Freeform Transparency

Introducing a novel fabrication technique for curved glass utilizing knitted moulds

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Abstract

Glass, a transparent and durable material with significant structural potential, is extensively used for architectural and structural applications in buildings. Existing approaches mostly use float glass, which is confined by planar designs, resulting in two-dimensional facades. Several examples of curved glass applications exist which, due to the limitations of current fabrication techniques, result in repetitive panels. Emerging architectural trends demand more fluid, three-dimensional freeform shapes, which present glass shaping processes cannot provide without incurring excessive costs and material waste in the fabrication process.

Research in other materials shows that flexible moulds are able to produce complex geometrical results. More recently, knitted fabric formworks have proven to be very successful in creating concrete shells of high complexity and low material usage and waste.

This thesis aims to address the gap by investigating the viability of using knitted basalt moulds for glass slumping, a novel fabrication approach that might allow for the manufacture of customizable, freeform curved glass components. The research investigates the possibility of this technology to accomplish extreme geometries while remaining simple and cost-effective in mould manufacture.

The methodology of this thesis consists of a thorough literature research, experimental testing and a design application. The literature study investigates and compares present glass curving technologies and also the moulds used for each method to visual, geometrical, structural, and sustainability criteria. Flexible mould applications in other materials are also researched and compared to the ones used for glass.

The second part of the thesis is an experimental exploration. Basalt yarn is chosen to create hand-woven and CNC-knitted moulds to test with glass slumping. The experimental phase involves testing several knitted basalt moulds and combinations with coatings to determine ideal material combinations in order to improve surface quality and geometric precision. After reflecting on the experiment results, experimental data is used to create a final prototype attempting to achieve geometrical control and repeatability to prove the potential of the proposed fabrication technique.

Finally, the third part of the thesis is a design application. Casa da Musica in Porto is chosen as a case study to recreate its glass façade in a freeform shape. Connection details between the glass panels are designed for the proposed facade design and the proposed fabrication of each panel is showcased.

Contents

1 Research framework

1.1 Introduction

1.1.1 Background

Glass is a transparent, durable material that may theoretically be infinitely recycled [Musgraves et al., 2019]. Its high compressive strength makes it a great material for architectural and structural applications in buildings. Currently, only float glass is used for structural applications, which due to its planarity leads to mainly 2-dimensional facades and building envelopes [Le Bourhis, 2014]. The tendency towards fluid freeform architecture has been clear in the past couple of decades. There are plenty of examples of curved glass surfaces for facades and roofs that try to facilitate 3 dimensional freeform buildings [Stavric et al., 2014]. Such surfaces can be formed by either curving flat glass or creating a curved shape with glass blocks or extrusions.

Flat glass can be formed with various methods into the desired curved form. Cold or hot bending of glass are the main techniques used by the leading manufacturers of curved glass [Datsiou & Overend, 2016; Bijster et al., 2016; Fildhuth & Knippers, 2011; Musgraves et al., 2019; Neugebauer, 2014; Nijsse,2009; sedak, Pu et al., 2022]. Each of these has several different methods for curving flat glass and the method to use per project is selected depending on the final strength of the glass required for redundancy, the curvature and geometry to be achieved, cost or other parameters. There is great potential to the geometry that can be achieved, especially when heating glass. Most of these methods require the use of moulds to curve glass panes.

Figure 1: Corrugated glass facade of the Nordstrom flagship store in NYC. Source: www.press.nordstrom.com

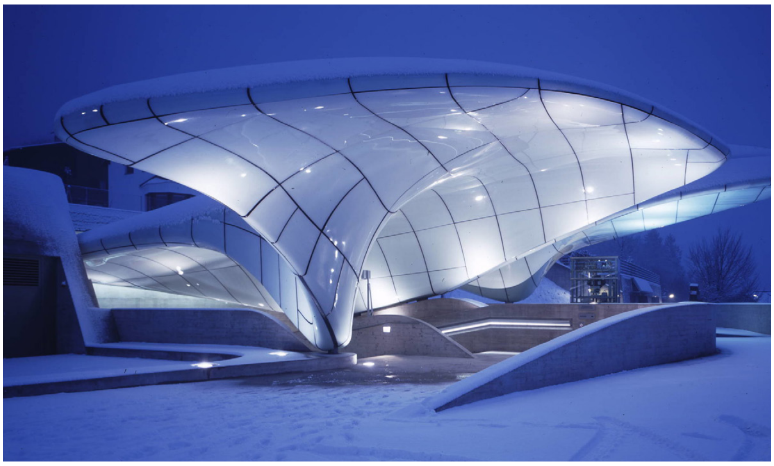


Figure 2: Freeform shaped glass structure of Nordkettenbahn station in Innsbruck. Source: www.zaha-hadid.com

Latest developments in the fabrication of curved glass geometries are casting [Cummings, 2002; Ioannidis, 2023; Oikonomopoulou, 2019], extrusion [Oikonomopoulou, 2019; SCHOTT; Snijder et al., 2018] and 3d printing [Antonelli, 2020; Klein et al., 2015]. Casting also requires the use of moulds and is mainly performed to produce small scale glass objects, like glass bricks, that can be combined to form a structural or architectural design. Larger cast pieces are not manufactured for these kinds of applications due to their lengthy annealing time. Extrusion of glass is also an interesting technique used for structural glass components, which are limited in size. The latest fabrication method to be developed is 3d printing. Due to the relatively short time of its existence, this fabrication method is still at an infant stage of development and is only used to manufacture small objects for decorative purposes, however showing great potential for the future.

Several types of moulds exist for curving & casting glass. There are permanent, disposable or adjustable moulds as found in the literature [Äppelqvist, 2015; Giesecke & Dillenburger, 2022; Ioannidis, 2023; Making 3D façades: the Pinbed; McDonnell et al., 2018; Oikonomopoulou et al., 2018; Oikonomopoulou et al., 2020; Pronk, 2021; Rietbergen, 2008; van Dooren, 2014; Wurm, 2007]. Each mould can be formed to shape single or double curved glass elements and might be reusable or not. Often, moulds affect the optical quality of glass. Depending on the temperature in the furnace, the contact time between glass and mould etc, different coatings and release agents are required to improve the finishing surface quality of glass. In some cases, texture in glass is desired and can be achieved with different techniques.

The majority of curved glass applications use curved float glass. Because of the usage of moulds and the significant expense of producing many different ones, curved glass is often applied by standardizing the components in a repeating manner. This leaves little room for freeform geometric possibilities. Different fabrication methods such as casting, extrusion or 3d printing can produce freeform glass components. However, due to their limitations, such as poor thermal performance, reduced transparency, expensive manufacturing costs, and so on, they have not been applied in the built environment for complex geometry projects. Recognizing this research gap, the purpose of this thesis is to investigate a different fabrication technique for freeform curved glass in a non-standardized way.

Figure 3: 3d printed sand mould for glass casting. Source: Giesecke & Dillenburger, 2022.

Figure 4: Cold bending of glass panel. Source: Glass Performance Days (www.gpd.fi).

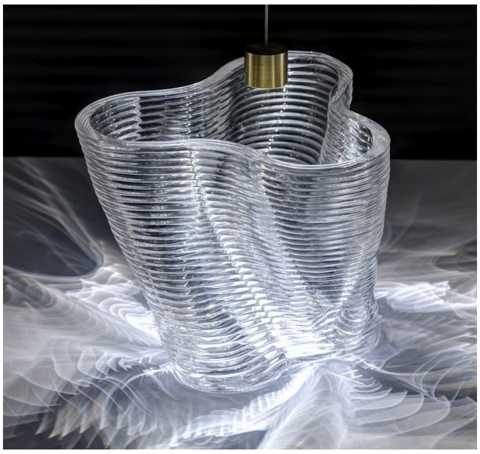


Figure 5: Glass I : 3d printed glass piece. Source: www. oxman.com

In other materials, like concrete, research and practice have shown that complex geometries can be easily formed with the assistance of unconfigurable (flexible) moulds [Pronk & Dominicus, 2011]. Starting with Isler in the 1960s, his hanging chain models have been a guide to creating thin shell structures of freeform and complex geometry [Isler, 1961]. Moulds made with the use of textiles have proven to be great in following Isler's principles. Such moulds can be either inflatable [Belis et al., 2016; Pronk, 2021; Pronk & Dominicus, 2011; Whitehead, 2021] or used as flexible formwork in tension [Veendaal et al., 2011; West, 2016]. More recently, knitted moulds have pushed the boundaries of flexibility in achieved geometry and show great potential due to the minimized use of material and manual labor, which lead to a more sustainable lightweight structure with decreased cost for manufacturing [Popescu, 2019].

Figure 7: Hanil Company Visitors Center façade: prefab concrete panels formed with open through fabric moulds. Source: www.archdaily.com

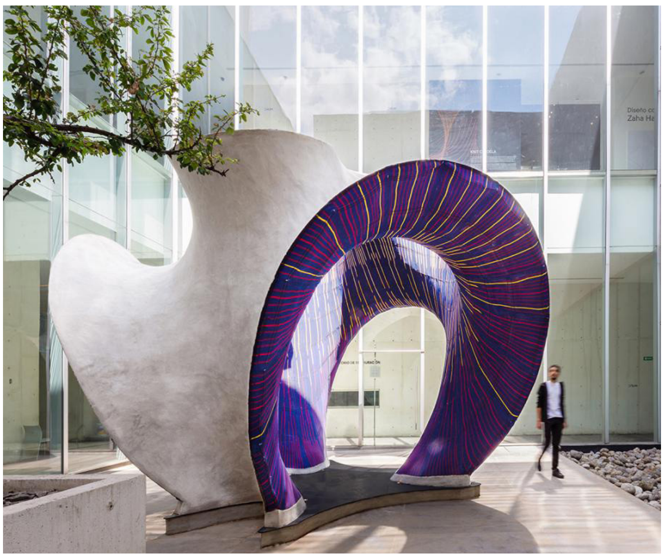


Figure 6: knitCandela: concrete shell pavilion made with knit textile formwork. Source: www.worldarchitecture.org.

1.1.2 Problem statement

Despite all the advancements in glass curving methods, there are plenty of limitations in creating freeform buildings. Most of the buildings with 3-dimensionally shaped glass envelopes comprise of panels of similar curvature that form the final shape, which leads to repetition in the facades. More fluid freeform envelopes are tessellated, and the final 3dimensionality is achieved by using small planar glass panels.

Geometrically, it has been proven in research that glass can achieve great curvatures with the right combination of temperature and mould. Several built examples also prove that freeform glass envelopes are feasible, however, the main problem/negative aspect of them is the extremely high manufacturing cost. Freeform shapes are divided into panels which are unique surfaces and, therefore, require individual moulds. Adjustable moulds which might be a solution to lowering the cost of manufacturing are a technology well developed for other materials, whereas for glass, while they exist, they are not fully proven to work on large scale in the industry and they are not easily accessible.

Currently, there is no known manufacturing technique for freeform non-standardized glass panels that can achieve extreme geometries and remain simple and lightweight in the manufacturing of the mould itself, therefore, not increasing the cost of the process at a high level.

1.2 Research framework

1.2.1 Research question

As stated above, currently there is no way to curve float glass in freeform non standardized panels in a simple way. However, research on other materials shows great promise in what may be feasible by combing flexible moulds with glass. The aim of this thesis is to develop a novel fabrication technique that enables an easily customizable production of freeform, curved float glass components while resulting in little waste. This leads to the question: is it feasible to create a knitted mould for glass slumping? Thus, the main research question of this thesis is:

What is the potential and limitations of utilizing knitted basalt moulds for the creation of customizable, freeform curved float glass components?

To be able to answer to this question, the following sub questions emerge and will guide this research:

- Which are the geometrical limitations of this method?
- Which is the best combination of materials for the mould in terms of glass surface quality, coatings/release agents for de-moulding, final achieved geometry, and possibility of texture on glass?
- How can this fabrication method be improved in terms of visual & aesthetic quality, structural redundancy & sustainability?

1.2.2 Methodology

In order to explore this topic, the thesis is divided into three main parts.

The first is a literature review, which will serve as the foundation, comprising extensive research on relevant papers and publication. Existing glass curving techniques will be analyzed and compared qualitatively in terms of a set of criteria for visual, geometrical freedom and structural aspects. Moulds currently used for glass curving will be thoroughly researched, as well as flexible moulds used for other materials. Similarly, moulds will be qualitatively assessed with a set of criteria on visual, geometrical freedom, fabrication limitations and sustainability aspects. Furthermore, suitable textiles and coatings for knitted moulds to be used for glass will be examined.

The second part is an experimental part. Lab experiments will be conducted to determine if this novel fabrication technique is feasible, under which conditions and which are the limitations.

The final part of the thesis is prototyping. Given a selected case study and depending on the findings of the experiments, a prototype will be developed for a glass panel to be used as façade or roof element.

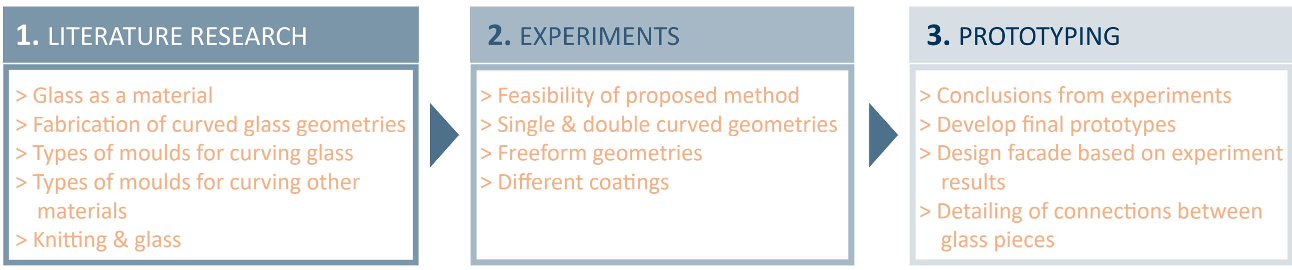


Figure 8: Methodology of thesis.

1.2.3 Timeline

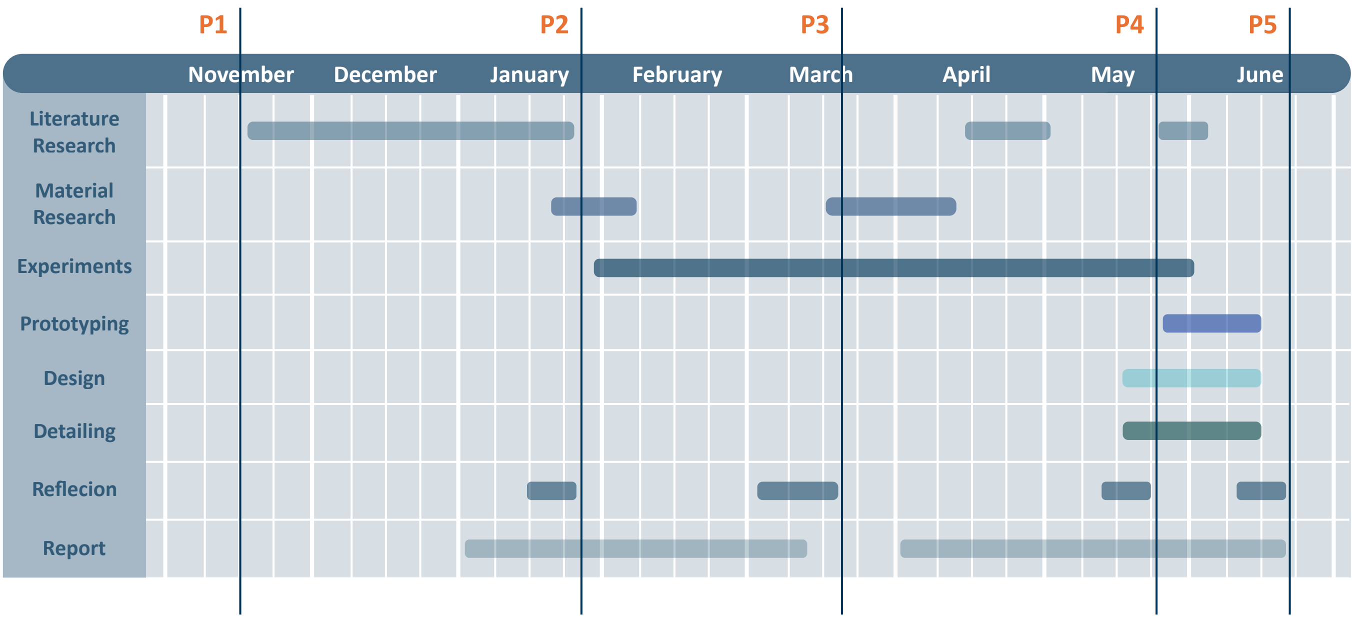


Figure 9: Timeline overview.

2 Case study

Depending on the outcome of the experiments, a glass component will be developed for a facade application, and therefore, the appropriate case study is chosen. For a freeform façade component, the corrugated glass façade of Casa da Musica in Porto is chosen.

2.1 Casa da Musica

Casa da Musica was designed in 1997 by OMA as a new cultural center in Porto, Portugal. ABT was the consulting engineers for the façade and specifically the glass windows. The biggest opening measures 25 by 12m and the vision of OMA was to use as little steel as possible. Use of corrugated glass panels was an approach that offered the possibility of large glass surfaces while maintain much better resistance to wind loads than flat glass, therefore requiring less structural elements for its support [Nijsse & Wenting, 2014]. The manufacturing limitations of the time it was built, which allowed only a maximum height 4.5m for the manufacturing of the corrugated glass panels, lead to the division of the 12m high opening in 3 parts, which coincide with the position of the floor slabs [Nijsse & Wenting, 2014]. The glass panels are mounted to steel beams with flat profiles at the levels of the building slabs, which also help to adjust the tolerances of the corrugated glass [Nijsse,2009].

Similar to the use of corrugated glass in the exterior façade, OMA requested a glass wall in the big auditorium. So, there were two corrugated glass walls around the foyer separating it from the theater area, one exterior providing airtightness and watertightness and one interior [Nijsse,2009].

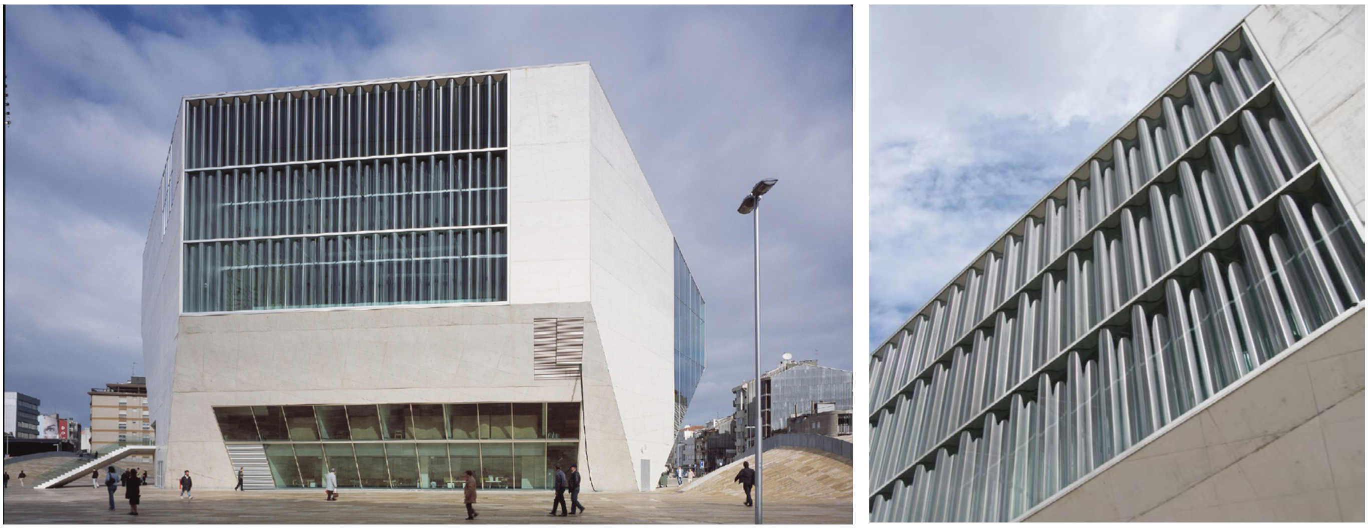


Figure 10: Casa da Musica in Porto, biggest opening with corrugated glass. Source: left: www.archdaily.com, right: Nijsse & Wenting, 2014.

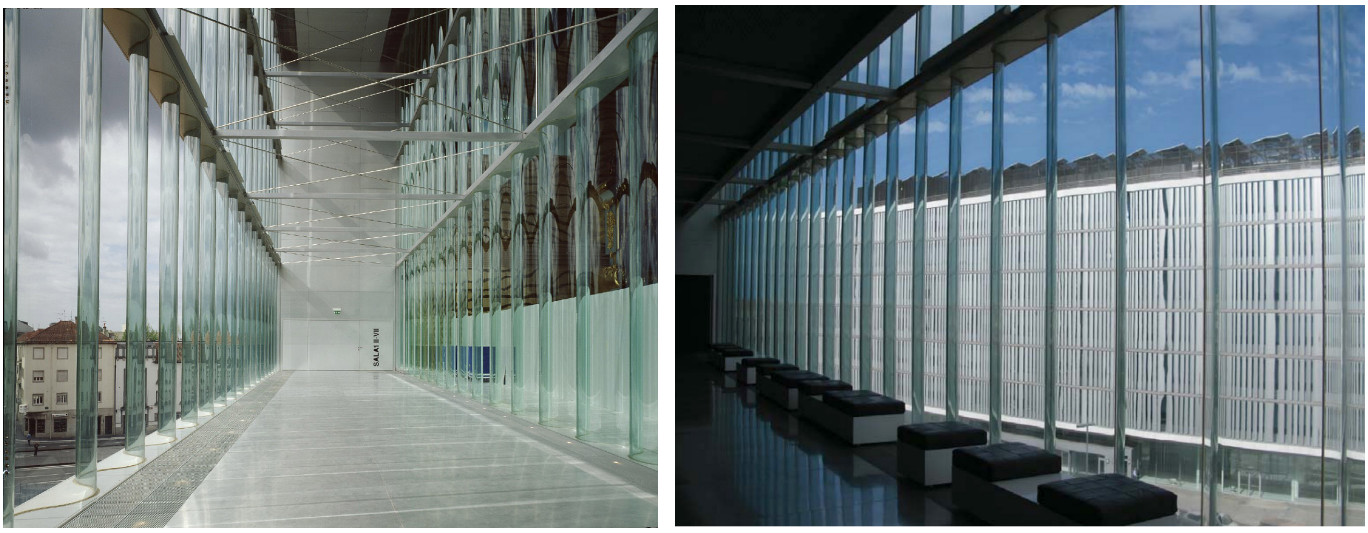


Figure 11: Casa da Musica. Left: Foyer space, between two corrugated glass walls. Source: www.archdaily.com, Right: Smaller corrugated window, interior view. Source: Nijsse & Wenting, 2014.

3 Glass

3.1 Types of glass

Glass can be divided into different types based on its composition (oxide constituents). There are 6 main types of glass: soda-lime, borosilicate, lead, aluminosilicate, 96%silicate and fused silica (quartz).

Soda-lime glass is the most used type in the industry and the composition used for the float glass production. It is durable and less expensive than the rest types of glass, however, it is not as resistant to high and quick temperatures changes. Standard applications of soda-lime glass are bottles or architectural elements like windows [Thwaites,2011]. **Borosilicate** has better thermal and mechanical properties. Its lower thermal expansion coefficient makes it more resistant to thermal shocks and reduces the annealing time. Borosilicate glass is used to make scientific glassware and other items that require localized heating [Thwaites,2011]. **Lead** glass is softer due to its low viscosity, and therefore, can be processed and formed easier, but is more vulnerable to scratching. It is a type of glass used for art installations and is not suitable for architectural applications [Oikonomopoulou, 2019]. Finally, **aluminosilicate, 96% silica and fused silica** glass can withstand far greater operational temperatures and heat shocks, thus requiring more energy for their forming and increasing the length of their annealing process, making them the most expensive types to manufacture. Application of these type of glasses are more specialized, like mobile screens or spaceship windshield [Oikonomopoulou, 2019].

In the case of this research, since the main objective is an architectural component, soda-lime glass or borosilicate glass would be suitable to use. In general, soda-lime glass requires lower working temperatures than borosilicate glass (has a lower melting point) [Oikonomopoulou, 2019], therefore requiring less energy for forming it into a curved geometry and thus, it is the most suitable on to use for the experiments of this thesis.

Glass type	Mean melting Point at 10 Pa.s*	Softening Point	Annealing Point	Strain Point	Density	Coefficient of Expansion 0°C - 300°C	Young's Modulus
	[°C]	[°C]	[°C]	[°C]	Kg/m³	10^{-6}/°C	GPa
Soda-lime (window glass)	1350-1400	730	548	505	2460	8.5	69
Borosilicate	1450-1550	780	525	480	2230	3.4	63
Lead silicate	1200-1300	626	435	395	2850	9.1	62
Aluminosilicate	1500-1600	915	715	670	2530	4.2	87
Fused-silica	>>2000	1667	1140	1070	2200	0.55	69
96% silica	>>2000	1500	910	820	2180	0.8	67

** These values are only given as a guideline of the differences between the various glass types. In practice, for each glass type there are numerous of different recipes resulting into different properties.*

Figure 12: Properties of different glass types. Source: Oikonomopoulou, 2019.

3.2 Material properties

Glass is an isotropic material with slightly different characteristics depending on the constituents. According to Oikonomopoulou [2019], its Young's modulus and compressive strength are equivalent to those of other construction materials, including aluminum and stainless steel. Unlike other materials, it does not yield [O'Regan, 2014], resulting in brittle breakdown at normal temperatures. As a result, its behavior is nearly completely elastic [Oikonomopoulou, 2019] and can only be compared to that of other brittle materials, such as unreinforced concrete.

Glass's brittle nature leads to a significant difference in allowed tensile and compressive stresses. Although glass has great compressive strength, it has comparatively low tension resistance due to its inability to endure plastic deformation. As a result, tensile stresses can induce component breakage. The substantial difference between compressive and tensile strength explains why glass is utilized for structural elements under compression or parts subjected to bending, such as façade panels.

Material	Compressive strength (MPa)
Aluminium (T6)	469
Structural steel (A36)	400
Concrete	40
Glass	>1000

Figure 13: Theoretical compressive strength of most common structural materials. Source: Ioannidis, 2023.

Flaws in glass design impact its resistance to stress, making it a significant factor to consider. According to Oikonomopoulou [2019] flaws operate as stress concentrators, boosting local tensile stress levels and causing quick exceedance of permitted limits and breakage. Geometric flaws do not expand while in compression, hence they have no effect on compressive strength. Faults and imperfections in glass often occur during the casting process and fall into the following categories [Oikonomopoulou, 2019]:

Inclusions: such as bubbles, stones, and cables. Various elements can contribute to the formation of each category. However, their varied mechanical and thermal expansion qualities create local stress concentrations inside the glass structure, which can cause collapse. After pouring the glass melt, auxiliary routes on the mold may be used to remove inclusion imperfections as they ascend to the higher surface.

Edge and surface defects. These issues typically arise during machining and have a significant influence on glass strength. To address these types of faults, options include mechanical polishing to minimize the length of the flaws or adding a safety factor to the permitted glass strength limits.

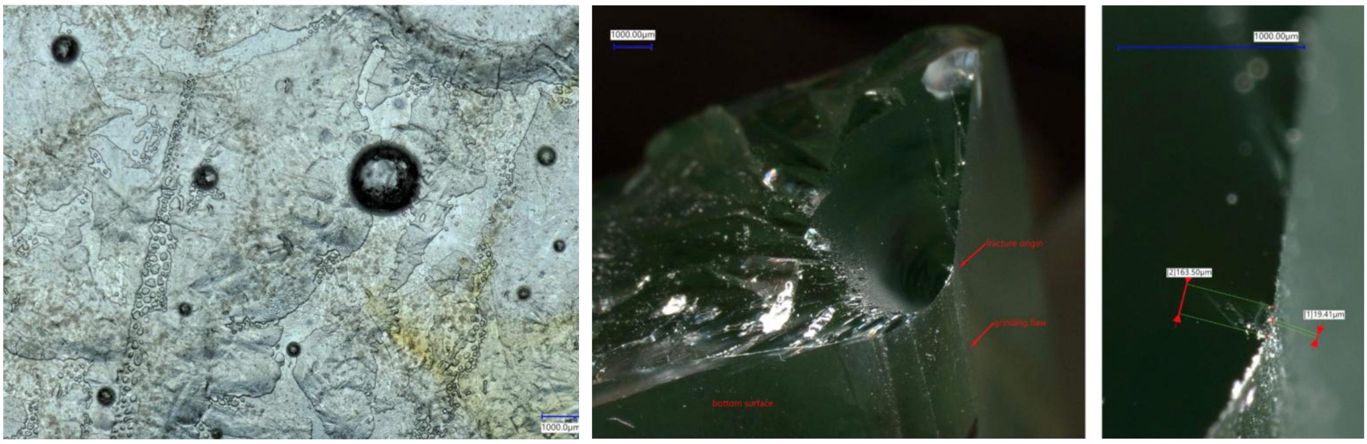


Figure 14: Casting defects as seen in the microscope. Left: Inclusions. Middle& Right: Edge Crack. Source: Telesilla Bristogianni.

3.3 Glass in architecture: float glass applications

Currently, the main type of glass used in the building industry is flat glass, which is almost exclusively produced by the float glass method. This manufacturing method invented by Pilkington in 1959 [Pilkington] comprises melting raw materials at 1550 °C and pouring molten glass at 1100 °C into a molten tin bath, where it floats and creates a smooth ribbon. The glass thickness, which is initially 6 mm, may be changed between 2 and 25 mm using top rollers. After exiting the tin bath at 600 °C, the glass solidifies and enters an annealing chamber for controlled cooling that prevents residual tensions. The cooled glass is inspected, defects are removed, and it is cut to size. Standard size is 6 x 3.21 m, but oversized plates can also be produced. Advantages of this method are that it is cost-efficient, widely available, results in optically perfect quality and offers the possibility to produce large pieces of glass.

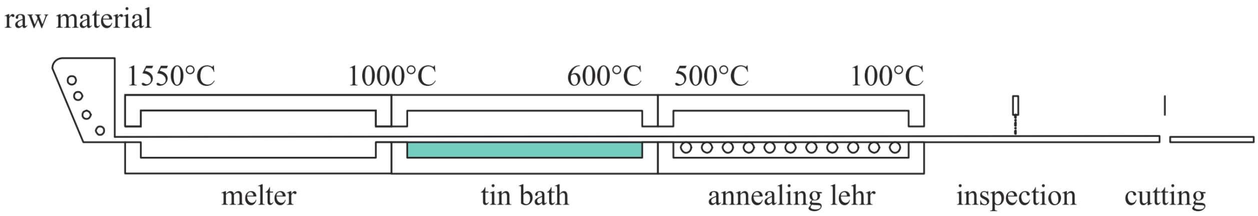


Figure 15: Float glass production process. Source: Louter, 2011.

The float glass production method has changed the use of glass in architecture. It has enabled the construction of all-glass envelopes in buildings, but also, the application of structural glass facades [Cruz,2013].

Some characteristic examples of full-glass envelopes in architecture are the Louvre pyramids and De-Rotterdam towers. In structural glass applications in facades, Apple has pushed the boundaries of the industry over the past years with iconic retail stores, such as the 5th Avenue Apple store in NYC or the Apple Store in Piazza Liberty, Milano. However, all the components that shape these buildings are virtually 2D, restricting the variety of shape into a more planar architecture.

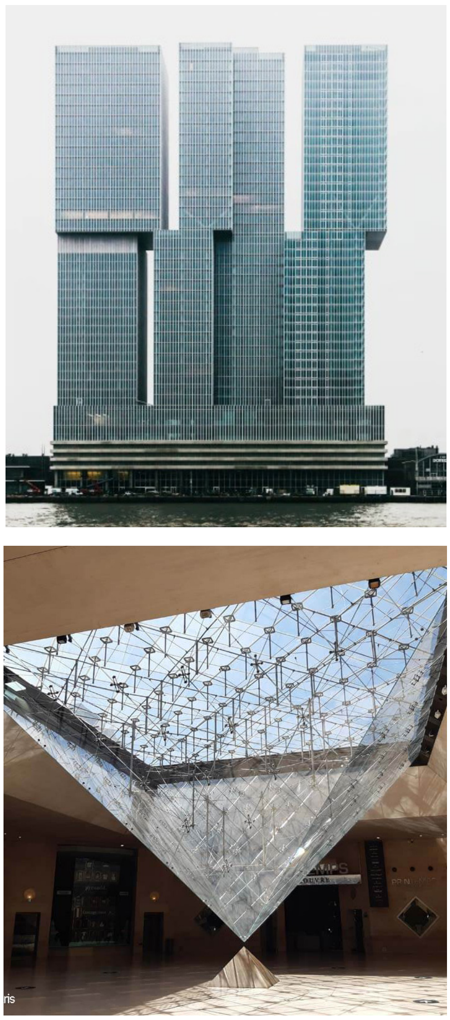


Figure 16: Up: De Rotterdam. Source: www. archello.com. Down: Louvre pyramid. Source: www. worldinparis.com.

Figure 17: Up: Apple Fifth Avenue. Source: www.apple.com. Down: Apple Piazza Liberty. Source: www.eocengineers.com

During the last decades, there has been a tendency in architectural design for more freeform envelopes. Continuous double curved glass forms are very difficult and expensive to manufacture, therefore, the most common way to build these envelopes is by tessellating the geometry into triangular or quadrilateral meshes and then creating a supporting structure out of rectilinear steel bars and filling parts by flat glass [Stavric et al., 2014]. Such built examples are the Great court in the British Museum and the Fiera Milano roof. Nevertheless, the result of a parametric building out of planar elements is not as visually transparent, continuous, and pleasing as it would have been if it comprised of curved elements.

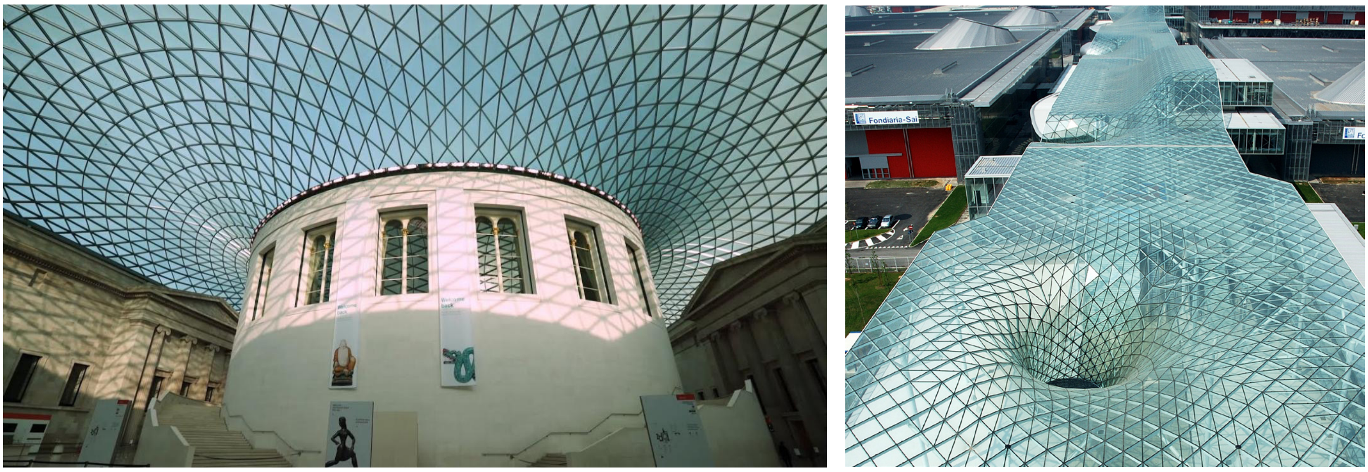


Figure 18: Left: Great Court British Museum. Source: www.britishmuseum.org. Right: Fiera Milano. Source: www.archdaily.com

3.4 Curved glass in architecture

3.4.1. Curved glass facades

Curved glass can be manufactured in various ways, as will be discussed extensively in the next chapter (chapter 4). There is a possibility to create both single and double curved glass elements. The way to curve glass is mainly by using moulds (see chapter 5), and in the case of complex geometries, that means using different moulds to produce each of the components, which raises the cost and waste of the production. Therefore, a common approach is to use the same mould to create multiple components that will be used, for example, in a façade. Several buildings have curved facades comprising of identical single curved panels, such as the Steve Jobs Theater building or the Apple Pudong store in Shanghai.

Figure 19: Up: Steve Jobs Theater. Source: www.dezeen.com.
Down: Apple Pudong. Source: www. architectmagazine.com

An attempt to create curved facades with big curvatures is by corrugating the glass panels. Well known examples of this method are buildings with corrugated glass facades, such as the Museum aan de Stroom (MAS) in Antwerp and Casa da Musica in Porto. These facades introduce a more playful solution for glass facades; however, they still comprise of standardized elements which give a sense of repetitiveness.

Figure 20: Left: MAS Museum, Antwerp. Source: www.neutelings-riedijk.com. Right: Casa da Musica, Porto. Source: www.archdaily.com

3.4.2 Freeform potential

Freeform glass facades have been a topic of discussion and exploration for the past 15 years approximately, as stated earlier. “Liquid” architecture often requires freely developable surfaces. For a smooth high-quality surface, double curvatures in elements is the key, however, such solutions are usually the most expensive [Kosic et al., 2014

Built examples of facades and envelopes made of curved glass panels showcase that this type of architecture is possible with non-standardized, freeform panels. The residential building *Infinity* in Belgrade has a façade form inspired by water and consists of 238 geometrically different glass panels. All panels are single curved, produced with different convex and concave moulds, and thus, had a very high manufacturing cost [Kosic et al., 2012]. The Nordkettenbahn in Innsbruck is another example of a curved glass envelope with extreme geometries. The surfaces are double curved and therefore require the use of unique moulds for each piece, with a very high manufacturing cost as well [van Dooren, 2014].

Figure 21: Left: Infinity residential building. Source: Alfirevic, 2013. Right: Nordkettenbahn station. Source: www.baunetzwissen.de.

But are these examples the limit of freeform glass geometries? In art, glass is a material often used to create freeform pieces. Some artwork examples push the boundaries of geometry achieved with the material, due to the fact that they are not developed as standardized components.

From old times, there have been cases of blowing or slumping glass through a steel net to create curved geometries with the boundaries of the steel that keeps the glass in a specific shape. The venetian lamp is an example of such a technique. Examples of mixed media, like the venetian lamp, that combine a steel or copper structure as boundary or cage to control the glass formed by blowing are shown in the following images. However, these examples don't portray the full potential of freeform shaping with glass.



Figure 22: Left: Glass blown inside net of steel wires by Tony Patti. Middle: Glass blown in knitted copper wire cage by Tony Patti. Right: Copper Basket by Josh Simpson. Source: www.glassblower.info.

More recently, glass master Mary Shaffer has experimented a lot with slumped and cast glass geometries creating innovative and extreme forms. Her hanging series pieces *Artimus* and *Mountain stream* are examples of slumped glass and metal net forming, while her cast glass curtain works *Bright blue curtain* and *On edge* showcase the geometrical possibilities of curving glass in extreme curvatures to create freeform shapes.




Figure 23:
Left side:
up: artimus. down: mountain stream. Source: Mary Shaffer, www. maryshaffer.com.

Right side:
up: Bright blue curtain by Mary Shaffer. Source: www. maryshaffer.com. down: On edge by Mary Shaffer. Source: www.sculpturemagazine.art.

Pipaluk Lake is another artist pushing the boundaries of glass forming. She shapes glass sculptures by using old glass sheets, often from windows, and metal threads and plates. After forming the metal net, she lets multiple glass panes slump onto the net in the kiln and form shapes inspired by parachutes. Her work showcases how extreme curvatures can be achieved with glass slumping and how flexible the material can get. For example, the artwork *suspension I*, seems like an artistic take on Isler's hanging chain models with glass. These examples are inspiring to see what the potential of creating freeform glass panels for architectural applications might be with the use of older form-finding techniques.

Figure 24: Left: Framework by Pipaluk Lake. Source: www.pipaluklake.com.
Right: Suspension I by Pipaluk Lake. Source: www. slash-paris.com.

3.5 Shaping potential of architecture introducing texture to glass

The mixed media examples shown before might be examples for the geometrical freedom potential, however, they also introduce a new dimension of the material, which is texture.

Glass used in building envelopes produced by the float glass industry is thoroughly inspected for flaws in terms of finishing quality and there are many ways to post-process glass to achieve a transparent, glossy surface. Although texture in glass might be unwanted for a clear transparent result, there are several cases when texture is a desired property in architectural design, in order to create privacy between two spaces due to optical distortion for example. Fusion Glass Designs Ltd is one of the world's leading decorative structural architectural glass companies that produce textured glass panels. Some of the ways to achieve textures on float panes – techniques also used by Fusion Glass Designs Ltd - is by re-forming the glass on sand beds in a furnace or by heating and fusing the glass onto a fire-resistant substrate with the desired texture [Wurm, 2007].

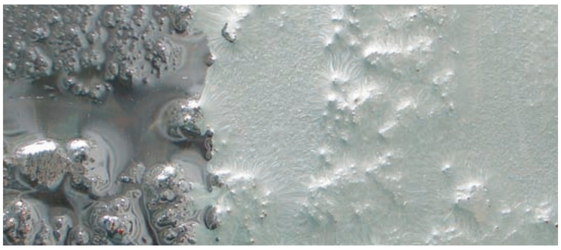


Figure 25: Up: Glass textured on sand bed. Down: Glass panels textured with substrate. Source: Wurm, 2007 (Fusion Glass Designs Ltd).

In artistic installations there have also been attempts to introduce texture to glass by using alternative means. During the Hidden Carbon project by the EPFL+ECAL Lab in 2010, Claire Baudrimont used nets of carbon fiber to produce glass blown vases with the subtle texture of the carbon mould [ECAL]. Another example is the Glass knit by Mariana Popescu, a series of glass blown objects into a textile knitted mould [Mariana Popescu]. The knit textile is burned during the process as it needs to remain in contact with the hot glass for long time to make the impressions, however, it poses a very interesting question on if this texture could be achieved using different glass softening techniques and fire-resistant textiles.

Figure 26: Left: Textured vase by Claire Baudrimont. Source: www. ecal.ch. Right: Process of texturing the glass with carbon fiber mould. Source: www.art-folio.ch.

