.

This is why the element should be able to hold at least 50% of the load of the subcolumn.

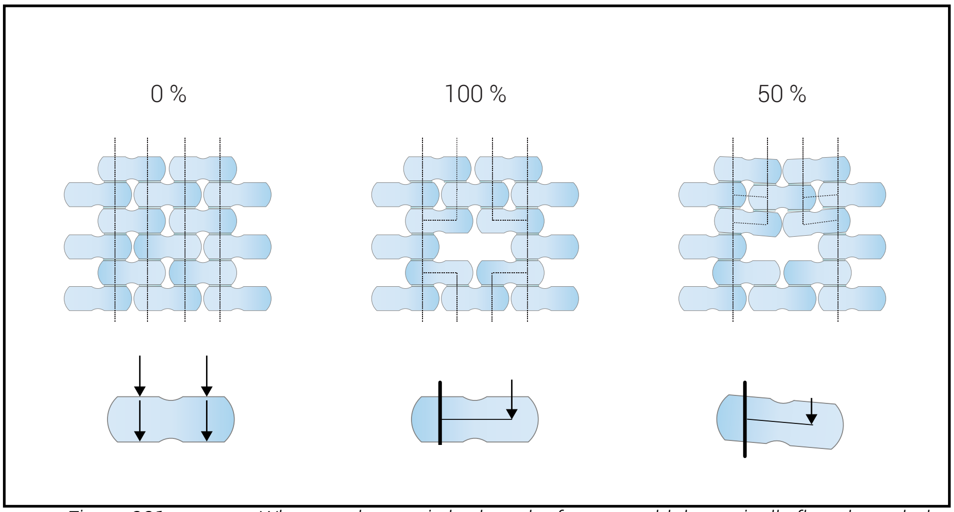


Figure 221. When an element is broken, the forces could theoretically flow through the elements above

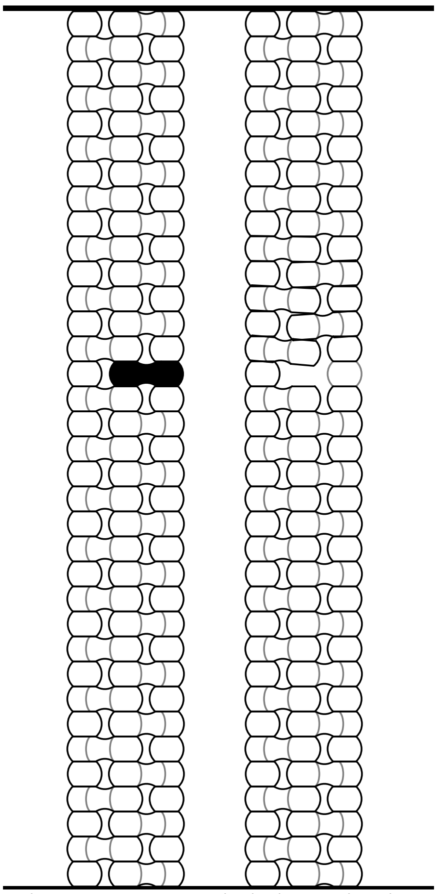


Figure 223. Block element breaks and the others will buckle a bit and take parts of the load

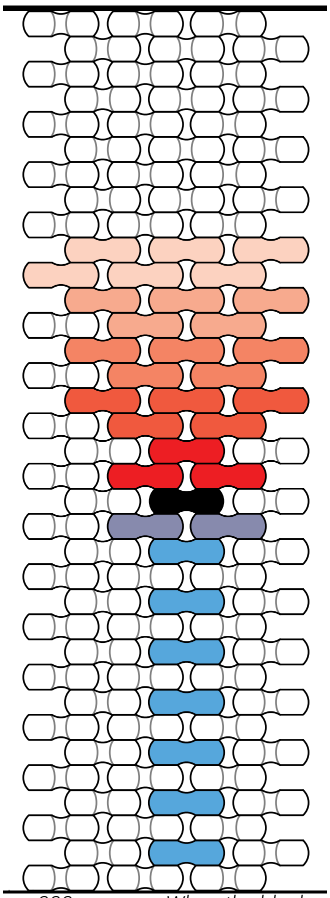


Figure 222. When the black element breaks, the blue ones will not carry load, and the red to orange will take over the loads

1. The length between the interlocking components
This length is based on the diameter of the column and the number of subcolumns. With the formula:

$L_{interl} = \sin(360/n_{subcolumn}) \cdot d_{column}$

2. The diameter of the interlocking sphere
This diameter is based on the diameter of the flat force-transmitting part. It is approximately half the size of the flat diameter.

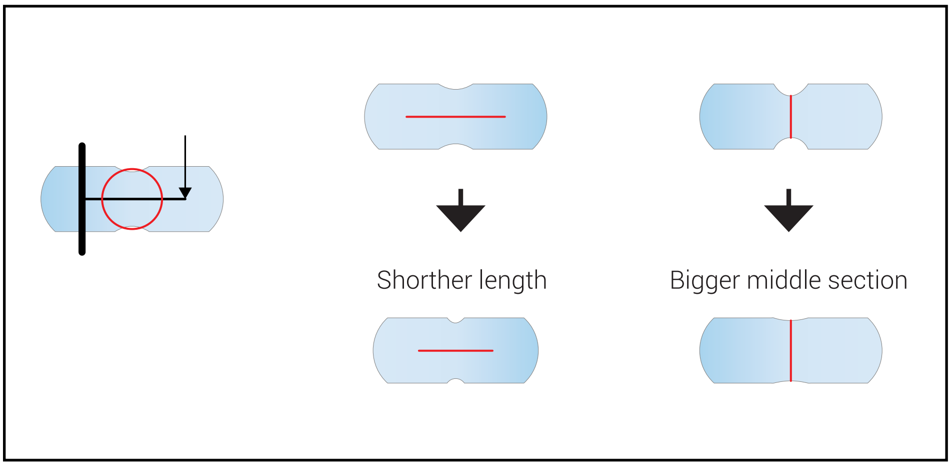


Figure 225. Determination of the length between the interlocking of one element

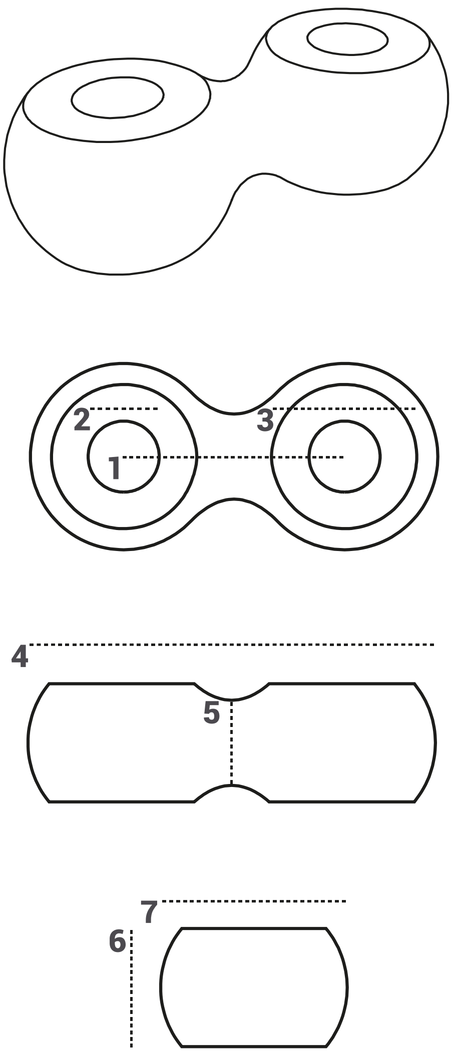


Figure 224. Dimensions of the element

3. The diameter of the flat force-transmitting part

This diameter is based on the minimum diameter corresponding to the moment of area that is given by the formula of Euler of the sub-columns. .

$$I_{subcolumn} = F_{critical} \cdot L_{buckling}^{2} / (\pi^2 \cdot E_{borosilicate})$$

To know the diameter of the flat part the following formula is used:

$$d_{min.flat} = I_{subcolumn} / (\pi/4)^{1/4}$$

This diameter is the minimum diameter when the full area would be used. But, because the middle of the circle has to be free of force, the centre has to be excluded.
The aim is to create an interlocking part of about half the size of the flat part. The moment of area could be applied with the following formula:

$$I_{subcolumn} = \pi / 4 \,.\, (r_{flat}^{4} - r_{sphere}^{4})$$

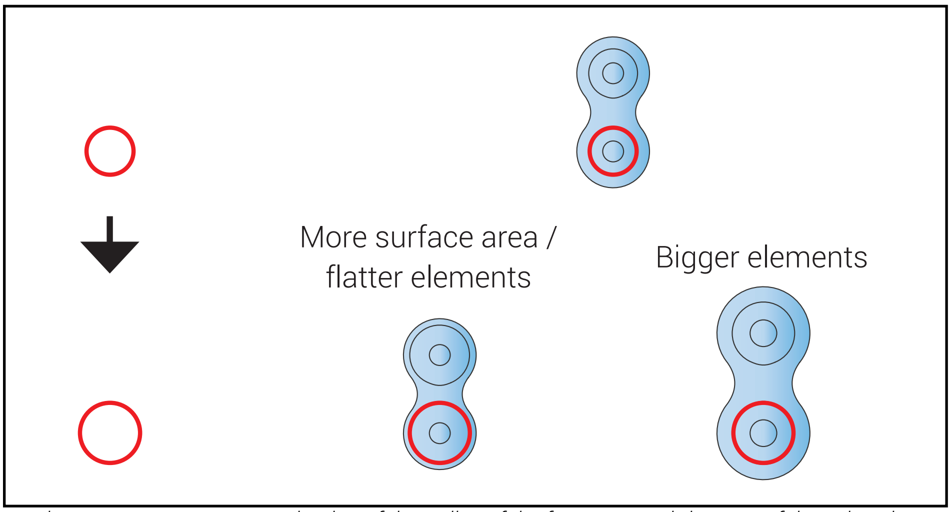


Figure 226. Determination of the radius of the force-transmitting part of the sub-columns

4. The length of the total component

The length of the total component is calculated by the following formula:

$$L_{total} = L_{interl} + d_{bigsphere}$$

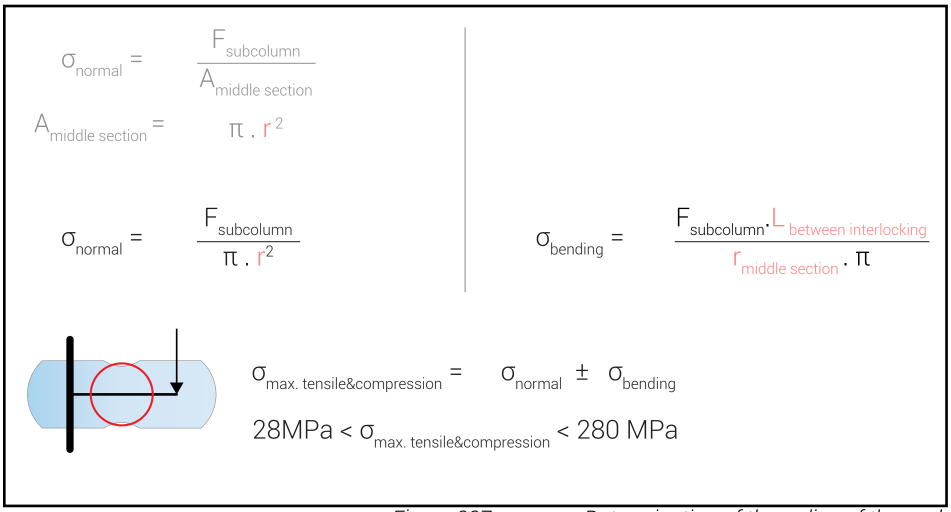


Figure 227. Determination of the radius of the neck

5. The diameter of the neck

The (minimum) diameter is calculated; so that it is able to hold 50% of the total force of one subcolumn in case one component breaks and is unable to carry any load anymore. All the elements above the broken one will rotate a little bit, and the load will be divided to the elements above.

The following formula calculates the total force applied on one subcolumn:

$$F_{subcolumn} = F_{total} \,.\, 50\% / n_{subcolumn}$$

The diameter itself is calculated the way a clamped beam with a force would be calculated. For the diameter of the middle, this formula was used:

$$d_{middle} = (2 \,.\, F_{subcolumn} \,.\, L_{interl} / (\sigma_{maxtensileglass} \cdot \pi))^{1/3}$$

6. Height of the component

The height of the component is calculated by the diameter of the big spheres minus the depth of the flat part.

$$H_{component} = d_{bigsphere} - h_{flat}$$

7. Diameter of the big spheres

The diameter is based on the rest of the elements. It has to be bigger than the diameter of the middle (5.) and the force-transmitting part (3.). But it is limited to the total volume of the sphere. Due to annealing time, it has to be limited to a certain volume (with a maximum weight of 15kg).

The total volume of the sphere is calculated by the total volume of the sphere:

$$V_{sphere} = 4/3 \,.\, \pi \,.\, r_{sphere}$$

This volume is reduced by two other components:
- the volume of the interlocking sphere (2.)
- the depth of the flat force-transmitting part (3.)

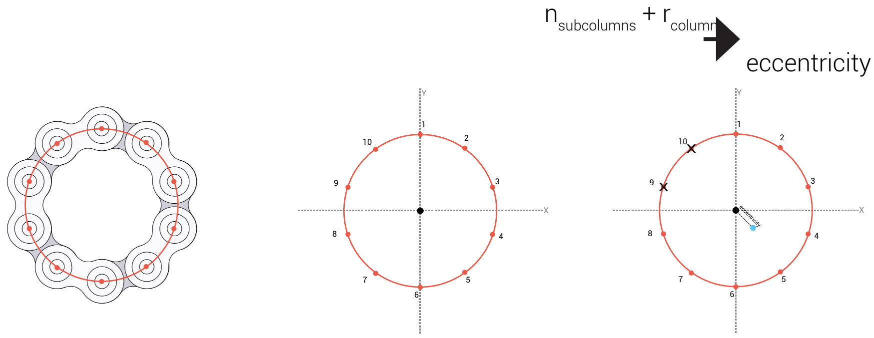
8. Number of subcolumns

The number of subcolumns ($n_{subcolumn}$) is kept as low as possible because of the intolerances that may appear, the amount of work building the column and the visual effect.

This column is designed so that one element in the column can break and therefore lose all of its strength (it will only be dust), and the column is still able to hold all the forces.