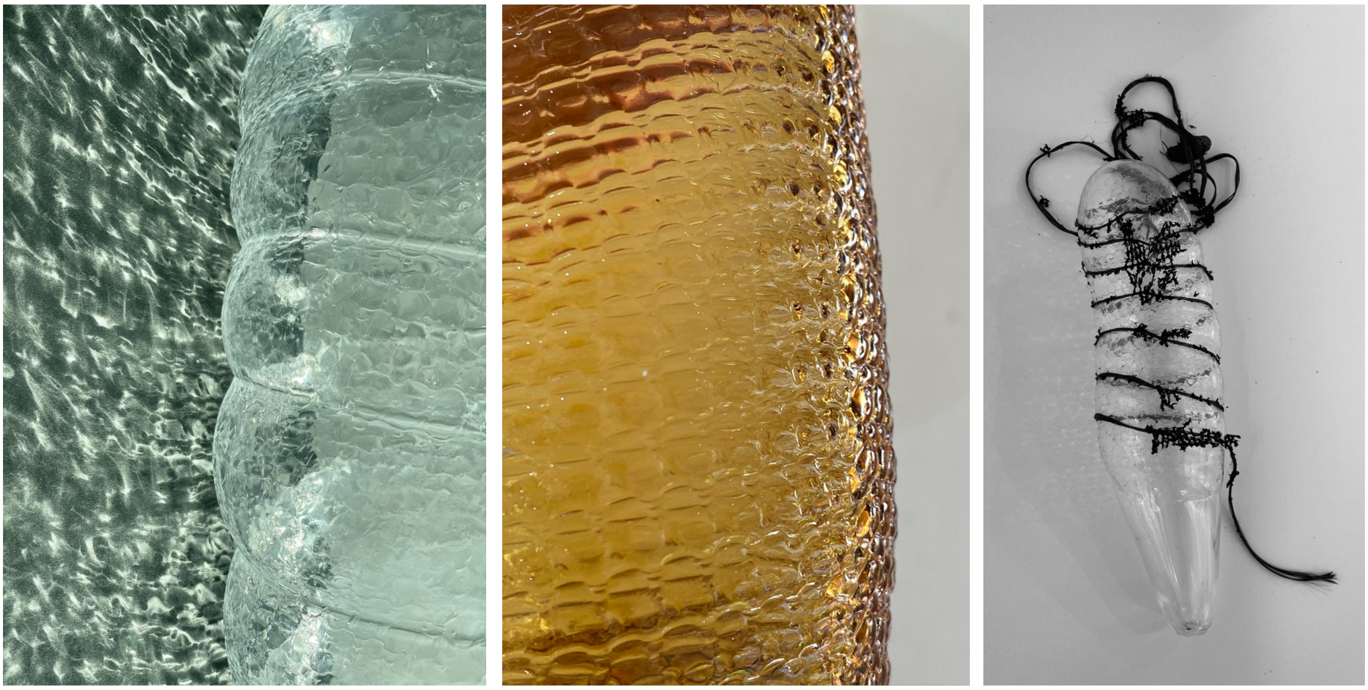


Figure 27: Left & Middle: Textured object with knitted mould by Mariana Popescu. Right: Glass blown object with the remaining of the knit textile mould. Source: www. maadpope.com.

4 Fabrication of curved glass geometries

There are several methods for the fabrication of curved glass geometries used in the built environment but also for glass decorative elements. These methods include cold bending, hot bending, extrusion and 3d printing of glass and will be discussed in detail in this chapter. Following this discussion, a comparison of the methods to a set of assessment criteria is presented and conclusions are drawn.

Assessment criteria

According to the scope of this thesis, the fabrication methods for curving glass that are promising to investigate further will be determined based on the following criteria:

- Visual
    - *Transparency*: how optically transparent is the final element, the best being a flawless optical result of transparent glass with limited distortion.
- Geometrical freedom
    - *Possible curvature (radius)*: how small can the radius of the curvature get; the smaller the radius the bigger the geometrical freedom we get for freeform glass; possibility for extreme curvatures is considered best.
    - *Consistency (thickness) of glass*: does the glass retain its thickness after being curved or does it get compromised changing the glass's strength at that point, best being the glass staying consistent to its original thickness.
    - *Scalability*: how big can the curved glass element be; the bigger it can be the better for this assessment.
    - *Ease of customization*: how easy it is to customize the resulting elements by using this method.
- Structural
    - *Redundancy*: is it a structurally redundant element; the more redundant the better.
    - *Increased strength*: can the strength of the element be increased by tempering the glass or by using already tempered pieces; the best being it is possible to have increased strength.

ASSESSMENT CRITERIA / FABRICATION METHODS		
VISUAL	GEOMETRICAL FREEDOM	STRUCTURAL
> Transparency	> Possible curvature (radius) > Consistency (thickness) of glass > Scalability > Ease of customization	> Redundancy > Increased strength

Figure 28: Table of ssessment criteria for curved glass fabrication methods.

4.1 Casting

Casting is a method of producing hollow or solid glass elements, with curved geometry or not, and the process of it can be primary or secondary. Primary casting refers to the process of producing glass from raw ingredients, while secondary casting refers to remelting solid glass pieces at a temperature that they can flow into a mould and be shaped in the desired form [Cummings, 2002]. In secondary casting, the glass pieces are placed in a pot with a hole at the bottom, so when the temperature is above its transition point, glass melts and flows downwards into the mould. A difference between the two processes is the ovens they require: in primary casting one oven is used for melting the glass and another for annealing, whereas, in secondary casting only one oven is used for both steps [Ioannidis, 2023].

Figure 29: Glass casting: prinamry (left) and secondary (right) casting process. Source: left: Marcel Bilow, right: Oikonomopoulou, 2019.

Casting glass according to Oikonomopoulou is "*currently the only method that allows for the creation of 3-dimensional glass objects of a substantial, monolithic cross-section and/or complex geometry*" [Oikonomopoulou, 2019]. In theory, there is no limit to the scale of the desired object to be cast, however, the lengthy annealing time that is needed for large monolithic objects is a major drawback [Oikonomopoulou, 2019]. Consequently, although monolithic cast objects of any geometry and curvature would be possible to produce with the right mould, it is not a viable or reasonable option due to the annealing time. Thus, cast glass has so far been used in architectural projects in the form of blocks, tessellating the final surface. Consistency in glass thickness is also compromised slightly, as cast glass blocks experience shrinkage during their annealing [Oikonomopoulou, 2019].

Regarding visual quality and transparency, cast glass blocks can be completely colorless and transparent, however, particularly in hollow blocks, the multiple layers result in great distortion, something that happens less with solid blocks [Oikonomopoulou, 2019]. Furthermore, the mould used for casting plays a crucial role in this aspect as well, as the contact with the glass might lead to a rough surface which affects the optical result [Ioannidis, 2023].

Structurally, cast glass cannot be successfully thermally or chemically tempered [Oikonomopoulou, 2019]. This means that its strength cannot be improved and cast glass has lower strength than strengthened float glass which is currently used for structural glass applications [Oikonomopoulou, 2019]. Therefore, monolithic cast glass is not redundant, however, in a tessellated example, the structure as a whole is redundant if one block breaks.

Several characteristic examples exist that demonstrate the use of cast glass blocks for the creation of curved geometries. The sculpture 'Qwalala' by artist Pae White on a smaller scale and the Atocha Memorial in Madrid with its cylindrical envelope exhibit self-supported curved walls from solid cast glass blocks. Mirage in Apple Park is the latest sculpture that is realized with cast glass cylindrical columns placed in a curved wall design.

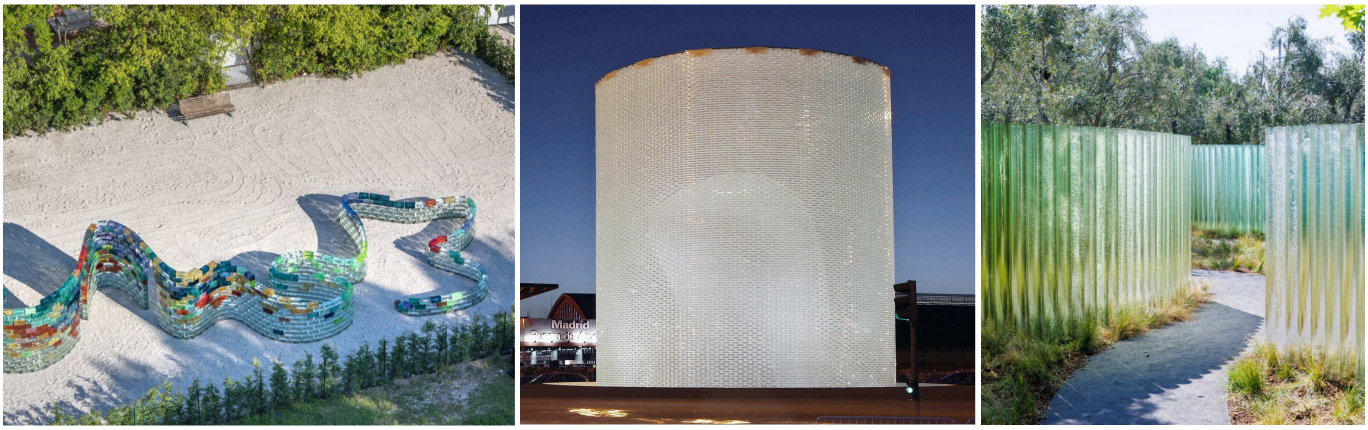


Figure 30: Left: Qwalala sculpture. Source: www.sbp.de. Middle: Atocha memorial. Source: www.stylepark.com. Right: Mirage sculpture. Source: www.dezeen.com.

The Qaammat pavilion in Greenland is also a great example of a curved structure in more than one dimension: a conically shaped structure comprising of solid cast blocks. Another interesting project is the Glass Vault showing great potential for more freeform geometries with the use of cast glass and robotic assembly.

Figure 31: Left: Qaammat pavilion. Right: Glass vault. Source: www.restructgroup-tudelft.nl.

4.2 Cold bending

Cold bending is a glass curving technique that allows elastic and reversible deformation of flat glass panes in ambient conditions with the use of little equipment. This aspect makes cold bending an energy efficient process that can be implemented on site and can generate single or double curved geometries [Datsiou & Overend, 2016]. Transportation of flat glass to be curved on site is also more efficient than already curved panels and the cost of replacements is much lower than hot bent pieces [Musgraves et al., 2019]. Furthermore, cold bending produces an extremely smooth, flawless glass surface look.

Deformations of glass with cold bending can be applied in two ways: i) by fastening to supports or ii) by laminating the glass panes in place with a stiff interlayer. The latter technique is also referred to as warm bending.

The low strength of annealed glass does not allow cold bending of single or double curved forms with smaller radii in a safe manner. Heat strengthened, fully toughened, or chemically tempered glass can be used to achieve bigger single or double curvatures [Datsiou & Overend, 2016]. The highest curvature that can be accomplished in cold bent glass is restricted by the maximum surface tensions created during the cold bending process which can be safely withstood by the toughened glass panel during its service life [Datsiou & Overend, 2016]. Cold bent glass has a more limited degree of curvature than hot bent glass because cold bending must stay within the glass's elastic bending limit. According to Fildhuth and Knippers "*Synclastic and anticlastic shapes can be produced having radii from 17m to 40m depending on the pane dimensions, the shape and the available deformation technique. Small sizes allow for larger curvature. The maximum conceivable size could be about 14.00m x 2.80m*" [Fildhuth & Knippers, 2011]. For single curved surfaces Fildhuth and Knippers claim that smaller radii can be achieved (which depend also on the glass thickness) than the ones for double curved surfaces mentioned above, however, still only allowing a limited degree of geometrical freedom.

4.2.1 Fastening to supports

Cold bending includes applying out-of-plane stresses to the glass surface to form the required shape of the glass plate, which is held in place by mechanical fixings, such as clamps. For this type of cold bending, there is usually no need for a mould to form the desired curvature, thus lowering the production cost of curved glass elements. To ensure that the glass bending remains within the elastic bending limits, this technique is usually used for developable surfaces, like cylindrical or conical ones [Musgraves et al., 2019]. Typically, thermally pre-stressed glass panes are used in cold bending to avoid static fatigue. It is possible to cold bend already laminated glass with multiple panes or insulated glass units [Musgraves et al., 2019].

A well-known example of a cold bent glass façade is the entrance to the Van Gogh Museum in Amsterdam. The façade consists of insulated glass units (IGUs) which are cold bent on site by an electric robot curving machine and fixed in place by clamps with bolted connections. The minimum radius of the curvature achieved in this project is 11.5m [Bijster et al., 2016].

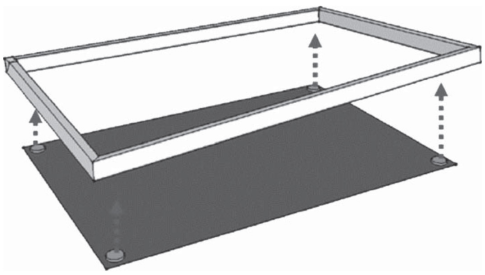


Figure 32: Cold bending glass by fastening to supports. Source: Neugebauer, 2014.

Figure 33: Van Gogo Museum entrance. Source: www.archdaily.com.

4.2.2 Lamination bending

Lamination or warm bending is the type of cold bending where a glass with multiple plies is bent in place while being laminated. The process as described in the Springer Handbook of Glass [Musgraves et al., 2019] follows these steps:

1. The multiple plies of glass with their interlayer sheets in between are stacked
2. The stack is cold bent onto a temporary rig
3. With an autoclave lamination, the interlayers become rigid, preserving the bent glass shape

The stack of glass fixed at its mould is heated at a temperature around 120°C and at a pressure of 1-12 bar. At that temperature, the interlayer softens, and the glass plies become attached to each other [Neugebauer, 2014].

After the lamination process is complete, the rig is removed, and the glass laminate is curved due to the shear of the interlayers. An initial springback (flattening) of some extent is expected to happen instantly and further flattening is to be expected due to creep at a later time. To avoid that from happening the curved glass can be fixed onto a rigid substructure [Musgraves et al., 2019].

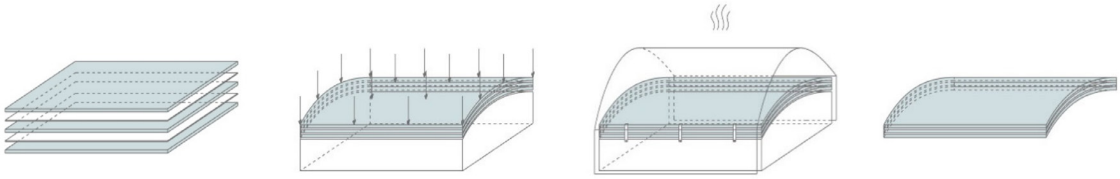


Figure 34: Cold bending glass by lamination bending. Source: Coult et al., 2022.

Characteristic examples of curved glass with lamination bending are the facades of the Apple Marina Bay Sands and the Steve Jobs Theater buildings. At the Apple Marina Bay Sands, all curved glass elements are conically shaped, single curved glass IGUs with a minimum curvature radius of 11.4m [Coult et al., 2022]. Coult et al [2022] state that there was a high production cost for the conical panels caused by their large size and geometrical complexity which reached the limit of the manufacturing capabilities.

The Steve Jobs Theater façade by Eckersley O'Callaghan comprises of structural single curved glass panels of 7m height. Each panel consists of four layers of 12mm thick plies that are bent by lamination [Steve Jobs Theater & personal communication with EOC engineers].

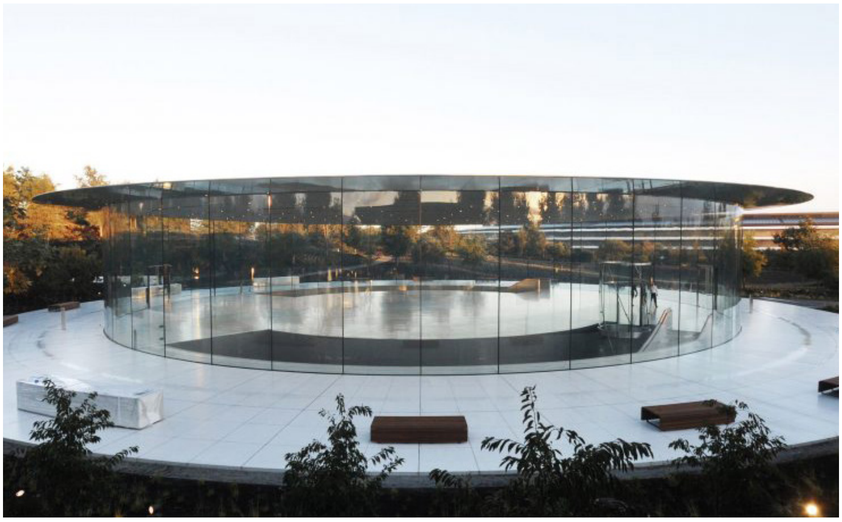


Figure 35: Left: Apple Marina Bay Sands. Source: www.apple.com.Right: Steve Jobs Theater. Source: www.dezeen.com

4.3 Hot bending

The most common method for bending flat glass is hot bending. This technique includes heating the glass over its transition temperature of 570°C until it becomes viscous and forms into place. Both single and double curved surfaces can be produced by hot bending [Musgraves et al., 2019].

According to Neugebauer [2014], the difference between molten glass (which is in a liquid state) and solid glass is that there are no bonds between the molecule particles. The movement of individual molecules causes the blow up of their in-between bonds. Thermal energy in the furnace provides the energy needed to blow up these bonds. As the temperature rises, more bonds are blown up, and this results in softer glass. That is how larger curvatures in glass are formed with smaller bending radii. Extreme curvatures in glass are possible at temperatures around 800°C [Neugebauer, 2014].

The most common methods for hot bending are slumping and roller bending.

Hot bent glass is almost impossible to thermally temper after its bending. That is due to the high temperature demanded for the tempering, which will bring the glass to a rubbery state and will deform from its desired bent shape [Musgraves et al., 2019]. However, the combination of bending and tempering of glass is possible. Sedak is a leading manufacturing company that is able to apply simultaneous bending (in all 3 axes) and thermal tempering at once with roller bending. This is usually applied in projects with repetitive cylindrical, J-shaped or spherical geometries [sedak]. Double curved and freeform geometries are usually produced by slumping. With slumping it is not possible to have thermal tempering of the glass, so it is crucial to laminate the glass as it is vulnerable to impact. However, as is stated in Sedak's production capabilities, it is possible to chemically toughen the bent glass products [sedak].

Concerning the scale of the glass panels that can be hot bent, although there can be large pieces dimensions are limited. The limitations come from the existing company production capabilities. Sedak for example, allows a maximum length of 18m for roller bent glass and 11.5m for slumped glass [sedak].

To better understand the production methods of slumping and roller bending, a detailed description follows along with characteristic examples in the built environment.

4.3.1 Slumping

Slumping is the most common hot bending method. A flat sheet is horizontally placed on top of a mould and heated. The heat makes the glass sag under its self-weight and follow the curvature of the mould underneath. Multiple glass panes can be curved at the same time using intermediate sheets to separate them, which is a useful step for laminating the curved glass later without having differences in the curvatures [Musgraves et al., 2019], however, curving more than one panes at the same time for lamination is a complex and costly process [Pu et al., 2022].

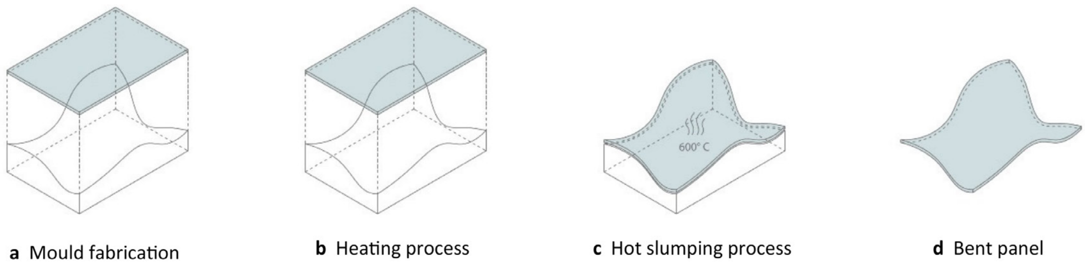


Figure 36: Hot bending glass by slumping. Source: Coult et al., 2022.

Complex geometries are possible with slumping. In a single glass pane, multiple radii can be achieved making this method ideal for freeform glass applications [Pu et al., 2022].

Glass plates of different curvatures require different moulds. Different mould materials and techniques will be discussed further in the next chapter, however, Datsiou and Overend [Datsiou & Overend, 2016] argue that this factor makes the slumping method inefficient in terms of energy use and cost. Furthermore, the visual quality (transparency) of slumped glass can be affected by the mould used [Datsiou & Overend, 2016] but also, the curvature might affect the optical distortion of the glass. In the scope of this thesis, as freeform glass is desired and the possibilities for extreme curvatures are explored, slight visual distortion in glass is not taken into consideration as it is considered inevitable to happen.

In some cases, slumping may lead to inconsistency in the glass panels. Due to the sagging of the material, there is a possibility that the thickness of the glass changes, especially at higher curvatures. When there is need for an extreme curvature, the top part in contact with the mould will have smaller thickness due to the sagging of the material, which leads to having weaker points in the panel [Nijsse,2009]. Finite element simulation is used to measure the results and inconsistencies caused during slumping by scanning the slumped glass and comparing it to the 3d modeled geometry.

There are several examples in the built environment using slumped glass in facades in the form of corrugated glass panels. The corrugated façade examples usually comprise of panels of the same repeated curvatures. Corrugation of the glass is used to create relatively thin glass façades with only few steel elements, which lowers the building cost compared to thicker flat panels of big spans. As Nijsse [2009] explains "*By corrugating or folding the flat plate a three dimensional action is possible and the lever of the pressure and tension areas in the material is enlarged dramatically compared to the thickness of the plate itself*". Such examples are Tiffany's flagship store in NYC, the Museum aan de Stroom (MAS) in Antwerp and Casa da Musica in Porto.

In the Tiffany's store, slumped IGU's are spanning over the 8.8m height façade. The height is divided into 3 with the longest glass panel being 5.2m tall. The IGU's consist of laminated multi-radii slumped glass outer lites and either monolithic or laminated heat strengthened flat inner lites depending on the façade area they cover. The panels are fixed to a steel reinforced frame spanning full height [Pu et al., 2022].

MAS museum has 5.5m tall corrugated glass panels due to manufacturing constraints of the furnace size, but also transportation on site. The connection between two glass panels vertically is accomplished by using a steel corrugated profile [Nijsse,2009].

In Casa da Musica, 4.5m high corrugated panels were used. They are mounted to steel beams with flat profiles at the levels of the building slabs, which also help to adjust the tolerances of the corrugated glass [Nijsse,2009].

Figure 37: Tiffany's flagship store NYC. Source: www.archdaily.com.

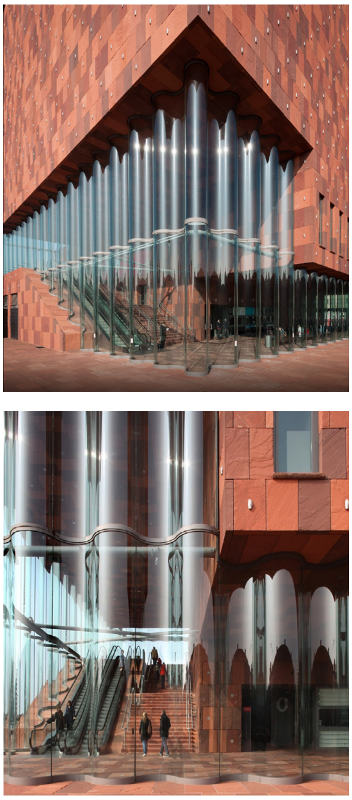


Figure 38: MAS museum Antwerp. Source: up: www.behance.net, down: www.neutelings-riedijk.com.

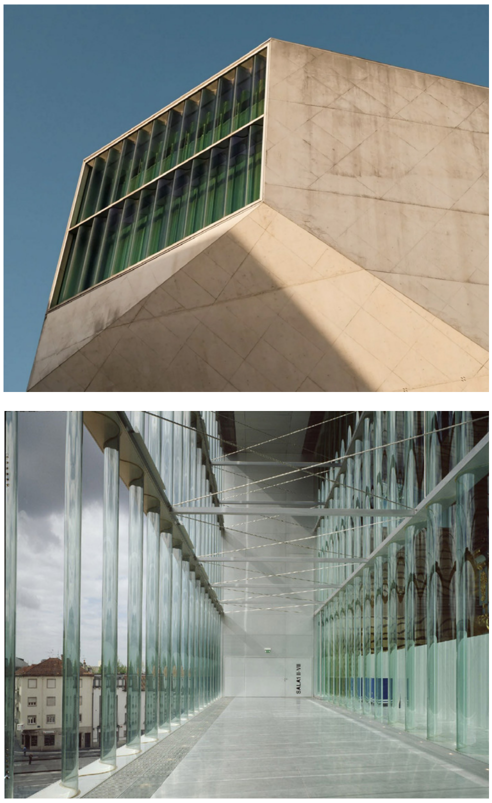


Figure 39: Casa da Musica in Porto. Source: up: www.portugal.com, down: www.archdaily.com.

Other than the built environment, there are examples of slumped glass that exhibit interesting curvature possibilities in design. Oki Sato, founder and designer of Nendo design studio, has designed the Melt collection of furniture made of glass that sags under its own weight onto a mould. This is a great example of how big of a curvature can be achieved by slumping and what the possibilities might be for other components in architecture.

Figure 40: Melt collection chair by Nendo.
Source: www.dezeen.com.

4.3.2 Roller bending

Roller bending is another hot bending method which also requires the glass to be heated above its transition temperature. It can be performed horizontally or vertically with simultaneous toughening bending. For horizontal roller bending, bending is performed during the toughening process of glass (simultaneous bending / thermal tempering). First, the heated glass is formed in shape by adjustable tilting rollers. Then, the glass is subjected to cold air jets in order to achieve the correct residual stress profile of toughened glass. In the vertical roller bending procedure, before being toughened, the glass pane is dropped vertically into the furnace and pressed into a mould [Datsiou & Overend, 2016].

As far as the visual quality of the glass is concerned, there is not always a perfect result with this method. The transparency and distortion of the glass plate are affected by the rollers, their straightness and position to one another [Datsiou & Overend, 2016].

In the built environment, examples of roller bent glass in facades can be seen in Apple's stores around the world. Two of the facades that have been curved by this method are the Apple Wangfujing in Beijing and the Apple Pudong in Shanghai both engineered by Eckersley O'Callaghan [personal communication with EOC engineers]. The Apple Wangfujing uses 8.5m tall curved insulated glass panels, while in Apple Pudong the façade panels are 13m tall curved, toughened and laminated in one piece.

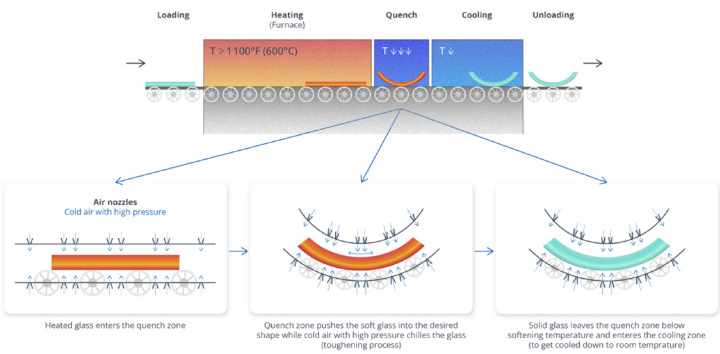


Figure 41: Hot bending glass by roller bending.
Source: Guardianglass.

Figure 42: Up: Apple Wangfujing. Down: Apple Pudong.
Source: www.eocengineers.com.

4.4 Extrusion

Glass extrusion is a method used for the production of glass hollow or full profiles, such as tubes or rods. The Danner process is the most common process for manufacturing a continuous tube. A strand of molten glass flows continuously onto a revolving, slightly downward oriented mandrel. As air is sucked off the end of the mandrel by a tractor mechanism, it is blasted down a shaft through the middle of the mandrel, creating a hollow area in the glass. During the Vello process, molten glass flows down from the furnace through a ring. For the tube to have a hollow section, a pipe inside the ring provides the shape needed. For both processes, the glass is placed horizontal while still soft along a roller track where it is finally cooled and cut in sections of the desired length [Oikonomopoulou, 2019].

SCHOTT is the leading manufacturing company of glass profiles by extrusion. In terms of size and scale, the profiles are mostly cut at the standard length of 1.5m, however they can be customized up to 10m. The hollow tubes (DURAN tubing) can have a diameter of up to 465mm [SCHOTT]. DURAN Tough is a product of SCHOTT designed for interior or exterior solutions, such as partition walls, that offers high visual transparency but also safety in case of breakage due to the polymer coating that is applied [SCHOTT]. DURATAN is another product of SCHOTT which is even more applicable to challenging projects because of its higher resistance to tensile stress due to the fact that it is a thermally prestressed glass profile [SCHOTT]. However, this does not mean that the profiles mentioned above are either transparent visually as a total surface, as the tubes put close together create great optical distortions, neither that they are structurally redundant. Also, in terms of scalability, there are many limitations to the size of the tubes due to the manufacturing procedure.

A characteristic example of the application of extruded glass profiles is the Johnson Research Tower by Frank Loyd Wright. In this project as early as the 1950s, FLW used hollow glass tubes for the façade. The story behind this choice of material is that FLW was so unhappy with the choice of the building location that he wanted to purposely create a facade that would distort the view from the inside so a visitor could not see the surroundings [information from guided tour at the building]. It is true, as can be seen from the pictures, that glass tubes affect the visual quality of the façade and even though they are transparent, they create huge distortions.

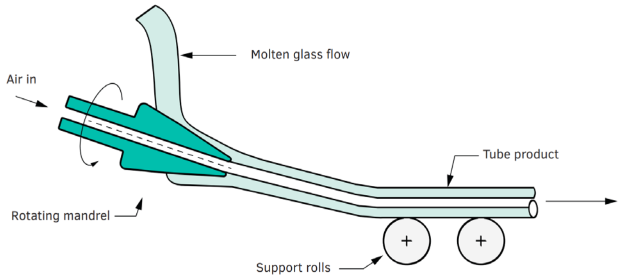


Figure 43: Glass extrusion. Source: Oikonomopoulou, 2019.

Figure 44: Johnson Research Tower extruded glass facade. Source: up: www.elevatorscenestudio.com. down: Oikonomopoulou, 2019.

Glass extruded profiles have been used also for structural applications. In the Glass Tube Field by Foster + Partners and Carpenter Lowings in London, glass hollow tubes have been used as supports of the curtain wall façade between two buildings [Glass Tube Field]. The Glass Truss Bridge is another project by the Glass Research Group at the TU Delft Campus that uses glass rods as described in [Snijder et al., 2018].

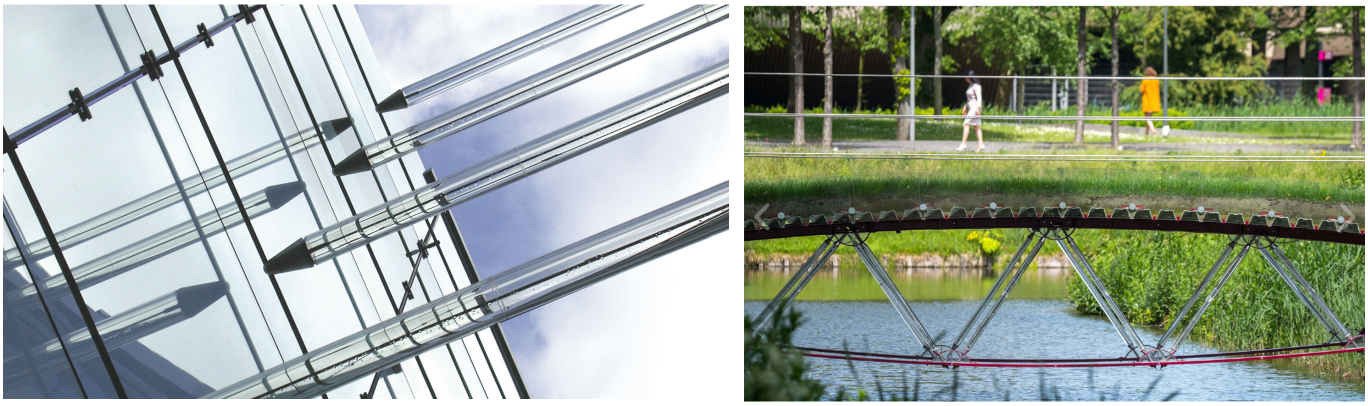


Figure 45: Left: Glass tube field. Source: www. carpenterlowings.com.
Right: Glass truss bridge. Source: www.restructgroup-tudelft.nl.

Al these examples of glass profiles are not able to be manufactured in such a manner to change their shape into a more freeform curved one, therefore they are limited to creating curved shapes in 2 dimensions by using many of the components together. An example that might have potential in creating a different shape of extruded glass is a channel glass profile. Such profiles have been used in the Pier 17 building in NYC [Medina, 2018]. This example does not follow a curved shape, however, it exhibits potential in creating curved extruded glass profiles.

Figure 46: Pier 17 - channel glass profiles facade. Source: www.metropolismag.com.

4.5 3d printing

Glass 3d-printing is another method of fabricating curved glass parts but is still at an early stage of development. In 2015, the Mediated Matter Group in collaboration with the Department of Mechanical Engineering and Glass Lab of MIT developed the first glass 3d printer (G3DP). The printer has a dual-heating chamber function: the upper chamber acts as a kiln and the lower part as an annealing chamber [Antonelli, 2020]. The glass in the upper chamber is heated at approximately 1040°C (1137.8°C according to [Antonelli, 2020]), melts and gets poured through a nozzle into shape. The object is formed in the lower chamber of the printer, where the layers of glass cool controllably while they remain hot enough to adhere to the next layer [Klein et al., 2015]. The G3DP2 is the most advanced printer by Mediated Group Matter, which can be used for larger scale and more detailed structures [Antonelli, 2020].

In large scale explorations, the *Glass II* was produced with the G3DP2 printer. It is a 3-meter-tall installation of 3 columns. The columns cross section is symmetrical and flowerlike [Antonelli, 2020]. Each column is self-supporting, pre-stressed and made up of 15 segments. Several other objects of smaller scale have been created within this research group, but also by decorative designers. Evenline has created a series of decorative objects made of 3d printed glass.

There are several limitations to this fabrication method. The scale of the objects that can be printed remains small, even at large installations such as *Glass II*, which need to be divided into parts. Furthermore, visually the 3d printed glass objects are not transparent as the surface consists of many small layers that cause distortions as discussed in extruded glass. In terms of structural integrity, this technique is still very vulnerable as the glass cannot be toughened. Finally, 3d printing shows great promise to the geometrical freedom aspect. Extreme curvatures in 2d are possible to generate, however, the shape needs to be closed or symmetrical to have stability and there is not much freedom for curvatures in the 3rd dimension as the soft glass will collapse under its own weight.

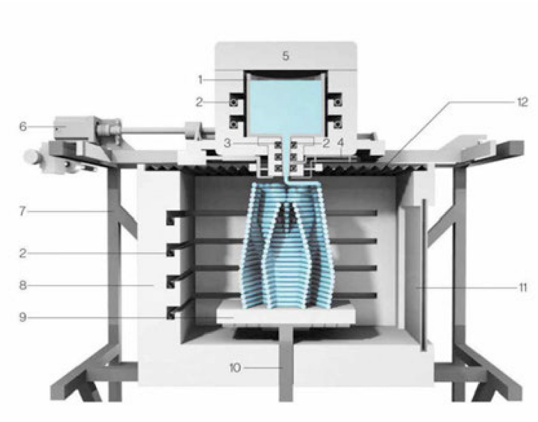


Figure 47: Glass 3d printer in cross section: 1.crucible, 2.heating elements, 3.nozzle, 4.thermocouple, 5.removable feed access, 6. stepper motor, 7. printer frame, 8. print annealer, 9.ceramic print plate, 10. z-driven train, 11. ceramic viewing window, 12. insulating skirt. Source: Klein et al., 2015.

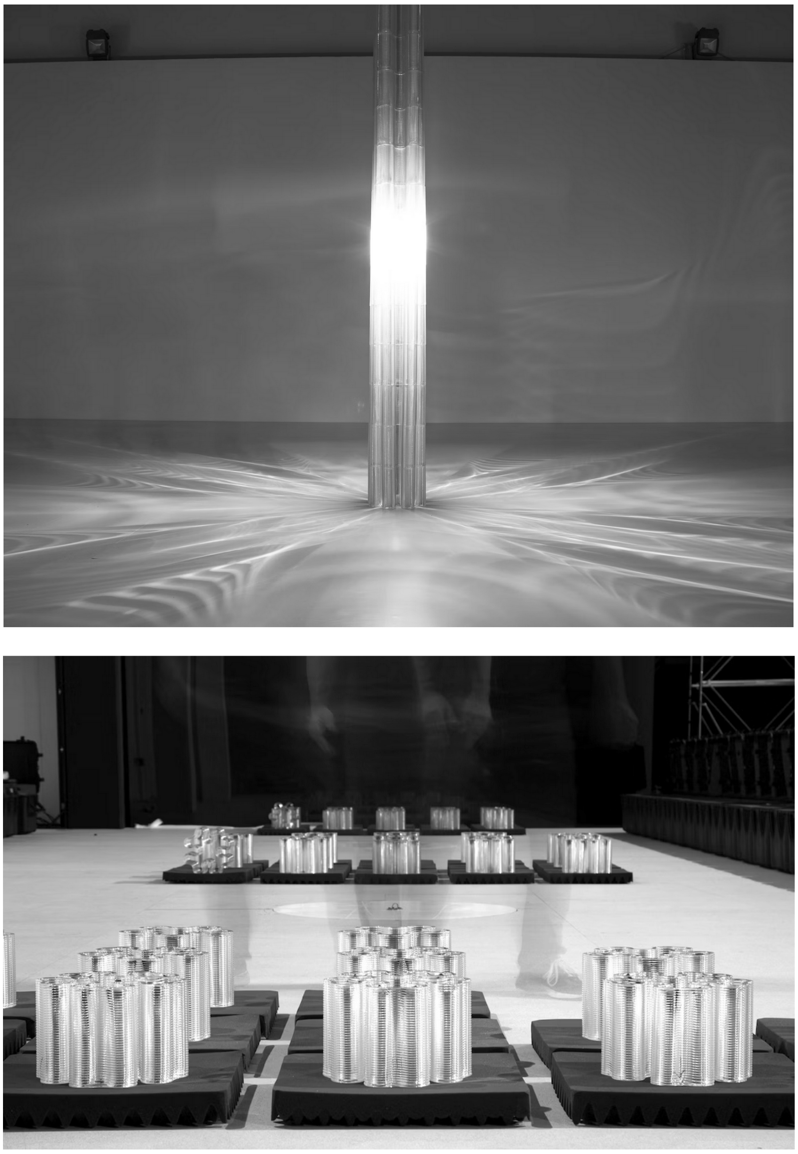


Figure 48: 3d printed objects. Source: www.evenline.co.

Figure 49: Glass II - 3d printed glass column. Down: disassembled. Source: www.oxman.com.

4.6 Fabrication methods comparison and conclusions

All different methods for fabricating curved glass geometries have advantages and disadvantages. Previously discussed methods are summarized in the following table, which contains a qualitative comparison of each method to the assessment criteria stated at the beginning of this chapter.

Fabrication methods		Assessment criteria						
		Visual	Geometrical Freedom				Structural	
		Transparency	Possible curvature (radius)	Consistency (thickness) of glass	Scalability	Ease of customization	Redundancy	Increased strength
Casting	monolithic	-	++	+	-	+	--	--
Casting	tessellated	-	+	+	-	+	++	--
Col bending	fastening to supports	++	--	++	+	-	+	++
Col bending	warm bending	++	--	+	+	-	++	++
Hot bending	roller bending	+	+	-	+	+	+	++
Hot bending	slumping	+	++	-	+	+	+	+
Extrusion		--	--	++	--	-	-	-
3d printing		--	-	++	--	++	--	--

Symbols :
- ++ very
- \+ medium / positive
- \- medium / negative
- -- little

Figure 50: Fabrication methods qualitative comparisson table.

Moulds are essential to several of these fabrication methods. They contribute to the customization of elements and make the fabrication method easier or more complicated. Moreover, moulds affect directly the visual quality of the produced glass, determining the final result. Casting and slumping are the fabrication techniques that require a mould to create a curved glass shape, whereas cold bending can be performed with or without a specific mould. Moulds are a crucial element to the production of freeform non standardized components and, therefore, will be discussed in detail in the next chapter.

Casting is a good method in terms of geometrical freedom aspects of possible curvatures, especially with monolithic glass, as the shape a cast glass object can take is very flexible. In case of non-standardization of a project's components, different moulds should be generated for each piece. Cast glass is easily customizable using different moulds for creating these cast geometries. In terms of transparency cast glass creates distortions and with tessellated surfaces there is not a very smooth and transparent final looking surface. Scale of cast glass needs to remain small due to the huge annealing time. Consistency of glass is compromised slightly due to shrinkage. In terms of redundancy, if used as tessellated the whole structure is redundant. However, due to the fact that cast glass cannot be toughened, monolithic cast glass is not redundant.

Cold bending leads to great results in terms of the visual and structural criteria, since fastening to supports or warm bending while securing the glass from its edges does not mess with the surface quality and glass that is already of increased strength can be used to curve or to be laminated and become stronger. However, cold bending has major disadvantages in terms of geometrical freedom in both methods of fastening to supports and lamination bending. While thickness of glass might be consistent and the scale of glass can relatively big, limited only by production and transportation, the bigger the glass pane the less curvature can be achieved. That leads to the conclusion that cold bending is not an ideal solution for curving freeform geometries.

Hot bending exhibits good results in terms of geometrical freedom criteria, especially slumping. Possible curvatures are possible with both methods and extreme curvatures have been proven to be feasible with slumping. Consistency of glass is compromised with both methods due to the high temperatures especially for extreme curvatures. Both methods can result in big scale panels limited only by manufacturing capabilities and they are easily customizable through adjusting the rollers or moulds for slumping. These methods also showcase advantages in structural criteria as they can both produce panels that can be laminated, but also roller bending can have simultaneous thermal tempering of the glass and curved glass by slumping can be chemically tempered after. Therefore, slumping seems the most prominent of the hot bending methods for the scope of this research.

Extrusion and 3d printing do not show many advantages in comparison to the stated criteria. Visually, both methods create huge distortions. Although using 3d printing for freeform geometry shows potential for the future, so far only symmetrical shapes can be produced without overhangs, while extrusion tubes are limited to the tubular shape. Both methods have high accuracy and result in consistent results. Scale of extruded profiles as discussed is very limited, while 3d printed objects are also produced at a small scale at the moment. 3d printing is the method most easy to customize, while extruded glass is not as flexible. In terms of redundancy both methods cannot be toughened, only extruded glass can be chemically tempered, therefore leading to structurally weaker elements. The possibilities in scale in combination with the structural disadvantages make both methods unfit for experimentation at the present research.

5 Types of moulds for curving surfaces

Most of the fabrication methods discussed in the previous chapter require a mould for shaping the glass in the desired form. In the following pages, an overview of the available moulds used for glass is given followed by moulds used to shape other materials into complex geometries. At the end of this chapter, a comparison of the moulds to the assessment criteria is made and conclusions are drawn.

Assessment criteria

The assessment criteria used to assess the existing moulds for creating curved surfaces are the following:

- Visual
  - *Transparency*: how optically transparent is the final element, the best being a flawless optical result of transparent glass with limited distortion.
  - *Finishing quality*: how smooth and glossy is the final surface; glossy/smooth being the best option and opaque being the worst.
  - *Texture on surface*: does the mould leave texture imprinted on the surface; if it does then it is assessed higher than if it does not.
- Geometrical freedom
  - *Possible curvature (radius)*: how small can the radius of the curvature get; the smaller the radius the bigger the geometrical freedom we get for freeform glass; possibility for extreme curvatures is considered best.
  - *Consistency (thickness) of glass*: does the glass retain its thickness after being curved or does it get compromised changing the panes strength at that point, best being the glass staying consistent to its original thickness.
  - *Dimensional accuracy*: how precise is the final form compared to the original design
  - *Size limitation for product*: how big can the curved glass element be; the bigger it can be the better for this assessment.
  - *Freeform geometry production*: is it possible to have freeform glass surfaces with this mould; if yes then it is marked as best.
  - *Ease of mould customization*: how easy it is to customize the mould shape; best being very easy.
- Fabrication limitations
  - *Need for post-processing/coatings*: if the mould needs to be coated or if the glass needs to be post-processed after de-moulding then it is not considered good for this assessment
  - *Cost*: how much does it cost to produce this mould
- Sustainability
  - *Waste production*: how much waste is produced from this mould and from glass; much waste is worse.
  - *Reusability/recyclability*: can the mould be reused or recycled; if yes, it is best.

ASSESSMENT CRITERIA / MOULDS			
VISUAL	GEOMETRICAL FREEDOM	FABRICATION LIMITATIONS	SUSTAINABILITY
> Transparency > Finishing quality > Texture on surface	> Possible curvature (radius) > Consistency (thickness) of glass > Dimensional accuracy > Size limitation for product > Freeform geometry production > Ease of customization	> Need for post-processing /coatings > Cost	> Waste production > Reusability/recyclability

Figure 51: Table of assessment criteria for moulds used for curving glass.

5.1 Moulds used for glass

There are several moulds used for creating solid objects or curving flat glass. Divided based on the fabrication method, the different moulds used are presented here.

5.1.1 Casting moulds

Casting moulds can be divided into two categories: disposable or permanent moulds.

Disposable moulds are made of more brittle material and are preferred for fewer operations. They are used for the kiln-casting method. Depending on the level of accuracy required, different materials are used for the disposable moulds, as they require post-processing of the glass which changes the dimensional accuracy of the object. Low-cost silica-plaster for casting below 1000 °C offers lower accuracy, whereas high-cost milled alumina-silica fiber ceramics is used for high accuracy (ex. telescope mirror banks) but with higher manufacturing cost [Oikonomopoulou et al., 2020]. In any of the options, post-processing of the glass is necessary for a fully transparent result.

Disposable 3d printed sand moulds have proven to be a great solution as it is a cost-effective method that can achieve high accuracy. 3DPM can be used for casting complex shapes with undercuts, showing promise for freeform geometries. In the experimental research of Giesecke and Dillenburger [2022], 3DPM are used both for hot pouring and kiln casting (primary and secondary casting). They point out that before casting the moulds should be completely dry to not form bubbles in the glass due to humidity, but also, coatings should be applied on the mould to maintain its visual and finishing quality [Giesecke & Dillenburger, 2022]. If no coatings are applied the sand grains get attached to the glass and in several cases in their experiments, even with coating, the mould leaves a coarse texture on the glass. Only single reuse of the 3DPM was tested by Giesecke and Dillenburger and they state that second reuse might be possible with a segmented mould, however the tests for third reuse for slumping glass on 3DPM show that the mould cracks and breaks [Giesecke & Dillenburger, 2022]. In theory the sand from the moulds could be reused or recycled if cleaned first [Ioannidis, 2023].

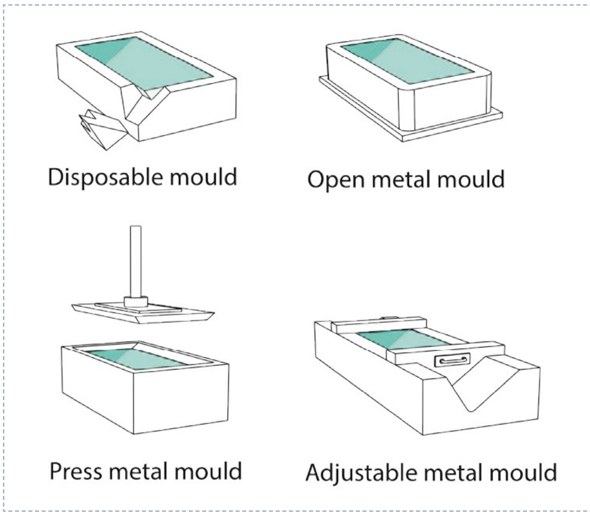


Figure 52: Main casting mould types. Source: Oikonomopoulou et al., 2018.

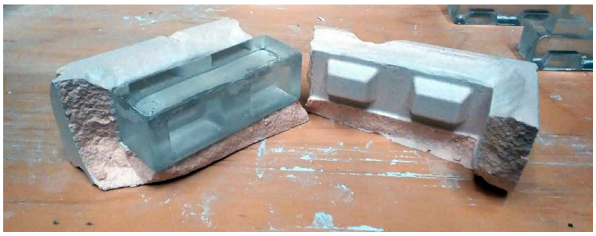


Figure 53: Disposable mould out of plaster and silica sand. Source: Oikonomopoulou, 2019.

Figure 54: Up: 3d printed sand mould for casting. Source: Giesecke & Dillenburger, 2022. Down: 3d printed sand mould for a structurally optimized cast glass column. Source: Bhatia, 2019.

Permanent moulds are made of steel or graphite and are used with the hot-pouring (melt-quenching) technique. Permanent moulds have high accuracy in dimensions, especially in pressed-moulds, and high accuracy in surface detailing with graphite moulds. Glass has a glossy transparent outcome with permanent moulds without the need for post-processing, however the use of release agents on the mould is crucial for the de-moulding process [Oikonomopoulou et al., 2018]. These moulds have a high manufacturing cost which would make them an unsuitable option for geometries of high complexity.

Some adjustable moulds also exist. They can produce components of different sizes in different directions simultaneously at the price of compromising accuracy. Moulds out of 3d printed PLA and laser cut MDF have been produced and used to create wax models which are then used for kiln casting (lost wax technique) [Oikonomopoulou et al., 2020]. Another example is the adjustable graphite mould, which adjusts the length of the components, used for the components of the Ice Falls project by James Carpenter.

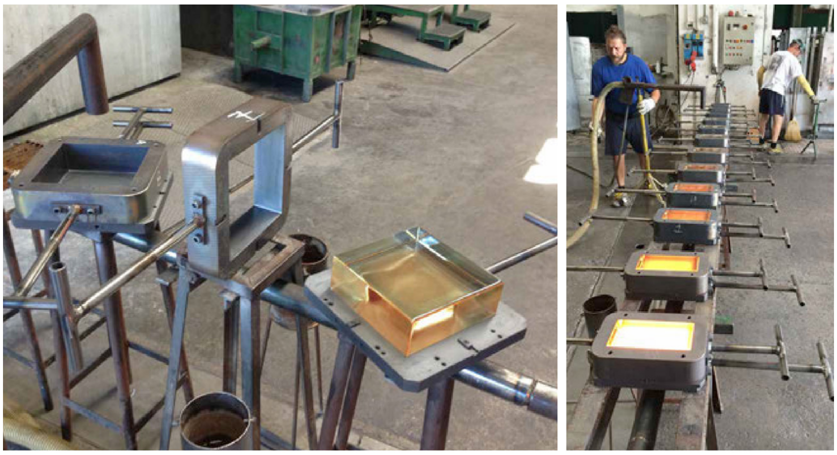


Figure 55: High precision open steel moulds used for the manufacturing of the glass blocks for the Crystal Houses façade. Source: Oikonomopoulou, 2019.

Figure 56: Adjustable graphite mould at John Lewis Glass Studio for the components of the Ice Falls project by James Carpenter. Source: Oikonomopoulou, 2019.

Characteristics	Mould type							
Reusability	Disposable			Permanent				
Material	Silica plaster	Alumina silica	Sand	Steel/Stainless steel			Graphite	
Adjustability	-	-	-	Adjustable	Fixed	Pressed	Adjustable	Fixed
Production method	Investment casting/ lost wax technique	Milling	3d printing	Milling/cutting and welding			Milling/grinding	
Manufacturing costs	Low	High	Low	Moderate to high			High	
Top temperature	900-1000 °C	~1650 °C	unknown	~ 1200°C/1260°C			unknown	unknown
Glass annealing method	Mould not removed for annealing			Mould usually removed for annealing/only maintained if high accuracy is required			Mould not removed for annealing	
Release method	Immerse in water	Water pressure	unknown	Release coating necessary			Release coating necessary	
Level of precision	Low/ moderate	High	High	Moderate/High	High	Very high	Moderate/ High	High
Finishing surface	Translucent/rough			Glossy			Glossy with surface chills	
Post-processing requirements	Grinding and polishing required to restore transparency			Minimum or none post-processing			Minimum or moderate post-processing	
Applicability	Single component/low volume production			High volume production			High volume production	

Figure 57: Table of different moulds and properties. Source: Oikonomopoulou et al, 2020 edited by Koniari, 2022.

5.1.2 Cold bending moulds

Moulds used for curving glass with cold bending belong to the permanent category of moulds. Cold bending of glass performed on site or at the manufacturing factory can be curved directly onto the desired frame to be placed on the building or it is bent on a mould that just provides the right curvature which can be used for multiple glass pieces.

In the first case of bending and attaching to the mould, the glass is first placed on the mould flat and mechanically forced into shape with clamps, as can be seen in the images. The glass is then glued or screwed into the mould/frame, and it is ready to be installed [Äppelqvist, 2015]. In the second case, the glass panel, which for the case of resin laminated glass as seen in the picture, is placed on the mould, and clamped until the resin cures and it obtains its shape by lamination [McDonnell et al., 2018]. This is a different lamination procedure than lamination bending with an autoclave.

Cold bending of an IGU is performed in a similar but slightly different manner. The glass lites are fastened with support in the desired shape, as is the frame. Then, structural silicone is applied between the members and is let to cure in the desired position. The release of the panel from its bending rack causes increased strength to the silicone due to the spring back, until it is placed and fixed on the building [Beer, 2020].

As stated also in chapter 4, cold bending moulds result in perfectly transparent and smooth surfaces on the glass. The nature of the mould, having minimum contact with the glass, does not leave texture on the surface and the thickness and final shape of the glass pane remains consistent. There is not much curvature than can be achieved with these moulds nor freeform geometries. However, the mould itself is economical to produce since is already part of the final frame or because it is used multiple times in the same project, therefore creating limited waste.

Figure 58: Left: Cold bending on final frame. Source: Glass Performance Days (www.gpd.fi).
Right: Cold bending by lamination. Source: McDonnell et al., 2018.

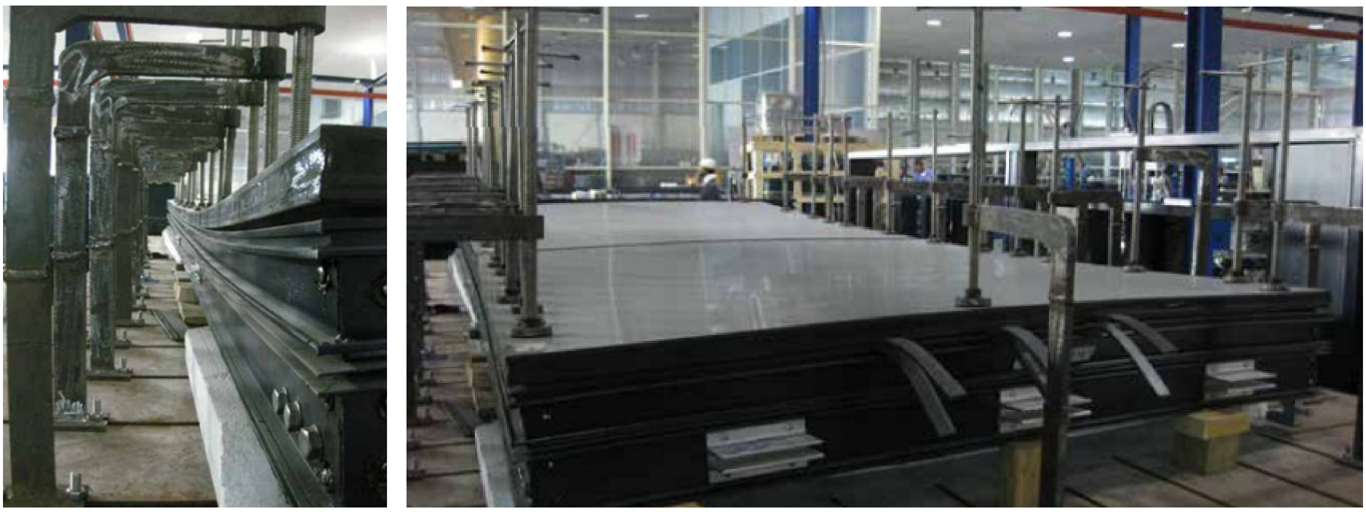


Figure 59: Cold bent IGUs with structural silicone. Source: Beer, 2020.

5.1.3 Hot bending moulds

From the hot bending techniques analyzed in the previous chapter, only slumping uses moulds to form glass into the desired shape. Roller bending curves glass panes into the roller bending plants, which have rollers that pivot and turn to produce the final curvature without an additional mould [Wurm, 2007]. Moulds for slumping can be used to produce both single and double curved geometries and are divided into three categories: permanent, adjustable and 3d printed.

Steel permanent moulds are a common option. The Nordkettenbahn in Innsbruck by Zaha Hadid is a great example of curved glass by slumping, achieving extreme geometries. Steel-rod moulds have been used to fabricate each unique glass panel. The glass sags onto the steel mould and for extreme curvatures, the vacuum technique facilitates the process [van Dooren, 2014]. The fact that each piece is unique makes permanent moulds a very costly, laborious, and wasteful technique. The use of steel moulds does not leave any texture on the glass surface and the combination with the slumping method makes it feasible to create freeform geometries, however, extreme curvatures might lead to optical distortion. Steel moulds can be reused several times for the production of the same curvature and probably the steel could be melted down and reused.

Figure 60: Up: Steel-rod mould of the Nordkettenbahn. Source: Rietbergen, 2008. Down: Nordkettenbahn by Zaha Hadid. Source: www.zaha-hadid.com

There are several prototypes of adjustable moulds for curving glass. Vollers and Rietbergen developed one of the first prototypes which was a mould consisting of four parts: base, sheet supports for steel rods, lifting system with two bars and steel surface rods. To define the desired curvature CNC cut plates are connected to the base and are the only parts required to change in order to produce new geometries. First, the glass was laid flat on the steel surface rods and heated to its transition temperature, and then the supporting system was detached to let the steel surface and the glass sag into place [Rietbergen, 2008].

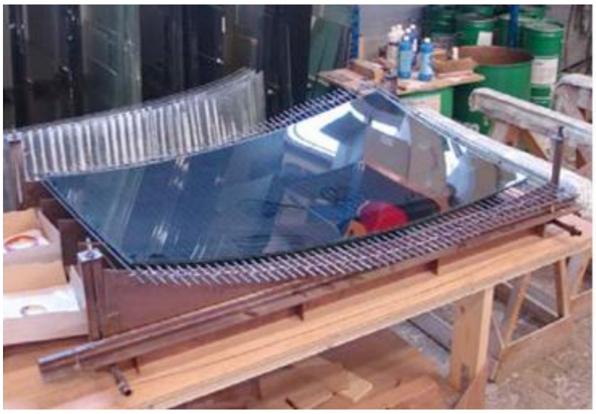


Figure 61: Adjustable mould for slumping. Source: Rietbergen, 2008.

The evolution of that mould was the *Pinbed Wizard* also by Vollers. A 14 by 14 steel pin array protrudes from the tabletop and is computer-controlled for optimal precision [Making 3D façades: the Pinbed]. Each pin is separately adjusted by an actuator, or motor, allowing for a wide range of forms, making it a great mould for freeform geometries production. A flexible material, such as rubber or aluminum, is stretched over the tops of the pins to serve as a shaping mould [Making 3D façades: the Pinbed]. The glass is then placed over this plate, and a second mould is lowered from above. This adjustable mould works in combination with a TopHat oven which heats the elements only at the top part of the mould and bends the glass. The maximum dimensions achieved are 900x1800mm with 400mm curvature [Vrijgebogen glas is nu mogelijk met Free-D Geometries]. Some of the curved

Figure 62: The pinbed wizard. Source: K. Vollers.

glass elements were showcased in the Material Xperience 2017 exhibition. The distance between the pins can be bridged by the glass itself, eliminating the requirement for an interpolating layer. Controlling the curing of the material results in a smooth, imprint-free surface [Pronk, 2021].

Another adjustable mould was developed by Raun and Kristensen who established a company for flexible moulding, ADAPA. The logic behind this mould is similar to the P*inbed Wizard*. According to the website of the company, images show the use of ADAPA mould prototypes that are able to produce double curved glass, however, it is not clear yet if this mould can be used for glass for architectural applications.

A different type of adjustable mould used in combination with slumping, are moulds that comprise of 4 plungers and a steel mesh in the middle acting as an adjustable membrane. First prototype of this kind was the *Sierra Papa 2* mould by Schuurmans and Pronk. This mould allowed for double curvature and freedom in geometry, however, it compromised the visual criteria as there were great optical distortions on the glass due to the contact with the steel mesh [van Dooren, 2014].

Pronk and Belis developed another adaptive 'mesh' mould. The flexible mould enclosing the glass pane between two steel wire nets, which are tensioned with four corner clamps, is able to produce anticlastic geometries. However, it was tested only with a top temperature of 640°C which leads to a smooth surface with minor imprinting on the surface [Pronk, 2021].

Figure 63: ADAPA mould up: pins configuration, down: with glass in the kiln. Source: ADAPA.

Figure 65: Left: Adaptive anticlastic mould by Pronk and Belis and right: flexible clamp for steel mesh. Source: Pronk, 2021.

Figure 64: 'Sierra Papa 2' before and after hot bending of glass. Source: Schuurmans & Pronk, 2011.

The last category of moulds used for glass slumping is 3d printed sand moulds. Giesecke and Dillenburger [2022] have conducted tests for slumping and the results of their research are the following observations: So far, the only size limitation is the kiln size for this method, however, only small size parts did not exhibit stress cracks in the printed moulds, so that is a limitation to the size. With this technique and moulding, steep and narrow curvatures are feasible, however, the curvature depends on the heat curve. For peak temperatures of 675°C steep curvatures are not achieved as well as with higher temperature schedules, however wider curvatures exhibit better results than when heated to 800°C, because in 800°C the edges of the glass are pulled away compromising the dimensional accuracy. Furthermore, the thickness of the glass at lower temperatures remained consistent, opposing to higher temperatures, where they were significantly varying, making the glass fragile at the tips of the geometry. As with 3DPS cast moulds, the sand leaves texture on the glass, however, coatings are not needed to remove the glass from the mould.

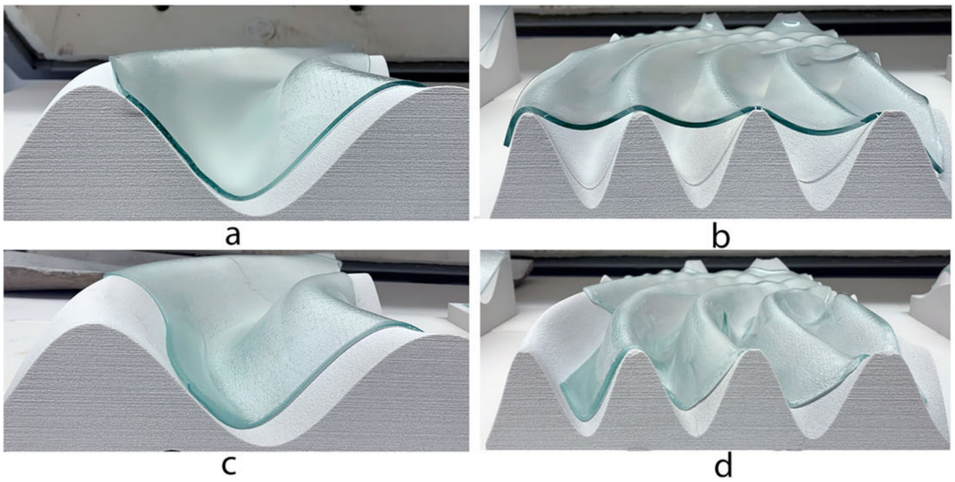


Figure 66: 3DPSM slumped panes with: a) 675 °C and wavelength A, b) 675 °C and wavelength B, c) 800 °C and wavelength A, d) 800 °C and wavelength B. Source: Giesecke & Dillenburger, 2022.

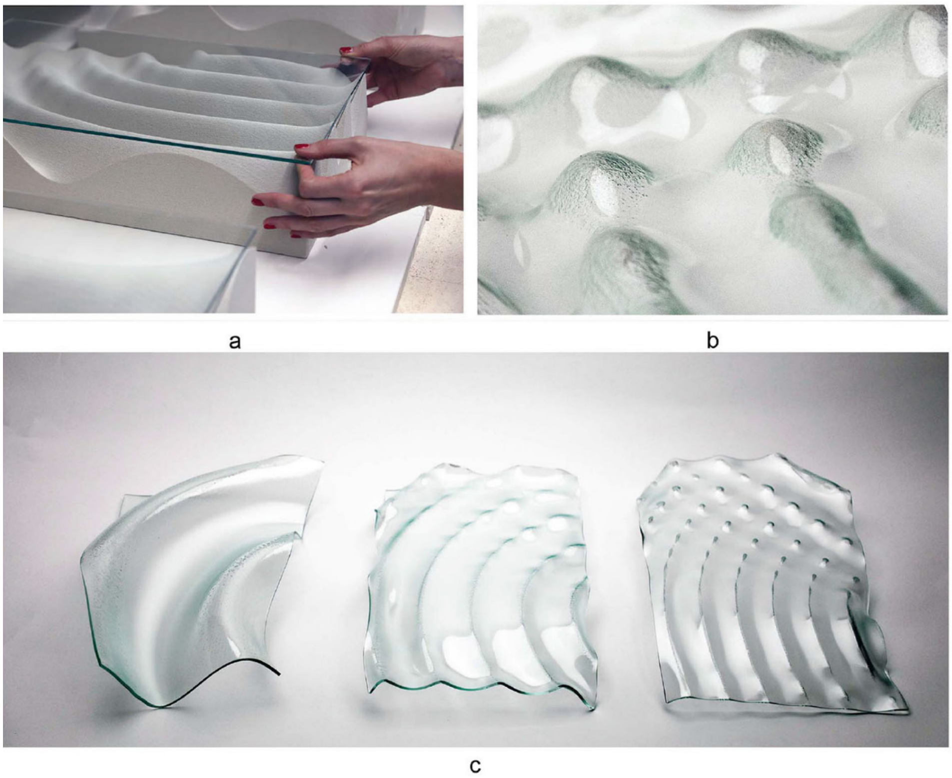


Figure 67: a) Placement of float glass on 3DP mold. b) Close up of freeform glass part. c) Doubly curved glass panes with varying curvature. Glass size: 30 × 48 cm, 6 mm glass thickness, Kilning schedule C applied. Source: Giesecke & Dillenburger, 2022.

5.2 Unconfigurable (flexible) moulds for other materials

Following the examination of moulds used to create curved glass, an analysis of moulds used for other materials is necessary. The scope of this research narrows down the search of such moulds to moulds that are flexible, can produce various geometries and extreme curvatures, while minimizing the use of materials for the mould but also for the produced component.

"*Form-active structure systems are systems of flexible, non-rigid matter, in which the redirection of forces is effected by a self-found Form design and characteristic Form stabilisation*" [Engel, 1997]. Pronk and Dominicus use this definition of flexible structures to describe structures that are capable of producing double curved surfaces and can be used for making moulds for other materials [Pronk & Dominicus, 2011]. Such structures are prestressed membranes, inflatable membranes, chains and cables structures [Pronk & Dominicus, 2011]. This type of moulds can produce freeform building elements.

Heinz Isler introduced in 1959 at the first IASS conference in Madrid new form finding methods [Isler, 1961]. Two of these methods were utilizing inflatable membranes and hanging cloth moulds and were based on the manipulation of fabric to create thin shell structures, which are designed to minimize bending moments and therefore, reduce the stresses and required material in the structure.

The idea of these moulds has evolved over the years, introducing more possibilities to achieving extreme geometries. Inflatable moulds, fabric and knitted formworks but also computer-driven adjustable moulds are used to create extraordinary geometries and thin shells with various materials.

Some of these unconfigurable (flexible) moulds used to curve materials other than glass are to be discussed in the following paragraphs.

5.2.1 Inflatable moulds

According to Pronk and Dominicus [2011] "*Inflatable membrane structures contain at least one direction, a circular cross section. In most cases, they are synclastic. Under certain conditions, it is also possible to contain monoclastic and even anticlastic surfaces".*

Pneumatic membranes (pneus) are space containers that rely only on differential pressure for support. These membranes are extremely lightweight, are very easy to deploy and can theoretically cover very large spans using cables [Whitehead, 2021]. Isler and Otto both experimented with this type of inflatable moulds in the 1960s.

Inflatable moulds have been used to create shells both from concrete and from ice. A relatively recent example of the use of inflatables with concrete is described in Flexible Forming for Fluid Architecture [Pronk, 2021]: Rob van Hove (NL) was granted a patent in 2005 for the manipulation of inflated formwork for the building of a cross vault (WO2007061299). In 2008, he completed a prototype in Eindhoven, and in 2011, he completed a building in Veghel.

Figure 68: Prototype cross vault by R. van Hove Left: inflatable mould, Right: concrete shell. Source: Pronk, 2021.

Ice shells, which are curved thin-walled ice constructions, have been utilized as temporary winter shelters in northern Japan since the 1980s. Blowing snow and spraying water in alternating layers onto a pneumatic spherical formwork is the building method for these ice shells [Belis et al., 2016].

A team of TU Eindhoven built the Pykrete dome in the winter of 2013/2014 in Finland based on the techniques of Kokawa's group. However, by using a wood fiber-ice composite material they achieved increased strength in a dome of 30m diameter [Belis et al., 2016]. Another example was the structure inspired by Felix Candela's work build in 2015-2016 as part of B. Ronsse's MSc thesis. The geometry comprises of 8 hypar shells in radial pattern that form an overall diameter of 15m. The inflatable mould was built from PVC coated polyethylene fabric that did not have a rope net over it (like the Pykrete dome), but 4 ropes tensioning its valleys. Here, a cellulose-ice composite was used.

Inflatable moulds prove to be great solutions for construction of shells with big complex geometries and less material use. However, they seem unfit for controlled freeform geometries.

Figure 69: From top to bottom image:

***1:** Spraying of snow and water on inflatable mould in Japan. Source: Kokawa et al., 2012.*

***2-3:** Pykrete dome. Up (2): spraying of inflatable mould. Source: Belis et al., 2016. Down(3): Inside of dome. Source: http://www.structural-ice.com*

***4-5:** Ice Candela shell. Up (4): inflatable mould and Down (5): final shell. Source: Belis et al., 2016.*

5.2.2 Fabric formworks

Fabric formwork/moulds are divided into two categories according to [Veendaal et al., 2011]: filled or surface moulds.

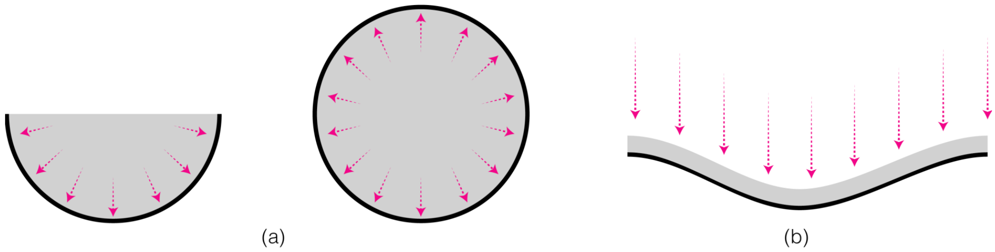
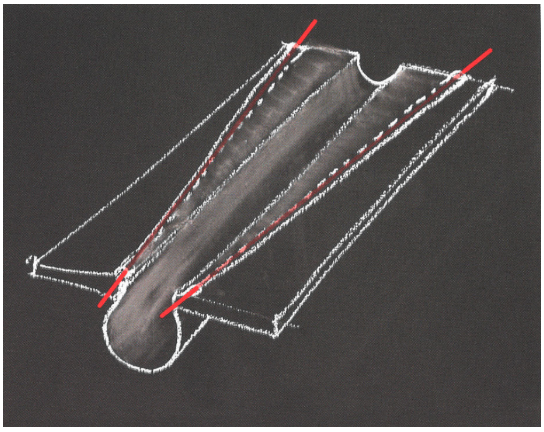


Figure 70: Fabric formwork mould types: a) filled, b) surface moulds. Source: Popescu, 2019.

In the scope of this research only moulds that can produce surfaces such as façade or roof elements are considered and not structural elements such as columns and beams, therefore only open through filled moulds and surface moulds will be assessed later on.

Starting with the filled moulds category, one example of how an open through mould can be formed is seen in the image below. The image illustrates the process of forming a flat sheet into a variable-section mould by hanging it between two table rigs. This setup allows for multiple shapes to be formed by changing the depth of the hanging sheet or the position of the rigs [West, 2016]. Image 71 illustrates how an identical piece of fabric can produce two different geometries.

A realized example of fabric-cast façade using the aforementioned technique is the Hanil Company Visitors Center in Korea. The open through moulds used in this project to create the precast concrete elements have deep convex and concave curvatures, where woven PE fabric is laid on top of plastic pipe impactors of various dimensions to create the final mould shape. Steel reinforcement is then placed, and concrete is poured between the fabric and the plywood side panels that



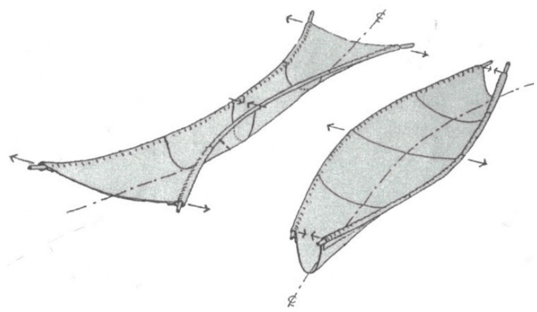


Figure 71: Up: Open through mould. Down: Different geometries produced by the same fabric. Source: West, 2016.

Figure 72: Left: Open through mould. Source: West, 2016. Right: Hanil Company Visitors Center façade. Source: www.archdaily.com

Surface moulds are hanging sheet moulds which can be achieved by horizontal or vertical hanging of fabric and are formed by gravity. Funicular, thin shell compression vaults and hanging curtain shapes are application of this type of moulds, if they are inverted [West, 2016]. Some of the most common applications of surface moulds are large scale elements with big spans like roofs, canopies, floors etc.

In the series of images below (see figure 73), the process of creating a horizontal hanging mould is showcased: first, the fabric sheet is laid over the rigid frame and then pretensioned in place, then, it is sprayed with a fiber-reinforced concrete, and finally, the rigidified mould is ready to cast concrete shell vaults [West, 2016].

Fabric can also be hung vertically to serve as a mould for direct cast curtain panels or rigidified fabric moulds for invert cast curtain panels. For small moulds, the rigidifying layer is applied to the fabric while flat, and then it is lifted and hang into place to dry and be formed by gravity [West, 2016]. This method is also done by diagonally hanging the sheet, where, by restraining the edges and including buckles in specific spots, one can increase the stiffness of the thin shell [West, 2016].

Figure 73: Horizontal hanging mould. Source: West, 2016.

Figure 74: Left: Vertical hanging mould. Right: Diagonal mould. Source: West, 2016.

The images below show how a structural shell is created by inverting the hanging moulds in steps. First, the fabric hangs freely and is sprayed with a thin layer of plaster to rigidify in tension. Then it is inverted, converting it into a compression shell for casting [West, 2016]. This type of moulding allows the creation of double curved surfaces with deep curvatures which assist with the buckling resistance of the overall geometry.

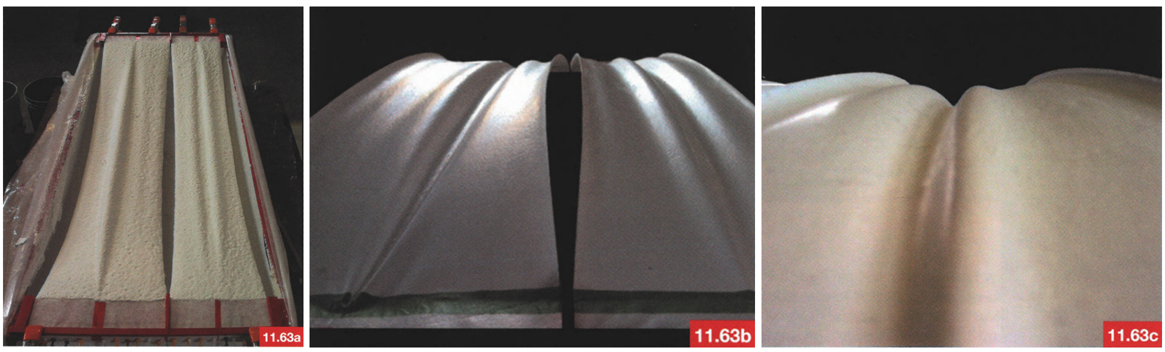


Figure 75: From hanging mould to inverted thin compression shell. Source: West, 2016.

Realized projects that use the hanging fabric method are the Sicli factory in Geneva by Isler, built in 1969, and more recently the NEST HiLo project developed at ETH Zurich. While traditional formwork was built to support the construction of the Sicli roof, the idea of creating a thin shell that follows the properties and ideas of the hanging cloth were applied by Isler. In the HiLo case, tests were performed with hanging moulds and tensioned fabric to create the thin shell concrete roof.

Figure 76: Up: Sicli roof with formwork and Middle: Silci shell. Source: Delemontey, 2019.
Down: The Sicli pavilion. Source: www.structurae.net.

Figure 77: Second prototype of HiLo Up: mould and Middle: concrete form. Source: Block et al., 2017.
Down: HiLo roof. Source: www.parametric-architecture.com.

5.2.3 Knitted moulds

Knitting has progressively gained popularity in the field of technical textiles and composites due to the ease of fabrication enabled by their exceptional formability. CNC knitting technology allows for the direct fabrication of complicated three-dimensional geometries with integrated elements [Popescu, 2019]. The technique is easily adjustable not only to complicated geometry, but also to different fibers. Knitting has been used in an architectural context in sensory environments, temporary installations, as lightweight structural systems, or as permanent façade cladding [Popescu, 2019].

Knitted textiles are produced with the use of CNC knitting machines. The user designs the patterns as 2d diagrams and programs the machine to follow the functions that will produce the desired geometries. Popescu, describes meticulously how CNC knitting works and how one can generate patterns for computational knitting [Popescu, 2019]. Knitting allows for a wide range of geometrical freedoms, such as doubly curved surfaces and integrating features, such as channels and openings that help create the final shape of the knitted formwork. Furthermore, it is a process that minimizes waste, cost and physical labor [Popescu, 2019].

The knitCrete Bridge is a characteristic example of the use of a knitted mould for casting concrete. Popescu [2019] describes the elements of the formwork system of the bridge depicted in the axonometric, which consists of:

- *"The stay-in-place formwork layer is made of a custom knitted textile (c) with integrated channels for the insertion of shaping elements,*
- *Once tensioned into shape, the formwork is made rigid using a light layer of high-strength cement paste (f) and one of mortar (g),*
- *These paste and mortar layers are light enough not to load the structure excessively and provide sufficient strength and stiffness to support the final layer of structural concrete (h)".*

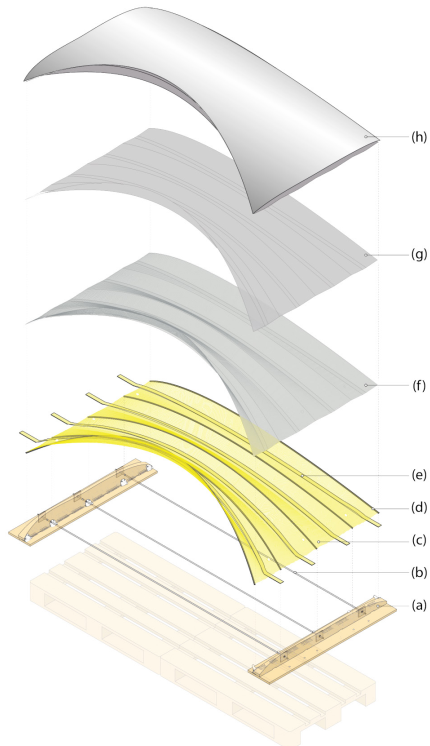


Figure 78: knitCrete Bridge system. Source: Popescu, 2019.

The finished knitted textile has channels for the insertion and guidance of GFRP rods and Aramid ribbons, openings for the passage of the bridge's steel tension, additional openings for elements controlling concrete thickness and also textured surface for better connection of the coating and mortar to the fabric [Popescu, 2019]. The knitting pattern was designed computationally as described before and the result of the pattern as well as the tensioned fabric in place can be seen in the images that follow.

Figure 79: knitCrete Bridge. Left: knitting pattern, Middle: mould tensioned in place. Source: Popescu, 2019.Right: prototype. Source: www.block.arch.ethz.ch.

Another very well-known built example is the knitCandela pavilion. As Popescu [2019] describes it "*KnitCandela is a thin freeform concrete waffle shell built using a custom prefabricated knitted textile as shuttering and a form-found cable net as the main load-bearing formwork. The digitally designed and fabricated textile provided integrated features for inserting and guiding elements such as cables and inflatables that helped shape the sophisticated mould*". KnitCandela showcases some of the possibilities allowed by knitted fabrics in terms of incorporating special features. It has a double-layered textile with aesthetic and technical side, pockets and openings for inserting inflatables that will create the final waffle effect on the shell, different loop sizes in the knit to control the depth of the inflation, channels for inserting cables, well designed seams to connect the different knitted parts and edge detailing to manipulate the concrete finishing [Popescu, 2019]. The knitted fabric is computationally designed in the same manner as knitCrete bridge. Part of the pattern and its corresponding final fabric on both sides can be seen at the image.

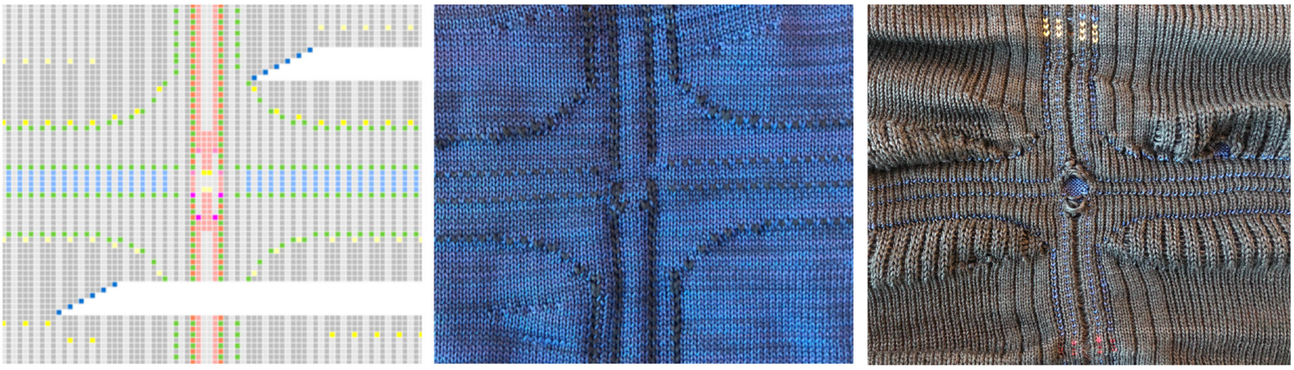
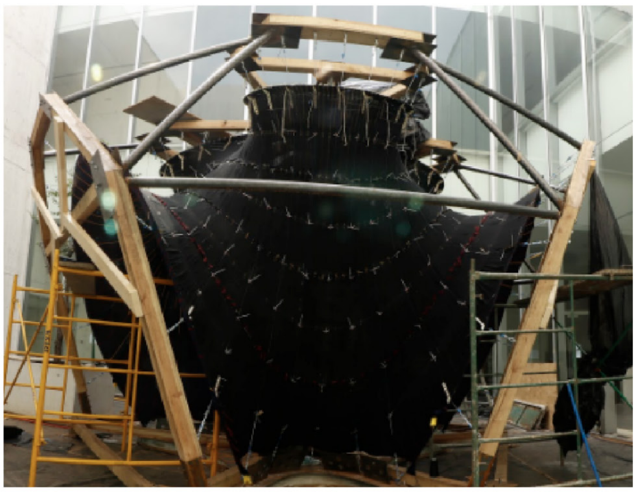


Figure 80: knitCandela pattern and textile front and back side. Source: Popescu, 2019.

(a)

(b)

(c)



(d)

Figure 81: knitCandela setting up of the fabric formwork. Source: Popescu, 2019.

After the knitted fabric is suspended and tensioned in place it is coated in order to become rigid. When dried, the fabric formwork is ready for the concrete layer to be applied on top and create the shell. After the concrete shell is completely rigid, the frame supporting structure and the cables are removed. The fabric could also be removed but remained as a stay in place formwork for aesthetic reasons.

Figure 82: knitCandela.
Source: www.worldarchitecture.org.

5.2.4 Flexible/adjustable moulds

Finally, there are adjustable moulds that allow for a great deal of flexibility in the produced geometry. To lower labor and material costs for achieving free-form building in concrete, a step toward mass-customization should be taken. Mass customization of double-curved free-form elements is possible with adjustable moulds that produce any curved surface using pistons, actuators, pin beds etc. The final surface can be moulded on this flexible formwork/mould by either casting a hardening substance such as concrete or laying a softening material such as a heated thermoplastic or glass sheet [Schipper, 2015].

Such adjustable moulds operate in the same manner as already discussed for glass. Some examples of computer-driven moulds used for concrete are the ADAPA mould (discussed also in 4.1.3), the mould concept by Spuybroek and the realized prototype by Vollers and Rietbergen (see figure 83). The last two adjustable moulds comprise of computer-driven vertical actuators (as well as the ADAPA mould) and a flexible layer formed into shape by the pins and acts as a formwork for the concrete layer [Schipper,2015].

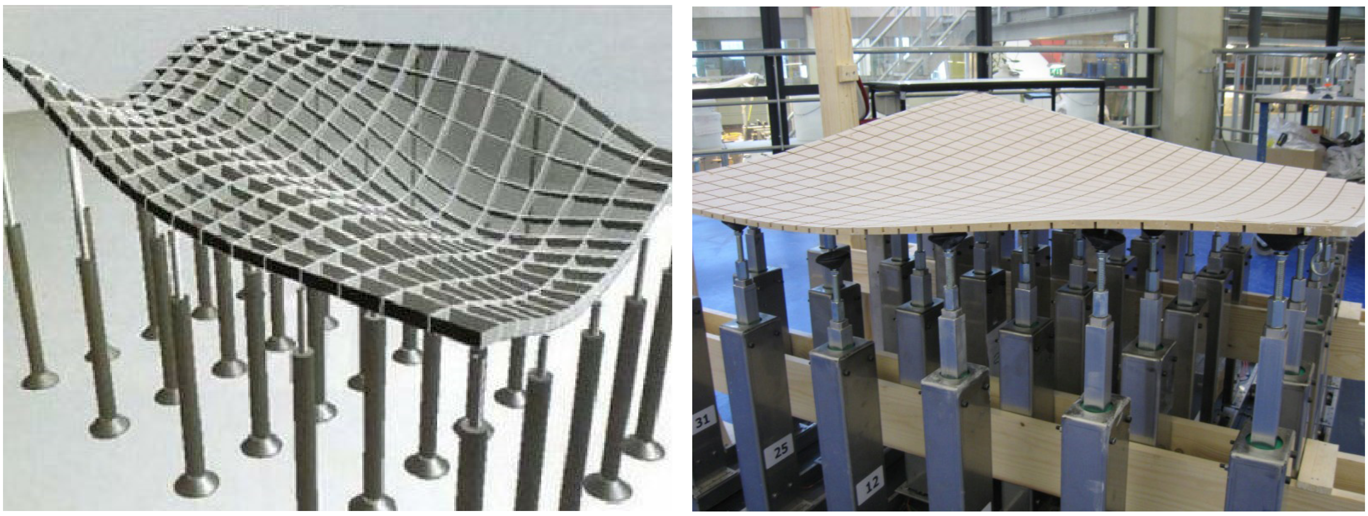


Figure 83: Left: Adjustable mould concept by Spuybroek. Source: Schipper, 2015.
Right: Adjustable mould prototype by Vollers and Rietbergen in 2009. Source: www.bft-international.com.

5.3 Mould types comparison and conclusions

Several moulds for curving glass and other materials have been discussed in the previous pages. All of those have advantages or disadvantages and choosing the right mould is directly linked with the application: the desired geometry, the repeatability of the components etc. In the scope of this MSc thesis, all aforementioned moulds are compared qualitatively to the criteria stated at the beginning of this chapter, and the results are seen on the following table.