When one element disappears, 2 subcolumns become non-load-bearing. When a column has 16 subcolumns, the centroid of the load will only shift a bit away from the broken element. But when a column has only 4 subcolumns, the centroid of the force will shift away a lot further away from the middle of the column. This distance is called the eccentricity.

When the eccentricity rises, the moment and therefore the bending stress on the elements grows, corresponding to these formulas:



$$\sigma_{bending} = \frac{F_{subcolumn} \cdot eccentricity \cdot r_{subcolumn}}{I_{section\ subcolumn}}$$

$$\sigma_{normal} = \frac{F_{subcolumn}}{\frac{1}{4}\pi \cdot (r_{outside}^{\ 4} - r_{inside}^{\ 4})}$$

$$\sigma_{max.\ tensile\&compression} = \sigma_{normal} \pm \sigma_{bending}$$

$$0\ \text{MPa} < \sigma_{max.\ tensile\&compression} < 280\ \text{MPa}$$

Figure 228. Determination of the number of subcolumns

$$M = F_{critical} \cdot eccentricity$$

$$\sigma_{bending} = M \cdot y / I_{column}$$

Next to the bending stress, normal stress is also applied to the column. This normal stress is calculated by this formula:

$$\sigma_{normal} = F_{critical} / A$$

A is the total area of the flat force-transmitting circles.

The minimum and maximum stress on the column will be calculated by:

$$\sigma_{max\&min} = \sigma_{normal} \pm \sigma_{bending}$$

These stresses have to be only compression and beneath the maximum compression (+) force of borosilicate glass of 280MPa.

It can only be compression because if there is tension, the components will be lifted and shifted, ending in complete failure.

When using more subcolumns, the elements become less elegant (ration between the length and the radius in the middle is lower). But they do reduce the volume per component. This is convenient due to the limited annealing time of one component.

9. Diameter of the column

When the diameter of the column is growing, the elements become more and more slender and therefore elegant. But also the elements become bigger unless the number of subcolumns will be increased.

To create components that are as elegant as possible the column on the first floor is much wider then the columns at the floor above would be.

At the ground floor, the d_{column} would be 800mm and has 10 subcolumns. This would give the floors above the chance to have more slender columns. With 8 subcolumns this would be about 650mm, and with 6 this would be 500mm. This way the same components will be all the same in the building but will create different columns.

$D_{totalcolumn} = d_{column} + d_{bigsphere}$

But the calculations will be done with the d_{column}.

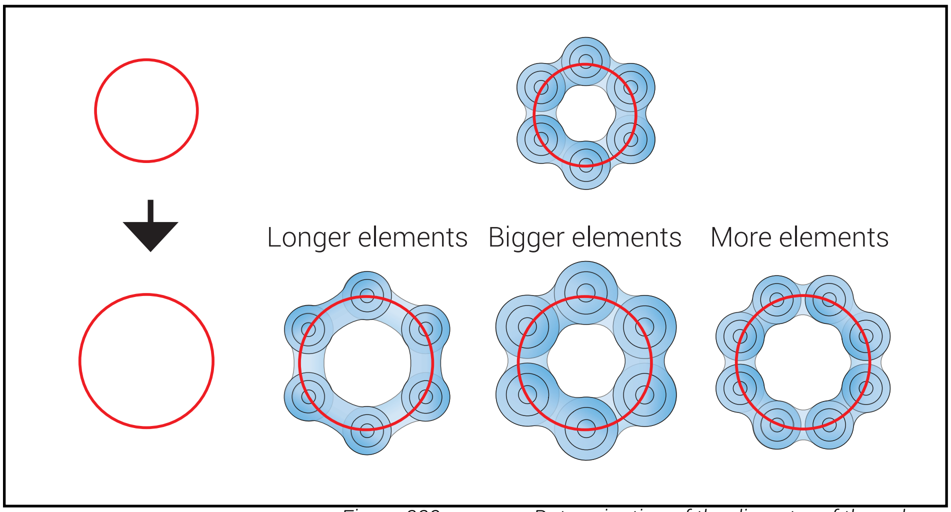


Figure 229. Determination of the diameter of the column

10. Total second moment of area column

The total moment of area of the column is calculated based on the number of subcolumns and their distance from the centroid of the force based on their coordinates.

Risk analysis

The two most important factors in a structural safe design are the residual load-bearing capacity and redundancy of a structural system. (Weller, 2009) Due to the safety factor of 4 that is applied in the calculations of the column, the residual load-bearing capacity is fairly high. Redundancy has been a great topic while designing this column. Due to the multiple components on one level, one element could break, and the column would still be able to withstand the applied forces. The designed column will be placed inside the hallway of the Glasspalace. When looking at the risks this column is facing these risks could vary a lot.

Because the building in which the column is placed, the Glasspalace is a public building, there will always be one or two security guards that will be in the same space as the column. Next to this, the building is surrounded by concrete blocks of about 0,5 m wide and high every 3 meters. Lastly, the column is placed in the middle of the building.

In the unlikely event of a car that would drive in the building, and only drive into the middle glass column, the glass column would break, due to the glass properties. When a scooter would drive into the column, the column would break when there is no interlayer in between the interlocking sphere and the glass components. When there is an interlayer, the column could be able to withstand these forces.

When a column is placed in a public building, people can touch the column and can scratch the glass. The glass will eventually become weaker, and more likely to fail.

When the glass breaks, the broken pieces should be kept together by The table shows the risks that the glass column, and therefore the building will face.

A risk analysis can be made by analysing the probability of the risk happening and the consequences that this risk will lead to. These two factors have to be multiplied by each other to describe the risk.

These risks should be analysed and, when they are high, ways must be found to prevent this risk.

To describe the risk according to the NEN 2608, the risk of damage (risico op schade, RS) is formulated. The following formula could conduct this:

Risk on damage = probability of fracture x exposure of the structural element x consequences at complete failure

RD = PF x ES x CF

We can see from the table that all the risks are beneath the 70, which would only mean lateral fracture n one side of the structure

Risk Analysis Table	**PF**	**ES**	**CF**	**RD**
in Ducth	WS	BS	ES	RS
4 people push against the column	0,5	0,5	1	0,25
Thermal shock of an element	0,5	0,5	3	0,75
People scratch the glass with keys on purpose	3	0,5	0,5	0,75
1 person leans agains the column	10	0,5	0,5	2,5
Car will drive into the structure and ruin the structure	0,2	0,5	100	5
a scooter drive onto the column	0,5	0,5	40	10
A truck will drive into the structure	0,1	0,5	100	25
Earthkuaque	0,5	0,5	100	25

Table 15. Risk analysis

	Maximum Force *HP*	Velocity *Nm/s*	Weight *kg*	Force component *N*	Force interlocking sphere *N*	Apllied stress *Mpa*	Failure
1 person		8	80	600	150	0,10	no
4 persons		8	320	2.400	600	0,40	no
Scooter	5	3.502	130	455.282	113.821	75,43	failure when no interlayer is applied
Car	200	147.150	1.350	198.652.500	49.663.125	32.911	total
Truck	750	551.813	11.250	6.207.890.625	1.551.972.656	1.028.478	total

Table 16. Calculation of the forces that could be a risk for the column

Numerical analysis

Numerical analysis is based on algorithms that are based on numerical approximation. These calculations are used to solve mathematical problems, like structural calculations. Different programs use this method, like; DIANA FEA, karamba (plugin on grasshopper) or ANSYS.

This numerical analysis is mainly essential to check if the hand calculations were done the right way. There are too many factors in this design that are new to the building industry that some assumptions are made and calculating with more details would be unwanted extra work. This is why trying to get more detailed results from a FEM method is not telling us more than the hand calculations. Experimental testing is necessary to know the output.

But one of the calculations is simulated in DIANA FEA; the one that would see what happened to the neck of the component if the upper component in a column would break. First, this is calculated by hand as a cantilevered beam. This is visible in the previous chapter.

Input

From the Rhinoceros model that is made, the middle section is constructed as a surface. This surface is converted into an IGS-file. This file can be imported into DIANA FEA.

Support is applied in the flat part on the left side of the component (red triangles).

The material borosilicate has to be created and attached to the geometry.

On the top flat right part of the component, a force is applied (yellow lines). The force that is applied is a distributed force. Normally all the load will be placed only on the flat part, but because this is a schematic reproduction of this component, and this will not be the critical part of the composition in this calculation. We can assume that the total flat part will be loaded.
This is calculated by:

$q = F_{subcolumn} / A_{sphere+flat}$
$q = 126100 \text{ N} / 18743 \text{ mm}^2$
$q = 6{,}7 \text{ N/mm}^2$

$q_{50\%} = 6{,}7 \text{ N/mm}^2 . 50\%$
$q_{50\%} = 3{,}36 \text{ N/mm}^2$

Also, the element geometry has to be created with a certain thickness.

Lastly, the geometry has to be meshed and calculated. After this the results become visible.

Output

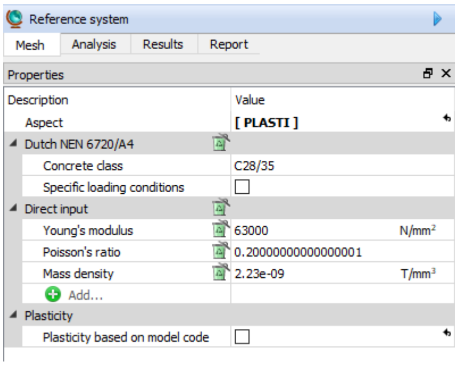
From this calculations, we could see that the DIANA FEA gives similar results as the earlier calculated hand calculations.

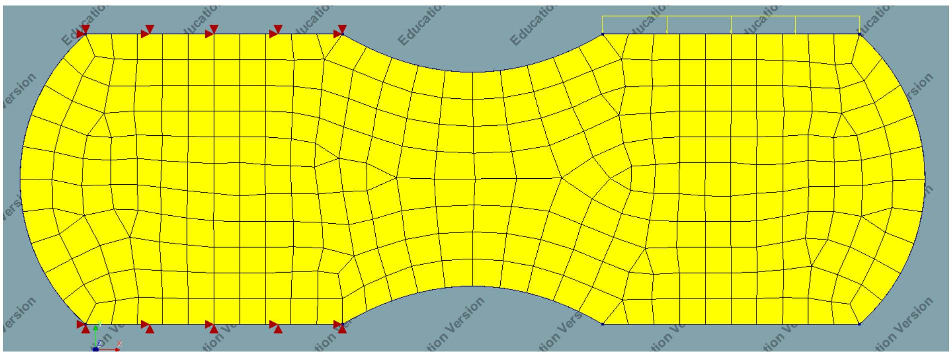
Because the component has different diameters on different parts of the neck, the assumption was made to calculate only with the smallest diameter in the hand calculations. In the calculation, in DIANA FEA the neck is smooth and has different thicknesses along its length.

After various analysis, we could see that the element could hold a bit more than was calculated

$F_{subcolumn} = 126 \text{ kN}$
$F_{subcolumn50\%} = 63 \text{ kN}$

But the load that the component was able to hold was more than 63 kN, it was 78 kN, before the maximum tensile stress in the element was reached of 28 MPa.





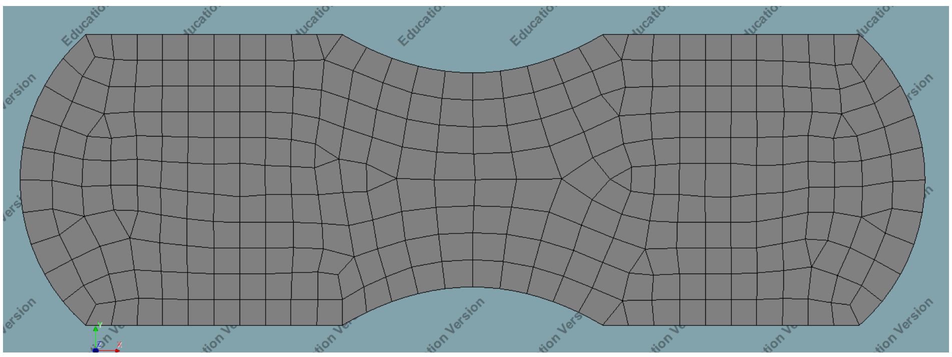


Figure 230. Input of the component in DIANA

$$\%_{\text{able to hold}} = F_{\text{actual}} / F_{\text{subcolumn}}$$
$$\%_{\text{able to hold}} = 78\ \text{kN} / 126\ \text{kN}$$
$$\%_{\text{able to hold}} = 62\ \%$$

This is why the result tells us that the neck could hold 62% of the force that would be applied on the sub column, instead of the 50% that was calculated with.