			Assessment criteria											
			Visual			Geometrical Freedom					Fabrication limitations		Sustainability	
			Transparency	finishing quality	texture on surface	Possible curvature (radius)	Consistency (thickness) of glass	Size limitation for product	Freeform geometry production	Ease of mould customization	Need for post-processing/ coatings	Cost	Waste production	Reusability/ recyclability
Mouds for glass	Casting	permanent steel/graphite	++	++	-	++	+	-	+	-	+	++	+	+
		displosable	+	-	+	++	-	-	+	+	++	--	--	--
		3d printed sand	-	-	++	++	+	-	+	++	++	--	+	+
	Col bending (on site)	permanent steel/timber frame with clamps	++	+	-	--	++	++	--	+	--	-	-	+
	Hot bending (slumping)	steel-rod permanent	++	+	--	++	-	++	++	+	-	++	--	--
		adjustable	++	-	+	++	-	+	++	++	+	-	++	++
		3d printed sand	++	+	+	++	-	-	++	++	-	--	+	+
Mouds for other materials	Unconfigurable / flexible moulds	Inflatable	n/a	++	--	++	n/a	++	+	+	n/a	n/k	+	+
		Fabric formwork	n/a	++	+	++	n/a	++	++	++	n/a	n/k	+	-
		Knitted	n/a	n/k	++	++	n/a	++	++	++	n/k	--	++	-

Figure 84: Qualitative assessment of different moulds for curving glass or other materials.

In terms of the visual criteria, most casting moulds would need post processing to create a good result. Steel moulds result in a very smooth, transparent surface with no distinct texture. Disposable moulds need to be coated or the glass to be post processed to result in a smooth surface and they can lead to texture on the glass. 3DPSM on the other hand need coatings for de-moulding of cast glass and depending on the coating the transparency changes and texture is imprinted due to sand grains. In terms of geometrical freedom all 3 mould types of cast glass can create glass with many different curvatures, however they are not so flexible in creating freeform geometries. Size of resulting glass is limited with all moulds and consistency is compromised slightly with all due to shrinkage but more with the use of disposable low-accuracy moulds due to the need for post processing. Cost is high for steel/ graphite moulds, whereas, very low for disposable and 3DPS moulds. In terms of sustainability, steel moulds can be reused several times, and they don't produce much waste since they are produced to cast multiple identical glass components. On the other hand, disposable moulds produce lots of waste since they are all disposed of after use and are not reusable or recyclable. With 3DPS moulds their fabrication method allows for the less production of waste, they can be reused 2 times as proven so far and the sand if cleaned and collected can be reused in the production of another mould.

In cold bending moulds, transparency and finishing quality are always good and the mould does not leave texture on the glass. The possible curvatures that can be produced with these moulds are not big and freeform shape potential is not existent. The thickness of glass remains consistent and the only limit in size is the limit of the glass pane dimensions. Furthermore, the mould is easy to customize in shape and since it most of the time is the frame of the final component is costly to create all the moulds, however that leads to very small waste production. Reusability is possible with these moulds since often times they are used to create several identical panels.

Hot bending moulds result in great visual transparency, but the finishing quality might be compromised by the distortions, the steel mesh in adjustable moulds or the rough surface that 3DPS moulds create. Texture can be given to glass with adjustable and 3DPS moulds as described. In terms of geometrical freedom, all hot bending moulds can lead to big curvatures and freeform surface shaping, while, at the same time the consistency of the glass thickness is compromised in extreme curvatures at the highest points, as well as the total dimensional accuracy of the final form. Size limitations exist in 3DPS moulds because of the capabilities of the printer to print moulds of certain dimensions and to adjustable moulds due to their more experimental phase of development. Furthermore, adjustable moulds are easier to customize, especially the computer driven ones, like the Adapa mould, but also it is fairly easy to customize 3d printed moulds. For slumping moulds, there is no specific need for post processing or use of coatings, and their manufacturing cost is relatively low except for the steel permanent moulds which are very expensive, since they are unique moulds for each component. That is the reason why waste is very high and reusability is not possible with these moulds. Adjustable moulds don't produce waste and are reused since they are reformed and reused for each unique component that needs to be manufactured with slumping. 3DPS moulds do not produce lots of waste as discussed also for casting.

Unconfigurable (flexible) moulds for other materials are also compared here, where they can.

The finishing quality of inflatable moulds is very smooth for the material that is cast on top, and they don't leave any texture. The curvatures they can achieve are pretty big and they can be moulds of very big sizes, however they don't seem very promising in the creation of freeform geometries. They don't produce a lot of waste and might be reusable.

Fabric formworks lead to a very smooth finishing quality on the concrete as well, and the fabric might leave texture on the surface. In terms of geometrical freedom, they are great in all aspects. They don't produce much waste but probably can't be as easily reusable.

Knitted moulds exhibit very promising results in terms of achieved geometry as well. The knitted fabric is easy to manipulate in any possible shape and is lightweight, material, cost, and labor efficient. Visually, their current use as stay in place formworks do not allow for a good comparison of the finishing quality on the concrete shell, however their texture is able to imprint texture on the glass (as seen in glass blown example). In terms of sustainability, knitted mould uses less material to create the mould and also serves as a stay in place formwork thus making it not wasteful and its reusability is not applicable for concrete as a stay in place mould, maybe it would be possible if it was detached from the shell. These aspects make it a promising alternative to test with glass forming.

The high geometrical freedom and complexity that knitted moulds can offer, alongside their other advantages, are the reasons why knitted moulds are chosen to investigate further as a novel mould for the fabrication of freeform glass components.

6 Improving the finishing surface quality

Several of the moulds discussed before require the use of coatings or post-processing in order to improve the finishing quality of the produced component's surface. Measures used for moulds curving glass will be discussed, as well as measures taken in contact surfaces of moulds with other materials.

6.1 Finishing quality of moulds for glass

6.1.1 Post processing methods

Several methods for post processing glass exist to improve the finishing surface quality. The most common ones are: i) coatings, ii) grinding & polishing, iii) fire-polishing, iv) acid / etching cream polishing.

Coatings

The most common way to improve the surface finishing quality of cast glass is by applying coating on the mould. According to [Coatings for Moulds and Cores, 2000] coatings are usually applied on moulds with one of the following techniques: a) dipping (immersion), b) brushing, c) swabbing, d) spraying or e) overpouring/ flow-coatings(flow). Some of the coating tested on casting moulds will be discussed later in this chapter.

Grinding & polishing

Several tools are used for grinding and polishing glass surfaces. Lapping is a machining operation that involves rubbing two surfaces together with an abrasive between them, either by hand or with a flatbed and it is the process for grinding and polishing glass [Thwaites, 2011]. Hand lapping is useful for complex curved surfaces where the machine cannot access the surface [Thwaites, 2011]. Abrasives are similar for both machine and hand lapping and will be discussed here.

Diamond blocks feature one surface that is coated with diamond dust and are used to remove debris before polishing the surface. The various colors of the blocks indicate their grit and concentration of dust. To use the blocks, they must be wet, and it is possible to cut them in smaller pieces to conform better to the glass surface [Beveridge et al., 2005]. They are a relatively inexpensive tool that can last a long time [Thwaites, 2011]. Alternatively to diamond blocks, carborundum blocks, sticks or powder may be used for grinding and polishing, which are not as hard as diamond [Beveridge et al., 2005]. Carborundum is silicon carbide (SiC), and its surface has numerous ridges, making it a very efficient abrasive. It is also used wet and has different coarseness grits [Beveridge et al., 2005]. Polishing is usually done with powders. Pumice is a material of volcanic origin which has different grits and is mostly used for fine polishing [Beveridge et al., 2005]. Corundum, or Aluminum oxide, also has a range of grits, is used wet as a powder and is particularly effective for refining areas already sanded with other materials. Finally, Cerium oxide is a powder in red color used after sanding with pumice for a smooth final polish [Beveridge et al., 2005].

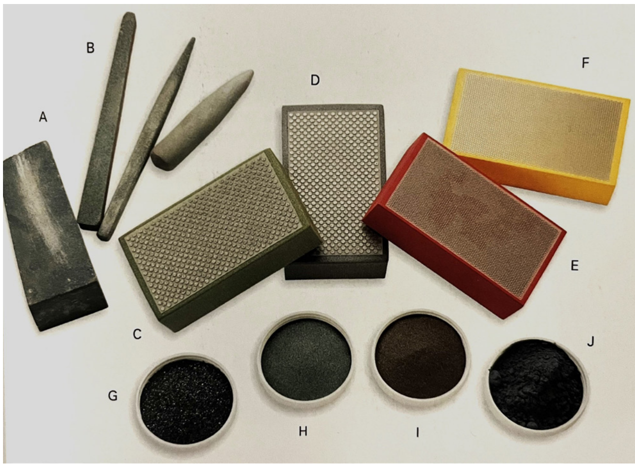


Figure 86: Grinding & polishing hand tools: A) carborundum block and B: sticks., C-F) Abrasive diamond blocks with different grits, G-J) carborundum powder with different grits. Source: Beveridge et al., 2005.

Silicon carbide grit grades (mesh size)	Diamond pad approx. grade equivalent	Coarseness	Used for what?
80,100,180	Green (80-100)	Very coarse	Rough grinding and shaping usually on flatbed machine
220	Black (180-200)	Coarse	Flatbed and/or hand-lapping; first stage of refining after very coarse work
320	Red (250-300)	Medium	Flatbed and/or hand-lapping, for refining; can be final matt surface
400	Yellow (500)	Fine	Hand-lapping, for further refining; can be final surface
600	Yellow (500)	Fine	Hand-lapping; pre-polish; can be final surface; translucent
800	Blue (800-1000)	Very fine	Hand-lapping; pre-polish; can be a final surface; extremely fine and translucent

Figure 85: Grit grades and equivalent diamond block. Source: Thwaites, 2011.

Fire polishing

Fire polishing is a unique way for polishing and rounding glass edges using fire. Heat from an open flame or heating filament softens and blunts glass edges, creating a smooth and polished finish. The temperature ranges from 700 to 1,000°C. This minimizes material damage from contact with the glass end [Sylvania, 2004].

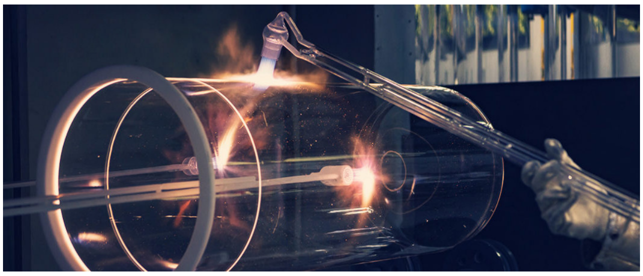


Figure 88: Fire polishing. Source: LTD Materials.

Acid / etching cream polishing

For giving a matte finish on glass, a creamy liquid chemical solution is applied. Acid creams may vary in composition by manufacturer, but they usually are a mix of sulfuric acid, sodium bifluorides, hydrofluoric acid and ammonia with other materials. Etching creams are applied on the glass surface where they induce a chemical reaction which eats away part of the glass creating a thin translucent off-white layer [Beveridge et al., 2005]. Such acids are very powerful and require specific conditions for storage and tools for their application. Strict health and safety regulations are bound to this method which can pose a high risk for the user [Thwaites, 2011]. Kiln cast glass is dipped in acid baths by manufacturing companies, however, at the risk of cracking due to the heat buildup caused by the acid [Thwaites, 2011].

Figure 87: Etching cream. Source: www.makehaven.org

6.1.2 Coatings for 3d printed sand moulds

The use of coatings on 3d printed sand moulds is crucial to improve the surface quality of the glass, especially in the case of casting glass.

Giesecke and Dillenburger [2022] have listed a number of requirements of the coatings for glass casting:

"• *Temperature resistance: Resistance to temperatures of 1200 °C (long time contact) for casting, 800 °C (long time contact) for slumping, and 1200 °C (short term contact) for blow molding.*

• *Non-aqueousness: Required to avoid dissolving the binder material due to water content.*

• *Coating application: Allow for even coating thickness that preserves the mold details through spraying, brushing, or immersion coating.*

• *Process compatibility: Compatibility of the 3Dprinted mold with the kiln and foundry casting process*"

Following various experiments in their research, Giesecke and Dillenburger came to the following conclusions concerning casting glass in 3DPS moulds: Optically transparent results were achieved using sodium silicate coating, however, the surface of the glass attained the grainy texture of the sand mould. Other coatings that were successful in transparent results were Zirkofluid®6672 and Zirkofluid®1219. These coatings result in a smooth glossy surface when used for kiln casting have a milky surface effect when used for foundry casting. Spraying a layer of Bonderite® LGP (graphite-water dispersion) on top of the coating solved this issue and resulted in smooth transparent surface [Giesecke & Dillenburger, 2022].

Coating	Aqueousness	Max. temperaturethe coating can endure[a]	Application method	Mold compatibility	Casting process applied	Glass surface [Specimen no.]
No coating	–	–	–	–	Kiln casting (900 °C)	Opaque, granular (Fig. 3a)
Paragon Glass Separator Dry (Paragon 2021)	Non-aqueous	1287 °C[b]	Brushing	Compatible	Kiln casting (900 °C)	Opaque, granular (Fig. 3b)
Bodmer Casting Slip Porcelain C40 (Bodmer 2021)	Aqueous	1280 °C (Bodmer 2021) (9% shrinkage)	Immersion coating	Cracks in mold	Kiln casting (900 °C)	Partially transparent, deformations from cracks (Fig. 3c)
Bullseye Shelf Primer Bullseye. Shelf primer 2022 and Boron Nitride Aerosol 3 M (Creative Glass Shop 2022)	Aqueous Non-aqueous	850–800 °C[c] (Creative Glass Shop 2022)	Brushing Spraying	Compatible	Kiln casting (900 °C)	Partially transparent, stained (Fig. 3e)
solution (Aldrich 2022) Sodium silicate	Aqueous	Not specified	Immersion coating	Compatible	Foundry casting (1200 °C)	Optically transparent granular surface (Fig. 3f)
Zirkofluid®6672 and Zirkofluid®1219 (Hüttenes-Albertus Group 2022)	Non-aqueous	Not specified	Immersion coating	Compatible	Foundry casting (1200 °C) Kiln casting (900 °C)	Milky-transparent (Fig. 3g) Optically transparent, slightly mat (Fig. 3d)
Zirkofluid®6672 and Zirkofluid®1219	Non-aqueous	Not specified	Immersion coating	Compatible	Foundry casting (1200 °C)	Optically transparent smooth surface
Bonderite® L-GP graphite-water dispersion (Silitech 2022)	Non-aqueous	Not specified	Spraying	Compatible		(Fig. 3h)

Figure 89: Mould coatings tested. Source: Giesecke & Dillenburger, 2022.

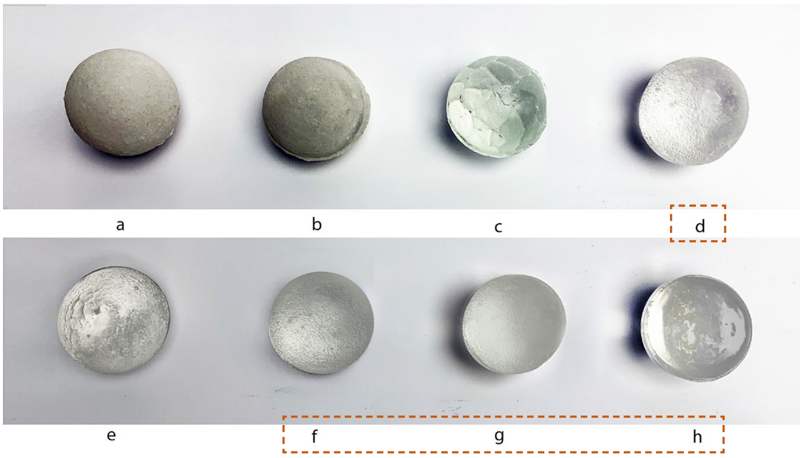


Figure 90: Glass surface results: f) Sodium silicate coating, d)Zirkofluid + kiln casting, g) Zirkofluid + foundry casting, h) Zirkofluid + foundry casting + Bonderite. Source: Giesecke & Dillenburger, 2022.

Ioannidis also experimented with 3DPS moulds and glass kiln casting in his MSc Thesis [Ioannidis, 2023]. In his experimental work, coatings were tested for quarz sand and ceramic sand moulds in different annealing schedules. The combinations resulting at the best surface quality according to Ioannidis are: a) quarz sand printed moulds with coating of Arkopal B5® or Crystalcast and Arkopal B5® and b) ceramic sand printed moulds with coating of Crystal Cast and Zirkofluid® 6672 or Zirkofluid® 1219 [Ioannidis, 2023].

However, there are some peculiarities and drawbacks when using each of these coatings which might result in dimensional inaccuracy or increased costs, as described thoroughly by Ioannidis [Ioannidis, 2023].

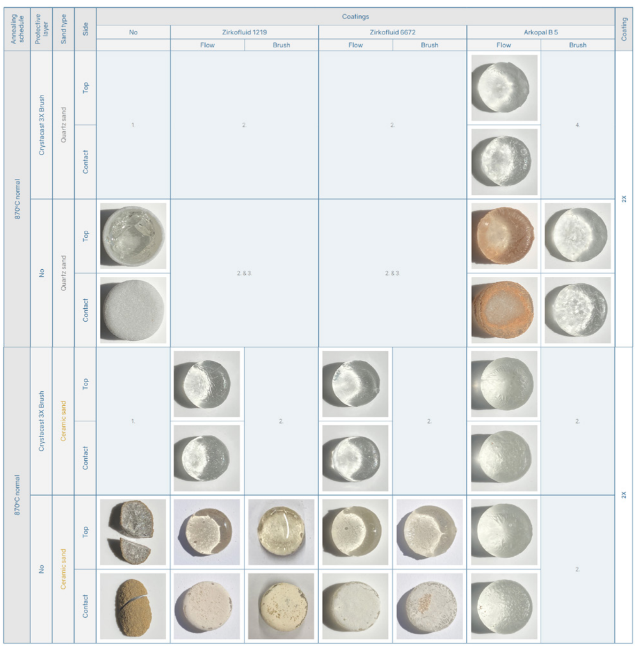


Figure 91: Surface quality of cast glass in contact with different coatings on different 3DPS moulds. Source: Ioannidis, 2023.

6.2 Finishing quality for other moulds

6.2.1 Coatings for knitted moulds

In the previous chapter, the geometrical possibilities of using knitted moulds for concrete were discussed. Nevertheless, knitted fabrics cannot be used directly as moulds because of their flexible nature and they need to be coated with a stiffening material in order to remain in the desired shape. Furthermore, by applying a release agent between the coating and the final surface, the mould can be removed, while in another case, the knitted fabric would be impossible to remove.

Popescu argues that a variety of materials may be used as coatings on knitted moulds. Such materials are polymers, gels, foams, and cements that can be applied in thin layers [Popescu,2019]. Cement coatings have been tested for the projects of knitCrete bridge and knitCandela described in the previous chapter.

For the knitCrete bridge project, a unique cement-paste coating was developed at ETH Zurich. As described by Popescu [2019] "*it is a stable highly fluid suspension consisting of a blended ordinary Portland cement, a polycarboxylate ether based superplasticizers and stabilizing Nanoparticles*". The coating cured inside a climate chamber for 7 days and resulted in a coated textile of 1.5mm thickness. The average deformation on the prototypes surface measured after 48 hours was very small. Next step was to apply repair mortar by spraying on top of the coating, which resulted in a total thickness of 4mm needed before casting the final concrete surface [Popescu,2019]. The direction of the ribbed texture on the textile surface was critical for bonding during the cement-paste coating process. This texture worked best when the ripples were orthogonal to the main flow direction of the liquid cement paste and they increased bonding with the next layer of mortar [Popescu,2019].

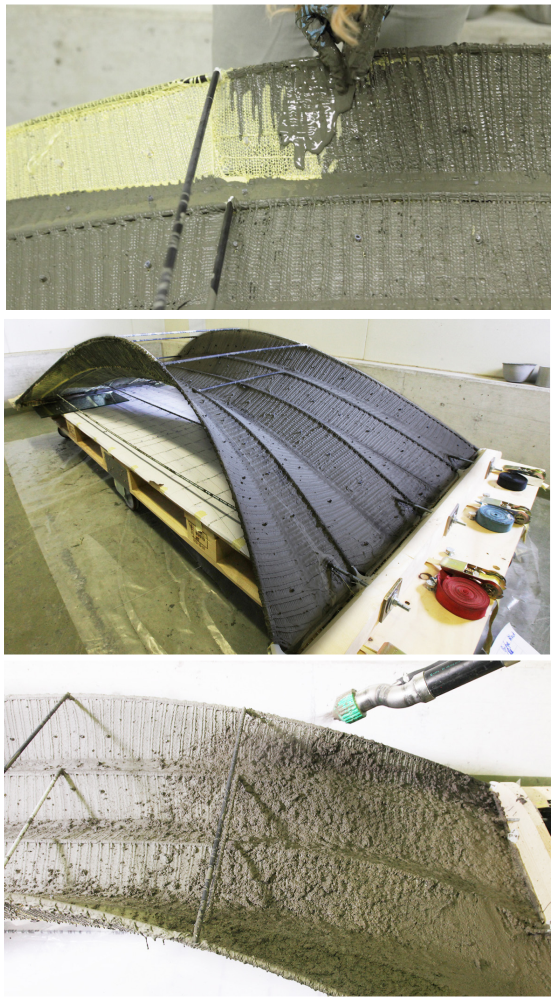


Figure 92: Up and Middle: Cement coating application on knitCrete bridge prototype. Down: Mortar application on top of coating, knitCrete bridge prototype. Source: Popescu,2019.

In case that this prototype was to be recreated in a way that the knitted formwork was to be removed, the application of the mortar would play a critical role in transferring or not the texture of the knitted fabric to the concrete surface. Moreover, the thickness of the cement coating is to be taken into consideration because it leads to slight differentiations in the final geometry accuracy.

In the knitCandela project, the knitted fabric was also coated after tensioning with a thin fast-setting cement coating developed at ETH Zurich. This cementitious coating is developed to stiffen in 2 hours in ambient conditions and is a mix of Calcium Aluminate Cement (CAC) [Popescu,2019]. The coating was applied by spraying a light layer of 1.5mm thickness onto the fabric before the concrete was applied on top.

Figure 93: Spraying of coating (up) & coated structure (down) of knitCandela. Source: Popescu,2019.

7 Knitting & glass

In *Flexible Forming for Fluid Architecture* Pronk classifies and describes all mould types tested for creating fluid forms with glass [Pronk,2021]. Following the qualitative comparison of moulds for curved components in chapter 5, this research concluded that knitted moulds show great promise in creating freeform non-standardized curved glass elements. As can be seen in the diagram by Pronk, knitted fabric has not yet been tested as a form active structure for glass.

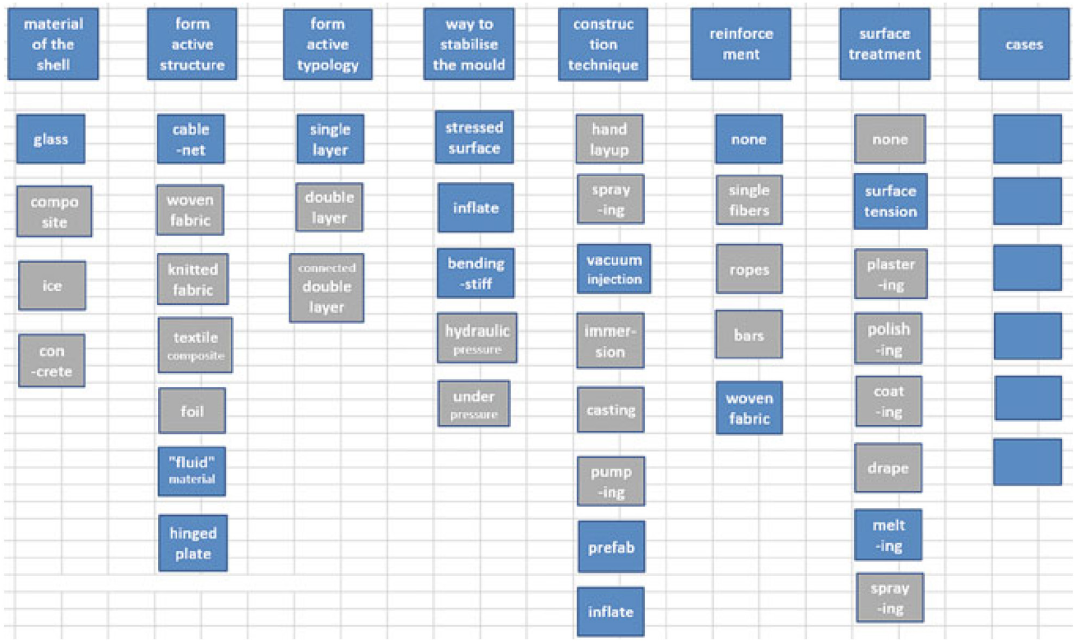


Figure 94: Diagram of flexibe moulding for fluid architecture with glass. Source: Pronk, 2021.

In art, this coupling of knitting and glass has been a source of inspiration. Ceramist Carol Milne has created a series of glass knit sculptures. She has used the method of casting glass in plaster moulds created with the lost wax technique in order to knit her sculptures with wax and then contain the shapes into the plaster mould.

Figure 95: Knitted glass sculptures. Source: Carol Milne (www.carolmilne.com).

Float glass in the form of flat glass panes needs to be heated at very high temperatures to be curved. Textiles are not materials that are meant to be put in a glass furnace because of their relatively low resistance to such temperatures. Therefore, this chapter investigates what types of yarns are suitable for these operations, as well as possible coatings that would help with maintaining the form of the mould for the time needed in the furnace, or for reuse of the mould. Finally, release agents are to be researched for easy detaching of the glass from the knitted mould.

7.1 Fire-resistant textiles

Several textile fibers exist that can withstand high temperatures. The company Final Advanced Materials [Final Advanced Materials] supplies the following high temperature technical textile fibers:

- Aramid
- E-glass
- Zetex
- Basalt
- ZetexPlus
- Silica
- Biosoluble
- Ceramic
- Zirconium

Aramid fibers have a high heat resistance. At 300 °C, the elastic modulus under stress retains more than 80% of its value at ambient temperature. At an average temperature of 200 °C, aramid fibers have great stability [Final Advanced Materials]. Aramid fibers have two textile formats Kevlar or Nomex threads. Kevlar has lower heat resistance than Nomex. Kevlar was used to produce knitCrete bridge fabric. Nomex is used for firefighters' suits, it does not ignite and when heated intensively it carbonizes, giving extra time before the material is destroyed [Nomex]. However, in comparison to the rest of the fire-resistant fibers, Aramid has the lowest heat resistance, 425°C [Final Advanced Materials] which does not make it suitable for glass curving since its softening point is much higher.

E-glass fibers have low thermal conductivity and can withstand temperatures over 600°C. In the form of thread, E-glass is a very flexible material that allows for high strength yarns that can be continuously exposed to temperatures up to 550°C and when coupled with ceramic fibers up to 700°C. It is commonly used for temperature resistant assemblies such as insulations, cables protection, reinforcements etc. [Final Advanced Materials].

Zetex and **ZetexPlus** fibers are made of fiberglass yarns that are treated, have low thermal conductivity and can withstand continuous exposure to 540°C. The peak temperature for Zetex is 700°C, while ZetexPlus is coated with vermiculite and can withstand up to 1095°C. Their application is again for several types of insulations, reinforcement of elastomers, cable protection, protective clothing etc. [Final Advanced Materials].

Basalt fibers are created by the pultrusion of volcanic rocks that have been melted in blast furnaces. They offer considerably greater characteristics than fiberglass. Basalt fabric exposed to flame may endure for several hours compared to a few seconds for the same density fibreglass fabric. Basalt materials are resistant to flame and can withstand continuous temperatures of up to 700°C [Final Advanced Materials]. Furthermore, "basalt fibre is the most environmentally friendly high temperature resistant material when it comes to both manufacturing and recycling it" [Final Advanced Materials].

Silicate fibers have great resistance to thermal impact, have low thermal conductivity and can withstand temperatures up to 1200°C. Silicate fibre-based textiles have different properties according to the content of silicon dioxide ($SiO2$), are very flexible and do not shrink under high temperatures [Final Advanced Materials].

Ceramic fibers have better thermal and mechanical performance than aramid, silica or glass fibers. They have low shrinkage rate, meaning they maintain their dimensions, can withstand continuous temperatures up to 1.370°C but have a tolerance of exposure to up to 1700°C [Final Advanced Materials].

Zirconium fibers produced by Zircar Zirconia have exceptional thermal strength and chemical resistance. The highest operational temperature is 2.200°C. ZYBF fiber is the outcome of converting organic fibers to ceramic fibers. They are woven flexible fabrics used for applications such as high energy battery separators, thermal insulation in crystal growth furnaces, and hot gas filtration [Final Advanced Materials].

Materials	Peak Temperature	Composition	Density	Thermal Conductivity (at 25 °C)	Dielectric Const.	Conventional Applications
Unit	**°C**	**%**	**g/cm^3**	**$Wm^{-1}.K^{-1}$**		
Aramid	425	100% aromatic polyamide	/	/	4	Cut-proof and abrasion-proof safety clothing
E-Glass	600	SiO_2: 55 CaO: 20 Al_2O_3: 15 B_2O_3, MgO	2.6	0.85 to 1	6.4	Temperature resistant assemblies
Zetex®	700	SiO_2: 55 CaO: 25 Al_2O_3: 15 MgO, B_2O_3	2.6	0.74 before treatment	6	Thermal insulating element
Basalt	700	SiO2: 58 Al2O3: 17 Fe2O3: 10 CaO: 8 MgO, Na_2O	2.7	1.65	/	Fire protection, high-temperature resistant assemblies
ZetexPlus®	1,095	similar to Zetex® + vermiculite coating	/	0.74 before treatment	6	High-temperature thermal insulating element
Silicate	1,200	SiO_2> 95	/	0.35	/	High-performance thermal product
Pure silicate	1,100	SiO_2: 99.95 – 99.99	2.2	1.38	3.7	High-performance thermal and dielectric product
Biosoluble	1,200	SiO2: 75 CaO+MgO: 20 Other: 5	/	/	/	Insulating and sealing element
Ceramic	1,700	Al_2O_3: 70 SiO_2: 28 B_2O_3: 2	3.05	/	5.7	High-performance thermal and mechanical product
Zirconium Oxide	2,250	ZrO_2 > 90	/	0.5	/	Very high performance thermal product

Figure 96: Fire-resistant fibers comparison. Source: Final Advanced Materials.

The criteria to choose the most appropriate textile for the moulds are first and foremost the temperature resistance, but also, their consistency to the original shape (no significant shrinkage) and their flexibility to be knitted in the CNC machine in a resulting textile that can be formed in complex curved shapes.

All aforementioned textiles except Aramid seem to be appropriate for use in slumping or casting temperatures, since glass's softening point is above 425°C. Since the most flexible method for creating freeform curvatures is slumping, this will dictate the temperatures to consider.

Depending on the method for curving glass, which dictates the max temperature, and the textile choice, a coating would need to be applied as well to make sure that the desired shape of the mould would stay in place for the duration of the operation.

7.2 Textile coating

Several coatings may be applied on textiles to rigidify their shape.

7.2.1 Heat-resistant cement

As discussed in the knitCrete bridge and knitCandela projects, various types of cement can be used to make a rigid geometrically complex mould from fabric. In order to be able to use cement in combination with glass in a glass oven, it is necessary to prepare a mix of heat resistant cement that can withstand the high temperatures required for glass slumping. The ready mixed cement for high temperature from Provetro Gruppe is a possible solution.

*Figure 97: Left: Heat resistant cement mix. Source: www.glsgmbh.de.
Middle & Right: Heat resistant cement used on textile formwork for sample preparation: cement on textile (middle) and result (right). Geometry & formwork developed by Kariouh and Popescu [2024]. Own images.*

7.2.2 Porcelain dip

Another solution may occur by observing the artwork of Helen Gilmour, *knitted tableware*. In her *teacup* piece, Gilmour knits the shape of a teacup with cotton yarn around a ballon and then dips it into porcelain. The work is then fired at 1280°C, where the porcelain becomes rigid while the cotton burns [Standen, 2017]. Even when the fabric is burned away, porcelain is a material that manages to maintain the desired shape, making it a great alternative coating for this research.

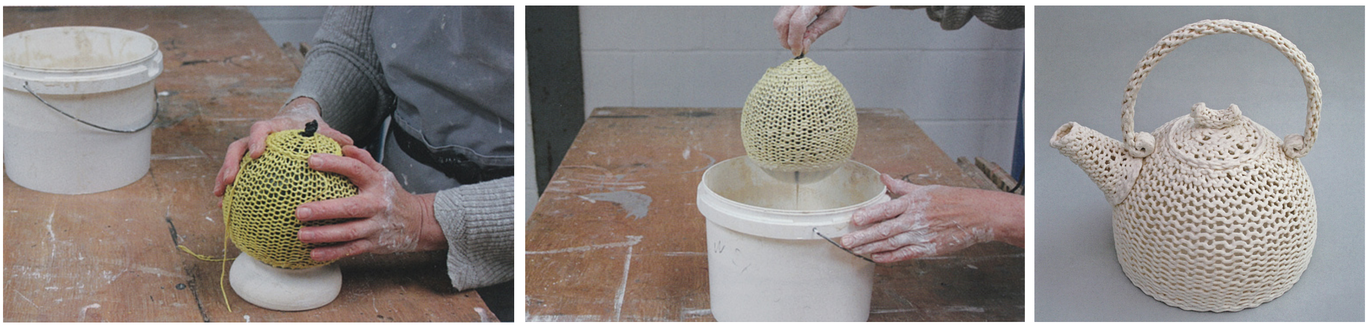


Figure 98: Knitted teapot ceramic piece. Source: www.ceramicartsnetwork.org.

8 Experimental work

In this chapter, the experiments conducted throughout the duration of this thesis are described and analyzed. The results of each experiment as well as decisions made are recorded and will be later utilized to draw conclusions on possible design decisions and future research possibilities.

8.1 Main objectives

A crucial initial step in starting the experimental work is to clearly define the main objectives that these experiments aim to achieve. In the case of this thesis, there is more than one objective: geometry, surface and redundancy.

In terms of geometry, the experiments conducted will attempt to achieve single and double curved glass surfaces with the use of textile moulds and record the limits of this method in order to inform future design decisions. Surface is the second objective of the experiments, where both the finishing surface quality and texture on the glass will be evaluated for each experiment and inform the design of the next experiments in order to achieve better results. Final objective of the experiments is structural redundancy, where the possibility of lamination of glass pieces curved with this method will be explored.

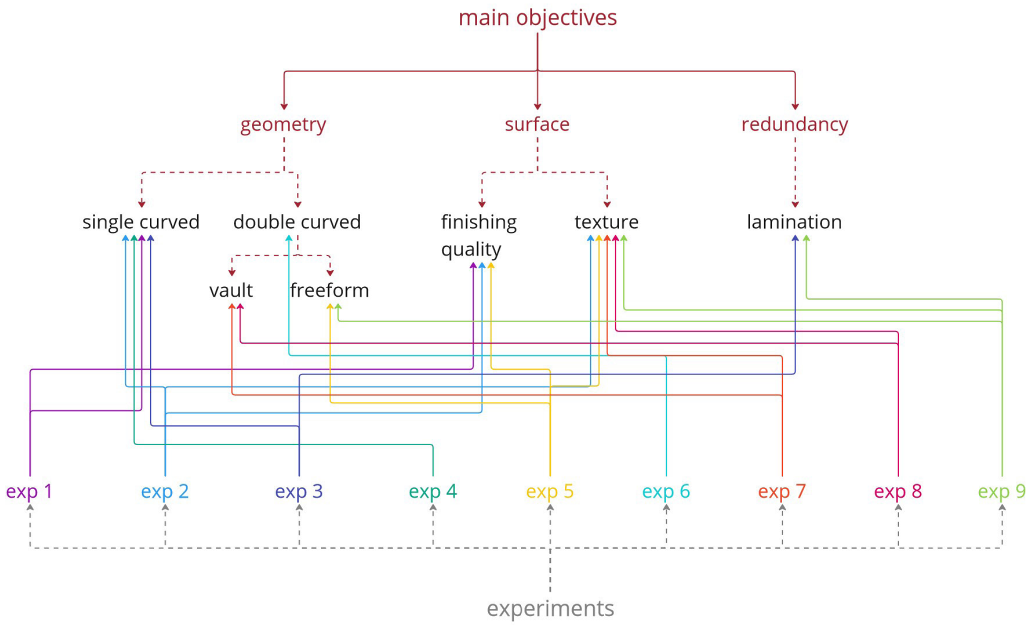


Figure 99: Diagram of main objectives and experiments regarding those.

8.2 Preparation and material choices

8.2.1 Textile

The yarn

In experimental work of papers found in literature, extreme curvatures with slumping usually occur withing 675 and 800°C. Therefore, from the fire-resistant textiles discussed in chapter 7, Zetex, Basalt and ZetexPlus seem to be appropriate for experimentation without the need to go for a fiber with higher resistance. According to the research of Sim, Park and Moon [Sim et al., 2005], thermal stability tests on basalt fibers proved that heating basalt in an oven at high temperatures for 2h leads to a very small decrease of its strength. Specifically, basalt fibers heated at 600°C proved to

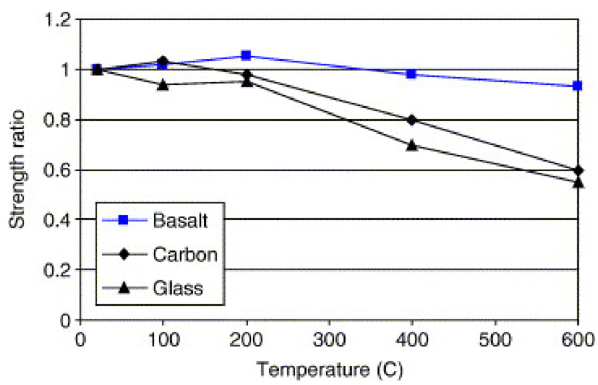


Figure 100: Strength variation of material fibers with respect to heat exposure. Source: Sim et al., 2005.

retain about 90% of their original strength. Since Basalt is also the most sustainable fire-resistant textile according to Final Advanced Materials [Final Advanced Materials], initial tests will be conducted with basalt yarn, and then the choice of yarn will be reevaluated if needed.

The technique

At the start of this thesis's experimental investigation, the CNC knitting machine available at the lab which is used to make the knitted textiles was not accessible. As a result, after a failed attempt to hand-knit a mould with basalt yarn, a series of hand-woven textiles using the basalt yarn was created instead.

The yarn or thread used to make woven and knit fabrics is the primary distinction between them. A knit fabric is formed of a single thread that is continuously looped to create a braided appearance. A woven fabric is made up of several threads, which cross at right angles to produce the grain. The difference between the two types of fabrics can be understood by their stretching abilities. A knit fabric stretches easily along both its axes, more along its breadth, while a woven fabric has extremely limited stretchability and only in the length axis.

For the experiments conducted in this thesis, the two types of fabrics will be tested and compared. While knitted fabrics are the ones that fall under the scope of this thesis, woven fabrics will initially be used to curve glass with consideration to their limitations.

8.2.2 Coatings

As discussed in earlier chapters, coatings may be necessary to enhance the finishing surface quality of glass in contact with the mould but also, to rigidify the textile mould into shape to form the glass easier into complex geometries. Based on the literature research of this thesis, the coatings that can be used to rigidify the shape of the mould are heat-resistant cement and porcelain dip. The availability of Crystalcast plaster in the lab makes it another possible coating to test in this respect, since Crystalcast is used to produce moulds for casting glass. According to the Crystalcast Product Information Datasheet "GRS Crystalcast is a plaster-bonded investment powder specifically designed

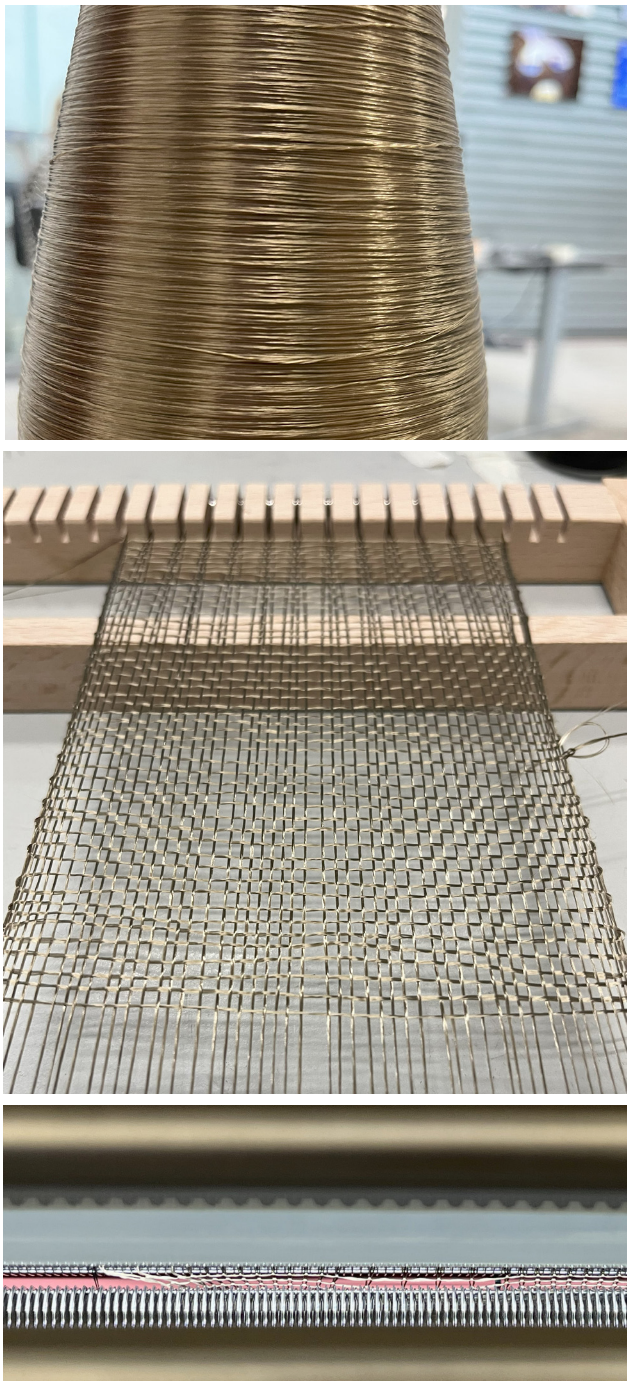


Figure 101: Up: Basalt yarn bobbin. Middle: Hand weaving process of basalt mould. Down: CNC knitting of basalt mould. Own images.

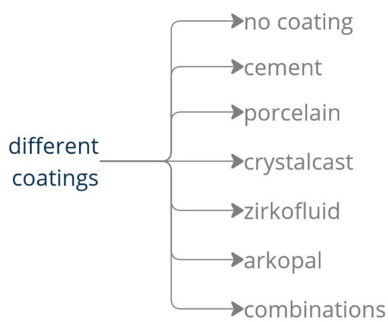


Figure 102: Diagram of possible coatings use for experiments.

for casting glass. The refractory content and permeability of Crystalcast enables firing cycles to temperatures as high as 900°C for as long as 10 days depending on the mould size. To enable the removal of filigree work from the mould without breakage and for ease of use, Crystalcast has been designed to have high strength during firing, yet removal from the cast item when cool is very easily achieved, limiting any chance of damage" [Goodwin Refractory Services LTD]. Based on the literature research on coatings for enhancing the finishing surface quality, Zirkofluid and Arkopal are two possible coating to test.

The experimental work is decided to begin without the use of any coatings and then gradually test different coatings according to the needs that come up depending on the results.

8.2.3 Firing Schedule

According to the literature, extreme curvatures with slumping usually occur withing 675 and 800°C. Therefore, the goal of the experimental work is to test slumping at both these two temperatures, starting with the lowest one and then moving on to the highest one according to the results of the experiments.

Creating the firing schedule for the slumping process in the oven is a crucial step to start the experiments. The first annealing cycle to be used is shown in the image, it reaches a maximum of 675°C and it lasts for 21 hours and then another 20 hours for cooling off.

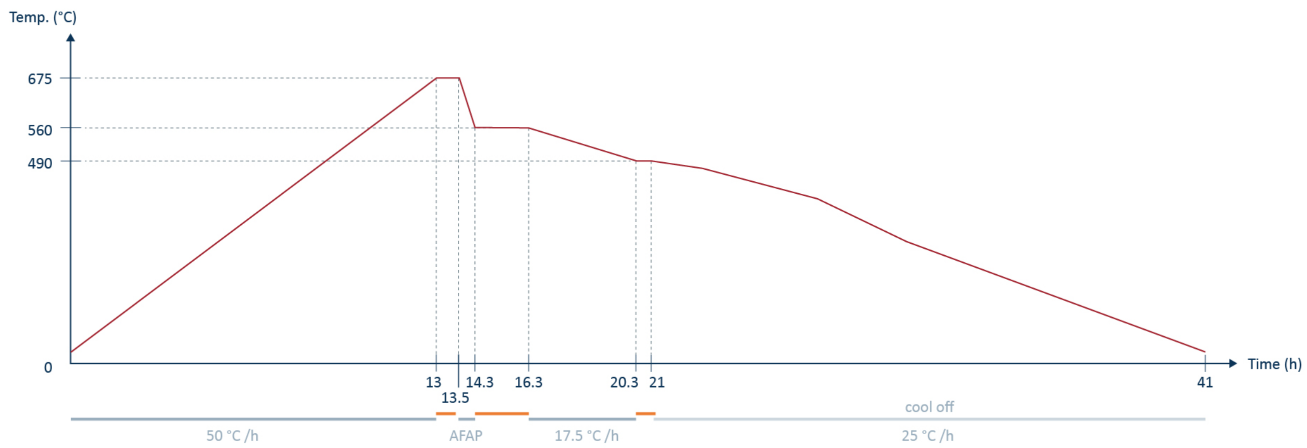


Figure 103: Firing schedule for experiments.

8.3 Experiments

8.3.1 Overview of experiments

In the experimental work of this thesis 9 experiments in total were designed and performed. Each of these experiments is designed in regard to different objectives of geometry, surface and redundancy as stated at the beginning of this chapter.

The experiments will be presented in this chapter not in chronological order but split in two parts based on the type of the supporting system of the mould, which is a 2-support system – where 5 of the experiments belong – or a 4-support system – with which 4 experiments were conducted. At the 2-support system category 4 of the experiments are set-up to achieve a single curved geometry, while 1 experiment is set-up to achieve a double curved geometry. At the 4-support system category all 4 experiments are set-up to create double curved geometries, 2 of which offer support at the corners of the mould, while the other two offer support at the edges. In terms of surface quality, 4 coatings will be tested on the mould or on the glass surface to test which one offers the best surface quality in terms of finishing but also texture on the glass. These coatings are Biosoluble & Thin fire paper layers, Crystalcast, Heat-resistant cement and Clearcoat Overglaze devitrification coating.

The set-up and results of each experiment will be discussed in detail in the following pages. Hereby, a table containing the overview of all the experiments' set-up details and goals.

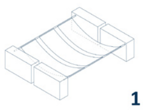
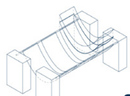
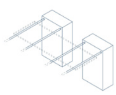
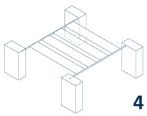
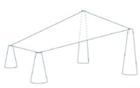
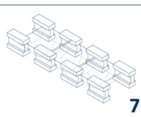
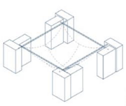
	set-up					goals	
	experiment	schedule	mould pattern	coating / protective layer	geometry	main goal	sub-goals
2 supports system	 1	675 °C	hand-woven x 3 densities	-	Single curved small curvature	Compatibility of basalt as mould material used in glass slumping	> single curved geometry slumping > finishing quality of glass > texture possibility imprinted by mould
	 2	675 °C	hand-woven x 3 densities	- no coating on mould - 2 extra thin layers (biosoluble + fire paper) placed on mould 2.C	Single curved bigger curvature	Assessing extreme densities of moulds for minimum limit of supports offered for slumping	> big curvature - single curved geometry > does glass slump between extremely loose weave of mould > finishing surface with coating layers
	 3	675 °C	-	-	Single curved corrugated	Measuring maximum deformation achieved by glass in narrow spans	
	 4	675 °C	CNC knitted	devitrification spray on 4.B	Single curved small curvature	Assessing different deformations per glass thickness and possibility for lamination	> possibility for similar resulting geometry with different thicknesses > possibility for simultaneous slumping > finishing quality with devit spray
	 5	675 °C	hand-woven	CrystalCast on mould	Double curved	Assessing compatibility of crystalcast coating on basalt mould for rigidifying the shape	> compatibility of basalt and crystalcast > freeform double curved shape > finishing quality & imprinted texture with crystalcast
4 supports system	 6	675 °C	hand-woven	-	Double curved small curvature	Possibility of double curved geometry by corner support in different heights	
	 7	675 °C	CNC knitted x 3 densities	-	Double curved vault	Assessing deformation caused by different patterns of knitted moulds in tension	> double curved geometry differences > possibility for different curvatures depending on knitting pattern
	 8	675 °C	CNC knitted	-	Double curved vault	Possibility for multiple curvatures in double curved shape by adjusting knit pattern of mould	> test of edge support in mould
	 9	675 °C	CNC knitted	Cement mould	Double curved	Assessing compatibility of cement mould with glass & comparison of cement and glass final geometries	> finishing quality & texture imprint with cement > possibility for lamination by repeating with different glass thickness

Figure 104: Overview table of experiments; set-up and goals.

8.3.2 Experiment 1 : Compatibility of basalt as mould material used in glass slumping

Set-up

At the beginning of the experimental research of this thesis the CNC knitting machine to prepare the textile moulds was not available for use. Therefore, a set of hand-woven textiles with basalt yarn were prepared instead. For the first experiment, 3 moulds were tested. The 3 moulds were produced with different densities, which are shown in the image on the side, that are mostly dense.

The 3 moulds are hung from steel bars and not tensioned creating a natural small curvature. After they are hung, plates of float glass of 30x10 cm dimensions and 4mm thickness are placed on top of them without any in-between protective layer or coating on the mould or the glass. The oven is set at the firing schedule of 675 °C.

The goals of this first experiment was to determine:

•The basalt resistance at this temperature

•The strength of the mould under the glass weight and the final deformation of the glass compared to the initial mould shape

•The compatibility of glass and mould in terms of surface quality

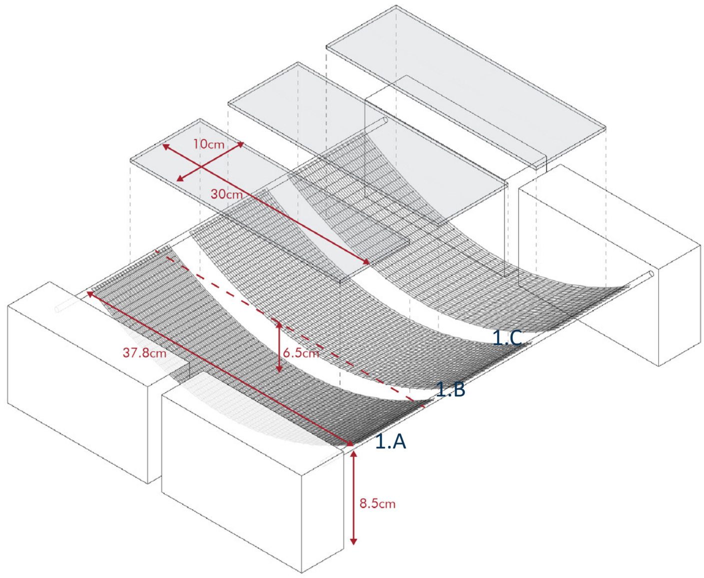
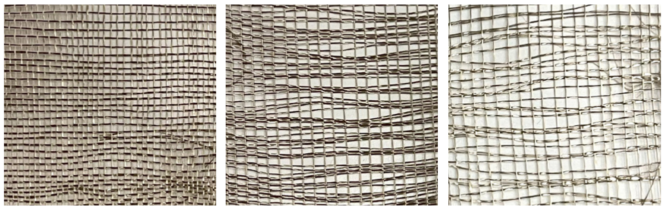


Figure 105: Diagram of experiment 1 set-up.



1.A	**1.B**	**1.C**
Dense weave	Uneven medium weave	Medium weave
grid: 0.2x0.2 cm	grid: 0.5x0.1 cm	grid: 0.6x0.6 cm

Figure 106: Hand-woven textile moulds. Own image.

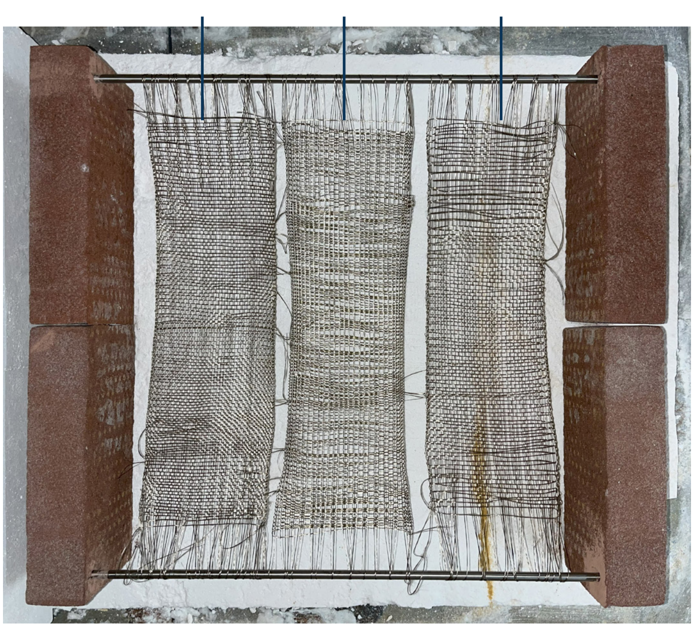


Figure 107: Experiment 1 set-up in the oven, plan view. Own image.

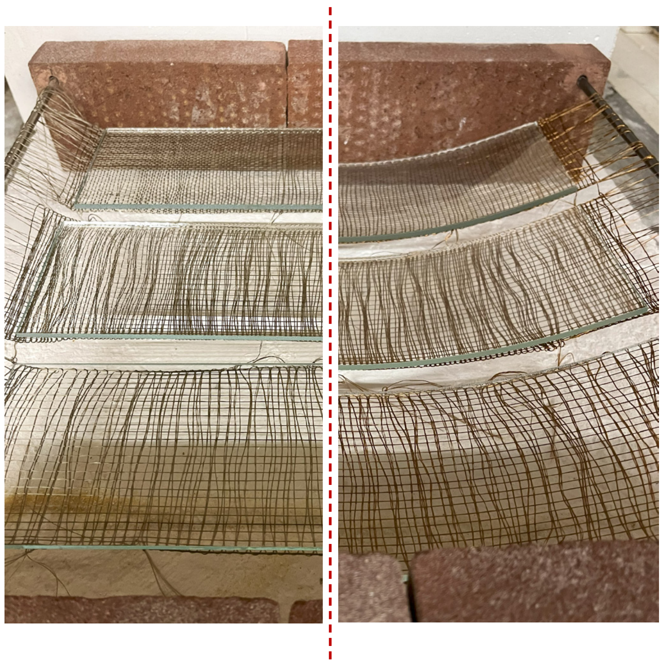


Figure 108: Placement of glass on moulds before (left) and after (right) slumping. Own image.

Results

After slumping the glass plates at the firing schedule of 675 °C, the first and most important conclusion that is drawn is that textile moulds made of basalt yarn can be used successfully to curve glass. The results of the first experiment are the following:

Geometry: Glass deforms perfectly following the mould's initial curvature. The structure of the woven textile proved to be quite rigid and did not allow for further sagging of the mould and the glass because the hand-woven basalt mould is not stretchable. There were very slight deformation differences; the looser patterns lead to slightly bigger curvature (in the scale of 1mm).

Finishing quality: The surface appears to be slightly foggy, probably due to light crystallization of the glass. This is a guess that needs to be tested and verified with the microscope and the results of the microscope study will be discussed further later on in this chapter. Glass was easily de-moulded leading to the conclusion that there is no need for coatings or release agents between basalt textiles and glass at this temperature for this purpose. Furthermore, the texture of the hand-woven moulds was imprinted slightly in the form of dots at contact points of glass support of all samples based on their density.

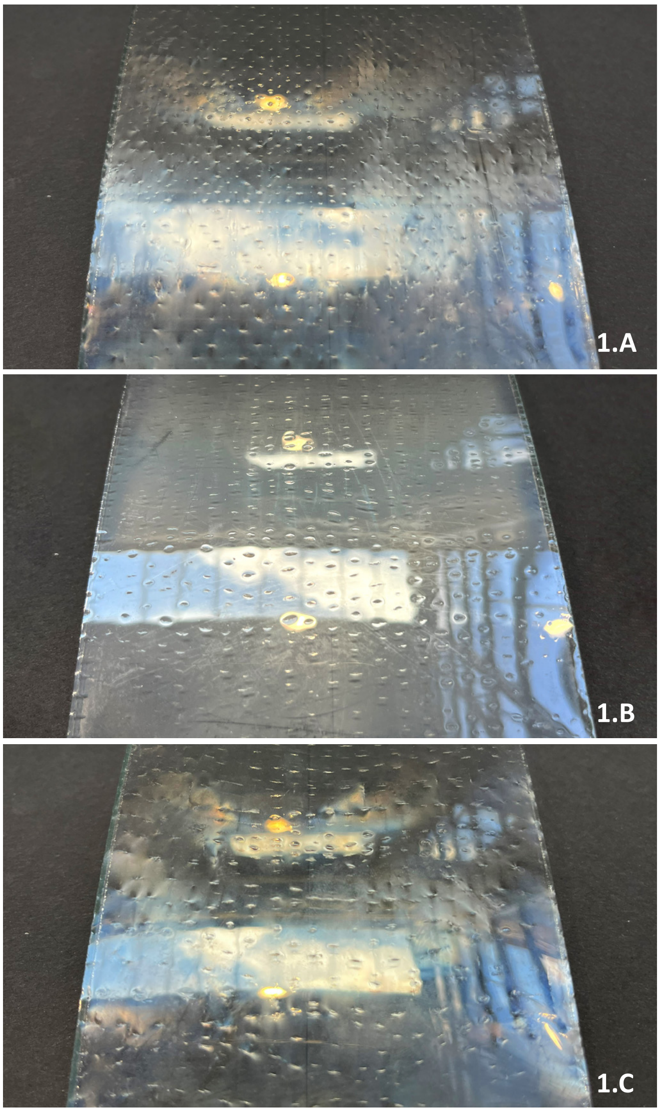


Figure 109: Imprinted texture from moulds. Own images.

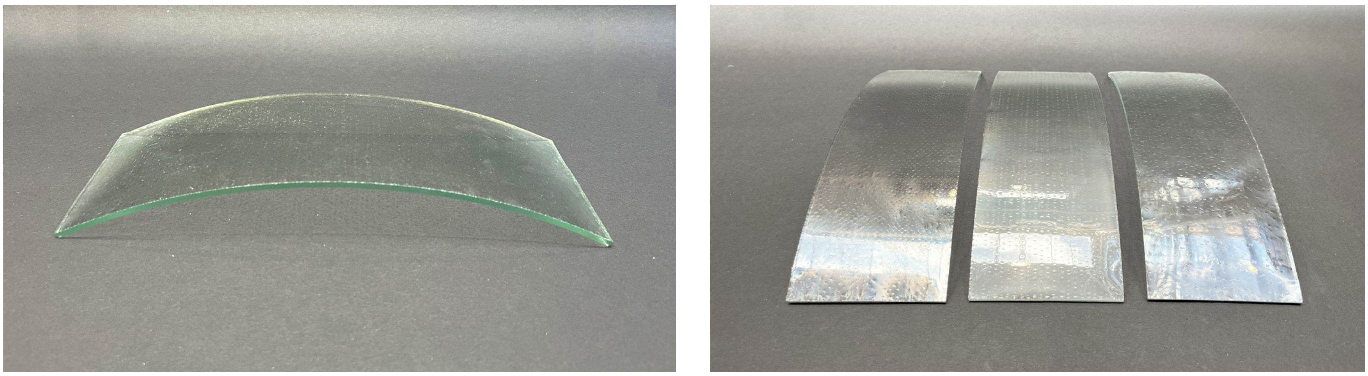


Figure 110: Curved glass results of experiment 1. Left: curvature and Right: comparisson of 3 glass results. Own images.

Results

Mould: The textile moulds did not break while in tension for the whole duration of the experiment (21 hours + 20 hours cooling). They got “baked”: changed color and lost most of their strength, as the basalt fibers now break with minimal pulling. When released from the tensile stress caused by the glass weight, the moulds started falling apart in pieces, something observed mostly to looser moulds that have less support point at the steel bars. Therefore, re-tensioning of the mould in its original place is not possible.

Reusability: Reuse of the mould is not possible after using it once in the oven. However, the mould might be able to be reused in a different set-up scenario, not as a directly loaded mould, but as a way to introduce even more texture to the glass at higher temperatures.

Structural: In terms of its structural integrity, there are no residual stresses in the glass with this slumping method. This was tested with a quick polarization test, which showed that even at the imprinted dots there were no stresses. This conclusion should be tested in the microscope for more accurate results.

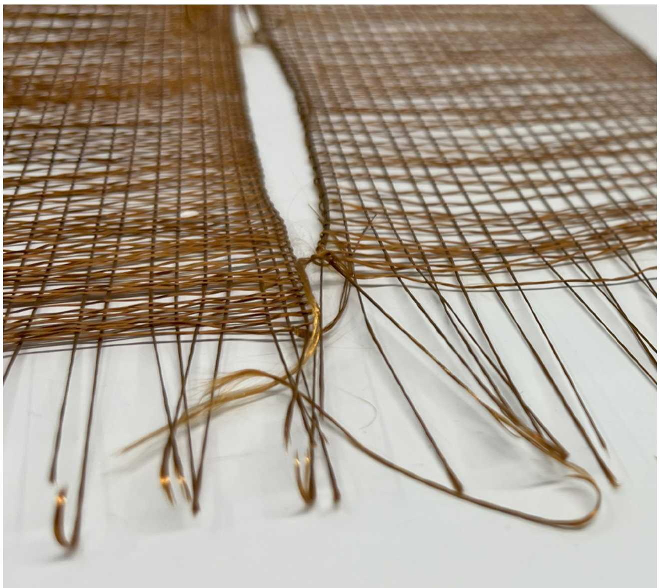


Figure 111: Breakage of supports of mould. Own image.

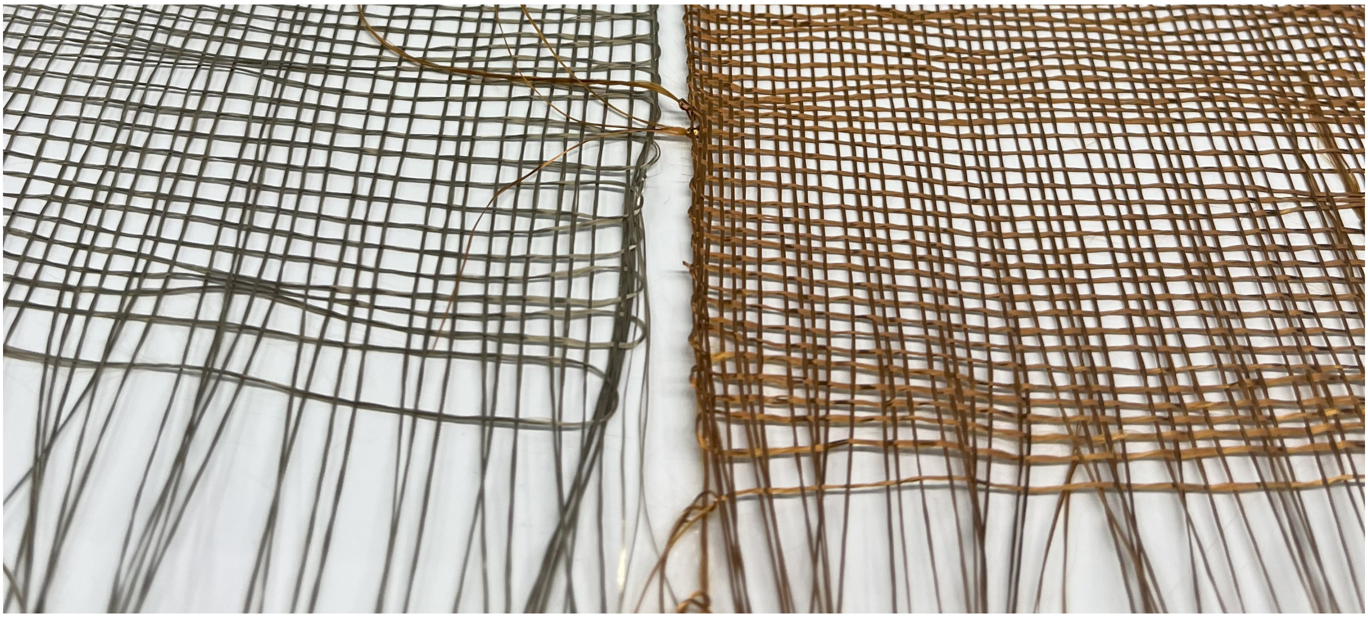


Figure 112: Basalt woven mould before (left) and after (right) being used for slumping in the oven. Own image.

8.3.3 Experiment 2 : Assessing extreme densities of moulds for minimum limit of supports offered for slumping

Set-up

Following the results of experiment 1, it was decided to test a single curved geometry with bigger curvature, but also more extreme densities at the hand-woven mould to determine if the glass would still deform evenly or if it would start sagging though the openings. Another test that was performed with experiment 2 is regarding the surface quality of the glass and the use of protective layers between the mould and the glass to check the imprinted texture on the surface but also the transparency.

Experiment 2 is performed with a similar set-up as experiment 1: 3 moulds are hung from steel bars and not tensioned creating a natural big curvature. After they are hung, plates of float glass of 30x10 cm dimensions and 4mm thickness are placed on top of them at the first two samples without any in-between protective layer or coating on the mould or the glass. The third sample has 2 protective layers between the glass and the mould, a layer of biosoluble paper in contact with the mould and a layer of thin fire paper in contact with the glass. The oven is set at the firing schedule of 675 °C.

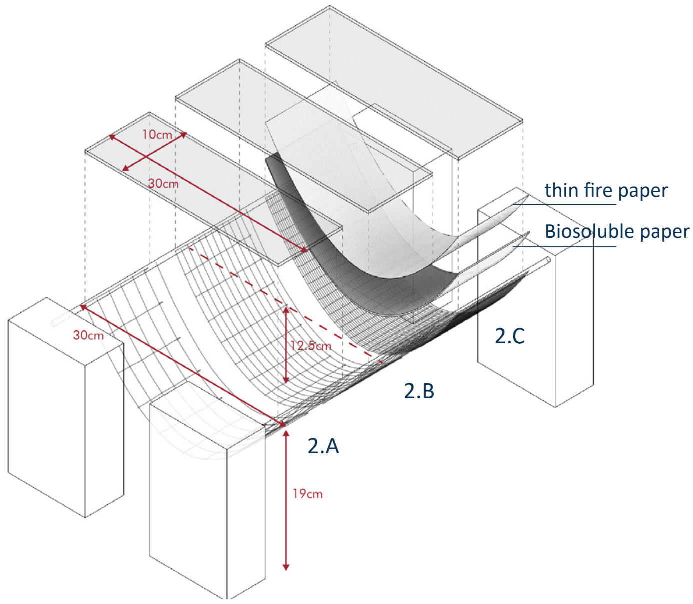


Figure 113: Diagram of experiment 2 set-up.

2.A
Extreme loose weave
grid: 3x4 cm

2.B
Very loose weave
grid: 2x2 cm

2.C
Loose weave
grid: 0.5x0.8 cm

Figure 114: Hand-woven textile moulds. Own image.

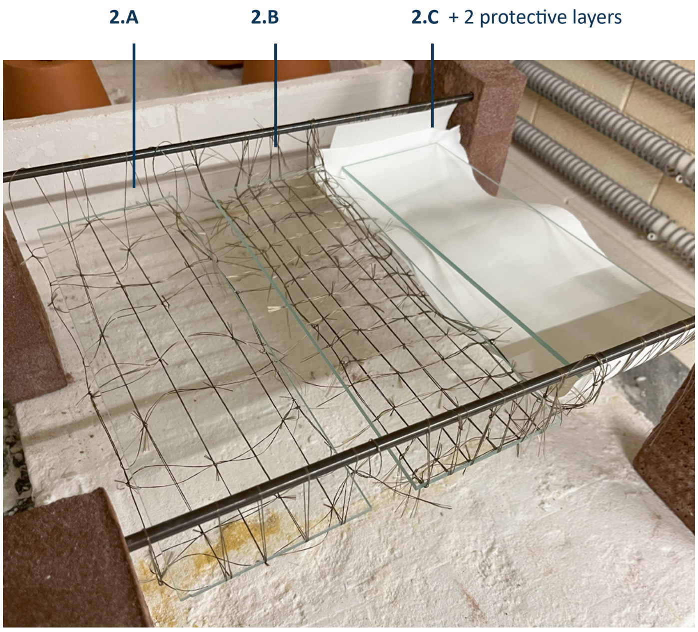


Figure 115: Experiment 2 set-up in the oven. Own image.

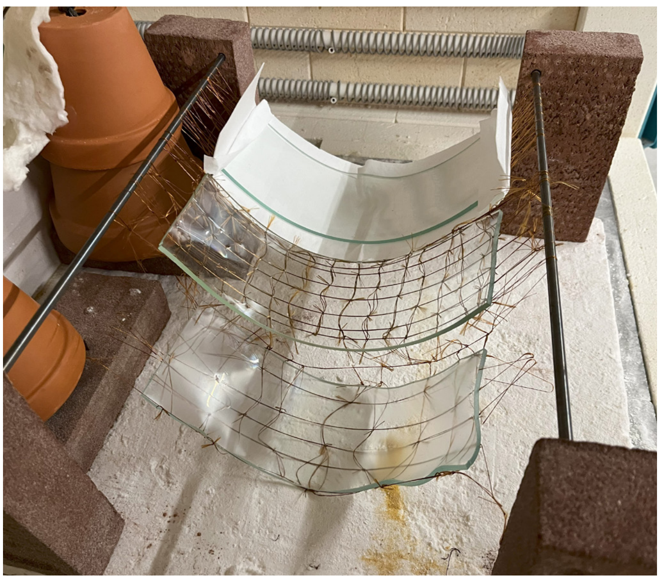


Figure 116: Experiment 2 slumping results. Own image.

Results

After slumping the glass at the firing schedule of 675 °C, the results of the second experiment are the following:

Geometry: Glass deforms perfectly following the mould's initial curvature. Glass did not fall through the looser mould gaps (2.A & 2.B); even the bigger gaps of 2.A which are 3x4cm were not enough to create even a slight fall-through effect, creating a limit as to how narrow a span it is possible to slump glass. Moreover, the edges of 2.A were observed to be not completely straight, which was caused by the dimension and position of the supporting warp direction of the woven mould on glass.

Finishing quality: There appears to be light crystallization of glass for 2.B and great crystallization of 2.A between the supports. A possible cause of this could be the presence of fire blankets in the oven (as discussed with T. Bristogianni at the lab). Glass 2.C exhibits the best result (less crystallization) out of the 3 in terms of surface quality. Texture is again imprinted on samples 2.A & 2.B in a very visible manner; the knots of the mould may have caused small cracks, something which needs to be examined in the microscope. Moreover, there appears to be a slight transfer of color from the mould to the imprints, which leads to a premature conclusion that there are inclusions of basalt material in the glass. On sample 2.C, the texture of the mould did not transfer to the glass because of the extra layers, however, there is little texture - the texture of the biosoluble paper.

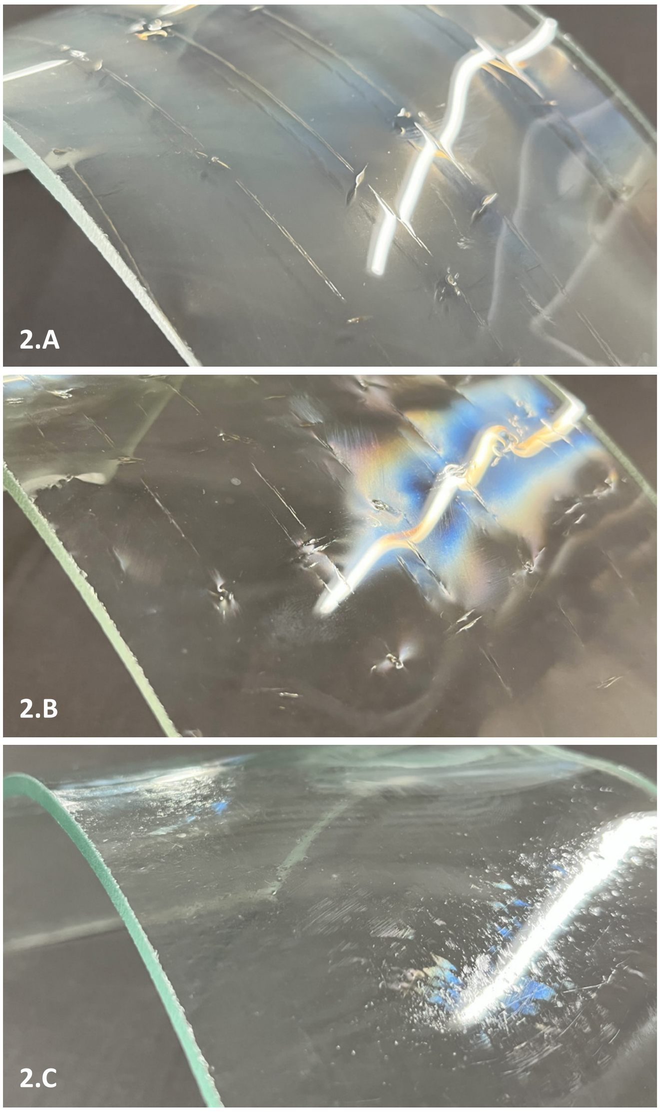


Figure 117: Imprinted texture from moulds. Own images.

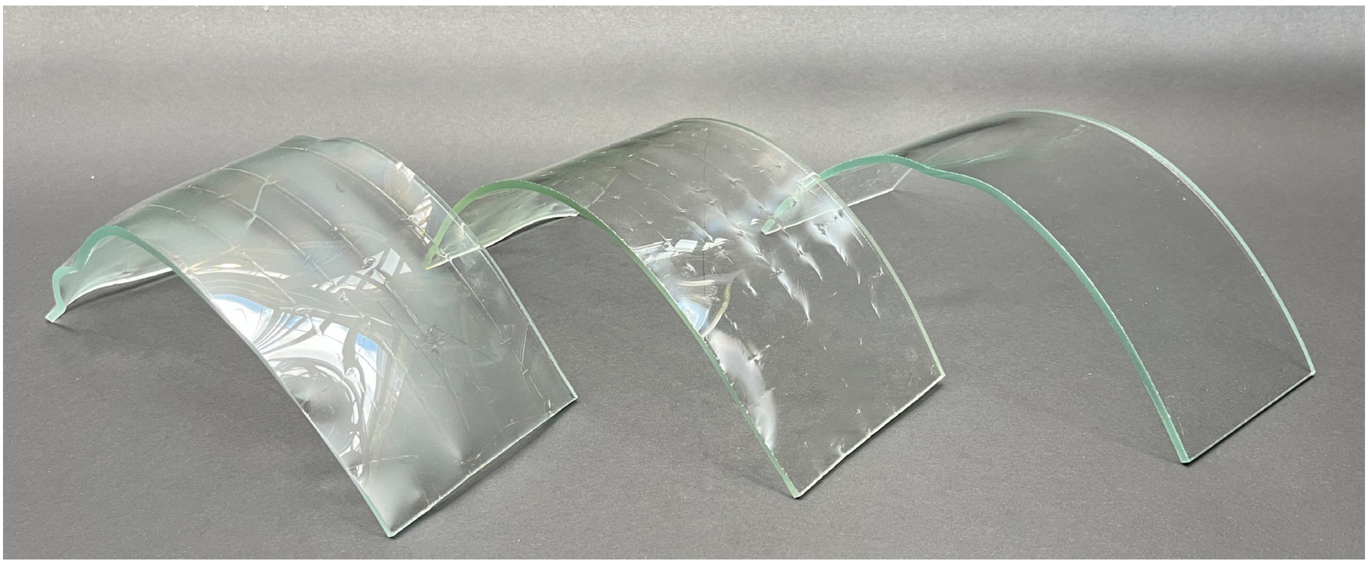


Figure 118: Curved glass results of experiment 2; left: 2.A, middle: 2.B, right: 2.C. Own image.

Results

Mould: Only the extreme loose mould (2.A) broke down during the slumping process, however, it managed to retain its shape long enough to shape the glass. 2.A broke because it had very few supporting loops of the mould onto the steel bar (the warp direction of the woven textile was not dense enough). Moulds 2.B & 2.C had similar result in their outcome as with experiment 1. The addition of protective layers on top of 2.C did not change anything for the mould itself. All moulds became slightly more brittle than experiment 1. This might be caused due to the bigger curvature, less supports and, thus, more tension on the fibers or due to the presence of other materials in the oven (fire blankets & papers). Regarding the extra layers placed on 2.C, the thin fire paper completely burnt away and the biosoluble paper did not burn but became thinner and easier to tear by hand.

Structural: In terms of its structural integrity, there are no residual stresses in the glass with this slumping method. This was tested with a quick polarization test, which showed that even at the imprinted spots there were no stresses. This conclusion should be tested in the microscope for more accurate results.

Figure 119: Biosoluble paper with remaining crumbs of thin fire paper. Own image.

Figure 120: Basalt woven moulds after being used for slumping in the oven. Own image.

8.3.4 Experiment 3 : Measuring maximum deformation achieved by glass in narrow spans

Set-up

Experiment 3 was a study to understand the maximum possible deformations of 4mm thick glass under its own weight. Inspired by the narrow and steep wavelength patterns in the research of Giesecke and Dillenburger [2022], the set-up of this experiment aimed to create a single curved corrugated geometry. 4 stainless steel bars were set up in parallel with 2 different spans: 1 bigger distance in the middle and 2 spans of equally smaller distance on the sides. The middle span was 10cm and the side spans were 6.8cm.

The bars could not be in direct contact with the glass, therefore, the protective layers of biosoluble paper and thin fire paper were placed at the contact points. The oven was set at the 675°C firing schedule.

Apart from measuring the maximum deformation of the glass plate in such narrow spans, another goal of this experiment was to see how the glass surface would react since there was no contact with a basalt mould.

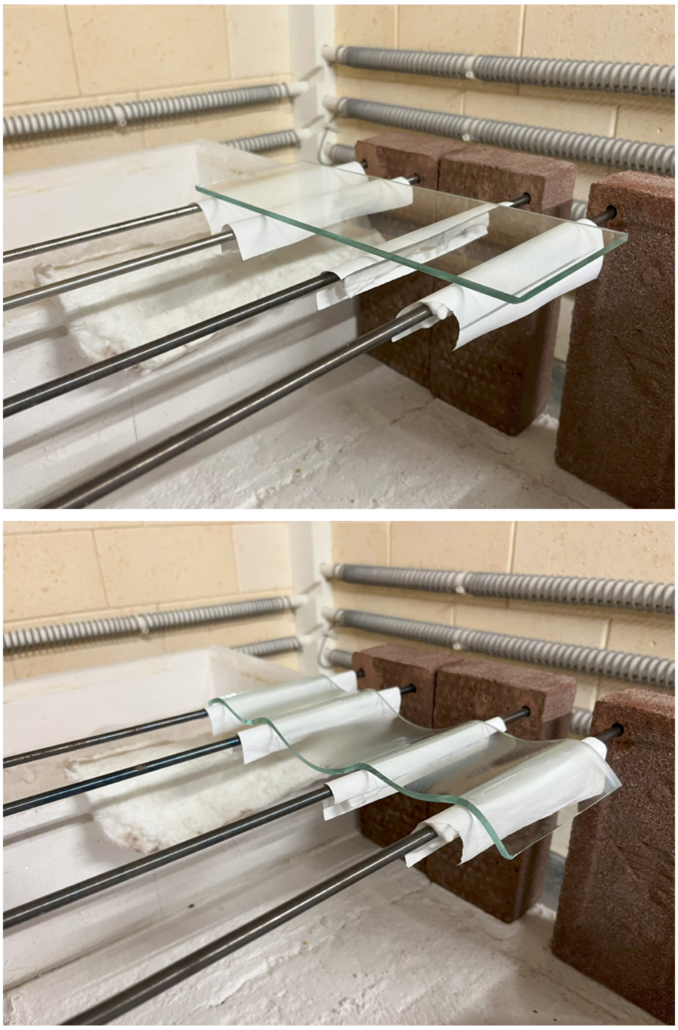


Figure 121: Experiment 3 in the oven, before (up) and after (down) slumping. Own image.

Results

Geometry: As expected, the glass did not deform a lot in the narrow spans. This result was expected based on the results of the research of Giesecke and Dillenburger [2022]. In the larger span in the middle the maximum deformation reached 2.5cm, which is (span/4). In the smaller spans at the sides the maximum deformation reached 0.4cm, which is (span/17). These results verify that for extreme curvatures of such narrow spans only higher temperatures would be likely to achieve the desired results.

Finishing quality: The glass surface did not remain completely transparent despite the absence of the mould. Middle parts of the spans exhibit a foggy surface of light crystallization again, showcasing that the basalt was not the causing factor for the crystallization. Rather, a possible cause for this is either the cooling time in the firing schedule, or the existence of other materials in the oven causing a reaction. Next step towards a transparent glass surface is to test a devitrification coating before modifying the firing schedule.

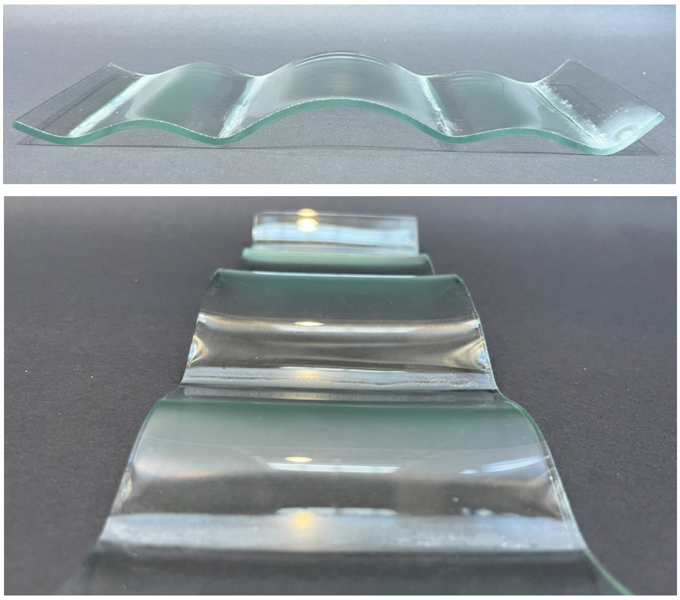


Figure 122: Experiment 3 resulting geometry from slumping under self weight. Own images.

8.3.5 Experiment 4 : Assessing different deformations per glass thickness and possibility for lamination

Set-up

In experiment 4, 4 CNC knitted moulds of the same dense knit/float pattern are used to curve glass in single curved geometry. The moulds are placed in a flat pretensioned position by supporting them on 2 sides with steel bars. Then, different thicknesses of glass pieces dimensioned 5x30cm are placed on top: 4.A has 8mm glass, 4.B has 4mm glass coated with a Clearcoat Overglaze devitrification spray on the surface in contact with the mould, 4.C has a 4mm glass and a 1mm glass on top of it with a layer of thin fire paper between them, and finally, 4.D has 1mm glass. The oven was set at the 675°C firing schedule.

The aim of this experiment is to test whether same boundary conditions can lead to similar curvatures in the glasses for better redundancy of the glass by future lamination of the pieces, and also if it is possible to simultaneously slump glasses resulting in identical curvature also for the same purpose of lamination. Additionally, the coating of the devitrification spray on 4.B is tested in order to investigate if it leads to a fully transparent surface of the glass and, therefore, enhances the finishing quality.

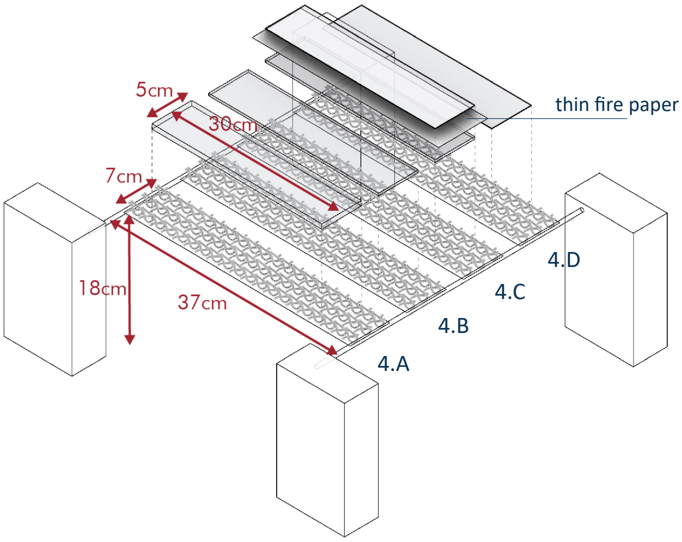


Figure 123: Diagram of experiment 4 set-up.

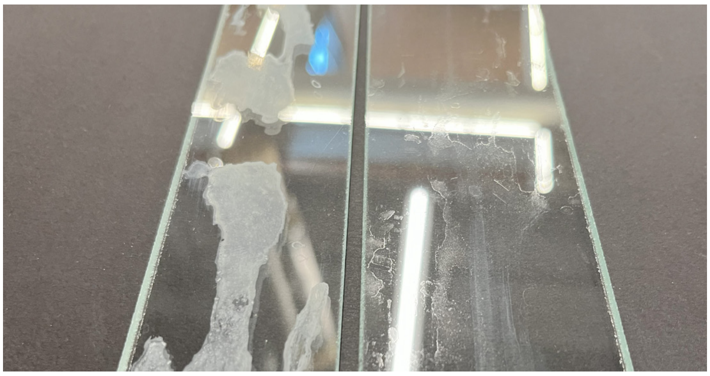


Figure 124: Application of Clearcoat Overglaze devitrification coating on glass. Application by brush. Left: thick layer - discarded. Right: thin layer - used. Own image.