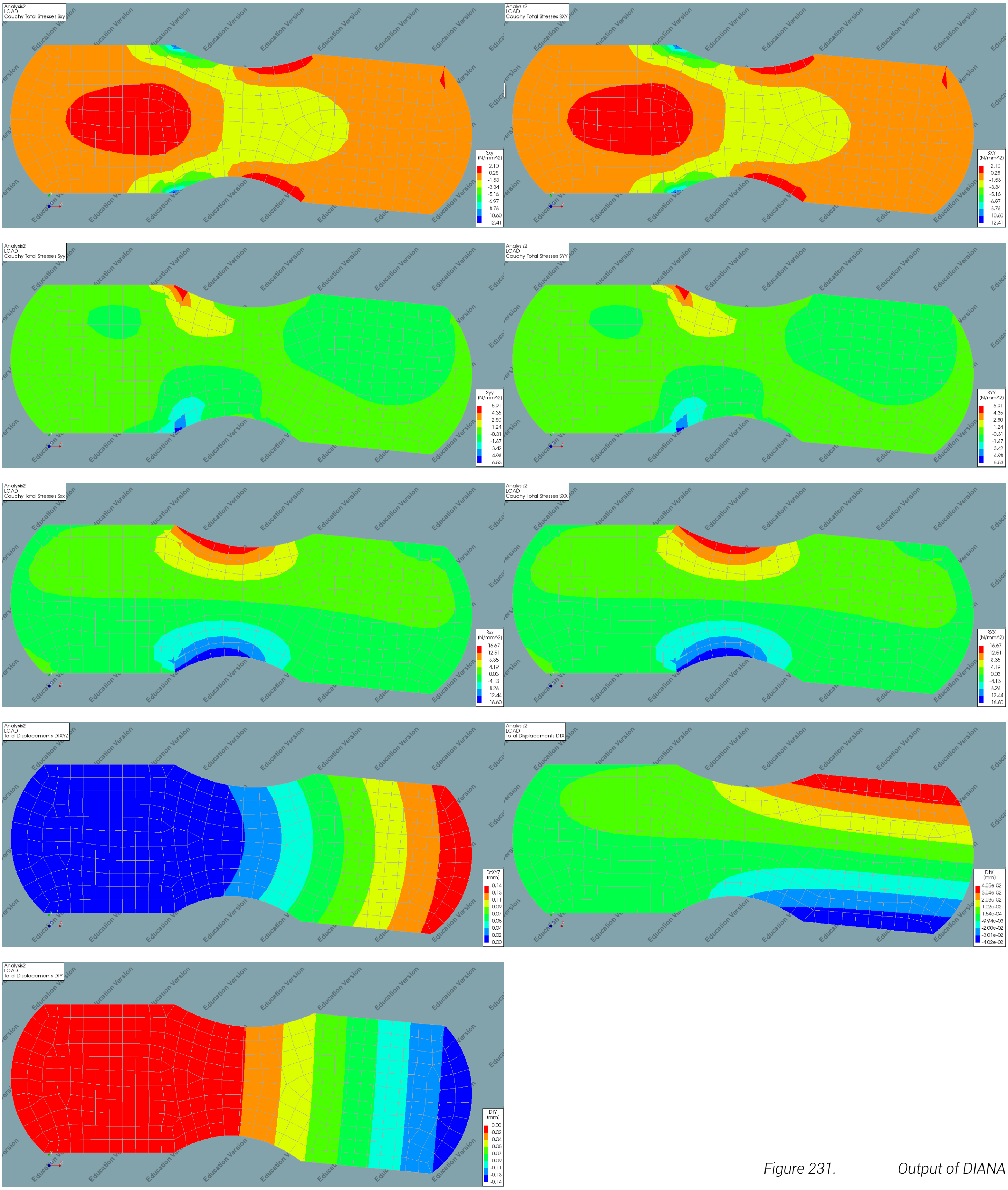


Figure 231. Output of DIANA

Experimental analysis

Building with structural cast glass is relatively new in the building industry. This is why the designs in cast glass should be tested to know if they have valid strengths to fit in the desired construction.

When testing a design, different factors should be paid attention to; the structural behaviour of the material, the breaking pattern, and the outputs of the pressure machine.

When these results are known, conclusions can be drawn from this test. These conclusions should be drawn very carefully, because of different factors; the manually manufacturing process, the limited amount of test and the different types of glass.

Set up

There are different types of setups that would be useful to test:

1. Compression Force on the component. Force will be applied on top of one component

2. Compression Force on the column. Force should be applied to a column of 3 or more elements directly on top of each other.

3. Buckling. The components should be placed in the position that they will have in the actual column. A compression force should be applied in the middle of the top of the column.

4. Redundancy column. The components should be placed in the position that they will have in the actual column, only one of the elements will not be placed inside the column. A compression force should be applied in the middle of the top of the column.

5. Shear force component. A pre-stressed horizontal stacked component should be loaded with a point load in the horizontal direction on top of the middle component.

6. Redundancy wall. The components will be stacked on top of each other, only one element will be missing in the middle. Compression force will be applied from the top.

Load cases

The column needs to be able to withstand the total load of the building that is applied on the column. This load is multiplied by a safety factor of 4, which gives the critical force of the compression. Next to that, it is necessary to see what happened if one of the elements breaks.
For the sugar glass, it is mainly interesting to see how it breaks. Next to this, the breaking force should be noted for possible further research.

Expectations

The sugar glass and the glass are both manually made, which will give some imperfections and flaws in the component. There is a chance that these imperfections will be the first place that the breaking will start. This is why it is important to look at the components closely before and after the test.

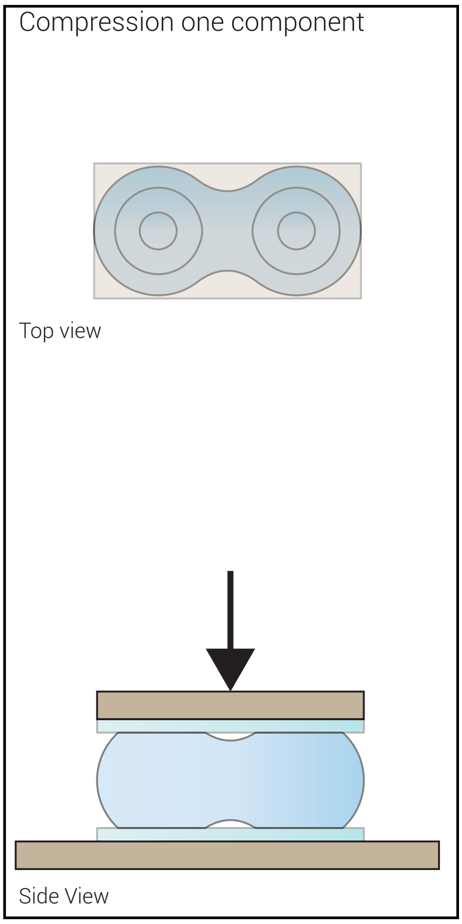


Figure 232. Test setup 1

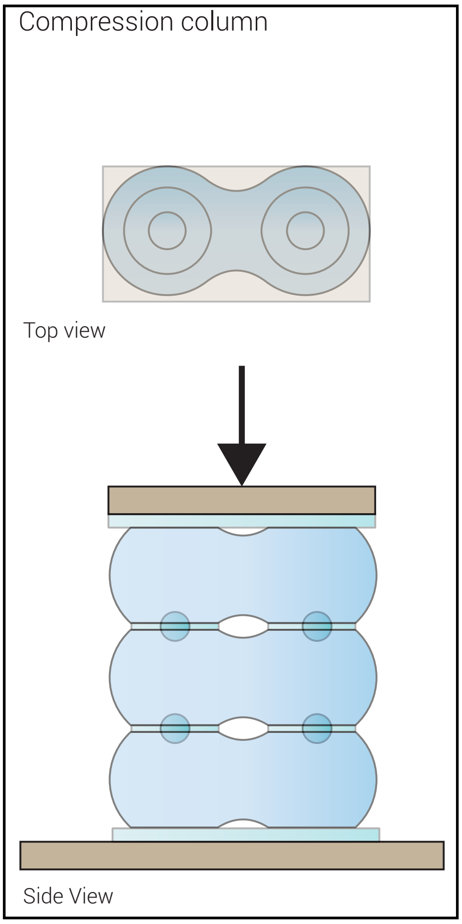


Figure 233. Test setup 2

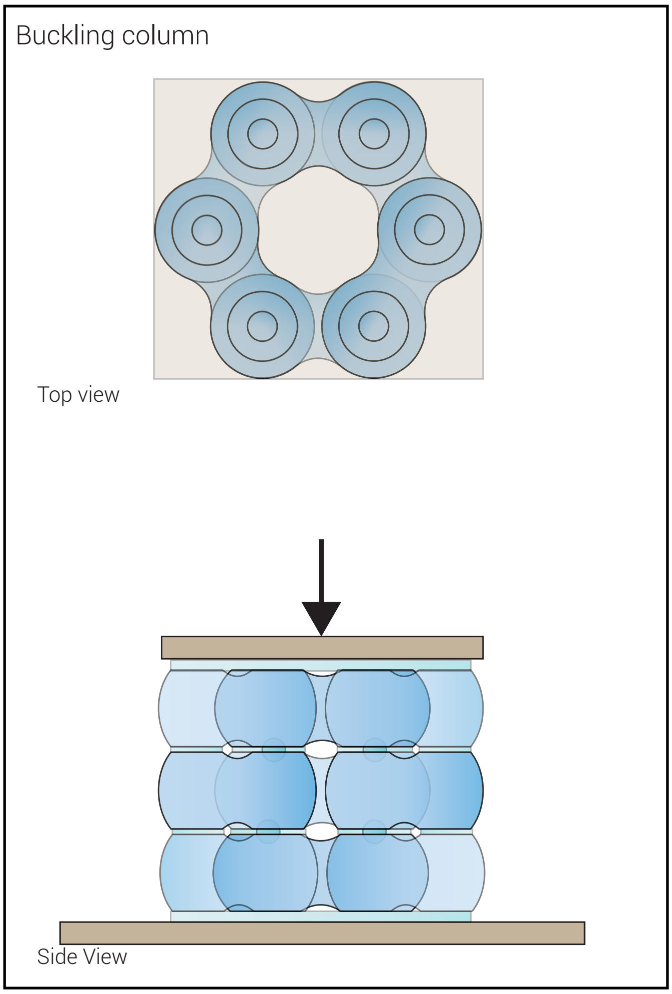


Figure 234. Test setup 3

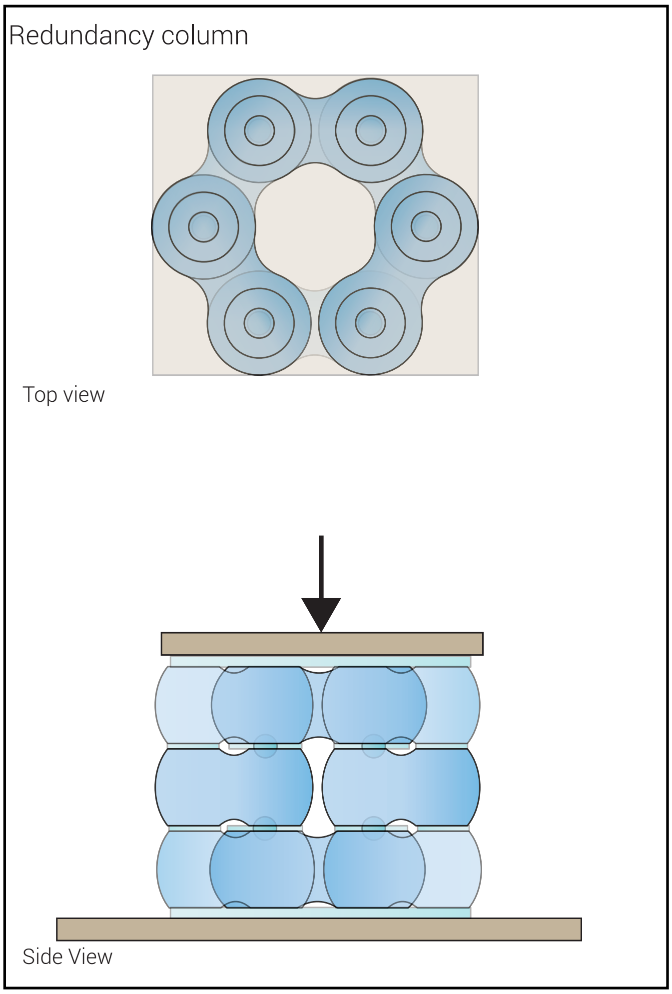


Figure 235. Test setup 4

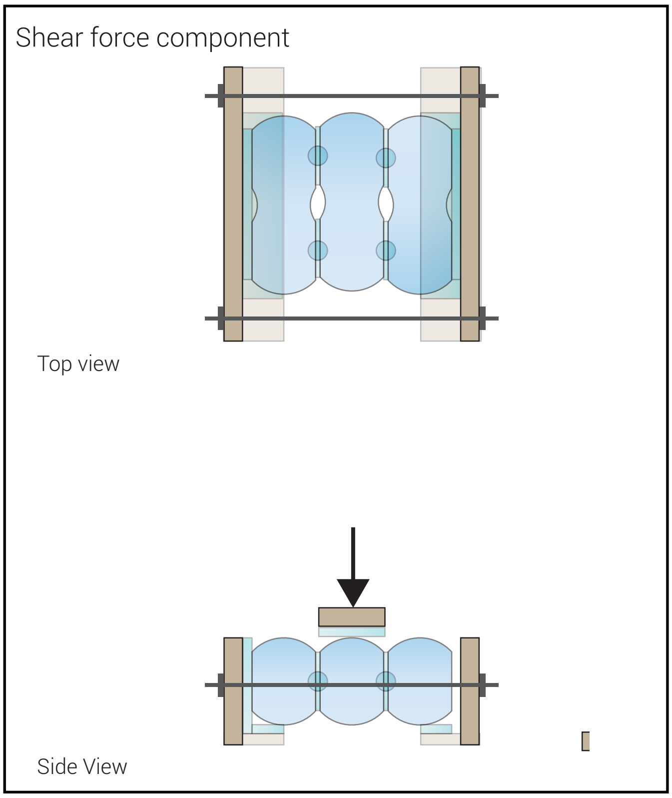


Figure 236. Test setup 5

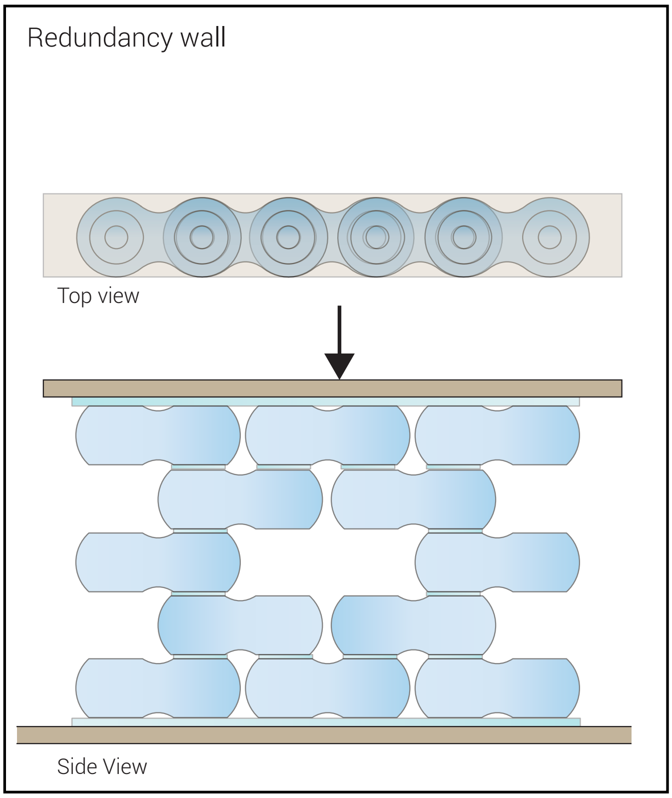


Figure 237. Test setup 6

Figure 239. Sugar glass components on top of each other

Sugar glass

Introduction

The tests of sugar glass cast elements will be done at the testing machine at the faculty of mechanical engineering at the TU Delft at the 15th of may 2018.
The temperature on this date in Delft was 24° C.
Testing cast sugar glass as a prediction of real cast glass, as far as we know, has not been done before. There have been tests in sugar glass in the 'molecular mobility in sugar glasses' by van den Dries in 2000. Sugar glass is used a lot in movies and photographing due to its similar breaking pattern to real glass. Because of this similarity, the sugar glass will be tested in cast sugar glass shapes to see if there will have a similar breaking pattern.
Known is that sugar glass is much weaker in strength then real glass (soda lime or borosilicate). This is why it is not useful to take the amount of force serious. The amount of force should be noted, but only to compare different sugar glass specimens with each other and also to compare the amount of force that is put on the glass with the amount of force that is put on the sugar glass.
The questions that are asked during these experiments are:
-What are the weakest points in the design of the components when shear force is applied?
-What is the maximum applied force before the sugar glass elements break?
-Where does the breaking pattern of the material start?
- Do the components made of sugar glass show the same breaking pattern as could occur on real glass?

Failure of glass

The failure of glass is characterised by its breaking pattern. As we could see from the chapter about strengthening glass when glass is thermally or chemically treated it will break differently from annealed glass. The type we will be comparing the sugar glass to will be the annealed glass. Annealed glass

When annealed glass breaks, it will break into large sharp pieces. Next to this, glass has a very high young's modulus, which could result in an elastic deformation that is very small. Due to its low tensile strength, in comparison to its compressive strength, the glass will break when it is deforming too much. Glass solely, is able to deform plastically only minimally.

Figure 238. Sugar glass components in a box and the testing-interlayers.

Set-up

Due to the limited amount of sugar glass pieces and limitations due to the maximum force of the pressure machine, some set-ups are not possible. The setup that is chosen for this test is the test setup 5: shear force. In this test, the shear strength of the component will be tested. In the chapter about the interlocking sphere, we can see that the shear force that will be applied to the actual component will be 2400 N per element. Due to this, a load of 600 N will be applied to each interlocking sphere. This would result in a stress of 0,4 MPa.
Because the element is scale 1:3 to the real element, the force that will be applied will be lower. The stress that it should hold will be 0,4 N/mm2. For this element the interlocking spheres will have a diameter of 20mm. Which would result in a surface of :

$A_{spheretotal} = 4\pi r^2 = 1.257\ mm^2$
$A_{circle} = 1.257 / 8 = 157\ mm^2$
$A_{total\ shear} = A_{circle} \times 4 = 628{,}3\ mm^2$

From this, the minimal shear force that it should be able to hold would be:

$F_{shear\ min} = A_{total\ shear} \times \sigma_{sphere}$
$F_{shear\ min} = 628{,}3\ mm^2 \times 0{,}4\ N/mm^2$
$F_{shear\ min} = 251{,}3\ N$

Note that this would be the shear force that would be applied when the material is glass. Testing in sugar glass, this force is not of a significant matter, the way it breaks is.

Equipment & Materials

Pressure machine: cLine materials

testing machine Z010 (Zwick/Roell (Fmax= 10 kN)

Components: 8

Interlayer of 1mm vivak: 8

Interlocking spheres: 10

Clamps: 4

Pieces of wood: 3

Metal plates : 2 of 20cm x 8cm

Neoprene

Figure 240. Test set-up

Components

1

2

4

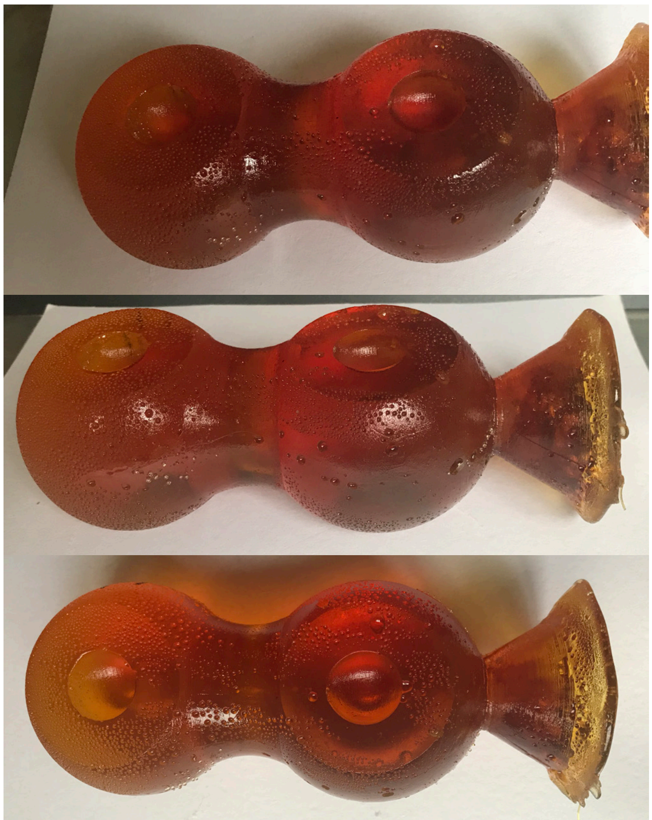
5

6

8

10

11

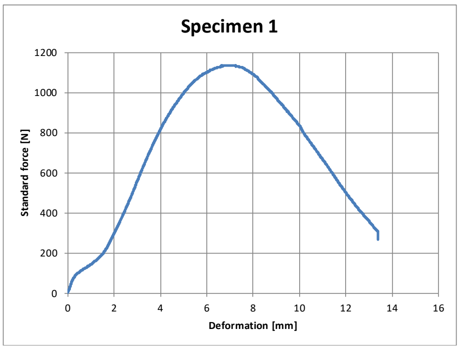


Specimen 1
Components: 5 - 11- 2

The first test was with a low speed.

One of the specimen (2) deformed when the force was applied slowly.

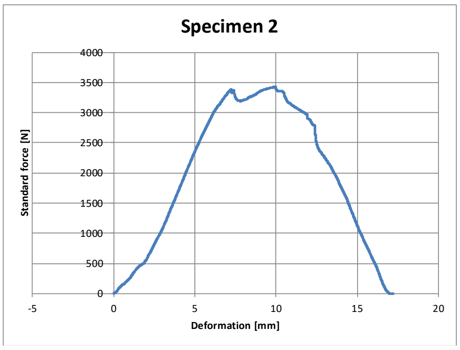
Component 11 and 5 were used again for specimen 2.



Specimen 2
Components: 5 - 11- 10

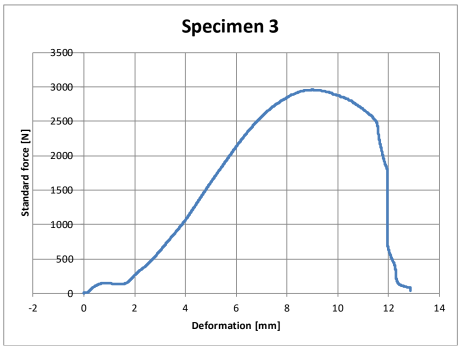
After the first test, the speed of the pressure machine was increased, to prevent deformation.

The components did not deform, but cracked all 3.



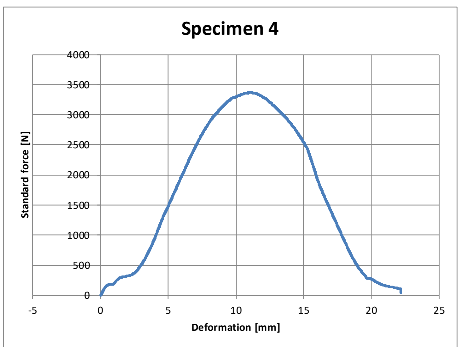
Specimen 3
Components: 6 - 4 - 8

3 new components were used. 2 of them broke, element 6 was undamaged.



Specimen 4
Components: 2 - 6 - 1

This was the last composition of components. Component 2 was reused, only the undamaged side was put towards the middle. Component 2 was deformed again but on the other side



Results

Specimen 1 and 4 showed an element that deformed. This would never happen
to real glass; it would break before it deforms. The interesting thing is that twice the same component deformed (component 2).
Specimen 2 and 3 showed a result of how the element breaks when shear force is applied.
In these specimens, we see failure that has a lot of similarities to the breakage of glass in the small deformation and the sudden breakage of the components
We can see that even the lowest Fmax that is reached with specimen 1 reached 1136 N, which is much more then the 251 N that is necessary for this column, even though this is sugar glass instead of real glass.
This would assume that the shear force that can be applied, also in real glass, will be much more then it needs to be.

Conclusion

From the different specimens, we can see that there is not a constant behaviour of the sugar glass. This is explainable, due to the different variables associated with the making and conserving of the sugar glass components. From this test, we can conclude that sugar glass that is produced manually with no optimal conserving environment and time is not valuable to compare the breaking pattern of glass.

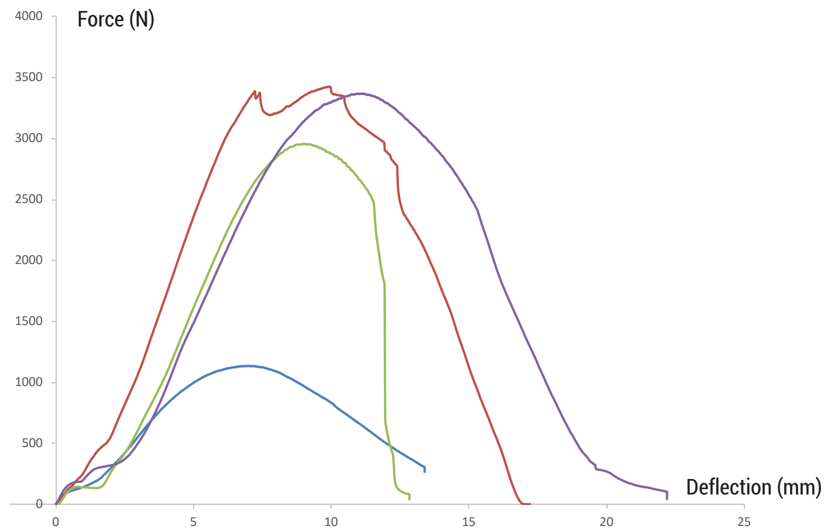
Recommendations

The production of the sugar glass was done with limited resources: no temperature measurement while boiling the sugar glass, no precise measurement and type of the ingredients differed from the prescribed ones, no exact timing of the cooling and the conserving time and environment were not ideal. Due to these variables, it is not possible to exclude the idea of using sugar glass as a breaking-simulation of real glass.

Further research should watch these variables closely and find optimal solutions for producing and conserving the sugar glass. After which, these should be tested and analysed again.

Figure 241. Cracked sugar glass

	F_{max} *N*	dL at F_{max} *mm*
Specimen 1	1136	6,96
Specimen 2	3426	9,93
Specimen 3	2957	9,03
Specimen 4	3369	11,16



Structural validation conclusion

Structural validation is analysis by three methods: analytical analysis, numerical analysis and experimental analysis. The analytical analysis consists of assumptions that have been made, hand-calculations of the minimum size of the component and risk analysis.

In the numerical analysis, one of the hand-calculations has been checked by importing the same calculation into DIANA FEA. The results were similar to the simplified hand-calculations. Checking all the outcomes of all the calculations was unnecessary, due to the multiple assumptions and ignorance about interlocking stacked cast glass columns. To know how this column will react to different set-ups with other load-cases, it has to be tested experimentally.

During the experimental analysis, the 8 sugar glass components were tested in shear force. Other test-setups were not optional due to the number of components and maximum force of the pressure machine. With this experiment, four tests have been done. Two of them failed due to deformation of one elements; the other two broke by cracks that were created in the components. With the first test (deformation) the speed of the pressure machine was low, the other three test were done at higher speed. The results of the test it was that there is not a guarantee that sugar glass will always break the same way as glass. This breakage depends on the brittleness of the elements which is influenced by the temperature during production, the cooling time and method of the element, the surrounding temperature and humidity during conservation and the conservation time.

Conclusions

Reflection

Aspect 1: the relationship between research and design.

To find the right shape for the component, reference projects are examined to a list of design principles which were constructed by literature studies. By examining other concepts, six concepts emerged. Like the reference projects, they got examined as well. From these six concepts, three of them seemed worthwhile to develop further. These three design where merged into two designs that both have an interlocking sphere in between the components. This sphere could be made of glass, but also out of another material, with or without an interlayer. The two shapes are named after their shape; robust and elegant. The elegant shape is chosen to develop further, because with this shape design-boundaries of the material glass could be found. With this shape design, the final dimensions were approached by hand calculations, that were checked by a numerical analyse in DIANA FEA.

Aspect 2: the relationship between your graduation (project) topic, the studio topic (if applicable), your master track (A,U,BT,LA,MBE), and your master programme (MSc AUBS).

This research is about the design of a column made of interlocking cast glass components. The graduation studio is the 'Sustainable Design Graduation Studio' which is the graduation studio of the MSc Building technology.

Structures that are actually built with cast glass components are not sustainable. Either they are glued together, which cannot be removed very easily, or they have a structure which is holding the glass components that makes it a sub-structure that is not fully using the interesting aesthetics of glass as a material. When using interlocking-dry stacked cast glass bricks. The bricks can easily be replaced or melted into something else, and still keep this aesthetics. This would be a great step forward to a recyclable building structure.

Next to this, this thesis focused on finding a way to make the research in glass more cost-, time-, energy- and material-efficient, which would make designing in glass more sustainable . This way done by searching for a material that could replace testing glass to know their breaking pattern. This Building Technology is a track of the MSc Architecture, Urbanism and Building Sciences. This track is the preparing the students to be the link between the architect and the structural engineer. There seems to be a disagreement between architects and structural engineers; architects would like to have an open space without any interruption in light and view, and the structural engineers would like to have enough loadbearing elements (walls and columns) to transfer the loads safely to the foundation. Columns normally give an option to keep the open space with some interruptions in view and light. When these columns would be made out of glass, these elements would be translucent to transparent. This will be a good compromise between architect and structural engineer, which would be a logical starting point for a thesis in the master track Building Technology.

Aspect 3: Elaboration on research method and approach chosen by the student in relation to the graduation studio methodical line of inquiry, reflecting thereby upon the scientific relevance of the work.

This research will be done in different phases. The first phase is literature research in different subjects that will be met to come to a design of a cast glass interlocking column: glass as a material, glass columns, cast glass structures and interlocking geometries. After which a conceptual sketches will be made considering design principles and challenges of this literature research and the context of the Glasspalace in Heerlen (case study). In the second phase, the design phase, the options of the design will be further explored. Together with the design principles and challenges and the designs that have been made before in interlocking cast glass, different designs will be made with a hands-on approach. Ending this phase with a shape-design of the column and its components.