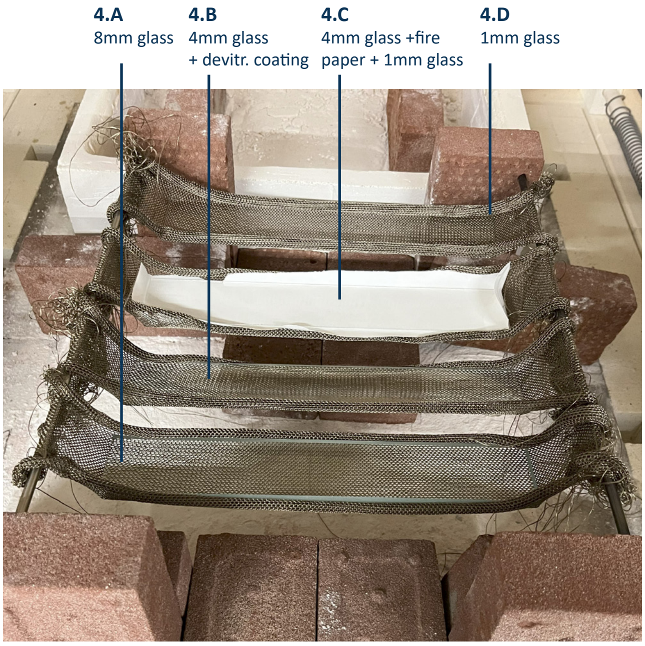


Figure 125: Experiment 4 set-up before (left) and after (right) slumping. Own images.

Results

Geometry: All glass pieces deformed in single curved geometries leading to different curvatures. 4.A led to a maximum deformation in the middle of 4.4cm, 4.B led to 3.4cm, 4.C to 3.6cm and 4.D to 3cm. Since the knit textile is stretchable, it is reasonable that the glasses deformed accordingly to their weight, thus leading to bigger curvatures for the thickest glass. The glasses of 4.C deformed in an exactly similar curvature, making it possible to laminate them later. Thus, the best way to achieve a laminated curved glass is to slump the two individual glass panes together.

Finishing quality: The surface of all samples turned out to have very light crystallization, with the 1mm having more crystallization than the others in the form of iridescent colors but still in a light way. Even 4.B which had the devitrification coating did exhibit very light crystallization in some parts of the glass, which means either that the coating was not properly applied or that the coating is not working successfully at these temperatures. In terms of texture, the mould supporting points were imprinted like dots on all glasses, however, with different intensities: the thicker the glass the stronger the imprint.

Structural:*In terms of its structural integrity, there are no residual stresses in the glass. This was tested with a quick polarization test.*

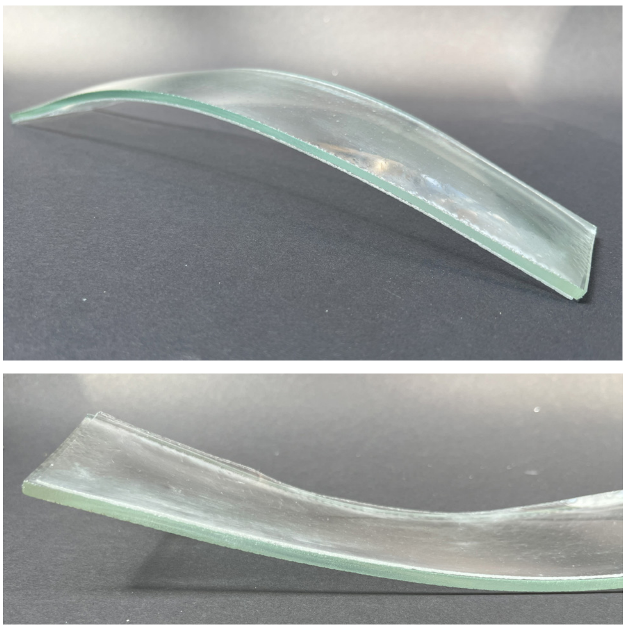


Figure 129: Simultaneous slumping result of 4.C: glasses of 1mm and 4mm follow the same curvature and appear as 1 piece exhibiting possibility for lamination. Own images.

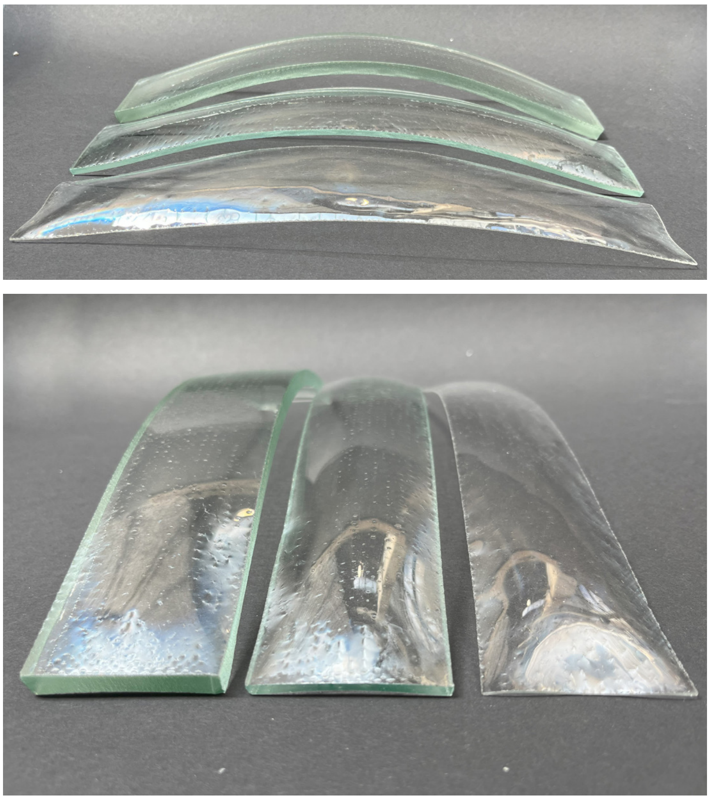


Figure 126: Resulting glasses of 4.A, 4.B, 4.D (left to right): difference in curvature. Own images.

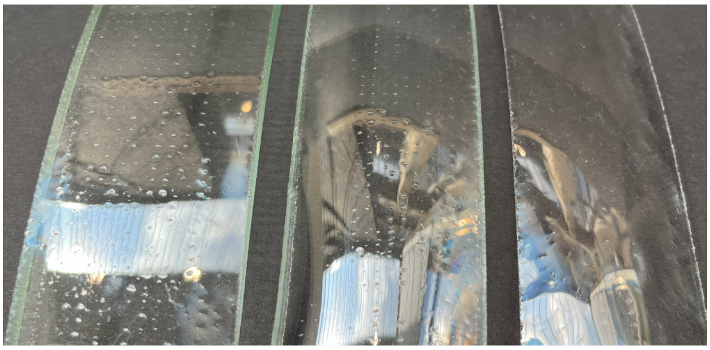


Figure 127: Resulting surface of glasses of 4.A, 4.B, 4.D (left to right); 4.B with coating results in slightly better surface than the others. Own image.

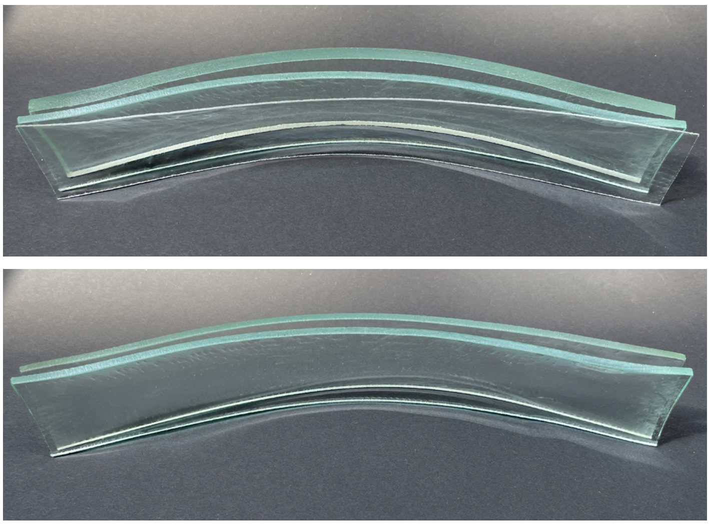


Figure 128: Difference in curvature between glass results of experiment 9 show no possibility for lamination. Up: 4.A, 4.B, 4.D. Down: the 2 glasses with same thickness (4mm) used in 4.B and 4.C. Own image.

8.3.6 Experiment 5 : Assessing compatibility of crystalcast coating on basalt mould for rigidifying the shape

Set-up

Experiment 5 was an attempt to create a double curved surface with side edges that are not in a straight horizontal line. In order to maintain the desired shape, a hand-woven mould is dipped into Crystlcast plaster and let dry in place. Once the plaster hardens and the geometry is stabilized, it is placed on supports in the oven with a 4mm thick glass plate of dimensions 10x30cm on top of it, supported by the two corners at the top height. The oven was set at the 675°C firing schedule.

The goal of this experiment is to check if Crystalcast can be used as a stabilizing coating on the mould to easily form intricate geometries without the need of extra supporting elements.

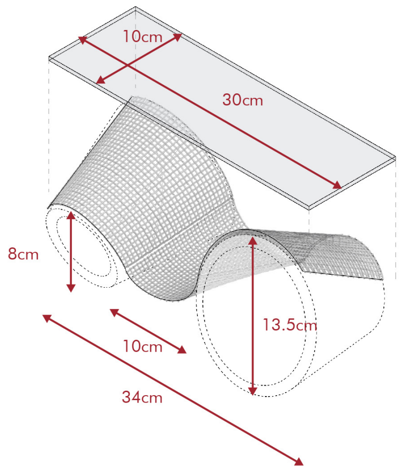


Figure 130: Diagram of experiment 5 set-up.

Figure 131: Setup of geometry with hand-woven loose weave mould. Own image.

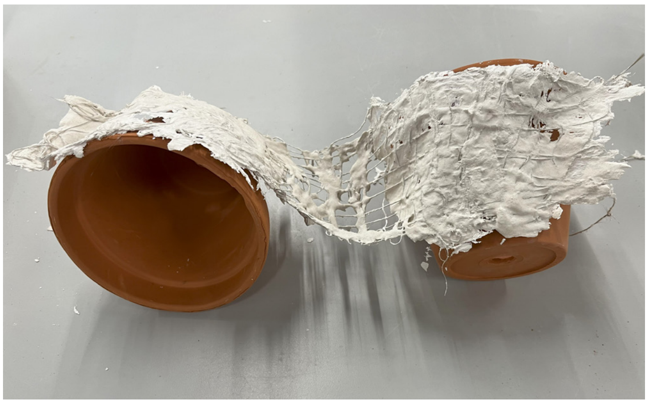


Figure 132: Hand-woven mould dipped in Crystalcast plaster and stabilized in place. Own image.

Figure 133: Set-up of experiment 5 in the oven. Before (left) and after (right) slumping. Own image.

Results

Mould: The mould collapsed under the weight of the glass which was only supported by the 2 highest edge points. The fact that it did partially collapse since the beginning of the set-up in the oven leads to the conclusion that the Crystalcast covered textile, which was not fired beforehand to become stiff as porcelain would demand, was not a valid option for stabilizing the geometry. After removing the glass and the mould from the oven, the mould started breaking into numerus pieces immediately. Crystalcast weakened the basalt fibers making them more brittle than they have been while not coated at all. In general, this was a failed experiment showing that Crystalcast coating on basalt textile is not a combination that can work to create a slumping mould.

Geometry: Since the Crystalcast covered mould collapsed, the glass did not form into the originally designed geometry, however, it did become double curved. One of the biggest problems was the non-horizontal (flat) edges to support the glass fully at the highest level and let it sag onto the rest of the mould.

Finishing quality: A surprising result of this experiment is that the glass surface turned out almost completely transparent with no visible crystallization, even though the same firing schedule was followed. Regarding texture, there were some visible spots like cracks on some of the support points and around them there was very light crystallization, but generally, Crystalcast eliminated the possible texture from the mould to be visible on the glass surface.

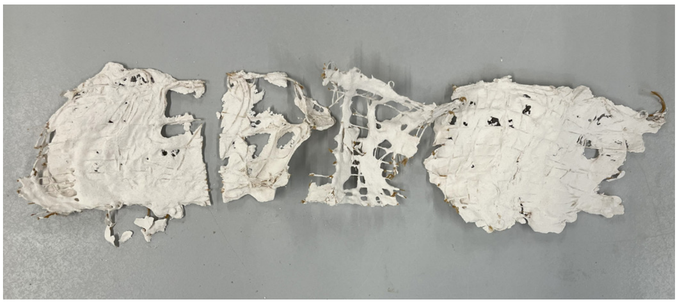
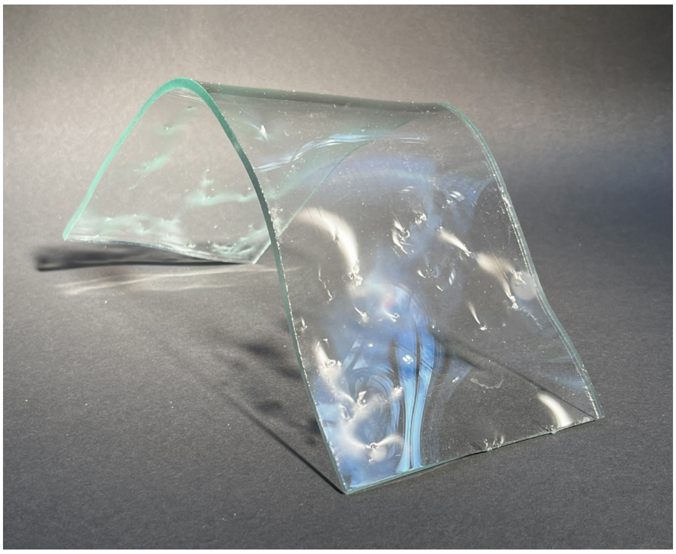


Figure 134: Broken mould after slumping process. Own image.



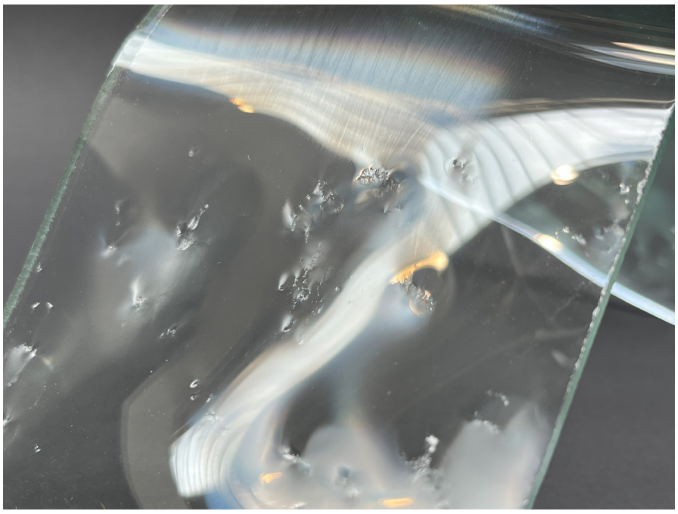


Figure 135: Resulting geometry & surface texture of experiment 5. Own images.

8.3.7 Experiment 6 : Possibility of double curved geometry by corner support in different heights

Set-up

Experiment 6 is an attempt to create a simple double curved geometry. A hand-woven basalt textile is secured within a flexible rectangular frame of 35x35 cm dimensions out of stainless steel rope and then, with the help of clay flower pots it is placed in the desired shape. The mould is supported from its 4 edge points, with two points of them being at the same height while the other two being set at different heights with small differences. Then, a glass plate of 30x30 cm dimensions and 4mm thickness is placed on top without any coating or protective layer in-between. The firing schedule of 675 °C is set for this experiment.

The goals of this experiment was to determine:

- If a double curvature is possible with this type of mould (hand-woven basalt textile)
- If the way of hanging the mould is successful – if this set-up can be improved and used later or not.

Since the moment of the glass placement on the mould, some problems and failure factors became evident (see circles in image below). The hand-woven mould which was not evenly tensioned everywhere started to break at its supports with the rope frame and due to the weight of the glass, parts and fibers of the mould started shifting towards the lower parts leaving big areas of glass hanging with no support underneath.

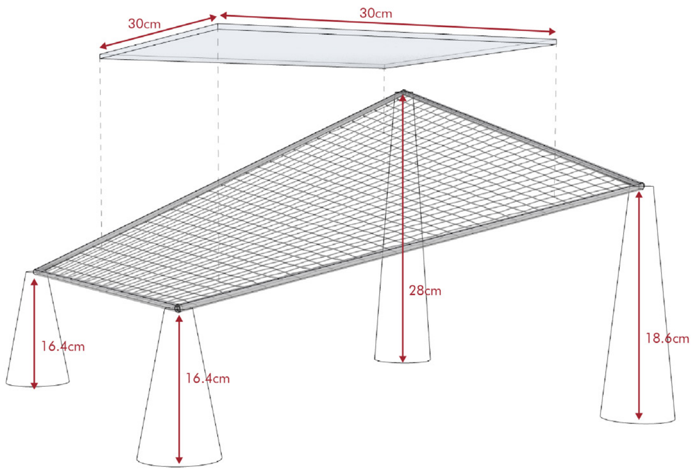


Figure 136: Diagram of experiment 6 set-up.

Figure 137: Mould of experiment 6: hand-woven basalt textile & stainless steel rope flexible frame. Own image.

Figure 138: Left: Set-up of experiment 6 in the oven. Right: placement of glass on mould and failure locations (circles). Own image.

Results

As expected, during the slumping process the mould broke even more at the weak support points. Therefore, the experiment failed to achieve what it was designed for. However, it did lead to a very interesting geometry. The main results of experiment 6 are:

Geometry: Collapse of the mould did not lead glass to be formed to the designed geometry. However, the glass eventually developed different double-curved geometries and it turned out into a freeform shape, which is of significant importance because it proves the hypothesis of my research question to be true.

Finishing quality: The resulting glass sample has a lot of crystallization especially at the sides. The cause of the crystallization is still unknown. Texture is imprinted in a very visible manner from the supporting threads, which look like small cracks in the glass surface. The sample needs to be checked with the microscope to determine if these are indeed cracks, inclusions or something else.

Mould: The mould broke from the beginning after the placement of the glass in some spots, thus, it was expected that it would break completely at its supports with the rope due to the weight of the glass. However, it supported the glass long enough to form it into a geometry. Moulds of these dimensions and technique prove to be a wrong set-up. A hand-woven mould cannot support such a big glass piece because there is not equal tension at all weaved parts and the weave concentrated in some parts. This shows that the technique of double curvature can work better with CNC-knitted mould.

Structural: In terms of its structural integrity, there are no residual stresses in the glass with this slumping method. This was tested with a quick polarization test, which showed that even at the imprinted spots there were no stresses. This conclusion should be tested in the microscope for more accurate results.

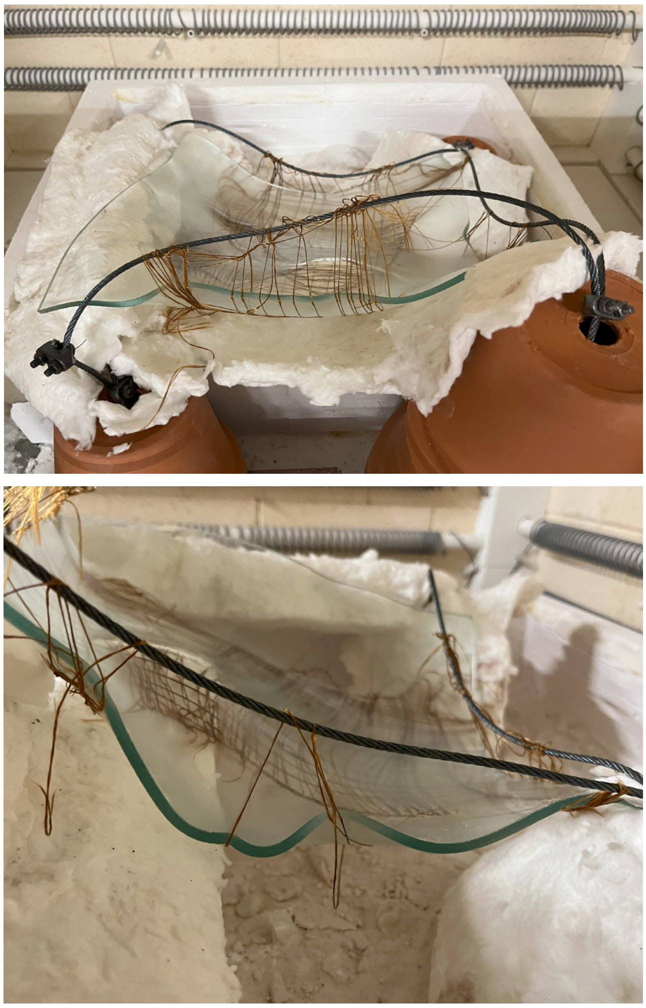


Figure 139: Experiment 6 in the oven, results after slumping. Own images.

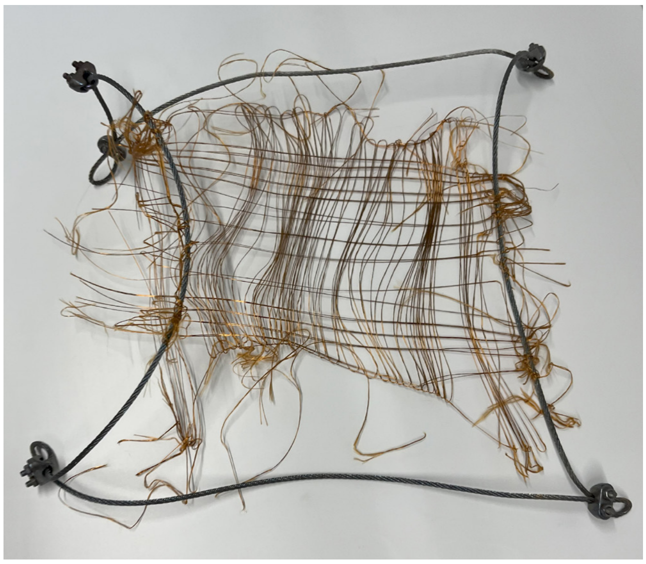


Figure 140: Mould after the slumping process. Own image.

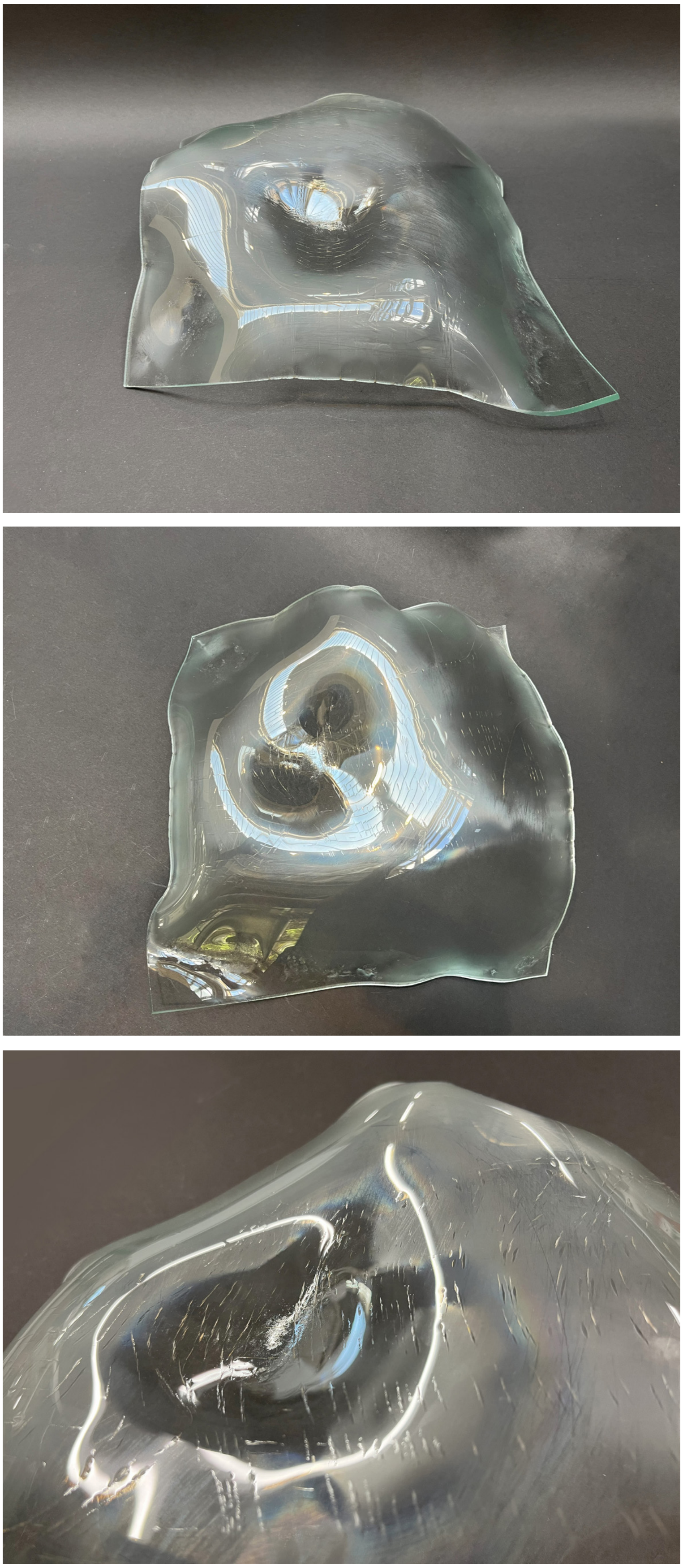


Figure 141: Experiment 6 result : freeform slumped glass shape and texture on surface. Own images.

8.3.8 Experiment 7 : Assessing deformation caused by different patterns of knitted moulds in tension

Set-up

Experiment 7 is the chronologically first experiment using knitted textile moulds. A Steiger Vega 3.130 CNC flat-bed knitting machine was used to produce all samples needed for this and future experiments with knitted moulds. For this experiment, 3 samples were produced with different knit densities: sample A was knit in a loose drop stitch checkerboard pattern comprising of alternating loose knit/float patterns, sample B in a dense knit/float pattern and sample C was a combination of the dense and loose knit/float pattern in a stripped pattern.

The knits were set-up to resemble a hanging model by supporting their 4 corners. All 3 textiles were slightly tensioned to form a flat horizontal surface, and sample C was tensioned more than the other two in the direction of its stripes to ensure a tighter textile shape when placing the glass plate on top. Float glass plates of 30x30cm size and 4mm thickness were placed on top of each knitted textile. The oven was set at the 675°C firing schedule.

The main goal of the experiment was to measure the deformation of the glasses and compare the different vaulted geometries. Additionally, for sample 7.C the aim of this experiment was to see if the combination of the two densities would lead to different vaulted shape, to stripped geometry of the glass or it would not make any difference.

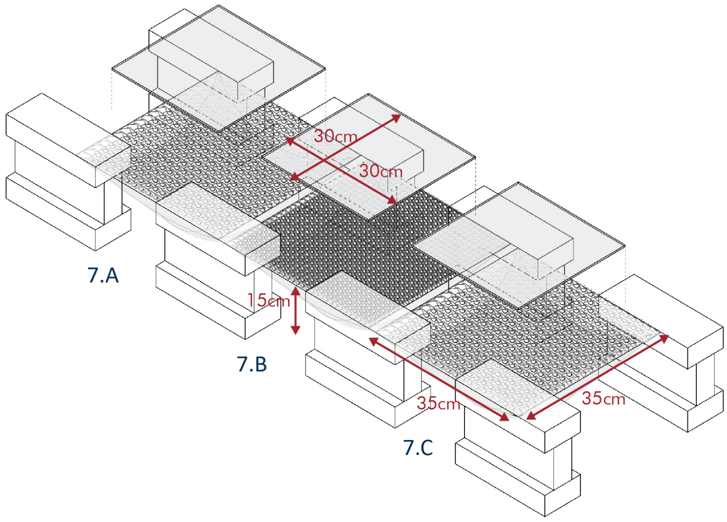
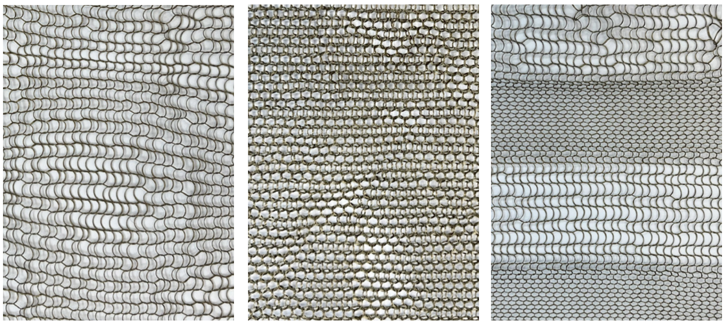


Figure 142: Diagram of experiment 7 set-up.



7.A
Loose drop stitch checkerboard pattern

7.B
Dense knit/float pattern

7.C
Stripped dense-loose pattern

Figure 143: CNC knit textile moulds. Own images.

Figure 144: Experiment 7 set-up in the oven. Left: placement of moulds, Middle: with glass pieces on top and beginning of unraveling of 7.A, Right: after slumping process. Own images.

Results

The brick supports in one side of the experiment set-up collapsed completely, causing bricks to fall on top of the glass pieces. This caused the failure of this experiment, however, some conclusions can be drawn from the results.

Geometry: The overturning of the bricks did not allow for shaping of the glass samples in the suspected vaulted geometry. However, the side of the glass that remained close to the unmoved set-up supports in sample 7.C show that the stripped geometry formed the glass locally in a slightly stripped shape. The impact is not particularly evident; it is understood by touching the glass. Therefore, it is considered valuable to recreate an experiment with such a pattern to check whether a pattern with different densities can actively affect the resulting glass geometry and deformations.

Mould: Mould 7.A with the loose pattern was the first to fail, something that was evident since the placement of the flat glass pieces. Due to constraints during the fabrication of the CNC knitted textiles regarding the particular setting required to produce basalt fiber knit, the textile of these moulds was “open”. This means that the ends were not secured properly and some loops of the knit started “running” causing the textile to unravel, and big holes started forming when the weight of the glass was placed on top. This caused additional breakage of the threads locally. An assumption of the cause of the bricks overturing was that this unraveling of the mould caused the sudden collapse of the supported glass piece towards on corner, which in turn cause the movement and overturning of the first brick supports. Due to the fact that all samples were connected together, this caused a domino effect on the supports of one side, causing the failure of all samples. The moulds after the firing schedule exhibit similar behavior as described in previous experiments with hand-woven basalt moulds.

Finishing quality: Texture was imprinted again in the glass from the knitted mould, forming interesting waving patterns of the continuous loops. In the places where bricks fell on top of the glass, texture is even more 3-dimensional causing an interesting overall effect. Surface crystallization is not as evident in these samples as in previous experiments.

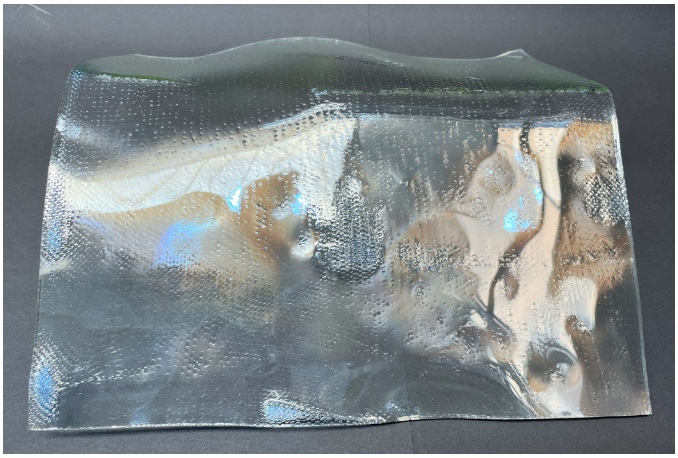


Figure 145: Resulting glass piece of 7.B. Own image.

Figure 146: Mould 7.B after the slumping process. Own image.

Figure 147: Unraveled and broken mould 7.A after the slumping process. Own image.

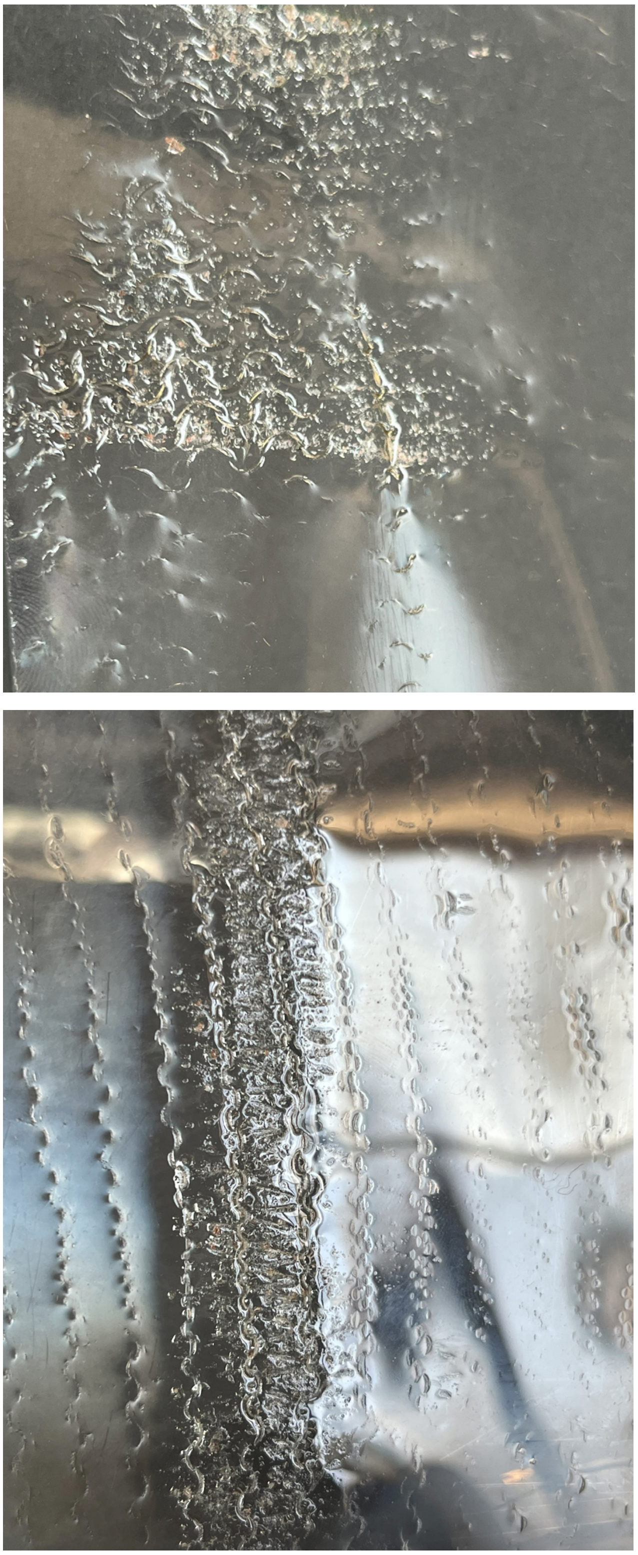


Figure 148: 3-dimensionality in texture due to brick contact: evident pattern of knit loops. Own images.

Figure 149: Imprinted texture from moulds. Own images.

8.3.9 Experiment 8 : Possibility for multiple curvatures in double curved shape by adjusting knit pattern of mould

Set-up

For experiment 8, a knitted mould is supported from all 4 edges. The edges form a controlled boundary for creating a vaulted geometry. To be able to create this boundary condition, channels were embedded to the design of the knitted textile and stainless-steel bars were inserted to hold it in place. The textile was slightly tensioned until flat, and then a glass piece of 20x30cm dimensions and 4mm thickness was placed on top. The oven was set at the 675°C firing schedule.

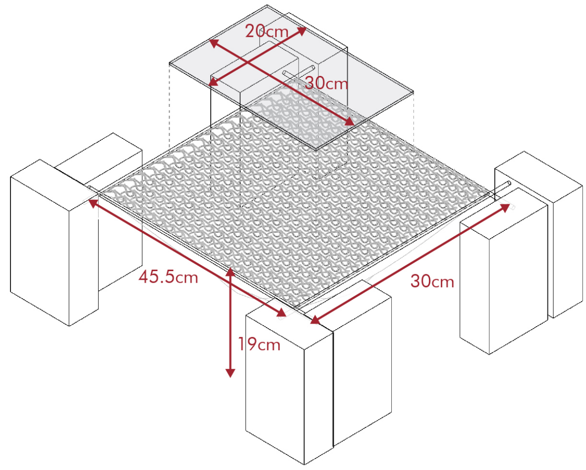


Figure 150: Diagram of experiment 8 set-up.

The knitted mould used for this experiment has a particular design. A pattern forming alternating bubble shaped parts of extremely loose knit in between very dense knit parts was designed. In this way, the dense parts were firmly laying flat when tensioning the fabric, whereas the extremely loose ellipsoid shape bubbles were hanging in between.

With this experiment the aim is to test if the use of different patterns in the knit will result in different curvatures in the glass. The particular knitted geometry wants to test how much the glass will deform in the bubbles which have a diameter of 8cm, creating a double curved bubble end result in the glass.

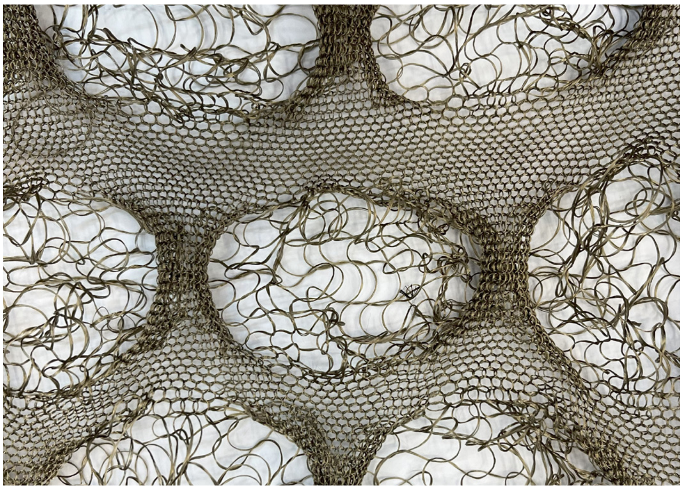


Figure 151: CNC knit textile mould - bubble pattern. Own image.

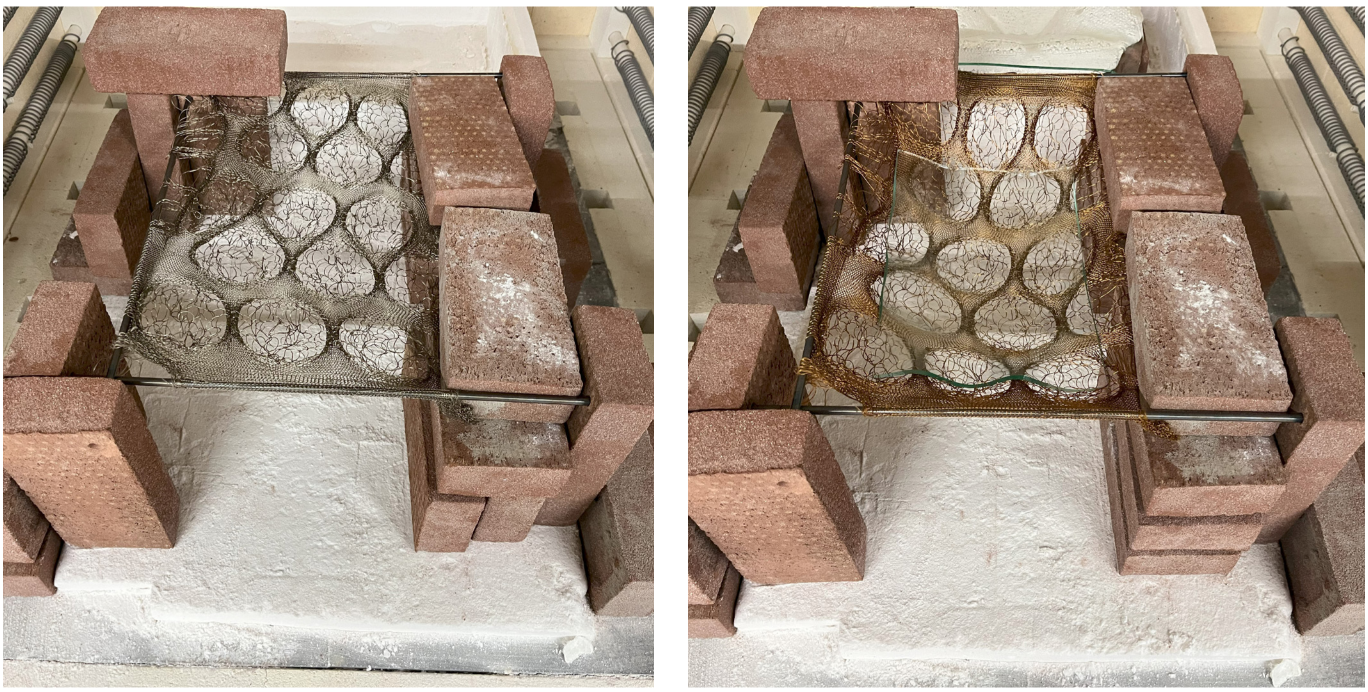


Figure 152: Experiment 8 set-up in the oven. Left: placement of mould, Right: after slumping process. Own images.

Results

Geometry: The resulting glass turned out to be somewhat like expected. It deformed in a general double curved vaulted shape with controlled geometry, with a maximum deformation of 4cm in the middle of the vault. Moreover, bubbled deformations are also visible, controlled and repeated evenly, however, the glass did not slump a lot through the bubbles. That might be due to the size of the bubbles, because if we observe the edges of the glass where the glass was not supported with the dense pattern of the knit we can see bigger deformations in the bubbles. This observation shows potential for bigger curvatures in bigger pattern scale, or at different temperatures.

Finishing quality: The resulting glass surface turned out to be transparent and not as foggy as other experiments. There is only a slight change in reflectivity with chrome colors visible on the glass. In terms of texture, while the area of the support and the tension resemble the previous experiment, there are only a few texture marks on the glass. They are forming the supporting edges of the knit at the bubble edges, while the rest of the dense knit in immediate contact with the glass did not leave any texture.

Mould: Similarly with all previous experiments, the basalt turned out brittle after the slumping process. One of the channels unfolded, however, the textile maintained its shape and continued being a good support until the end of the experiment.

Structural: In terms of its structural integrity, there are no residual stresses in the glass. This was tested with a quick polarization test, which showed that only at the edges of the glass there is a very small amount of stresses, which is negligible.

Figure 153: Bubble knit mould after the slumping process. Own image.

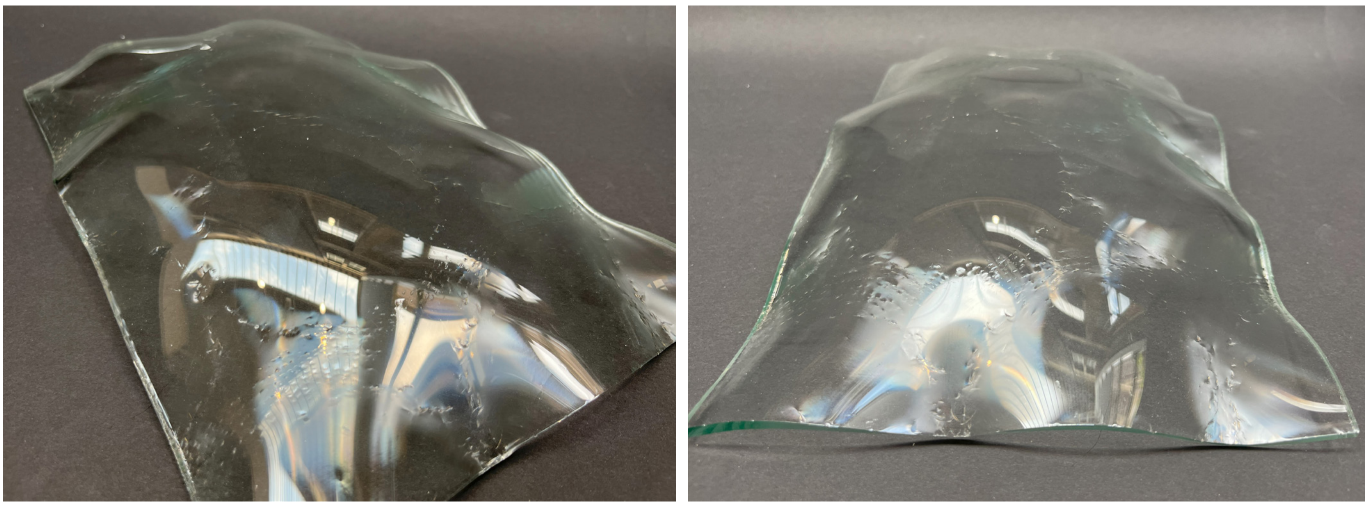


Figure 154: Experiment 8 glass result: vaulted geometry & bubble effect. Own images.