In the testing phase this shape- design will be tested with analytical analysis and numerical analysis. Later, the design final design with the calculated dimensions will be manufactured and tested physically. This experimental analysis will be about how the elements will break. This could be done with sugar glass and possibly real glass. After this, conclusions will be drawn about the research and the design.

The data found to create a cast glass column made of interlocking elements can be used as a database for technologies in the structural glass field, interlocking cast glass elements and column design. The directions that will be chosen in the design could help other designers in cast glass interlocking structures to make their own decisions based on the results of the design.

Furthermore, the design of the column that will be made can be applied not only in the Glasspalace, but in any other building. When applying this column physically in a building, big steps will be made towards the realisation of a building totally made out of glass. The application of this column can set an example for other architects and designers who desire a building completely made out of glass. With this, a glass building could become reality. Next to this, applying structural glass more and more, the regulations of structural glass should become easier applicable and therefore cheaper and more common.

Aspect 4: Elaboration on the relationship between the graduation project and the wider social, professional and scientific framework, touching upon the transferability of the project results.

In this thesis different elements are new in the research of structural glass. Ice has not been tested in this context, just like sugar glass. Both of them have potential of replacing the first cast glass elements in research. Next to this, a design with an element that has a slender neck has been designed. It could be said that glass has more potential in robust elements than in elegant elements. This is also due to the regulations that the structural glass currently has. When structural (cast) glass is more applied, the safety factors could be decreased, and therefore more shape freedom would arise. This thesis has been made under supervision of Faidra Oikonomopoulou and Marcel Bilow. Faidra is a researcher in structural glass at the TU Delft, who would be the perfect transfer from a thesis-report to further research in any of the mentioned topics.

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.

i & ii)
The idea of the elegant component was in the beginning that by slenderness of the neck, the column could be more transparent and use less material. Due to the calculations that determine the final dimensions and therefore shape of the component; the column and its elements have to become bigger to be still able to represent the wanted shape. This resulted in a column that somewhat more transparent but is using a lot more material then it would in components of another shape. The design turned out much bigger than I eventually thought it would be. The slenderness of the column made place for an interesting though robust column.

iii)
Application in the case study: the design asks for a lot of attention. The design is therefore placed in a building that is very clear and calm to look at. This is why the design would get a lot of attention in this building. But the building is already the most interesting building in the surrounding area; it does not need the extra attention. This is why it is questionable if the Glaspalace is the best to place for this column.
In this design of a column, a component will be produced that could also be used as a part of a wall or other construction parts. This makes it a multifunctional element. Because of its multifunctionality, there will only have to be a limited amount of moulds. These moulds are expensive and time consuming to make. Reducing these moulds is good for the environment and the price of the element.

Aspect 6: Explain the setbacks that occurred and what you learned from your mistakes

When after printing the first elements with the 3D printer, some problems occurred; the elements did not fit into each other because there was no tolerance taken into account. Next to this, the position of the printing was wrong. The next time an element was 3Dprinted, these improvements were applied. The first testing will be done with sugar glass because it is cheap and fast. Ice was the first option, but water needs to be cooled very slow, because otherwise internal cracks will appear. If it is able to predict the behaviour of glass due to its behaviour in sugar glass, research in (cast) glass could be much faster in the future.
Meanwhile, a testing method for the components was in development as well. The three designs were 3d printed to make silicone moulds of them. Later this silicone mould was used to produce ice-cubes and sugar glass in the shape of the component. The cooling process of the ice-components is complex this is why it is not possible to produce these ice components in a normal freezer. On the other hand, sugar glass seems to be a good solution to create the components in. The testing method is; making the components in sugar glass and comparing them to each other in breaking force and breaking pattern when shear force is applied. Later, between P4 and P5, the same element will be tested in soda-lime glass. This way the breaking pattern of the components made of sugar glass could be compared to the ones of soda-lime glass.
During the shear force tests that were done in sugar glass it turned out that sugar glass will not always react the same way to shear force as glass would. This could have something to do with the conservation time and temperature, the ingredients, the production temperature and the cooling time and temperature. This could be investigated further in research.

Conclusions

Glass is a material which is ten times as strong in compression as it is in tension. Borosilicate glass is the right type of glass to use in structures that have to be fire-resistant. It is possible to recycle glass 100%, but only when the glass is not joined with an adhesive.
Buckling in a column could be prevented by creating a large and round cross-section, which would result in a high second moment of area. A column made of interlocking elements was appointed to be the most interesting to research in this thesis. When evaluating structures made of cast glass, we could see that these have a substructure, or are bonded with an adhesive interlayer. Both of these options seem less logical to apply, then a dry connection with interlocking cast glass components.

For this interlocking mechanism, the protrusions and depressions-type are in the case of a free-standing column found to be the best option. limits on transparency, young's modulus, compressive strength, maximum service temperature, durability against UV radiation and flammability have found the suitable dry interlayer TPU (ester, aromatic, shore 85, flame retarded) After the literature study, a list of design principles and challenges has been made. This list was combined with designs that have already been made in cast glass, to create concepts. An elegant component design, combined with a spherical interlocking element has been chosen to develop further. When preventing buckling and making sure the column is stable, even when one element is missing, minimum dimensions of the component could be calculated. These dimensions and the component shape created the final design of the element and the column. This design is 3Dprinted, after which a mould of silicone was made.

This mould was used to produce ice and sugar glass elements. Ice and sugar glass were both selected to be evaluated on their breaking behaviour, breakage they could be similar to the cracking pattern of glass. It was not possible to create crystal clear ice, with the with the resources we had at our disposal. Sugar glass was a material that could be produced; later it turned out that, it is a material that is hard to conserve when wanting to keep its brittle features.

The sugar glass has been tested in by loading it in shear stress. These tests gave varying results: 2 of them broke in a similar way glass would, but 2 of them deformed permanently. It is not possible to draw binding conclusions out of this experiment. But it is thought that if the variables are optimal during the production and conservation of sugar glass, sugar glass is still an option to investigate concerning the cracking behaviour of glass.

The final design is an interlocking glass component that could construct a column with ten subcolumns. This design could create an exciting variety of reflectivity and transparency, which will give the design an interesting aesthetic look. It will be an eyecatcher in the room, due to its size, material and unique component shape. This design is based on the requirements of minimum load it should be able to hold for, and the dimensions of the Glaspalace, located in Heerlen. But due to the multifunctionality of the components, this design could be used as a column with more or fewer subcolumns, but also as an internal wall, in any other building.

Recommendations

During this research, the goal was to answer the main research question:

How can we design and produce a safe, engineering sound, re-stackable, free-standing column made of multifunctional cast glass interlocking components?

This was done by a design of a free-standing loadbearing column made of interlocking dry-stacked cast glass components. This design is completed for the graduation research but could be researched upon much more. Therefore different topics in this research are highlighted in this chapter.

In this thesis, ice and sugar glass has been produced with resources that were within reach. We saw that this approach did not give the wanted effect. Still, both of the materials could be produced in optimised circumstances and tested to research the breaking pattern of the components.

The component has, until now, only been tested in shear force in sugar glass on 1:3 scale. This is interesting, but examining the same element in the other test-setups would be valuable as well. The reaction of the components when they are placed in a column made out of 10 subcolumns, it is visible to see the behaviour of the components in connection with each other. This could show if the safety factors that are taken are right. With this research, the critical force could be adjusted, which could change the element to a, possibly, more slender element. The tests that should be done to confirm the strength of the component are shear force test, compression force test and redundancy test in the desired composition.

The material that could be used in the interlocking sphere is determined analytically. To know if these materials will hold the applied forces while being in direct contact with glass it is important that these materials will be tested experimentally. To know if marble and steel could be placed onto the glass directly in the interlocking part, we have to test this in real size and real shear forces. This way the research of combining other materials to glass could get more common.

The component design is easy to make in other materials apart from glass. The shape will not breaks easily, because of the absence of sharp angled corners. The component-shape could be poured with a liquid material that hardens, and, like the 1:1 mockup is made, with layers that are stacked. Pouring this shape is the most logical way to produce this component, due to its curved shape.

The size of the component and the column are based on the amount of force that will be applied to the column. Because this column is the column on the ground floor of a multiple-story building, the forces on the column are relatively high. To hold these forces, the component and the column became big. Next to this, the component could have been more elegant when the neck of the element would be smaller. This could happen when the column is placed in a building with fewer levels or a pavilion. The elegant shape could be fully appreciated when it is applied in a one-story building, like the Museum Voorlinden in Wassenaar. In a museum like this, the column will be appreciated and shown to the world as a new type of glass columns or walls which could also be seen as an art piece.

With these elements, columns of different widths could be made, but also walls could be constructed. Walls that are constructed with this component will have holes in them, they will mainly be used as internal walls. This is why these elements are very multifunctional and could, therefore, be used in many compositions and locations.
In the glasspalace, the column would replace other columns that are more slender and sleek. This is why it would be strange to say that the glass column design is elegant because it is much less elegant than the columns that are already there. Next to this, the glasspalace is one of the architectural delights of the area; it does not need another column to make the building attractive. But due to the cultural program of the building, it would be interesting to place a piece of the column in an exposition, to see what is possible with structural cast glass.

Producing this column will be very expensive. The components are enormous and will have to cool very long. Next to this, the components will weight more than 25 kg, which results in that at least two people will have to carry these components, or they have t be moved by machines. But it has to be said, that every innovative way of building starts with very high costs, and could become much less when more is known about this way of these type of constructions. Also, when the steel pressure mould is used multiple times, the costs per element become less and less.

During the calculations of this research, thoughts have been about using a steel element in the middle to prestress the column. This would bring the column even more in compression with an extra force that is applied. Due to the large force that is applied by the glasspalace, this seemed devious. But when the design is placed in a locating with lower applied, pre-stressing the column could help to reduce the thickness of the elements and column.

When an element breaks in this design, the elements are able to fly around in space and hurt people. To prevent this, thoughts were about making a layer around the component like a socket that would hold the pieces together. But due to the durability of the plastics, this would result in a setback of the aesthetics of the component. Other research should find out how to make the components safer when breaking, without compromising the aesthetics.

From the start of this research, fire safety has been on top if the requirement-list. There have been steps made towards a safe fire design; borosilicate is the glass type of which the components are made. Next to this, the holes in the structure will even the heat in and around the column. Also, sprinklers will be placed around the column. Yet, there still is a lot left to research concerning fire-safety of a cast glass column. Moreover, experiments with fire would be valuable.

Different research has been done in interlocking cast glass. But I think that researching interlocking bent float glass could be interesting as well. These could be easier to produce and therefore much cheaper.
My recommendation concerning designing in cast glass would be not to try to create an element that should look elegant. Glass is a material that is strong in compression, this should be visible in the design. When not doing so, an inefficient design will be created regarding material use.

References

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Table 17. Inhoud

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Appendices

Calculation of the load on the Glasspalace

	permanent load		Imposed Load	safety factor	
Roof (with roofterras, +25)	kN		kN	ψ	
Imposed load			23	0	0
Roof itself	155,23				
Column	3,66				
		159			
+23					
Imposed load			92	0,4	37
Floor itself	81,46				
Column	6,29				
		88			
+19					
Imposed load			58	0,5	29
Floor itself	81,46				
Column	7,25				
		89			
+15					
Imposed load			92	0,4	37
Floor itself	81,46				
Column	8,54				
		90			
+12					
Imposed load			92	0,4	37
Floor itself	81,46				
Column	9,95				
		91			
+9					
Imposed load			92	1	92
Floor itself	81,46				
Column	13,30				
		95			
+5					
Imposed load			115	0,25	29
Floor itself	81,46				
Column	32,33				
		114			
Total	G	725,34		Q	260,6571
partial factor	γ	1,2		γ	1,5
UGT	1261,4 kN				

Calculation of the load on the Glasspalace: input

Heights Floors

+0 to +5	5,65	m
+9	3,40	m
+12, +15, +19	3,20	m
+23	3,78	m
+25	2,93	m

Diameters of columns

+0 to +5	0,55	m
+ 9	0,46	m
+ 12	0,41	m
+ 15	0,38	m
+ 19	0,35	m
+ 23	0,30	m
+25	0,26	m

Weight of the columns per floor

Weight of glass	2500	kg/m3	24,53	kN/m3
Weight of concrete	2400	kg/m3	23,54	kN/m3
+0 to +5	1,32	m^3	32,33	kN
+ 9	0,57	m^3	13,30	kN
+ 12	0,42	m^3	9,95	kN
+ 15	0,36	m^3	8,54	kN
+ 19	0,31	m^3	7,25	kN
+ 23	0,27	m^3	6,29	kN
+25	0,16	m^3	3,66	kN