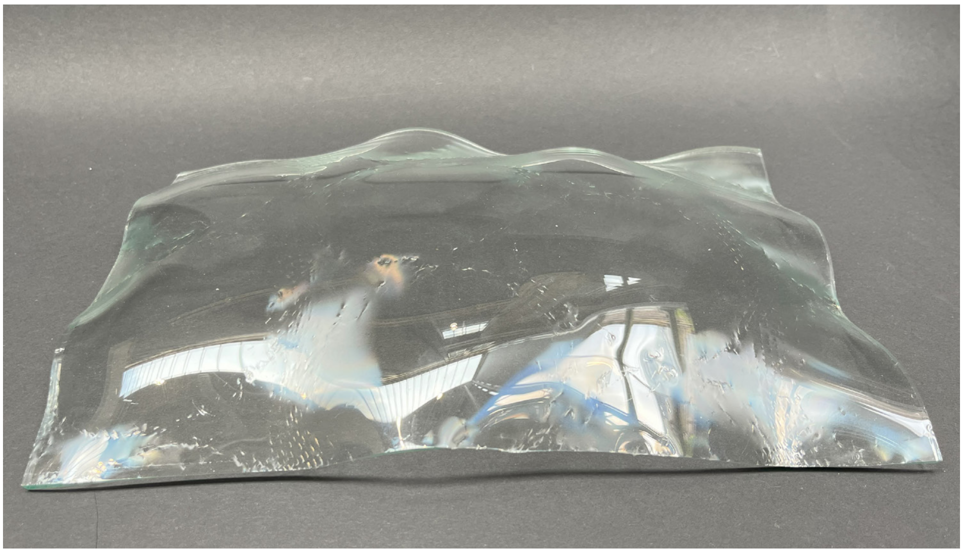


Figure 155: Experiment 8 glass result: long side view. Own image.

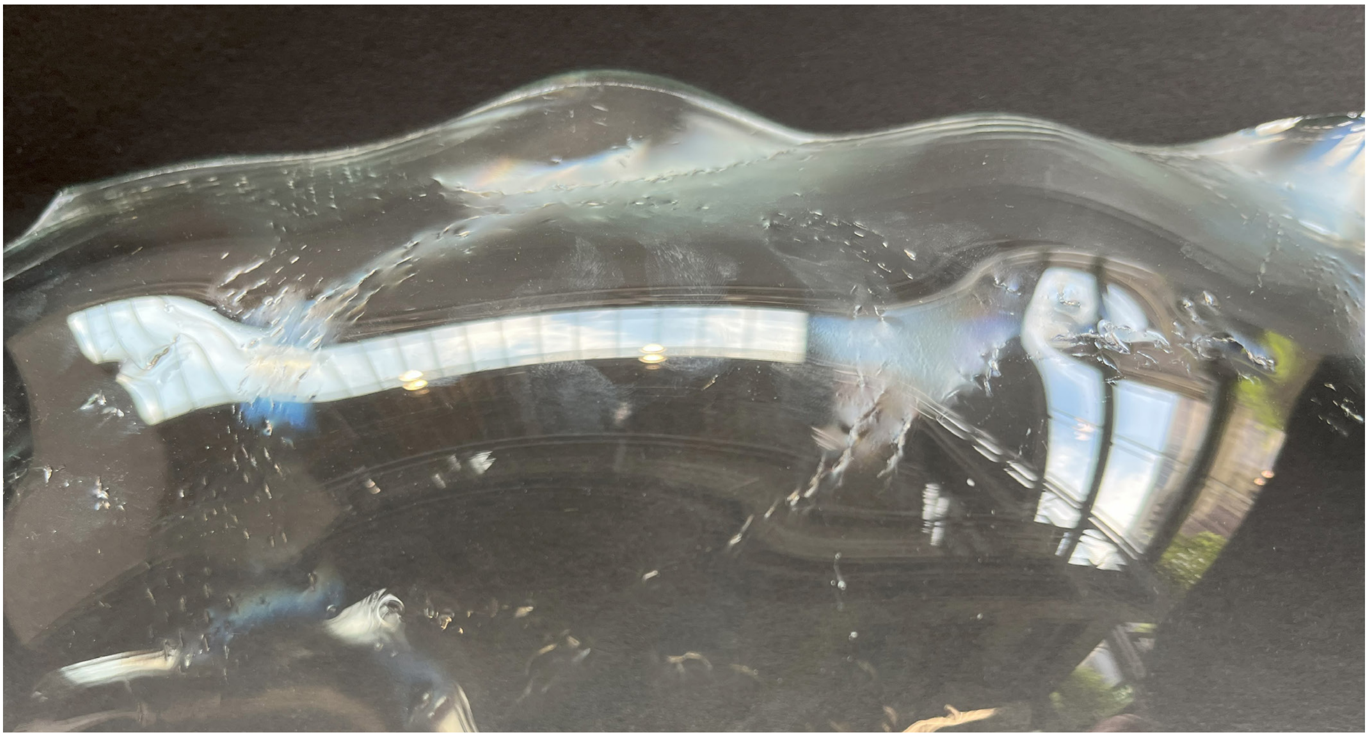


Figure 156: Experiment 8 glass: texture from the mould around the bubbles. Own image.

8.3.10 Experiment 9 : Assessing compatibility of cement mould with glass & comparison of cement and glass final geometries

Set-up

In experiment 9, a geometry for knitted formwork developed by Kariouh and Popescu [2024] was tested. The textile is set-up in tension and heat-resistant cement is used to form the complex shape. After the cement was hardened, the mould was used with the side in contact with the textile up in order to slump glass on top. The geometry has a size of 30x30cm and a glass piece of 30x30cm was placed on top. The experiment was performed 2 times, once with a glass piece of 4mm thickness and once with a 1mm thick glass. The oven was set at the 675°C firing schedule.

Main goals of this experiment are to compare the differences in deformation and final geometry between the concrete and the glass. At the same time, differences in deformation between the different glasses are compared to check if there is possibility for lamination afterwards. Furthermore, since cement was used as coating of the textile, the transfer of the texture is to be observed as well as the finishing surface quality of the glass in contact with cement.

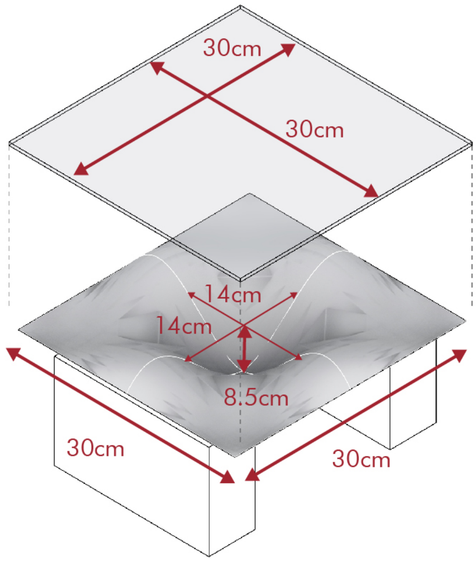


Figure 157: Diagram of experiment 9 set-up.

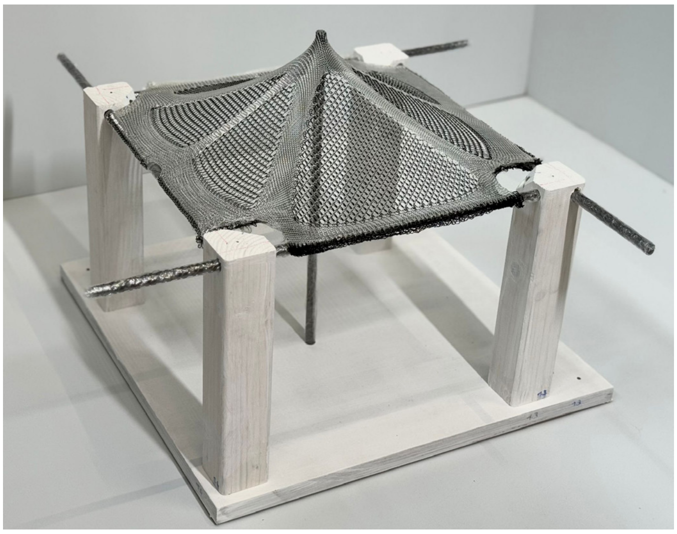


Figure 158: Set-up for cement casting. Source: Anass Kariouh.

Figure 159: Resulting cement mould for experiment 9. Own image.

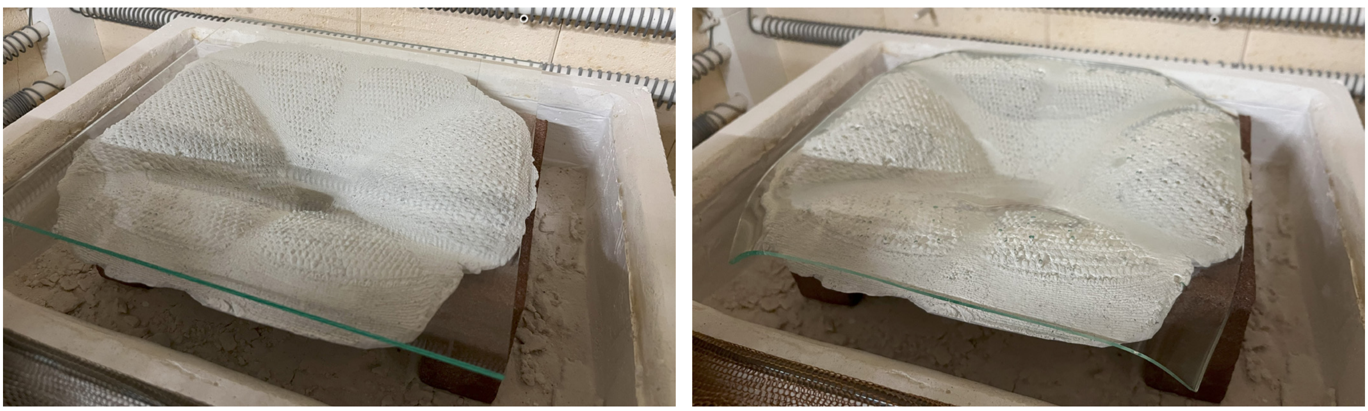


Figure 160: Experiment 9 set-up in the oven before (left) and after (right) slumping. Own images.

Results

Geometry: The deformed glass followed the supporting geometry of the concrete well. The curvatures at the edges of the mould were replicated with accuracy, however, the extreme curvature at the middle was not achieved by the slumped glass. The glass deformed in the middle evenly forming a double curved surface with multiple curvatures. The maximum deformation reached at the middle of the central deformation was 3cm for the 4mm thick glass which is height/2.8 (height: the middle vertical drop of the cement funnel shaped moud), and 2cm for the 1mm thick glass which is height/4. Limitation to the maximum achieved central extreme curvature might have been the temperature of the slumping process, or the composition of the glass. However, the factor limiting the deformation of the thinner glass in contrast to the thicker one is its weight, which is smaller and therefore the loading of the glass at the middle of the drop is less and thus, it does not deform as much.

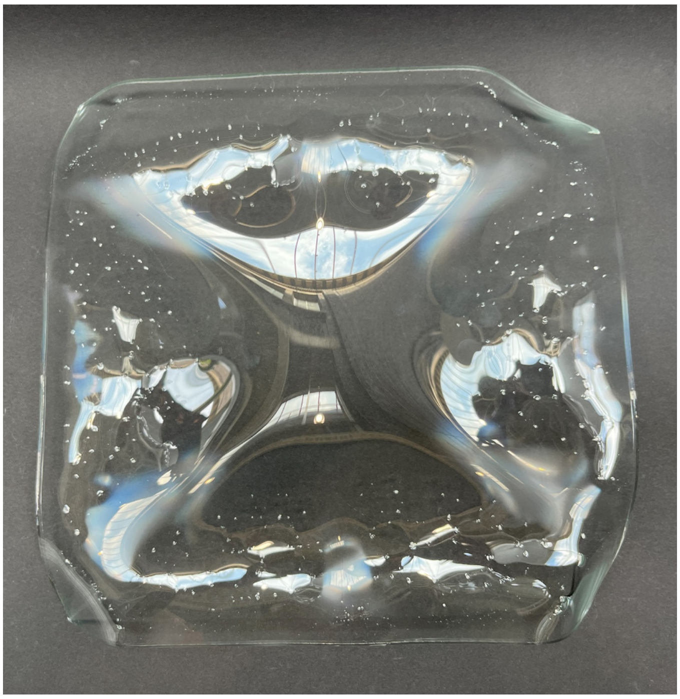


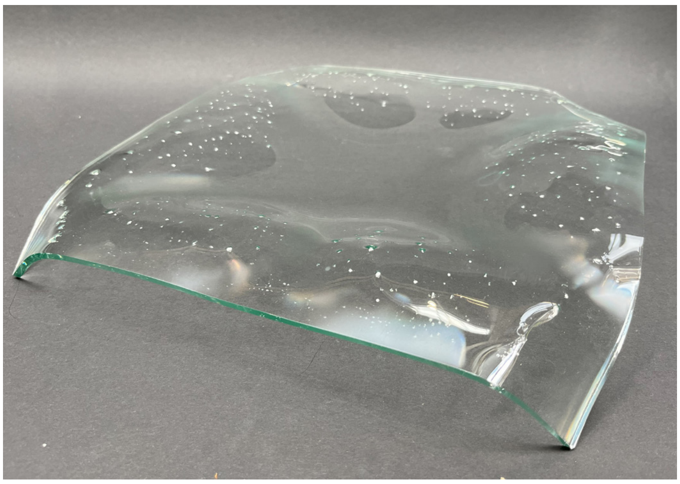
Figure 161: Experiment 9 glass result: plan view. Own image.

Finishing quality: The resulting glass surface turned out to be fully transparent with no visible crystallization. However, the texture of the mould, although not fully imprinted, created dotted marks on the surface, like inclusions of cement pieces. Although the cement pieces come off the glass easily, their inclusion might have caused micro cracks in the glass that are not visible without a microscope.

Figure 162: Glass texture: inclusions of cement - dot like texture. Own image.

Mould: The cement mould was intact after repeating the slumping process two times.

Structural: In terms of its structural integrity, there are no residual stresses in the glass. This was tested with a quick polarization test, which showed that even at the imprinted dots there were no stresses.



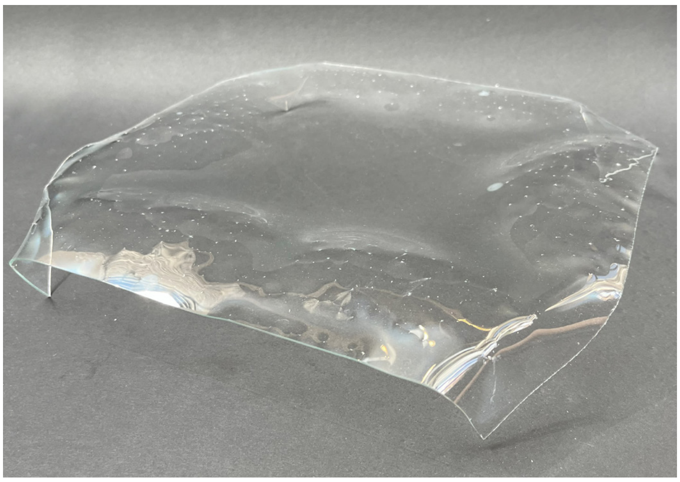


Figure 163: Experiment 9 glass results. Left: 4mm glass. Right: 1mm glass. Own images.

8.3.9 Decision making process

Following the detailed description of the experiments performed in this thesis, a summarizing table is made. The following table contains information about all experiments and their key set-up aspects as well as the main results. Furthermore, the decisions made after each experiment for what needs to be tested further are outlined.

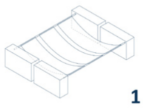
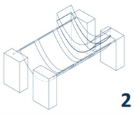
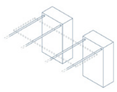
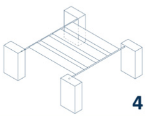
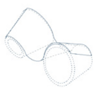
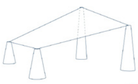
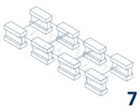
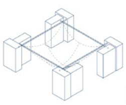
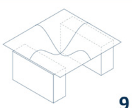
	set-up					results	
	experiment	schedule	mould pattern	coating / protective layer	geometry	results	decision
2 supports system	 1	675 °C	hand-woven x 3 densities	-	Single curved small curvature	- geometry achieved - no coating needed - surface quality: foggy - texture imprinted - no reuse for mould	> test extreme mould densities > test bigger curvature > add extra layers for surface quality
2 supports system	 2	675 °C	hand-woven x 3 densities	- no coating on mould - 2 extra thin layers (biosoluble + fire paper) placed on mould 2.C	Single curved bigger curvature	- geometry achieved - surface quality foggy but better for 2.C - texture imprinted	> test extreme curvature > test devitrification spray for surface
2 supports system	 3	675 °C	-	-	Single curved corrugated	- small curvatures possible in narrow spans - surface quality foggy even without mould	> use of devitrification spray for surface > test higher temperature for deformation limits of narrow spans
2 supports system	 4	675 °C	CNC knitted	devitrification spray on 4.B	Single curved small curvature	- same curvature with separate moulds not possible - simultaneous slumping successful - very light crystallization of surface - devitrification spray did not fully work	> different application method of devitrification spray
2 supports system	 5	675 °C	hand-woven	CrystalCast on mould	Double curved	- mould destroyed - basalt fiber weakend from Crystalcast - failed attempt	> use different material to rigidify geometry of textile
4 supports system	 6	675 °C	hand-woven	-	Double curved small curvature	- mould collapsed - freeform geometry achievable	> need a CNC knit mould for double curved geometries > find way to control freeform geometry
4 supports system	 7	675 °C	CNC knitted x 3 densities	-	Double curved vault	-failed attempt -mould unraveled -texture in loop pattern -less crystalization / more iridescent glossiness	> different set-up > different knitting process to avoid unraveling and having embedded channels for tensioning the mould
4 supports system	 8	675 °C	CNC knitted	-	Double curved vault	- different knitting patterns result in different deformations - total vault geometry + slight bubble effect	> try bigger bubbles to check potential
4 supports system	 9	675 °C	CNC knitted	Cement mould	Double curved	- extreme deformed middle geometry not followed completely - texture & inclusions of mould parts - transparent	> test difefrent glass thickness > test with higher max temperature

Figure 164: Decision making process table.

8.4 Microscope study

8.4.1 Defects classification

There are various classifications for glass defects in literature, aiding in evaluating the severity of each defect and identifying its cause with the aim of preventing recurrence. The existing classification systems are based on different characteristics. According to Aldinger and de Haan [Aldinger and de Haan, 2019] and Bartuška [2008], as summarized by Bristogianni [2022], the main categories of defects are:

- “Chemical: Crystalline, Glassy or Gaseous
- Location: Surface vs Volume distributed Defect
- Severity: Critical, Functional, Stress inducing, Strength reducing, cosmetic
- Process stage: Batch, forming, post-processing, handling, storing
- Defect frequency: Rare, occasional, repeating “

8.4.2 Experiment results under the microscope

The produced samples from the experimental work of this thesis were tested under the microscope to check their defects. A VHX-700 Digital Microscope was used to visually inspect the sample surfaces for faults and breakage processes that might cause failure. Few samples from multiple experiments were checked.

Sample 1B : Examination of glass surface texture

Sample B from experiment 1 was the first to test under the microscope. The images show that the texture marks imprinted by the mould are in fact small inclusions of basalt fibers in the glass. During the slumping process, parts of the basalt fibers got attached and trapped in the glass surface, thus creating a void in the glass matrix where they now exist, becoming a type of inclusion. Next, a polarization film was used to identify residual stresses in the glass. There are no signs of residual stresses in the glass sample, even at the inclusions there is no evidence of significant stresses in the glass. By zooming further, the inclusions were tested better for stresses and cracks. No cracks are evident or even small crack signs at the edges of the inclusion seem to be possible to start propagating at a later time. At the inclusion voids, some small dust or dirt particles seem to be trapped. These cause stress in the glass locally but their size make the stress negligible. Lastly, there are some lines visible on the surface of the other side of the one in contact with the mould. A possibility is that they are scratches from the glass plate cutting process with the waterjet and inspection with the microscope does not show signs of cracks at these lines. The most possible scenario by observing several samples of different experiments show that the lines tend to appear and form each time following the slumped geometry, leading to the assumption that they are v marks caused during the slumping process.

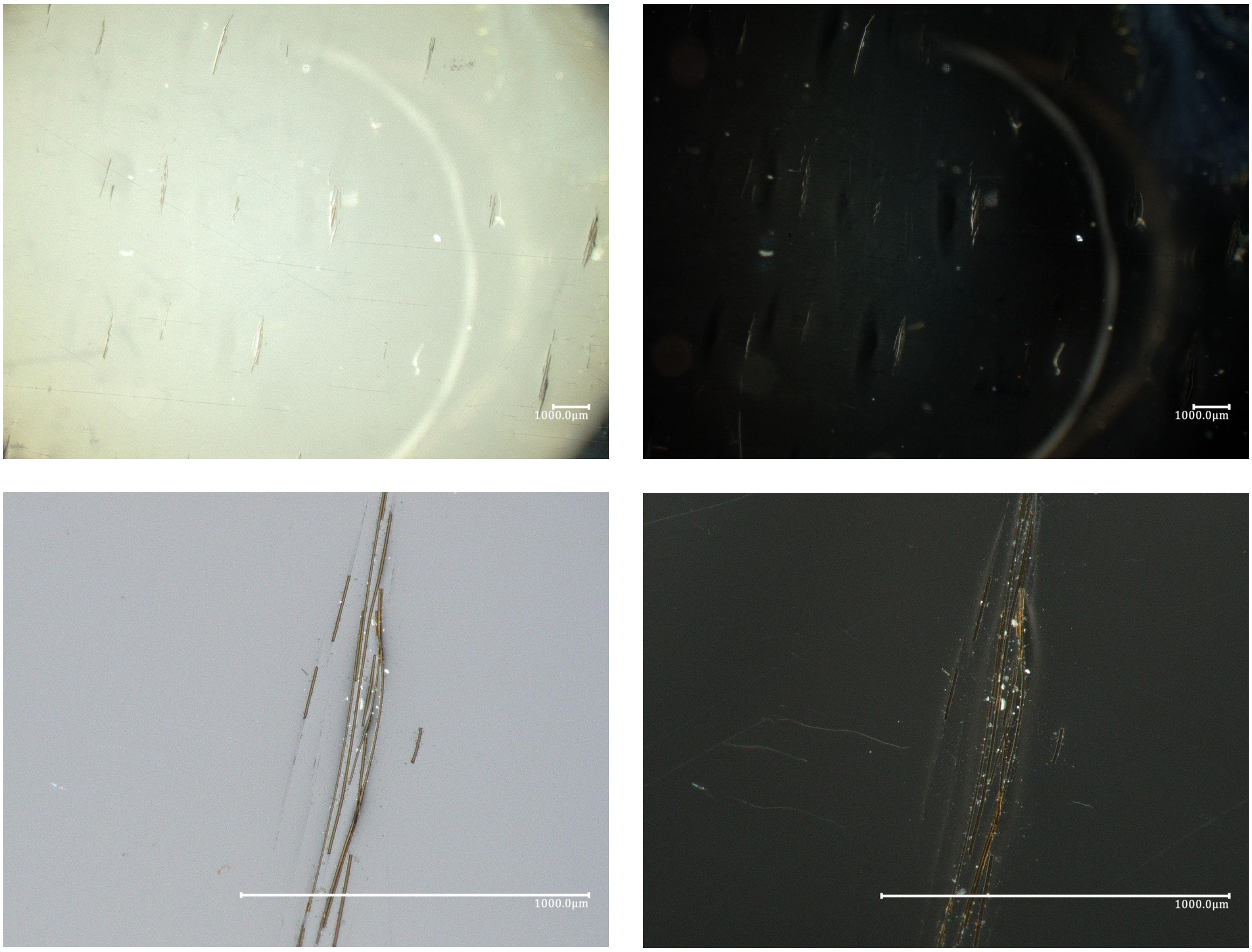


Figure 165: Sample 1B under the microscope. Up: basalt inclusions - left:pattern - right: with polarization filter. Down: Zoomed in images of basalt fibers inclusion with normal (left) and polarization filter (right). Own images.

Sample 2A : Investigation of the basalt traces in the glass

Moving on to the samples of experiment 2, the most interesting to inspect under the microscope was sample 2A that resulted from the extremely loose woven mould. In this case, the inclusions of basalt fibers were visible with the naked eye. The shape of the firmed inclusions is not as regularized as before, it is caused by the small knots at the textile mould which define the inclusions shapes formed in the glass. The inclusions are bigger in size with more fibers trapped, possibly because of the increased load on each of these supporting points during the slumping process. By using the polarized film, it is evident that there are no significant residual stresses in the glass due to the inclusions which do not cause problems in the glass. The colored light around the fibers that is more visible in some of the images taken with the microscope is caused by the light source behind the glass and the light refraction.

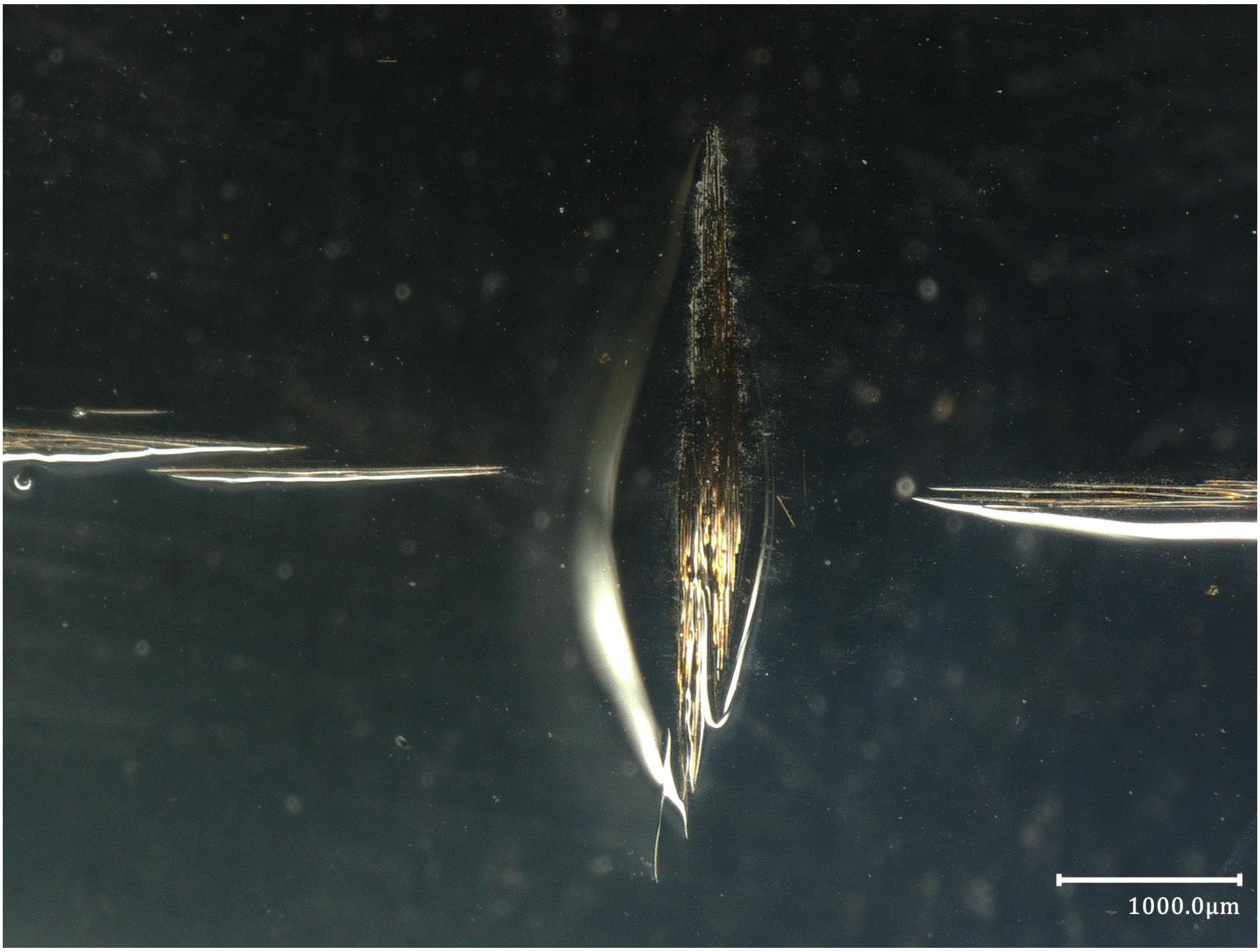


Figure 166: Sample 2A under the microscope: Inclusion of basalt fibers in dents created by the textile mould knots, view with polarization filter. Own image.

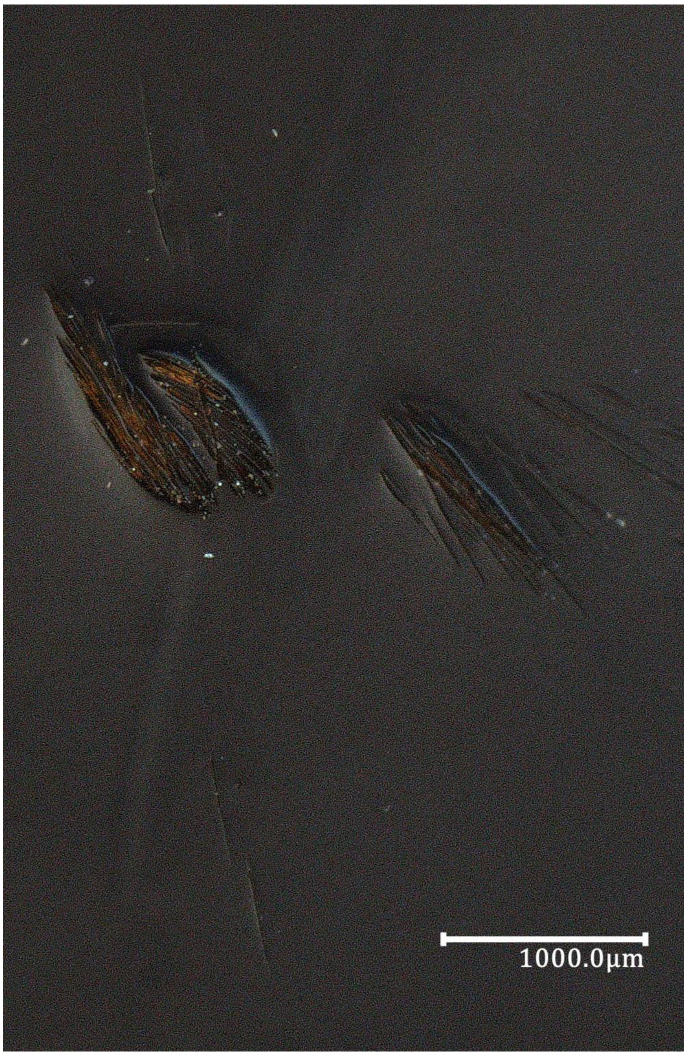


Figure 167: Sample 2A under the microscope: irregular shape of basalt fibers inclusions using polarization filter. Own image.

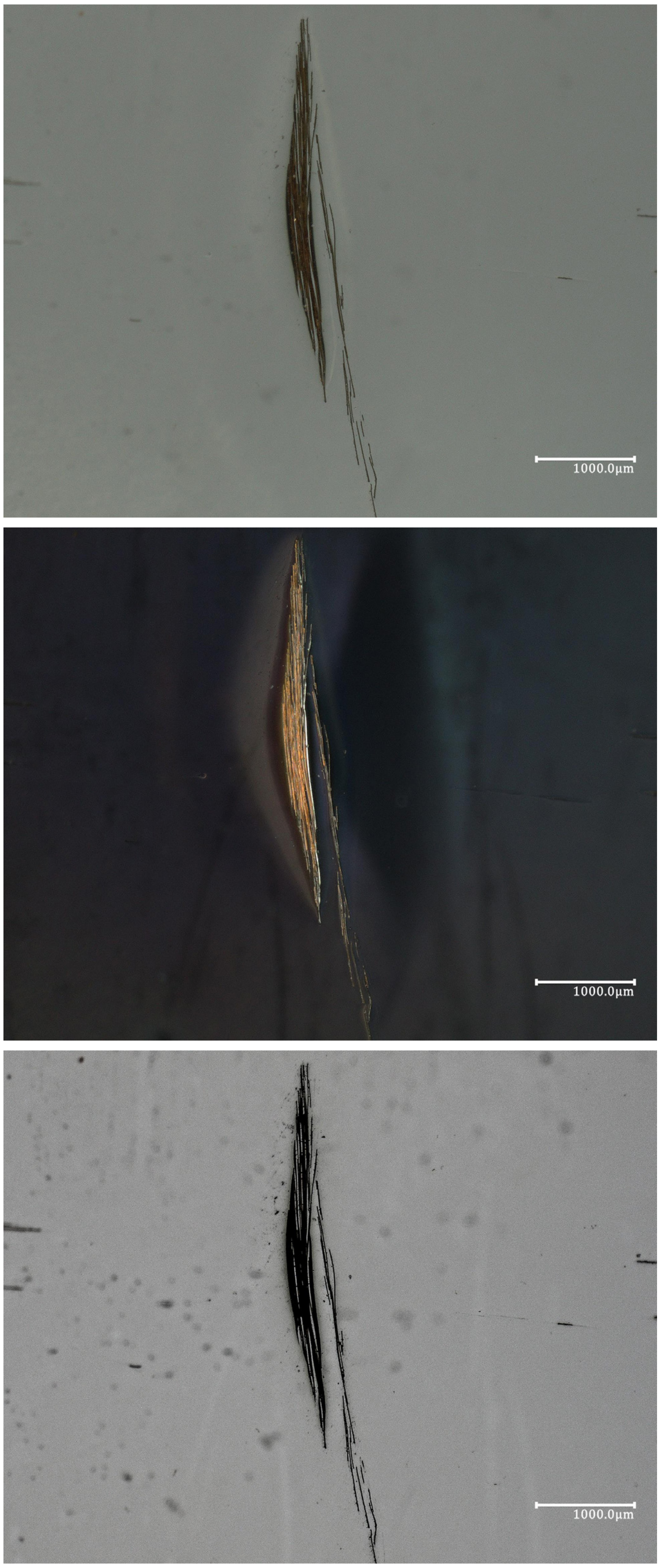


Figure 168: Sample 2A under the microscope: zoomed in inclusion - view with normal light (up), polarization filter (middle) and high contrast of fibers geometry (down). Own images.

Sample 6 : Investigation of stretch mark lines & checking for microcracks

The resulting sample of experiment 6 showcased similar results as the previous samples. Inclusions of basalt fiber are visible and formed in a linear manner and many of them are scattered single fibers. They do not cause residual stresses in the glass. In the images of this sample the stretch marks of the glass are more visible, yet they do not seem to cause any problem in the glass itself. Again, there are no signs of microcracks from the basalt or from the complex geometry formation.

Figure 169: Sample 6 under the microscope: basalt fiber inclusions and stretch marks on opposite glass surface. Own images.

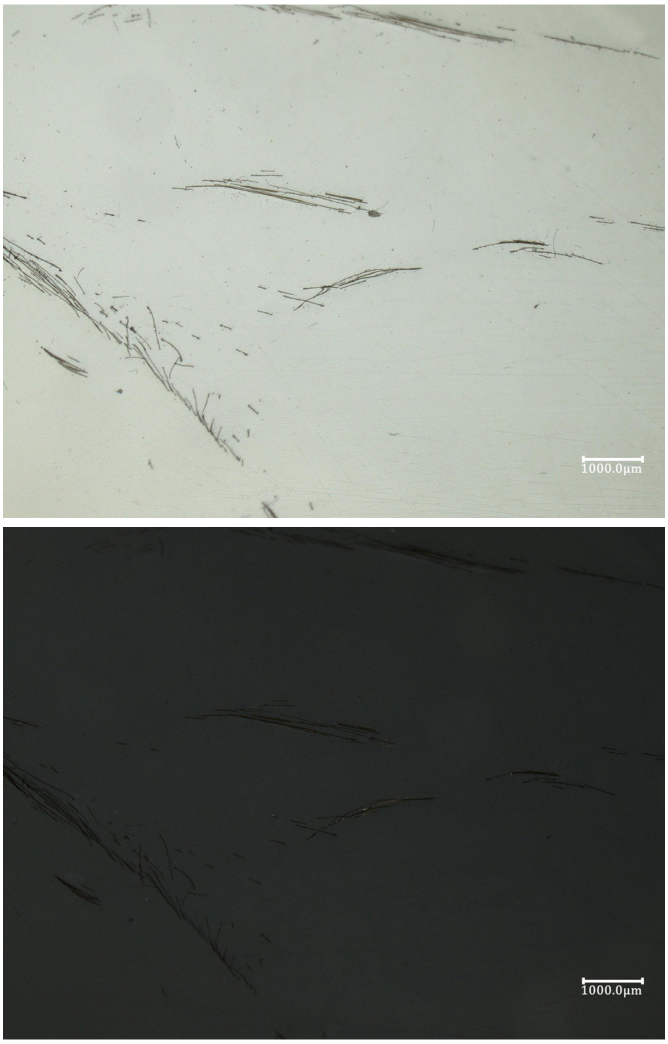


Figure 170: Sample 6 under the microscope: zoomed in basalt inclusions with normal (up) and polarization (down) filter. Own images.

Sample 7.A : Knit textile inclusions investigation

Finally, sample A from experiment 7 was tested under the microscope due to the knitted mould used, but also, the nature of the experiment's failure. This experiment failed when bricks from its setup fell on the glass and created a sandwich of the glass between the textile and the brick. Similarly as before, the main defect in the glass surface that was not in contact with the fallen bricks is in the category of inclusions. The knitted mould has led to inclusions of basalt fiber in the shape of the knit loops. Inspection with the polarization film did not show any residual stresses in the glass around the inclusions or the rest of the glass that was not in contact with the bricks. Another type of inclusion, like a stone, was detected in some places. It is safe to assume that these inclusions derive from the contact with the fire protective blanket layer at the bottom of the oven. The pattern around the inclusions suggests that this element was pushed in the glass with force, which supports the assumption that they are fire blanket particles pushed in the glass by the weight of the fallen bricks, causing small and not significant local residual stresses but not cracks. Finally, by measuring several fibers we are able to see that the separate fibers that form the continuous basalt fiber thread have a diameter of 10μm.

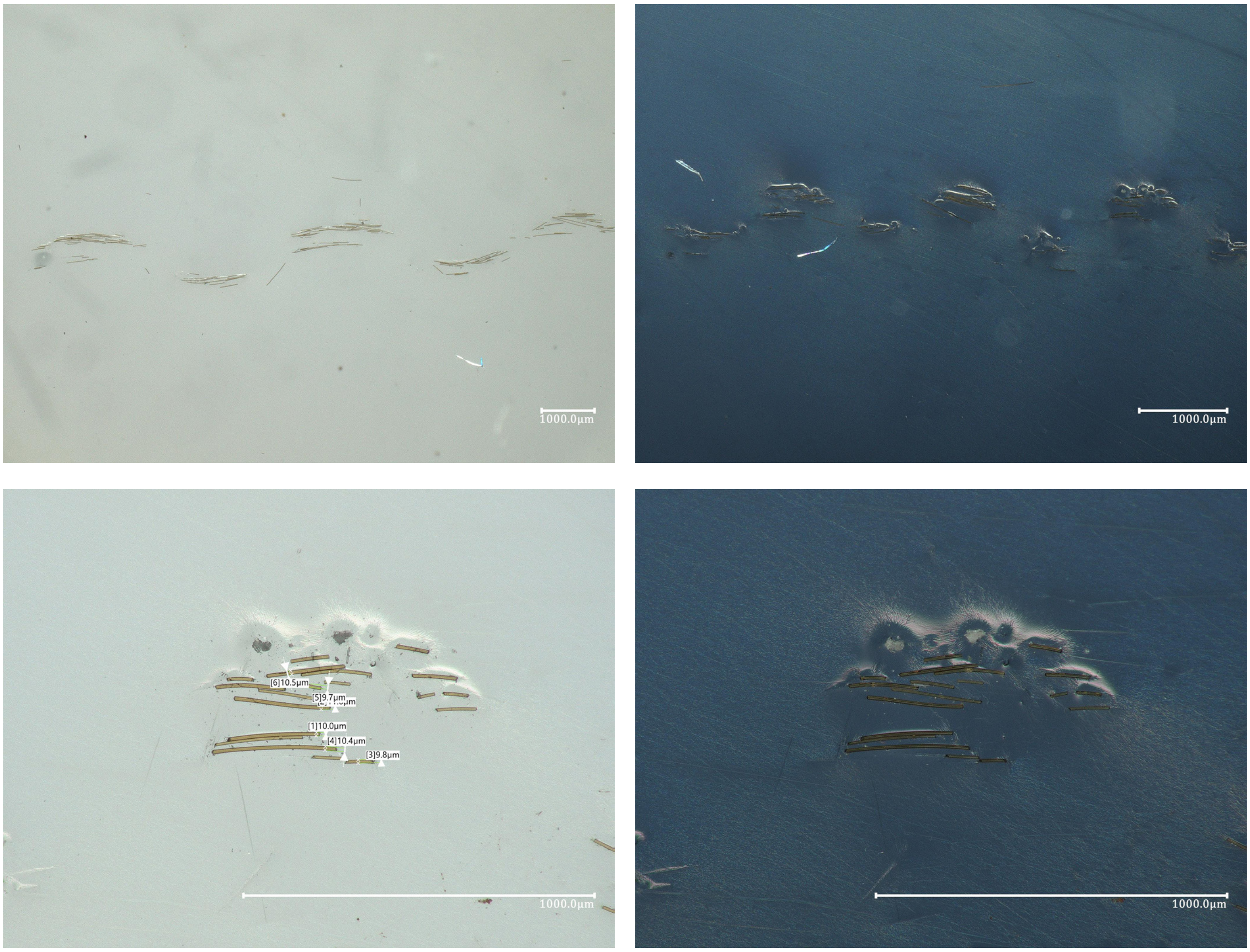


Figure 171: Sample 7.A under the microscope. Up: basalt fibers forming loop pattern of knitted textile with normal (left) and polarization (right) filter. Down: zoomed in basalt and stone inclusions and basalt fiber measurement. Own images.

8.4.3 Inclusions

Based on observations on the resulting glass components of the experimental work of this thesis, the defects that are detected under the microscope fall under the category of volume distributed flaws in terms of location, and more specifically inclusions.

According to Quinn [2020], inclusions are volumetric defects consisting of foreign bodies, which have a different composition than the normal composition of the glass or ceramic. These foreign bodies may originate from the original ceramic powders or be introduced as contaminants during processing. They are often identifiable due to their varying color or reflectivity compared to the surrounding matrix.

In glass, about 50 different inclusion types have been identified and recorded. Many of those are called stones. They may result from various factors, such as unreacted raw materials, contamination of raw or recycled materials, glass devitrification, and the introduction of refractory material grains broken off from the tank or pot walls.