Imposed Floor Load

	width	depth	area	
floor surface of column 15	4,95	4,66	23,067	m^2

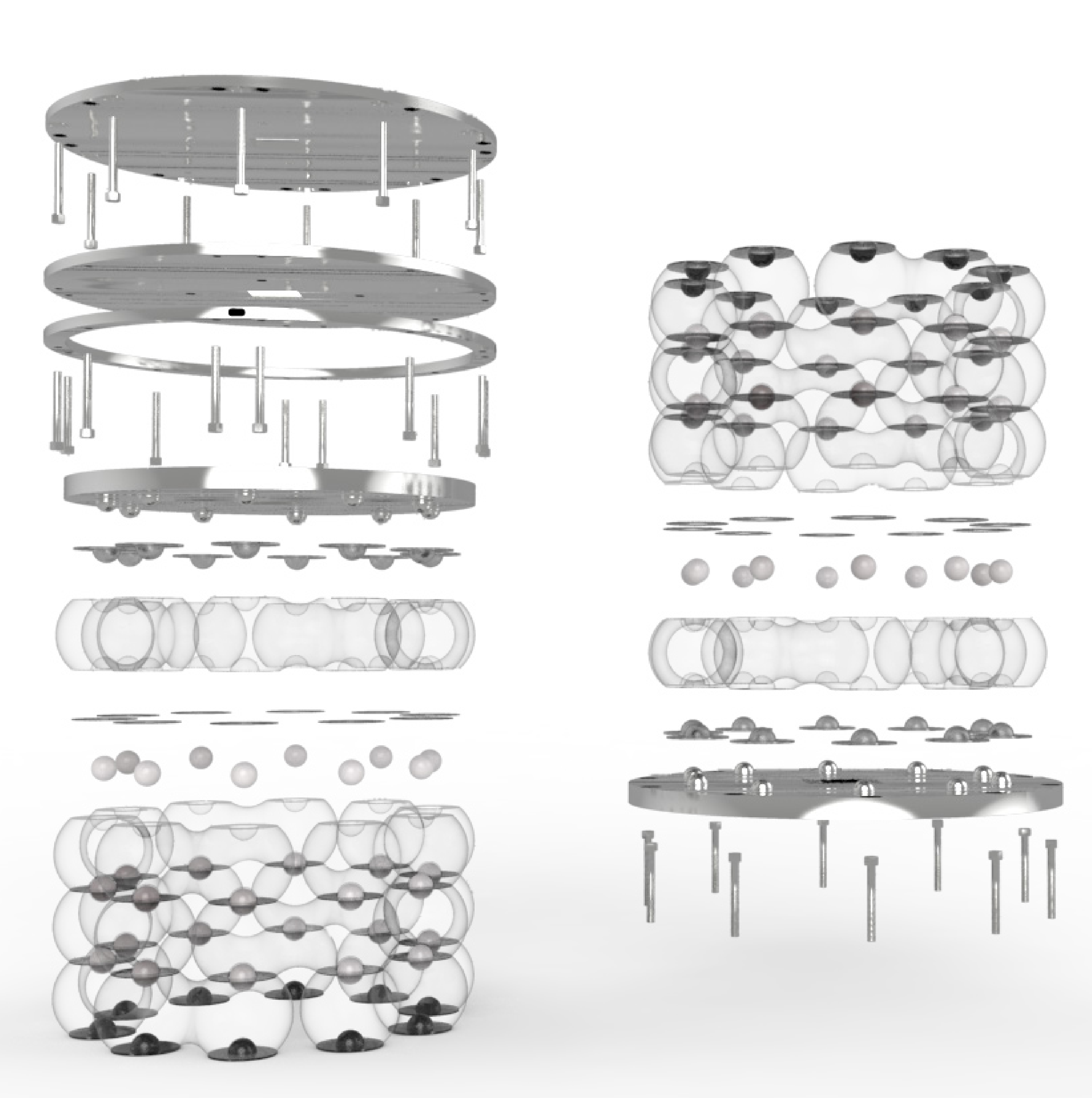
Floor	**Class**					Ψ
+0 to +5	C5	5	kN/m^2	115,34	kN	0,25
+ 9	E1	4	kN/m^2	92,27	kN	0,4
+ 12	E1	4	kN/m^2	92,27	kN	0,4
+ 15	E1	4	kN/m^2	92,27	kN	0,4
+ 19	B	2,5	kN/m^2	57,67	kN	0,5
+ 23	C5	4	kN/m^2	92,27	kN	0,4
+25	C5	1	kN/m^2	23,07	kN	0

Permanent Floor Load

	width	depth	area	
floor surface of column 15	4,95	4,66	23,067	m^2

Floor	312	kg/m2	3,06	kN/m2	70,60	kN
Floor finish	48	kg/m2	0,47	kN/m2	10,86	kN
Total permanent load per floor					81,46	kN
Roof	336	kg/m2	3,30	kN/m2	76,03	kN
Rooffinish	350	kg/m2	3,43	kN/m2	79,20	kN
Total permanent load roof					155,23	kN

Calculation of the load on the Glasspalace: input & endconnection



General

Column					
L	Total length of the column			5,65	*m*
Ftotal	Total Force	1261	*kN*	1261388,23	*N*
n	Buckling number			4	-
Fcritical	Total force x buckling number	5046	*kN*	5045553	*N*
Fposttension	Total force x buckling number	315	*kN*	315347	*N*
L buckling K value	The length needs to be *...			1,00	-

Glass					
E	Elastic modulus (YM) of borosilicate glass	63000,00	*N/mm2*	63000000000	*N/m2*
Max. Compressive stress		280	*Mpa*	2,8E+11	*N/m2*
Max. Tensile stress		28	*Mpa*	28000000	*N/m2*

Calculation of the radius of the column

Calculation of the Radius of column	BUCKLING OF SUBCOLUMN IS DETERMINATIVE			
eccentricity	distance form the middle place	16,97 mm	0,0170 m	L/333
wo	initial curvature	11,30 mm	0,0113 m	L/500

BUCKLING

Lbuckling		5,65 m
I		0,0002590 m4
R solid min	135 mm	0,13 m
Dsolid min	270 mm	0,27 m

Number of subcolumns	I	min Radius (I)	outside interlock		Max. sphere interlock		area	direct stress	bending stress	com-tension -28.000.000	Total stress (max 280 Mpa)	
6	0,0000432 *m4*	0,086 m	88 *mm*	0,09 *m*	0,0473 *m*	47 *mm*	0,017 *m2*	48597535 *Nm2*	29082403 *Nm2*	*19.515.132*	77679938 *Nm2*	78 *Mpa*
8	0,0000324 *m4*	0,080 m	82 *mm*	0,08 *m*	0,0447 *m*	45 *mm*	0,015 *m2*	42462925 *Nm2*	27099512 *Nm2*	*15.363.413*	69562437 *Nm2*	70 *Mpa*
10	0,0000259 *m4*	0,076 m	76,7 *mm*	0,08 *m*	0,0357 *m*	36 *mm*	0,014 *m2*	34856956 *Nm2*	25347958 *Nm2*	*9.508.998*	60204914 *Nm2*	60 *Mpa*
12	0,0000216 *m4*	0,072 m	74 *mm*	0,07 *m*	0,0398 *m*	40 *mm*	0,012 *m2*	34367234 *Nm2*	24455657 *Nm2*	*9.911.577*	58822891 *Nm2*	59 *Mpa*
14	0,0000185 *m4*	0,070 m	71 *mm*	0,07 *m*	0,0369 *m*	37 *mm*	0,012 *m2*	31176026 *Nm2*	23464211 *Nm2*	*7.711.815*	54640238 *Nm2*	55 *Mpa*
16	0,0000162 *m4*	0,067 m	68 *mm*	0,07 *m*	0,0296 *m*	30 *mm*	0,012 *m2*	26783084 *Nm2*	22472766 *Nm2*	*4.310.318*	49255849 *Nm2*	49 *Mpa*

RADIUS CENTER OF ELEMENT		Subcolumns	6		8		10		12		14		16		18	
		Force per subcolumn N	210231		157674		126139		105116		90099		78837		70077	
Diameter of total column		**Radius of total column** m	length	radius middle	length	radius middle	length	radius middle	length	radius middle	length	radius middle	length	radius middle	length	radius middle
500	*mm*	0,25	0,250	0,084	0,191	0,070	0,155	0,061	0,129	0,054	0,111	0,048	0,098	0,046	0,087	0,042
550	*mm*	0,275	0,275	0,087	0,210	0,072	0,170	0,062	0,142	0,055	0,122	0,050	0,107	0,047	0,096	0,044
600	*mm*	0,3	0,300	0,090	0,230	0,074	0,185	0,064	0,155	0,057	0,134	0,052	0,117	0,048	0,104	0,045
650	*mm*	0,325	0,325	0,092	0,249	0,076	0,201	0,066	0,168	0,059	0,145	0,053	0,127	0,050	0,113	0,046
700	mm	0,35	0,350	0,094	0,268	0,078	0,216	0,068	0,181	0,060	0,156	0,054	0,137	0,051	0,122	0,047
750	mm	0,375	0,375	0,096	0,287	0,080	0,232	0,069	0,194	0,061	0,167	0,055	0,146	0,052	0,130	0,048
800	mm	0,4	0,400	0,099	0,306	0,082	0,247	0,071	0,207	0,063	0,178	0,057	0,156	0,053	0,139	0,049
850	mm	0,425	0,425	0,101	0,325	0,084	0,263	0,072	0,220	0,064	0,189	0,058	0,166	0,054	0,148	0,050
900	mm	0,45	0,450	0,102	0,344	0,085	0,278	0,074	0,233	0,065	0,200	0,059	0,176	0,055	0,156	0,051
950	mm	0,475	0,475	0,104	0,364	0,087	0,294	0,075	0,246	0,066	0,211	0,060	0,185	0,056	0,165	0,052
1000	mm	0,5	0,500	0,106	0,383	0,088	0,309	0,076	0,259	0,068	0,223	0,061	0,195	0,000	0,174	0,000

Calculation of loads with eccentricity and 10 subcolumns

l	0,247	m
when		
subcolumns	10	
total force	1261388,23	N
breaking elements	1	
broken subcolumns	2	
diameter of the column	0,8	m
radius of the column	0,4	m
	36	
2,4,6,8	0,235114101	
radius interlocking outside	0,082	m
radius interlocking inside	0,045	m
area per subcolumn	0,0149	m2
I	3,23799E-05	m4
w	0,0113	m

coordinated of points		x	y
centerpoint		0	0
	1	0,000	0,400
	2	0,235	0,324
	3	0,380	0,124
	4	0,380	-0,124
	5	0,235	-0,324
	6	0,000	-0,400
	7	-0,235	-0,324
	8	-0,380	-0,124
	9	-0,380	0,124
	10	-0,235	0,324

						-	280.000.000.000
Distance away from the midpoint		distance	I	normal	bending	tension (only-)	compression
1		0,462348834	0,003175034	42462925	7556778	34.906.146	50.019.703
2		0,411150927	0,002510796	42462925	9555946	32.906.979	52.018.871
3		0,352595697	0,001846558	42462925	12993382	29.469.543	55.456.307
4		0,31094116	0,001436036	42462925	16707820	25.755.105	59.170.745
5		0,31094116	0,001436036	42462925	16707820	25.755.105	59.170.745
6		0,352595697	0,001846558	42462925	12993382	29.469.543	55.456.307
7		0,411150927	0,002510796	42462925	9555946	32.906.979	52.018.871
8		0,462348834	0,003175034	42462925	7556778	34.906.146	50.019.703
Radius		0,384					

						-	280.000.000.000
Distance away from the midpoint		distance	I	normal	bending	tension (only-)	compression
	1	0,450	0,003001731	56617233,2	22992092,57	33625140,63	79609325,78
	2	0,325	0,001568717	56617233,2	43995225,97	12622007,23	100612459,2
	3	0,214	0,000683066	56617233,2	101038619,8	-44421386,6	157655853
	4	0,214	0,000683066	56617233,2	101038619,8	-44421386,6	157655853
	5	0,325	0,001568717	56617233,2	43995225,97	12622007,23	100612459,2
	6	0,450	0,003001731	56617233,2	22992092,57	33625140,63	79609325,78
radius		0,330					

						-	#VERW!
Distance away from the midpoint		distance	I	normal	bending	tension (only-)	compression
	1	0,332	0,00163381	84925849,81	95045414,48	-10119564,68	84925849,81
	2	0,143	0,000305334	84925849,81	508578719,3	-423652869,5	84925849,81
	3	0,143	0,000305334	84925849,81	508578719,3	-423652869,5	84925849,81
	4	0,332	0,00163381	84925849,81	95045414,48	-10119564,68	84925849,81
radius		0,238					

Calculation of loads with eccentricity and 8 subcolumns

when		
subcolumns	8	
total force	1261388,23	N
breaking elements	1	
broken subcolumns	2	
diameter of the column	0,8	m
radius of the column	0,4	m
	45	
2,4,6,8	0,282842712	
radius interlocking outside	0,082	m
radius interlocking inside	0,045	m
area per subcolumn	0,0149	m2
I	3,23799E-05	m4
w	0,0113	m

coordinated of points		x	y
centerpoint		0	0
	1	0,000	0,400
	2	0,283	0,283
	3	0,400	0,000
	4	0,283	-0,283
	5	0,000	-0,400
	6	-0,283	-0,283
	7	-0,400	0,000
	8	-0,283	0,283

					-	280.000.000.000
Distance away from the midpoint	distance	I	normal	bending	tension (only-)	compression
1	0,461	0,003161967	56.617.233	13104314,28	43.512.919	69.721.547
2	0,371	0,002041697	56.617.233	20294591,21	36.322.642	76.911.824
3	0,290	0,001249547	56.617.233	33160351	23.456.882	89.777.584
4	0,290	0,001249547	56.617.233	33160351	23.456.882	89.777.584
5	0,371	0,002041697	56.617.233	20294591,21	36.322.642	76.911.824
6	0,461	0,003161967	56.617.233	13104314,28	43.512.919	69.721.547
	0,374					

						-	-
Distance away from the midpoint		distance	I	normal	bending	tension (only-)	compression
	1	0,385	0,002202439	84.925.850	59863919,04	25.061.931	144.789.769
	2	0,187	0,000522035	84.925.850	252562966	-167.637.116	337.488.816
	3	0,187	0,000522035	84.925.850	252562966	-167.637.116	337.488.816
	4	0,385	0,002202439	84.925.850	59863919,04	25.061.931	144.789.769
radius		0,286					

Calculation of loads with eccentricity and 6 subcolumns

when		
subcolumns	6	
total force	1261388,23	N
breaking elements	1	
broken subcolumns	2	
diameter of the column	0,8	m
radius of the column	0,4	m
	60	
2,4,6,8	0,346410162	
radius interlocking outside	0,082	m
radius interlocking inside	0,045	m
area per subcolumn	0,0149	m2
I	3,23799E-05	m4
w	0,0113	m

coordinated of points	x		y
centerpoint		0	0
	1	0,000	0,400
	2	0,346	0,200
	3	0,346	-0,200
	4	0,000	-0,400
	5	-0,346	-0,200
	6	-0,346	0,200

1	0,400
2	0,400
3	0,400
4	0,400
5	0,400
6	0,400
	0,400

						-	280.000.000.000
Distance away from the mid	distance		I	normal	bending	tension (only-)	compression
	1	0,436	0,0028	84925849,81	30967555,1	53958294,7	115.893.405
	2	0,265	0,0010	84925849,81	84054792,4	871057,3832	168.980.642
	3	0,265	0,0010	84925849,81	84054792,4	871057,3832	168.980.642
	4	0,436	0,0028	84925849,81	30967555,1	53958294,7	115.893.405
radius		0,350					

						-	-
Distance away from the mid	distance		I	normal	bending	tension (only-)	compression
	1	0,2	0,000594113	169851699,6	588383547	-418531847,3	
	2	0,2	0,000594113	169851699,6	588383547	-418531847,3	
radius		0,200					

Ratio of length of the component and the radius of the neck

N	Rflat	Rinterl		lenth	Rmiddle	diameter big sphere	flat part	weight spl	ratio (length:middler)	
6	0,088	0,047	500	0,250	0,084	260	34,7	20,5	3,0	with smaller spher also the middle is flat
			600	0,300	0,090			-	3,4	weight
8	0,082	0,045	500	0,191	0,070	220,0000	36,8	11,34	2,7	
			600	0,230	0,074	is not possible			3,1	not possible
			700	0,268	0,078				3,4	not possible
			800	0,306	0,082				3,7	not possible
10	0,077	0,036	600	0,185	0,064	200,0000	33,7	10,3	2,9	
			700	0,216	0,068	220,0000	31,6	12,7	3,2	
			800	0,247	0,071	230,0000	29,8	14,4	3,5	BEST!
			900	0,278	0,074	240,0000	28,3	16,8	3,8	column too wide+ weigth
			1000	0,309	0,076			-	4,1	
12	0,074	0,040	700	0,181	0,060	200,0000	32,8	8,6	3,0	
			800	0,207	0,063	210,0000	30,7	10,5	3,3	
			900	0,233	0,065	215,0000	29,8	11,4	3,6	column too wide
			1000	0,259	0,068	220,0000	29,2	12,4	3,8	column too wide
14	0,071	0,037	800	0,178	0,057	195,0000	34	7,9	3,1	
			900	0,200	0,059	200,0000	33	8,7	3,4	column too wide
			1000	0,223	0,061	205,0000	32	9,6	3,6	column too wide

Glass columns previous

Column Types	Structure	Name	Location	Architect&Engineer	Year	Length	Width	Interlayer	thickness of elements (mm)	number of glasss layers	Cross-section	axial loading (kN)	σ failure (MPa)	Realized
Bundled	Column	ABT office	Arnhem, the Netherlands	Rob Nijsse	2003	1,6	90	clear UV-curing adhesive	30	7	*		-	not realized
Bundled	Column	bundled glass column	Universiti Teknologi MARA,Malaysia	Mohd Khairul Kamarudin, Peter Disney and Gerard Parke	2016	1,5	3 x 24	structurlal silicone		3	O & *	13,37	26,4	Research
Bundled	Column	Bundled Cylinder	TU Delft, the Netherlands	Faidra Oikonomopoulou	2015	1,5					*	331-509	130-199	Research
Bundled	Column	transparent column	TU Delft, the Netherlands	Erik van den Broek	2016	2,4	(22)-30	between gl;ass and steel	22	-	*	112	63MPa	research
Cast	Art	Solid Water	Venice, Italy	Ronin Horn	2010	0,508	1420				O	-	-	Realized
Cast	Art	Danteum	Rome, Italy	Giuseppe Terragni, pietro Lingeri	1942			-	-	-	O	-	-	not realized
Cast	Column	Glass Columns	TU Delft, the Netherlands	Robert Akerboom	2016						O			Research
Cast	Column	Glass Tower	TU Delft, the Netherlands	Elisavet Felekou	2016	0,65	105x105	delo-photobond 4468	65	10 hor	□	1412	128	Research
Cylinder	Art	Glassbaum	Aachen, Germany	Ulrich Knaack	1998						O			Realized
Cylinder	Column	Tubular Laminated		Pastinink and Fred Veer	1999	0,55	40	UV curing resin		4	O	30	900	Research
Cylinder	Column			Achenbach and Jung	2003	4,1	150	no	5	1	O	221	97,3	Research
Cylinder	Column		TU Delft, the Netherlands	E. van Nieuwenhuijzen	2005	1,5	(95)-120	low-shrinkage clear resin	5	2	O	137-196	40,6-57,9	Research
Cylinder	Facade	Tower place	London, UK	Arup Facade engineering	2002			reinforcement with steel cables			O			Realized
layered sheets	Art	The Popano Park water feature	Florida, USA	Carey Jones, Malishev Wilson	2006						Random	-	-	Realized
layered sheets	Column	Stacked column	TU Eindhoven, the Netherlands	Roy van Heugten	2013	0,615	100x100	Silvertape 8502	12	50 hor	□	525	52,5	Research
layered sheets	Facade	Laminata house of glass	Leerdam, the Netherlands	Kruunenberg Architecten	2001						Rectangular			Realized
Profiled	Column	Several profiled columns	TU Delft, the Netherlands	Eline Ouwekerk	2011	1	116x100	Hercuseal polymer	8	1	H (□, T, x)	212-225	88,4-106,6	Research
Profiled	Column	Town Hall	St-germain-en-lave, France	Brunet Saunier Architecture	1994-2000	3,3	400x400	hard adhesive	10/15/10		x	430	16,06	Realized
Profiled	Column	Danfoss headquarters	Nordborg, Denmark	Schmidt Hammer Lassen Architects, Anne Bagger	2009-2010	5,5	449x449	clear silicone	12	3	x	575	18,53	Realized
Profiled	Column	Coffee-house	Goppingen, Germany		2006									Research

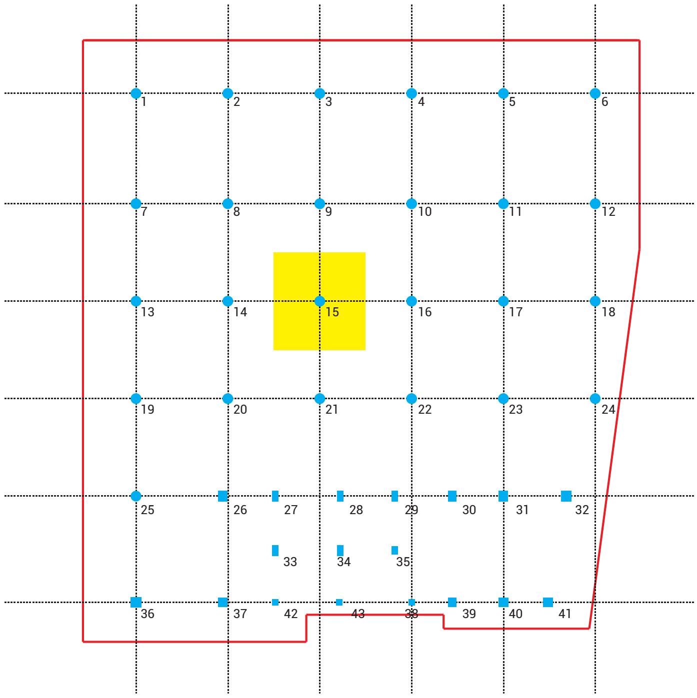
Cast glass structures & annealingtime bricks

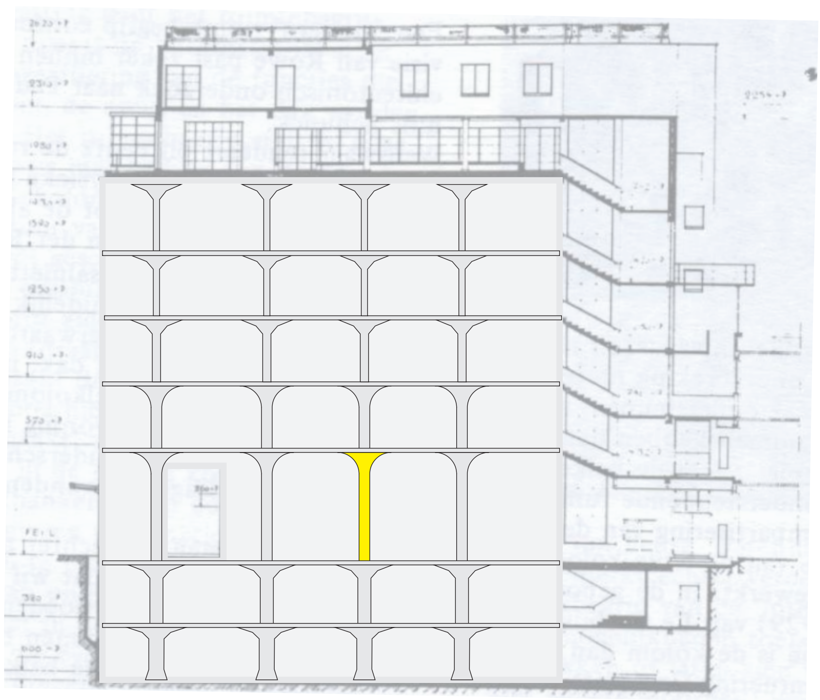
Name	Location	Structure	Height	Width	Area (m2)	Block length (mm)	Block width (mm)	Block height (mm)	Block Volumne (L)	weight (kg)	cooling time per block	Interlayer / substructure	Thickness interlayer (mm)	Curing time per block (sec)	Tolerance blocks (mm)	Year	Architect	Structural Engineer	Costs	Weight (kg)	Quantity Blocks	Glass Type	Time Realisation
Crown Fountain	Chicago, Illinois (USA)	2 towers	15,2	7 x 4,9	919,8	254	127	51	1,65							2004	Kreuck Sexton Architects ·Artist: Jaume Plensa	Halvorsen Kaye SE	€ 14.000.000,00		22500		4 months for producing blocks
Atocha Memorial	Madrid, Spain.	Shell structured facade	11,13	diameter 8 to 10,5	323,27085	300	200	70	4,20	8,40	20	liquid-acrylic adhesive , ETFE foil	2	240	1	2007	FAM Arquitectura y Urbanismo S.L.	Schlaich, Bergermann und Partner (SBP). Fhecor.	€ 6.000.000,00	135098	15100	Borosilicate glass	1,5 Year Project and development. 1 Year Construction
Optical Glass House	Hiroshima, Japan	facade	8,6	8,6	73,96	235	50	50	0,59			stainless steel bolds+ stailess steel flat bars				2012	Hiroshi Nakamura	Yasushi Moribe Horibe	?	11793	6000	Borosilicate glass	
Chrystal Houses	Amsterdam, the Netherlands	facade	10	12	120	210	105	65	1,43	3,69	8	Delo Photobond 4468	0,2-0,3	10	0.25	2016	MVRDV	F. Oikonomopoulou T. Bristogianni ·f. A. Veer · r. Nijsse	?		6500	Soda-Lime Glass	

Name	Length (dm)	Width (dm)	Height (dm)	Volumne (L)	Weight (kg)	Annealing (h)	Glass type
Chrystal Houses	2,1	1,05	0,65	1,43	3,50	8	Soda Lime glass
Atocha Memorial	3	2	0,7	4,20	8,40	20	Borosilicate glass
crystal houses test 2	2,1	1,575	0,65	2,15	5,37	22	Soda Lime glass
crystal houses test	2,1	2,05	0,65	2,80	7,17	38,0	Soda Lime glass
Opposites of white	10,6	3,71	3,14	123,48		2880	?
Nine Liquid Incidents	4,55	9,15	3,14	130,73	800	6480	?
Hale telescope	51	6,6	3,14	1056,92		7200	?

Name designer	Depth (dm)	Width (dm)	Height (dm)	Volumne (L)	Weight (kg)	Annealing (h)	Shape
Lida Barou	1,2	5	0,55	2,7	6,021	70 to 120	Rectangular
Robert Akerboom	?	?	?	?	?	?	Round
Mike Aurik	1,5	3	1,5	6,75	16		Rectangular
Erwin Jacobs.	1,5	3	1,2	5,4	13,5		Rectangular

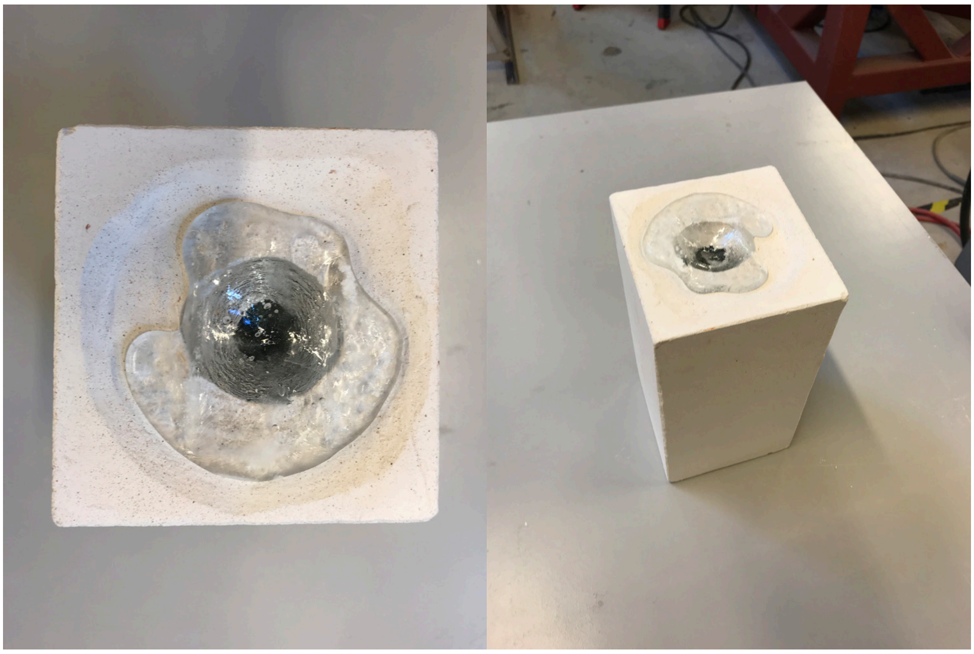
Plan and section of the glass palace, in yellow , the column that will be replaced and teh surface that it will bear.





Crystal cast & unprocessed glass

1



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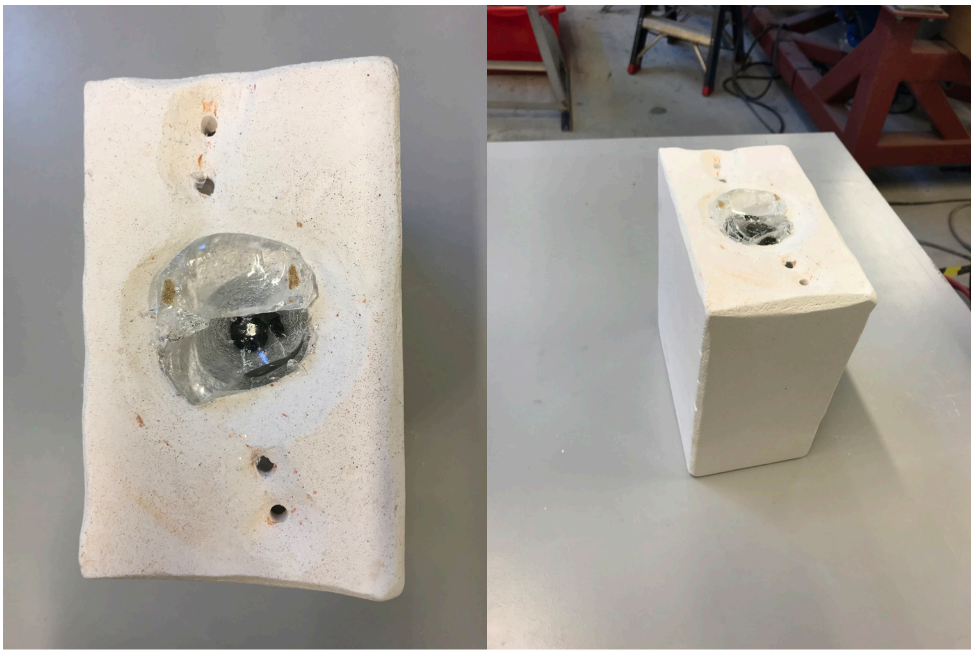




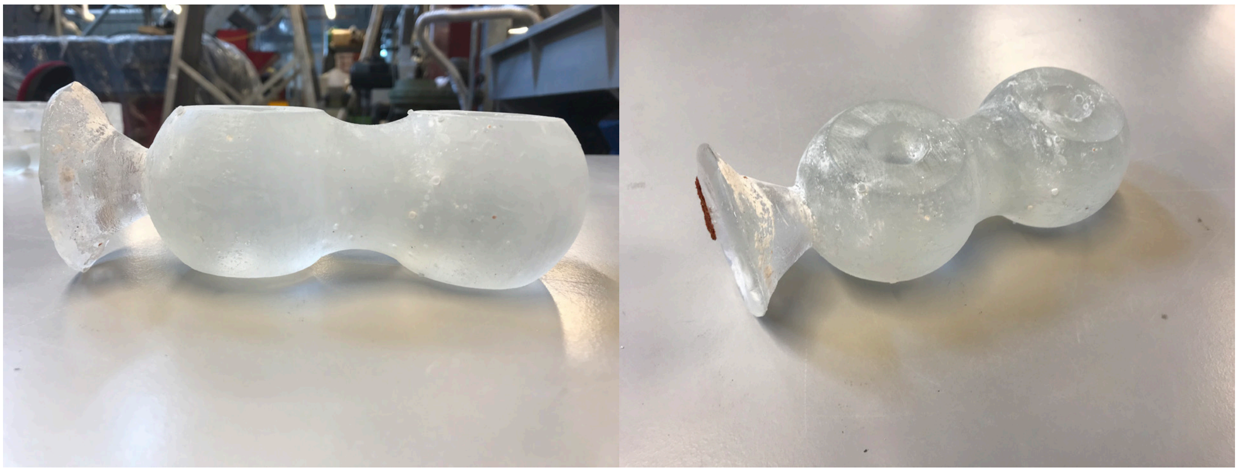

2


3


Unprocessed glass

1

2



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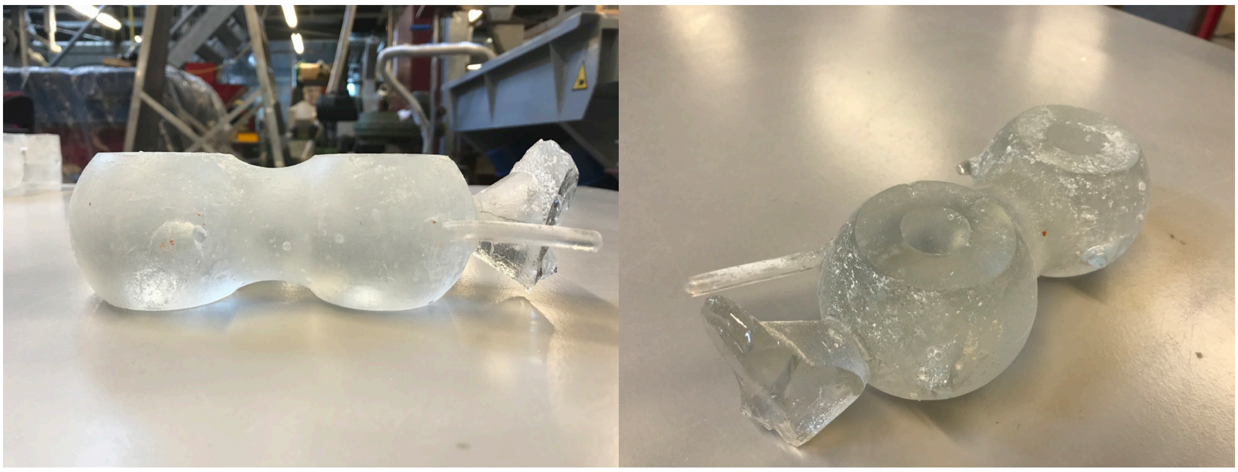
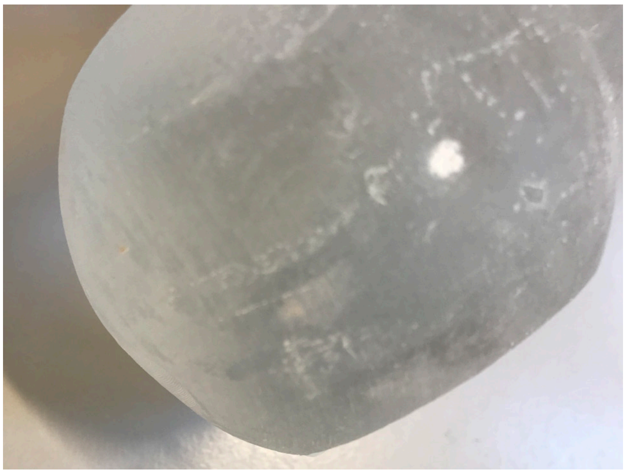
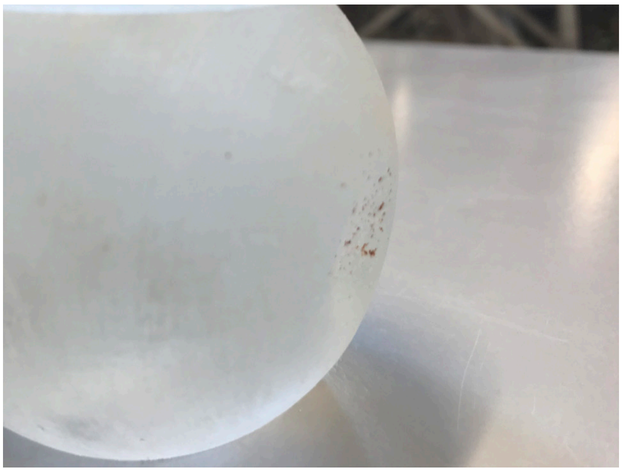




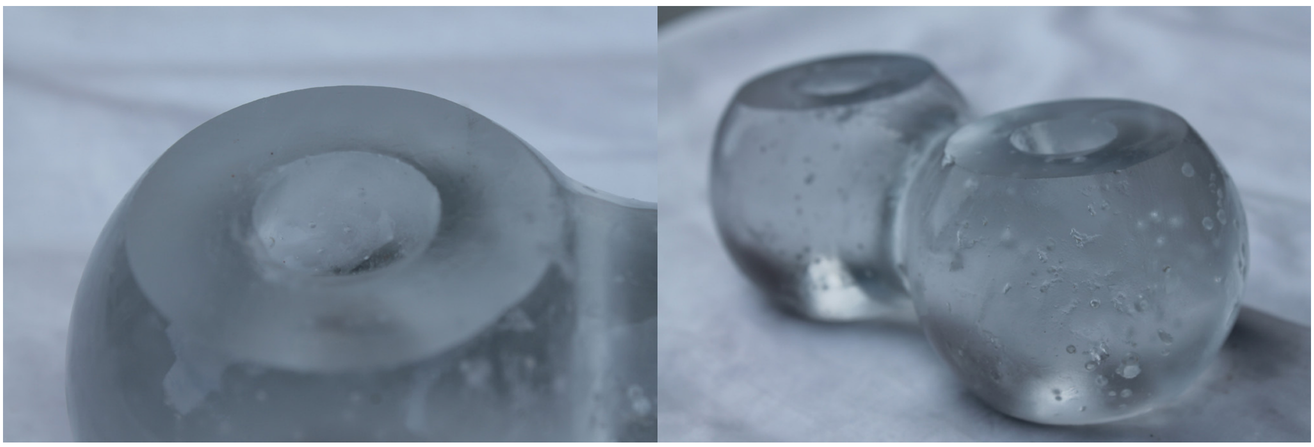


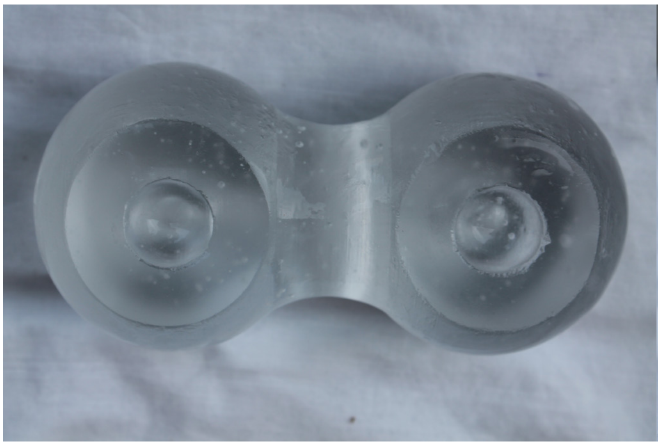
Processed glass

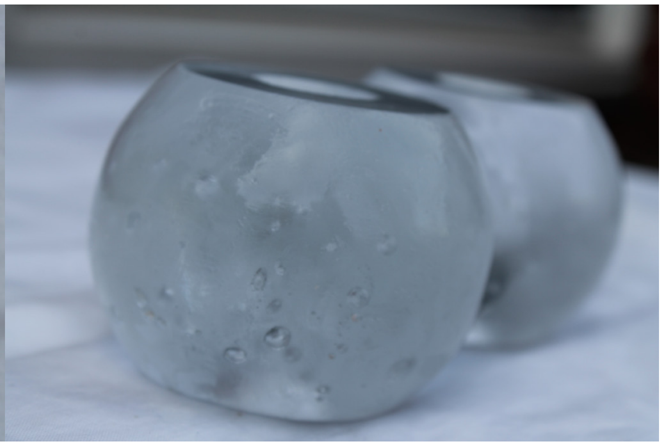
1

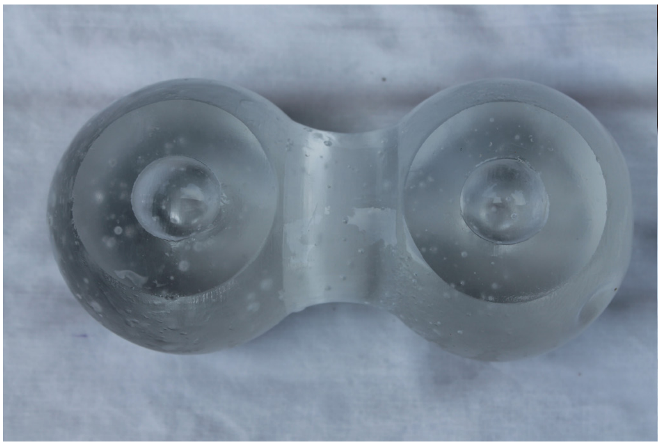
2

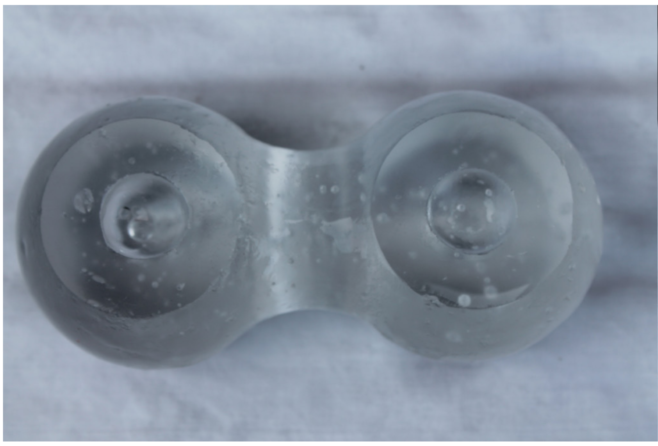
3





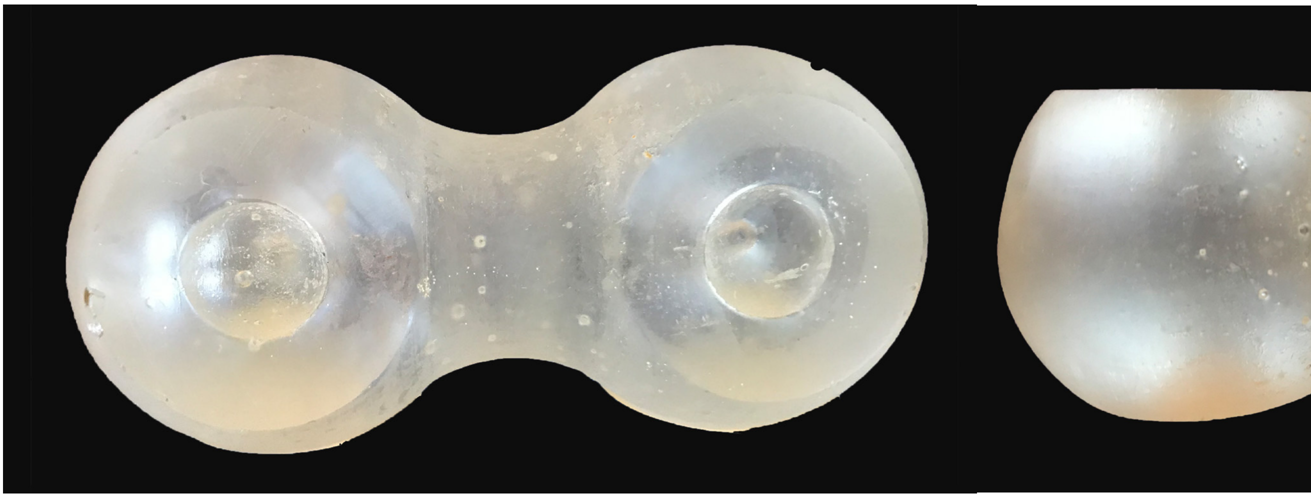






Polarised view

1



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3