Quinn [2020] reports that inclusions that are unintentionally incorporated during the glass making process, such as nickel sulphide, if subjected to tensile residual stresses may lead to sudden, catastrophic failure without warning, occurring at any time, ranging from days to months or even years after fabrication. However, inclusions have different thermal contraction coefficients than glass and they may pull away from the glass during cooldown. Inclusions that contract much less than the glass matrix during cooldown may lead to localized tensile residual stresses in the glass.

The behavior of inclusions varies depending on their particular characteristics, such as their elastic and thermal properties. The severity of the effect of these inclusions is related to the properties match or mismatch to those of the glass matrix [Quinn, 2020] and they can cause cracks in the matrix, crack themselves or detach and pull away creating a void in the glass. Evans [1982] assessed the probability of fracture of glass based on the inclusion's properties based on the graph shown at the image below.

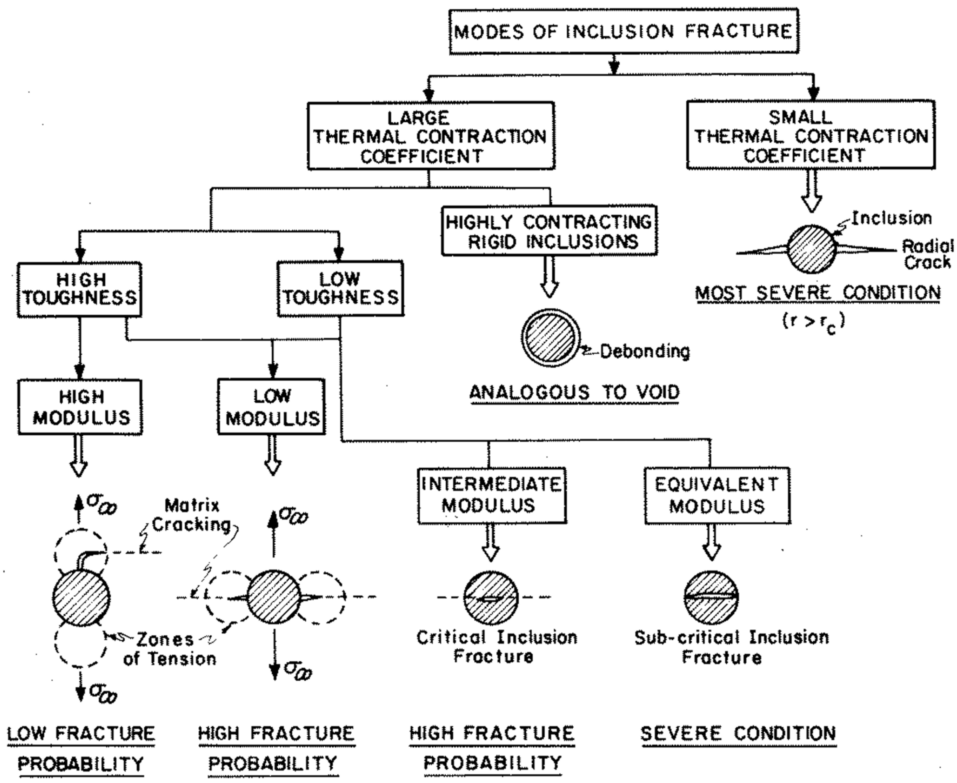


Figure 172: Severity of inclusions. Source: Evans, 1982.

According to the graph by Evans [1982], we need to check what the severity of basalt fibers inclusion is for the glass pieces by comparing their properties. The properties we need to compare between basalt fibers and soda-lime glass are the coefficient of linear expansion, the Young's Modulus (E) and the fracture toughness.

For soda lime glass, coefficient of linear expansion and E properties can be found at EN572-1:2004. The fracture toughness of soda lime silica glass according to the research of Quinn and Swab [2017] ranges between 0.71-0.88 $MPam^{1/2}$. Regarding basalt, Li et al. [2018] mention in their paper that continuous basalt fibers have a coefficient of linear expansion of 6.5-8 °C10^6 and E of 79.3-89 GPa. Since continuous basalt fibers are produced by extrusion of the basalt molten rock into filaments, it is safe to assume that basalt fibers have the same fracture toughness as the raw basalt rock. According to testing at different pressure and temperatures performed by Balme et al. [2004], basalt has fracture toughness ranging from 1.3-2.4 $MPam^{1/2}$.

	coefficient of linear expansion (°C10^6)	Young's modulus (GPa)	fracture toughness ($MPam^{1/2}$)
soda lime glass	9	70	0.71 - 0.88
basalt	6.5 - 8	79.3 - 89	1.3 - 2.4

Figure 173: Material properties comparison. Source: information from EN572-1:2004; Quinn and Swab, 2017; Li et al., 2018; Balme et al., 2004.

As can be seen from the comparison table, basalt and glass have comparable coefficient of linear expansion, and therefore, thermal contraction. Basalt fibers have higher stiffness than glass and also much higher fracture toughness. Thus, according to Evans' diagram, the inclusions of basalt fibers have a low fracture probability and pose no threat to the integrity of the glass.

8.4.4 Extra tests

Intensified stress test

Another important extra test to support the theory that basalt inclusions do not cause structural problems in the resulting glass is the intensified stress test. With two separate tests, float glass pieces with knitted basalt pieces in between are tested in different temperatures.

The first experiment tests two float glass pieces of 4mm thickness with a knitted basalt piece that has not been fired before and another one that has already been fired once. The glass "sandwich" is placed in the oven at the 675°C firing schedule. Initial results after firing show that the glass at the top has stronger texture and more evident basalt inclusions. A quick test with polarization filter shows no residual stresses in the top glass but shows some stresses at the bottom glass piece. The stresses are not very strongly highlighted and appear in specific spots of the surface that was in contact with the fire blanket underneath the experiment and not at the surface in contact with the basalt. They might be due to a coating of devitrification spray on this side that was left from previous experimentation or by the contact with the fire blanket.

The second experiment tests casting pieces of float glass with basalt knit in-between at a 1070°C annealing schedule. The basalt used was an already once fired piece of basalt. The resulting glass tile shows almost no signs of the basalt inclusion, which seems to have burnt away. There are only small traces of the basalt which are recognizable only by a yellow color inside the glass.

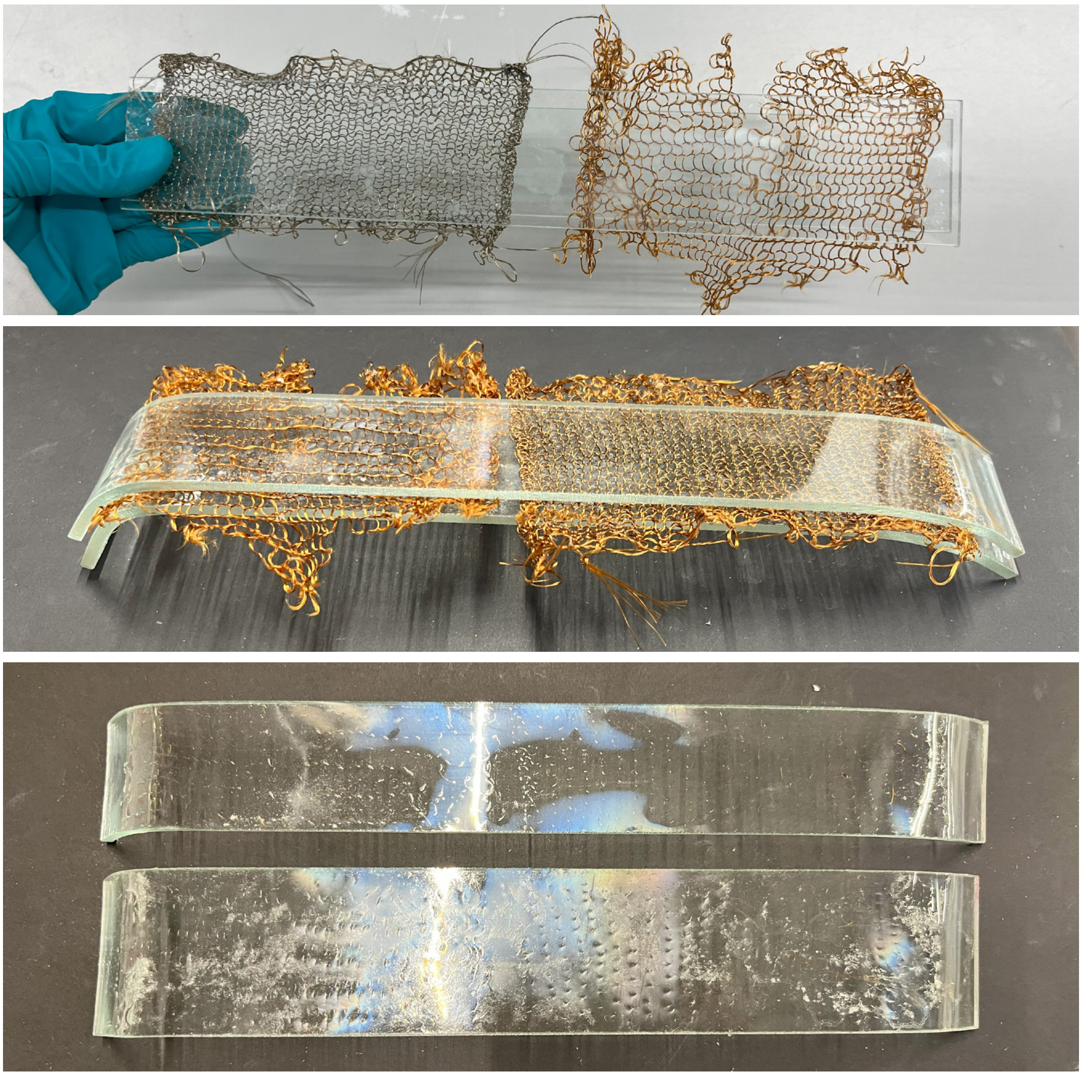


Figure 174: Intensified stress test 1: glass-basalt-glass sandwich. Up: before firing, Middle: after firing, Down: resulting surface. Own images

Figure 175: Intensified stress test 2: glass-basalt cast tile. Before (left) and (after) casting. Source: Left: T.Bristogianni, Right: own image.

Under the microscope both experiments do not exhibit stresses in the glass caused by the basalt inclusions nor microcracks. This was checked with a cross-polarization test. Few signs of residual stresses exist in both samples, however, they are caused by other factors, such as contamination by other materials present in the oven.

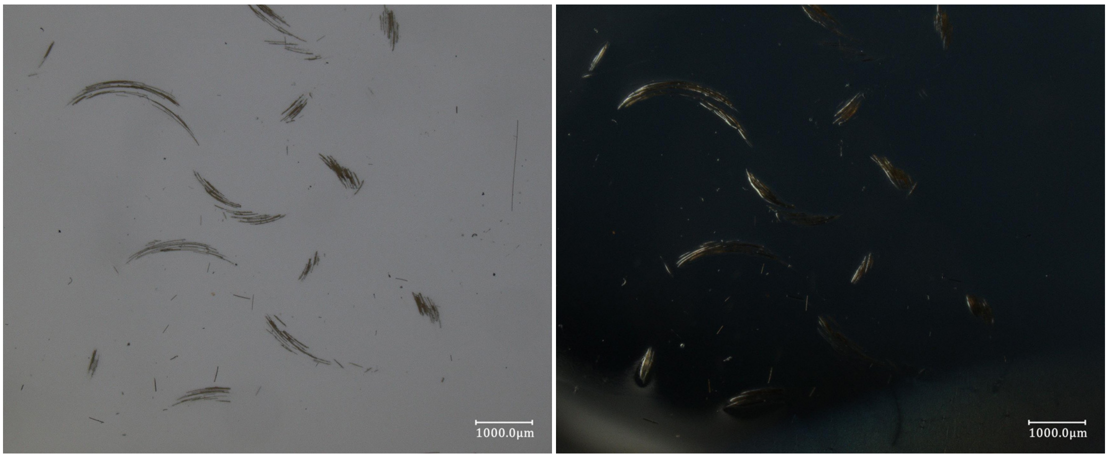


Figure 176: Intensified stress test 1 under the microscope: normal (left) and polarized (right) filter. Own images.

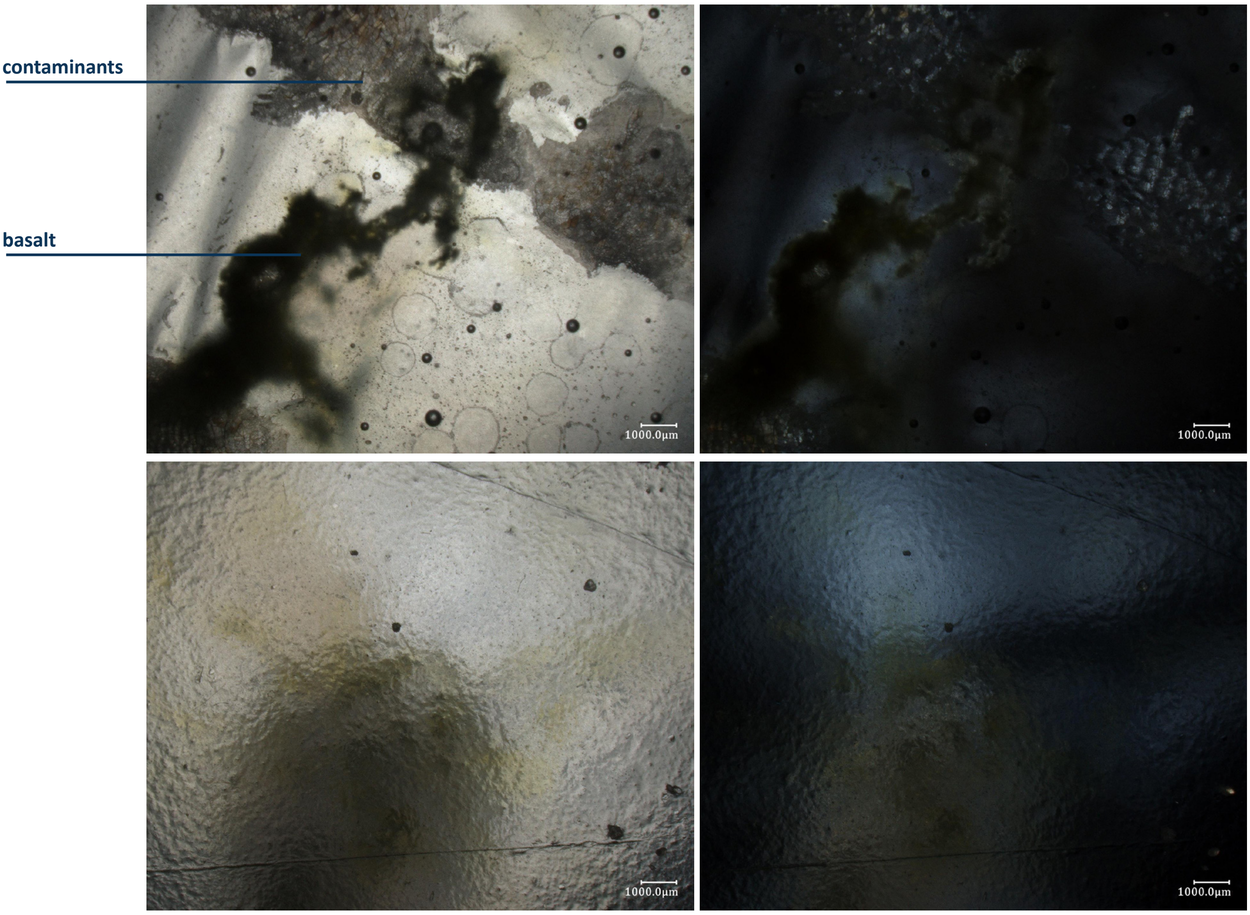


Figure 177: Intensified stress test 2 under the microscope: normal (left) and polarized (right) filter. Up and down images taken from 2 different sides of the tile. Own images.

Freeze test

In order to verify that the basalt inclusions are no threat to the glass, a freeze test is performed. A freeze test shows if the difference in contraction coefficients of the two materials results in microcracks in the glass. For the freeze test, the top sample of the intensified stress test 1 was placed in a freezer room facility for 24 hours at constant temperature below -20°C.

After removing the experiment from the freezer room, no cracks in the glass surface were visible by the naked eye. Under the microscope it was also verified that there were no microcracks formed around the basalt fiber inclusions. The visible lines in the following images from the microscope are not cracks. In fact, they are inclusions that were caused by the basalt mould where fibers were not trapped in the glass matrix and appear hollow. They appear more intense than other samples previously tested, and an assumption is the concentrated humidity at the time of the examination.

Therefore, it is safe to make the assumption that the basalt inclusions in the gass surface do not pose any serious threat for post-breakage of the glass.

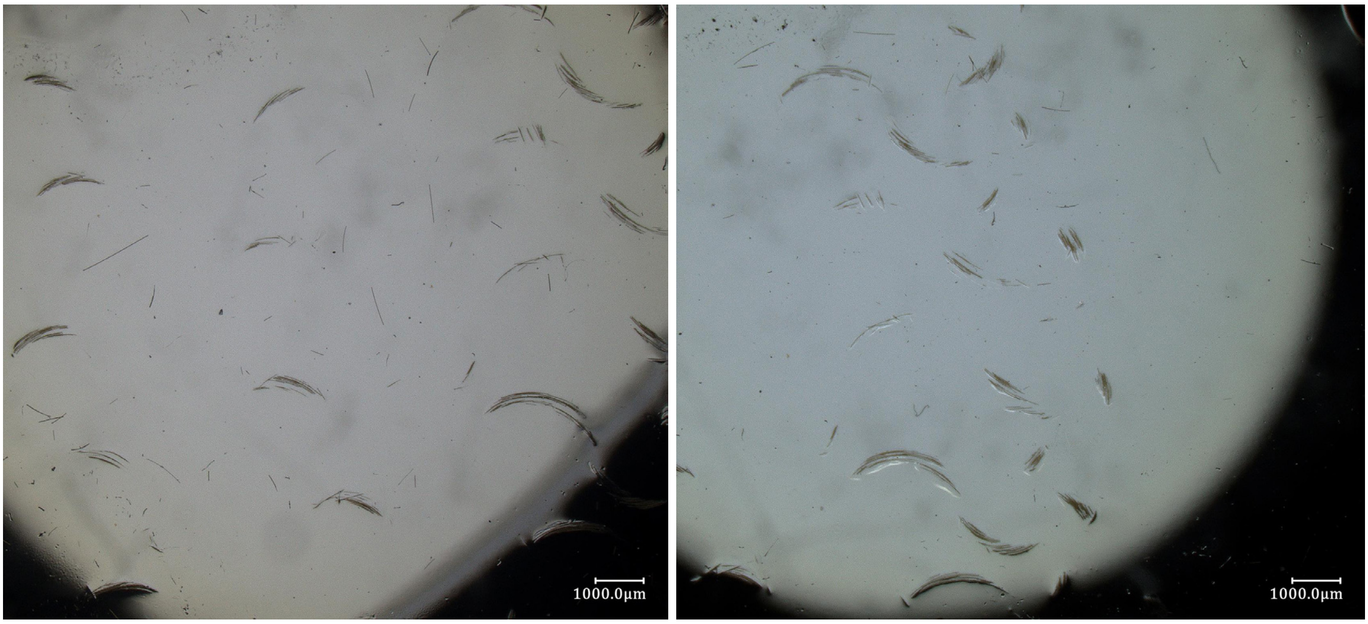


Figure 178: Sample's basalt inclusions before (left) and after (right) freeze test. Own images.

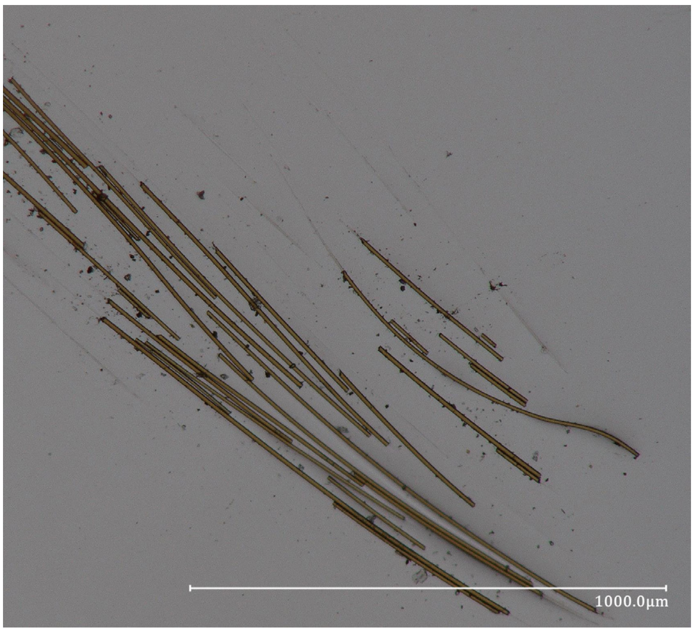


Figure 179: Zoomed in basalt inclusion after freeze test demonstrating no cracks. Lines following basalt fibers indicate hollow inclusions formed by mould. Own images.

9 Conclusions on experimental work

9.1 Experiments results & Discussion

After completing all the previously outlined experiments, it is critical to review the main objectives established at the start of the experimental work, gather the results of the experiments in relation to these objectives, and reflect on them. The findings of these experiments will inform the design of final prototypes as well as a façade element for the case study chosen at the beginning of this thesis.

The results of the experiments are organized as seen in the graph in categories of geometry, surface, and redundancy.

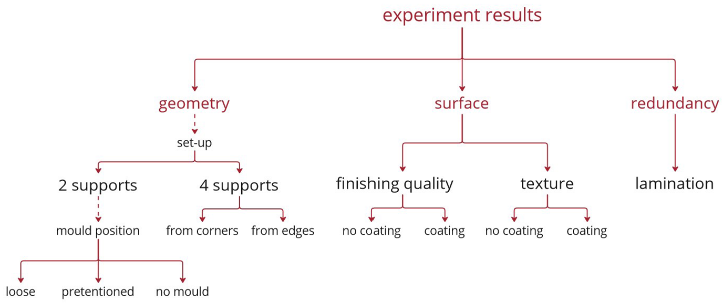


Figure 180: Diagram of experiment results categories.

Geometry

			experiment	glass size	glass thickness	span (a)	result
Geometry	2 supports	hand-woven mould : loose set-up	1	10 x 30cm	4mm	single curved a > 30cm	deformation = a/5.8
			2				deformation = a/2.3
		no mould	3	10 x 30cm	4mm	single curved a = 10cm	deformation = a/4
			3			single curved a < 10cm	deformation = a/17
		knit mould : pretensioned	4	5 x 30cm	8mm	single curved a > 30cm	deformation = a/6.8
					4mm		deformation = a/8.8
					1 + 4mm		deformation = a/8.3
					1mm		deformation = a/10
		support in 2 points : mould fixed in place by coating	5	10 x 30cm	4mm	double curved a = 34cm	failed
	4 supports	4 corners : different heights	6	30 x 30cm	4mm	double curved a = 35cm in both directions	accidental freeform - no control in geometry result
		4 corners : same heights	7	30 x 30cm	4mm	double curved a = 35cm in both directions	failed
		4 edges (knit mould)	8	20 x 30cm	4mm	double curved a1 = 30cm a2 = 45.5cm	vault geometry + extra bubble formations
		4 edges (cement mould)	9	30 x 30cm	4mm	double curved a = 30cm in both directions	multiple curvatures following the shape - middle deformation not as much as cement
					1mm		

Figure 181: Table summarizing experiment results regarding geometry.

In terms of achieved geometry, the experiments can be evaluated based on the support type of their set-up: either with a 2-support system or a 4-supports system. The 2-support system was used to produce mainly single curved geometries (experiments 1-4) but also a double curved one (experiment 5). The 4-support system was used for double curved geometries (as seen in experiments 6-9). This initial categorization can be further divided for the geometrical results of the experiments based on the mould set-up.

Starting with the 2-support system, the set-up for single curved geometries was controlled by bounding the 2 parallel sides with steel bars. For spans more than 30 cm it was observed that the glass can perfectly adhere to the mould's shape. This is especially true for a loose mould setup, which is defined as a mould that is neither pre-tensioned nor flat before the experiment begins. Hand-woven molds tested in this setting during the 2 performed experiments did not expand since the basalt fibers are not stretchable & the woven technique does not allow much stretchability of the textile either, thus, the glass conformed to the mould's exact shape. The maximum achieved deformation in this set-up was the initially formed curvature by the mould. However, this is not necessarily the maximum deformation that can be achieved when slumping glass with textile moulds since the glass was sagging without any resistance from the mould until it reached its curved shape.

The glass slumping without mould in narrow spans between steel bars resulted in very restricted deformation in the span center, resembling the achieved results of Giesecke and Dillenburger [2022]. With a higher maximum temperature and a different firing schedule, an extreme deformation would be likely to happen in such narrow spans.

Knitted moulds tested with a slightly pre-tensioned setup and different thicknesses of glass (see exp. 4) revealed deformation variances depending on glass thickness. This set-up is more representative of the actual effect of the textile moulds on the maximum achieved deformation of glass discussed earlier. Thinner glasses deformed less than thicker ones, which is a result that could be expected since the weight of the glass and, therefore, the loading on the mould is bigger as we get thicker glass. The deformation range shows that in order to achieve precise repetitive geometries the thickness of glass should remain the same every time or it should be calculated from the beginning, but also the density of the moulds (which stretched considerably even for the thinnest piece of 1mm glass) leading to the conclusion that denser moulds should be considered for more control over the final geometry based on the initial set-up of the mould, or more tentione should be introduced.

Finally, the attempt to create a doubly-curved rigidified hand-woven mould by the use of Crystalcast coating failed showing that the combination of the materials in this type of set-up is not possible to produce the desired complex geometry. It would be interesting to perform a similar test with the use of porcelain, which also starts in the same state as Crystalcast before firing and compare the results.

Regarding the 4-support system, there were two different set-ups tested, support by the corners (see exp. 6, 7) or support by the edges (see exp. 8, 9). Support by 4 corners did not work well in any of the two experiments tested. Both of the experiments with corner supports collapsed due to the poor construction of the moulds leading to altered or no results in terms of geometry. However, a failed attempt (exp.6) resulted in an accidental freeform double curved geometry exhibiting the shaping possibilities of the proposed method. Regarding this type of set-up of support by the 4 corners, the experimental part so far concludes that it is not as successful and should either be designed better for future experiments so that the textile near the corners does not rip and destroy the result, or it should be avoided altogether and prefer support by 4 edges.

The experiments tested in the 4-support system by edges support were both attempts to introduce different curvatures to the slumped glass by different means. In the case of the knitted mould without any coating (see exp.8) the mould was designed with 2 patterns in the knit, a very tight and a very loose one creating a bubble pattern with the parts of the bubbles made of the loose pattern already hanging down from the beginning. The mould was tensioned in place but not with a lot of tension. The method led to different curvatures but with very small differences, showcasing the feasibility and potential of using combinations of different patterns in the knit to produce complex and changing curvatures in the glass panels. However, as seen by the resulting geometry, the original size (dimateter) of the bubble design was not enough to create a big curvature difference leading to the conclusion that for more visible and extreme results either a bigger scale in the pattern is crucial or, for a smaller scale, a different maximum temperature during slumping is required. Moreover, to achieve a smaller deformation of the glass piece as a whole, it is essential to use an even denser pattern and introduce more tension to the initial set-up.

The other experiment testing multiple curvatures used cement as a rigidifying coating to achieve a complex geometry (see exp.9). The resulting glass achieved an interesting geometry of multiple curvatures, following accurately the shape of the mould at the sides. In the middle, the glass was not able to deform as much as the cement, creating an even curvature between the supports. The glass piece with 4mm thickness deformed more than the 1mm glass in the center due to its bigger weight, but still not deforming as much as the original mould geometry. This result shows that it is not able to achieve the extreme curvatures and complex geometries that are possible with cement/concrete using textile moulds, at least for this scale.

Comparing knitted and woven moulds, it becomes clear that the type of textile plays a major role in the possible achieved deformations of glass. Woven moulds are not stretchable and therefore, the initial setup will deform evenly under the weight of the glass up to a point, leading to a slightly different geometry than originally designed. On the other hand, knitted moulds do stretch due to their looped structure, thus, the pattern used for the knitting, as well as the pretension introduced at the initial set-up of the textile need to be calculated according to the glass size and thickness to produce the desired geometry.

Measuring the final resulting thickness of the glasses with a digital caliper, the initial set up of the mould in a loose or tensioned state appears to be influencing the results. Glasses deforming in a loose initial set up show thicker glass at the middle of the slumped piece, while pre-tensioned set-ups result in thinner glass in the middle. This is due to the weight of the glass at this point in combination with the resistance or not from the mould.

Summing up the main geometrical curvatures, synclastic curvatures are only possible by draping the textile down, thus, creating the shape upside-down. Furthermore, the multiple-curvature experiments show that the change of the curvature from positive to negative, where one side is above the height of the supports, is only possible when there are other supports (see exp. 9, 6). Therefore, to achieve such shapes without the use of coatings, a different set-up offering extra supports should be examined. Anticlastic curvatures on the other hand are possible with the correct tension in the textile. With a dense and very tensioned textile, glass may be supported at the initial level of the set-up in a flat position, creating a controlled surface for the edges for example, or for particular points.

Surface

In terms of surface, the experiments can be evaluated based on the finishing surface quality and the texture. Both categories are further divided depending on the use of coatings or not on the mould or glass.

				experiment	glass thickness	curvature	result
Surface	finishing quality	no coating	many contact / support points with mould	1	4mm	single curved	light crystalization + stretch marks
				7		double curved	almost completely transparent
				8		double curved	almost completely transparent
			few contact / support points with mould	2.A	4mm	single curved	great crystalization + stretch marks
				2.B		single curved	light crystalization + stretch marks
				6		double curved	great crystalization + stretch marks
				3		single curved	great crystalization
		coating	biosoluble & fire paper	2.C	4mm	single curved	almost completely transparent
			crystalcast	5	4mm	double curved	almost completely transparent
			heat-resistant cement	9	4mm	double curved	fully transparent
			devitrification spray	4	4mm	single curved	very light crystallization at some parts of the glass
	texture	no coating	many contact / support points with mould	1	4mm	single curved	visible smaller point imprints & small inclusions of basalt fiber
				7		double curved	
			few contact / support points with mould	2.A	4mm	single curved	strong imprints & visible inclusions of basalt fiber
				2.B		single curved	
			change in supporting pattern of mould	6	4mm	double curved	strong visible support point imprints
				8		double curved	visible imprints only at edges of changing pattern (bubble edges)
		coating	biosoluble & fire paper	2.C	4mm	single curved	very light texture from biosol. paper
			crystalcast	5	4mm	double curved	visible strong imprint spots/dots like cracks
			heat-resistant cement	9	4mm	double curved	visible strong imprint spots/dots like cracks

Figure 182: Table summarizing experiment results regarding surface.

Finishing quality

To begin with, the results in terms of the glass finishing surface quality will be examined. Regarding the use of moulds and glass without any coating in their contact surface, different results were observed based on the number of support points from the textile moulds, which is directly linked to the density of the weave or knit. The experiments with glass supported on many points show different results in terms of surface quality: glasses of experiments with hand-woven moulds, showcased light crystallization on their surface, while in contrary, experiments with knitted moulds in an initially flat position (e.g. samples 3.A, 3.C & 3.D, 7, 8) showcase a clear, almost completely transparent surface with very light iridescent colors. The difference might relate to the initial set-up or production method (weaving or knitting) of the mould, to the presence of other materials in the oven or it might have to do with the firing schedule and the slumping amount, but a clear conclusion is not easily drawn. Moulds that offered fewer support points to the glass (e.g. samples 2A, 2B, 3, 6), all resulted in great crystallization especially at the middle of the span between supports, with one exception showing slightly less crystallization than the others. The resulting heavy crystallization might occur due to the free slumping of glass at these parts where the span is bigger than a certain dimension. In almost all the above-mentioned glasses, signs of light white lines like stretch marks were visible on the surface, following the curvatures.

Regarding the use of coatings on the mould or glass, the use of a layer of biosoluble and a layer of thin fire paper between the mould and the glass resulted in an almost completely transparent surface (e.g. sample 2.C). However, the best finishing quality was observed with the use of Crystalcast or Cement coating, showcasing a completely transparent resulting glass. Finally, the use of the clearcoat overglaze devitrification spray (see sample 4.B) resulted in a lightly crystallized surface in the form of iridescent reflections at some parts of the glass. This might be due to an incorrect application of the coating, which left some parts uncoated, or due to the temperatures of the firing program, which might not be in coordination to what the devitrification spray needs to work properly.

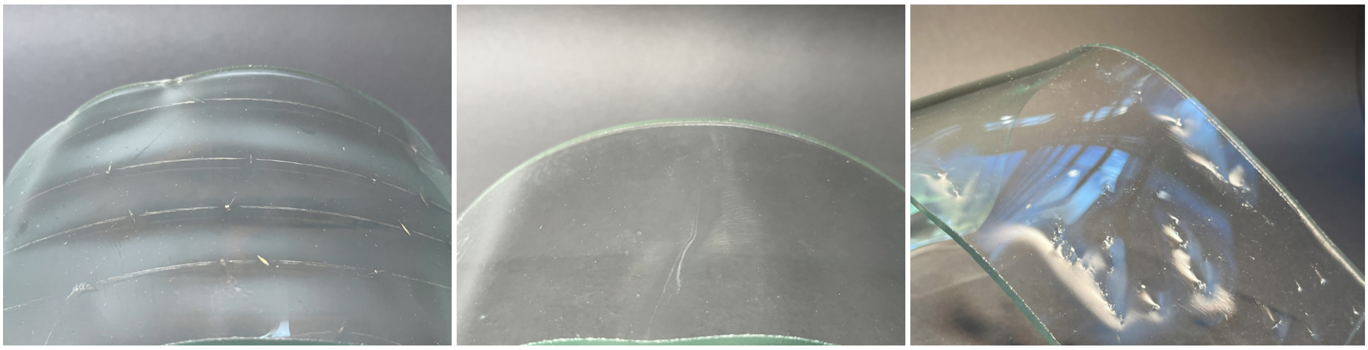


Figure 183: Finishing surface from worst (left) to best (right). Left: sample 2.A exhibiting heavy crystallization. Middle: sapmle 2.C with bio-soluble & thin fire paper coating layers resulting to almost completely tranparent result. Right: sample 5 with Crystalcast coating exhibiting completely transparet surface. Own images.

Texture

Following the finishing quality, surface of the glasses will be evaluated also based on texture imprinted from the moulds. Results in terms of texture are also evaluated based on the use of coating or not. In the case of not using any coating, all types of moulds leave imprinting surface marks on the glass, whether they have more or less supports. Dense moulds offering more support points to the glass lead to smaller imprints on the glass surface in the form of dots or small lines where the support is. However, this is also dependent on the glass thickness: as results thin glass has very light imprints, almost not visible, while thicker glass has very strong imprints (see samples of exp. 4). Moulds with fewer support points lead to stronger texture marks on the glass almost showcasing the whole mould shape (see sample 2.A), and also the texture is visible to be inclusions of basalt fibers in the glass matrix due to the different color. Moulds that were designed with uneven weave or knit patterns (e.g. samples 6, 8) show strong imprints at the points of the support's change, something very visible at the bubble knit pattern, where the bubble perimeter is very pronounced, while the in-between surface in contact with the glass has left almost no texture.

Regarding experiments with the use of coatings, the resulting texture is quite different. The use of biosoluble & fire paper resulted in glass with no texture from the mould underneath but with a very light, almost unnoticeable texture from the biosoluble paper. Crystalcast and Cement coatings also show no texture from the mould pattern, however, they result in few but strong spot imprints, that look deep and likely to have caused microcracks in the glass.

Results from the microscopic study exhibit that the texture in the glass which is in fact inclusions of basalt, does not pose any threat to the glass in terms of future breakage. The test of basalt sandwich between two glasses did not show the stress intensifying internally in the glass, but it showed that texture is imprinted stronger at the glass at the top.

Figure 184: Imprinted texture results. Up left: sample 1.A exhibiting more texture points. Up right: sapmle 2.B exhibiting stronger texture almost reveiling the whole mould shape. Down left: Texture from changing mould support by change of pattern resulting to texture only at the edge of the change. Down right: texture of sample 9 showing strong texture only from the cement coating and not from the textile. Own images.

Redundancy

		experiment	glass thickness	curvature	**result**
Redundancy	simultaneous slumping	4	4+1mm	single curved	perfectly aligned
	separate slumping	9	4mm	double curved	not same curvature
			1mm		
		5	8mm	single curved	not same curvature
			4mm		
			1mm		

Figure 185: Table summarizing experiment results regarding lamination.

The final criterion for the experiments was the possibility of redundancy, which is the possibility for future lamination. This is examined in two ways: whether it is possible to simultaneously slump glass pieces and whether it is possible to slump in the same conditions two glasses separately and then laminate them.

Simultaneous slumping tested (see sample 4.C) showed that it is possible to slump two pieces of glass using the knitted moulds and get an even and exact replicate of the curvature between the two glasses, even with their difference in thickness. This is very promising for the overall redundancy of a future glass panel application.

On the other hand, slumping two glasses of different thicknesses separately under the same conditions resulted in different curvatures. Different thicknesses result in different curvatures due to the different weight of the glasses, and thus, different loading of the mould, which leads to the conclusion that future lamination of curved glass by this method is not possible. Only by calculating the pretension of the knitted textile in relation to the glass weight could we achieve similar results in glass deformation. However, even in the case that two glasses of the same thickness were curved separately under the same conditions, it is quite safe to assume that they would not result in a perfectly aligned curvature, making it impossible to laminate them later. This is since if all the conditions are perfectly controlled the exact same curvature might be replicated, but two pieces of the same curvature do not create a fit with each other for lamination. Calculating the small difference needed to create perfectly aligned curvatures for lamination with this method seems a very uncertain and almost impossible task.

Finally, the difference between glass thicknesses and achieved deformation leads to the conclusion that for future simultaneous slumping in big spans or complex geometries, the thinner glass is advised to be placed on the bottom. In this way, the weight of the thicker glass will act as a load to the thinner glass resulting in a perfectly aligned curvature.

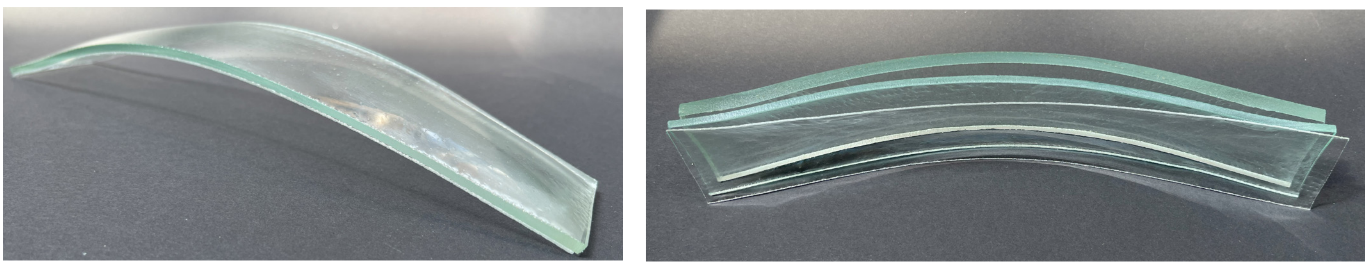


Figure 186: Left: simultaneous slumpig results of sample 4.C. Righ: slumping of different glass thicknesses under same conditions(samples 4.A, 4.B, 4.D). Own images.

10 Prototyping

Following the careful review & reflection on the limitations and potential of the performed experimental work presented in the previous chapters (chapters 8, 9), a final experiment is designed and executed carefully to serve as a final prototype showcasing the proposed novel fabrication technique of curving glass with basalt knitted moulds.

Aim of the prototype is to determine the level of control in the final achieved geometry by testing its replicability. In the following pages, the preparation, set-up and results of the experiment will be discussed in detail.

Design

The designed experiment utilizes a square basalt knitted mould with an X pattern. Two different knitting patterns are used, a tight one for the X shape and a loose one for the remaining triangles. The mould has embedded channels on two opposite sides which will be used to tension it in place with steel bars. The remaining sides are not supported, allowing for bigger deformations. The mould is tensioned on all sides and secured on the steel bars by the use of steel clamps. On the mould, two pieces of glass are placed simultaneously, one of 1mm and one of 4mm thickness. The oven is set at the firing schedule of 675°C.

Preparation

In order to determine the level of control over the resulting curved glass, the designed experiment will be performed twice, by creating two identical set-ups in the oven. Since this is an experiment that is not performed on an industrial scale and facility, a certain level of deviation between the two set-ups is to be expected.

There are various parameters that need to be controlled beforehand in order to secure two set-ups as close to identical as possible and, therefore, replicate the results. Starting by the glass pieces to be placed on top of the moulds, the 4 pieces of 30x30cm dimensions were weighted at a digital scale to ensure that the load on the two moulds will be the same. Small deviations were measured and thus, the right combination of the glasses was decided to have the smallest difference possible, which ended up being 1g.

The two moulds fabricated by the CNC knitting machine were almost identical. Their dimensions were different when out of the machine and when tensioned (see following images), with the dimension of the free edges being smaller than the glass pieces, leading to small cantilevers. Due to the designed pattern, peculiarities of the basalt yarn and not perfect calibration of all the machine operations required for the specific material, some holes were formed on the two moulds which were later secured by hand.

The two final combinations for the two samples can be seen at the table below. Thin fire paper is used as an in-between layer for the two glasses due to avoid fusing.

<table>
<tr><th colspan="12">Prototype Set-up Preparation</th></tr>
<tr><th colspan="5">glass</th><th colspan="4">mould</th><th colspan="3">combinations</th></tr>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td colspan="2"></td><td>a</td><td>b</td><td></td><td>A</td><td>B</td></tr>
<tr><td rowspan="2">thickness</td><td rowspan="2">4mm</td><td rowspan="2">4mm</td><td rowspan="2">1mm</td><td rowspan="2">1mm</td><td rowspan="2">dimension</td><td>relaxed</td><td colspan="2">37.5x14.5 cm</td><td rowspan="2">glasses</td><td rowspan="2">g.1
+
thin fire paper
+
g.3</td><td rowspan="2">g.2
+
thin fire paper
+
g.4</td></tr>
<tr><td>tensioned</td><td colspan="2">32.5x26 cm</td></tr>
<tr><td>weight</td><td>875g</td><td>877g</td><td>225g</td><td>224g</td><td>defects</td><td></td><td>1 defect at outer edge of X</td><td>2 defects at opposite outer edges of X</td><td>mould</td><td>a</td><td>b</td></tr>
</table>

Figure 187: Table summarizing preparation factors of the prototype set-up.

Set-up

The mould is supported on two opposite sides by stainless steel bars secured on brick supports. The remaining two sides are not supported, allowing for free sagging of the mould and glass once the slumping process has started. After placing the textile on the set-up, it is greatly tensioned so that the smaller side of the mould, between the steel bars, reaches the dimension of 32.5cm. Then, the textile is tensioned as well in the other direction until it reaches its maximum dimension of 26cm and the textile corners are secured in place by stainless steel clamps on the bar. Replication of the set-up in a mirrored form follows.

On top of each mould the glass piece of 1mm thickness is placed in direct contact. Then, a layer of two stripes of thin fire paper is placed and finally, a piece of 4mm glass on top of it. The thin fire paper is required to avoid the fusing of the glasses. The glass pieces have small cantilevers in each of the unsupported sides of the mould.

There are factors that might influence the final result in its exact replicability. First, a difference that might influence the final shape is the placement of the glasses. The layer of thin fire paper might cause the slight movement of the glasses, creating small differences. Second, the placement of the set-ups in regard to the oven is another influencing factor. The middle zone where both set-ups meet might be heated at a different rate than the other sides directly exposed to the oven resistances. This might influence the final deformation of the glasses.

As seen at the previous table, combination A was placed at the front part of the oven (where the door is) and combination B at the back.

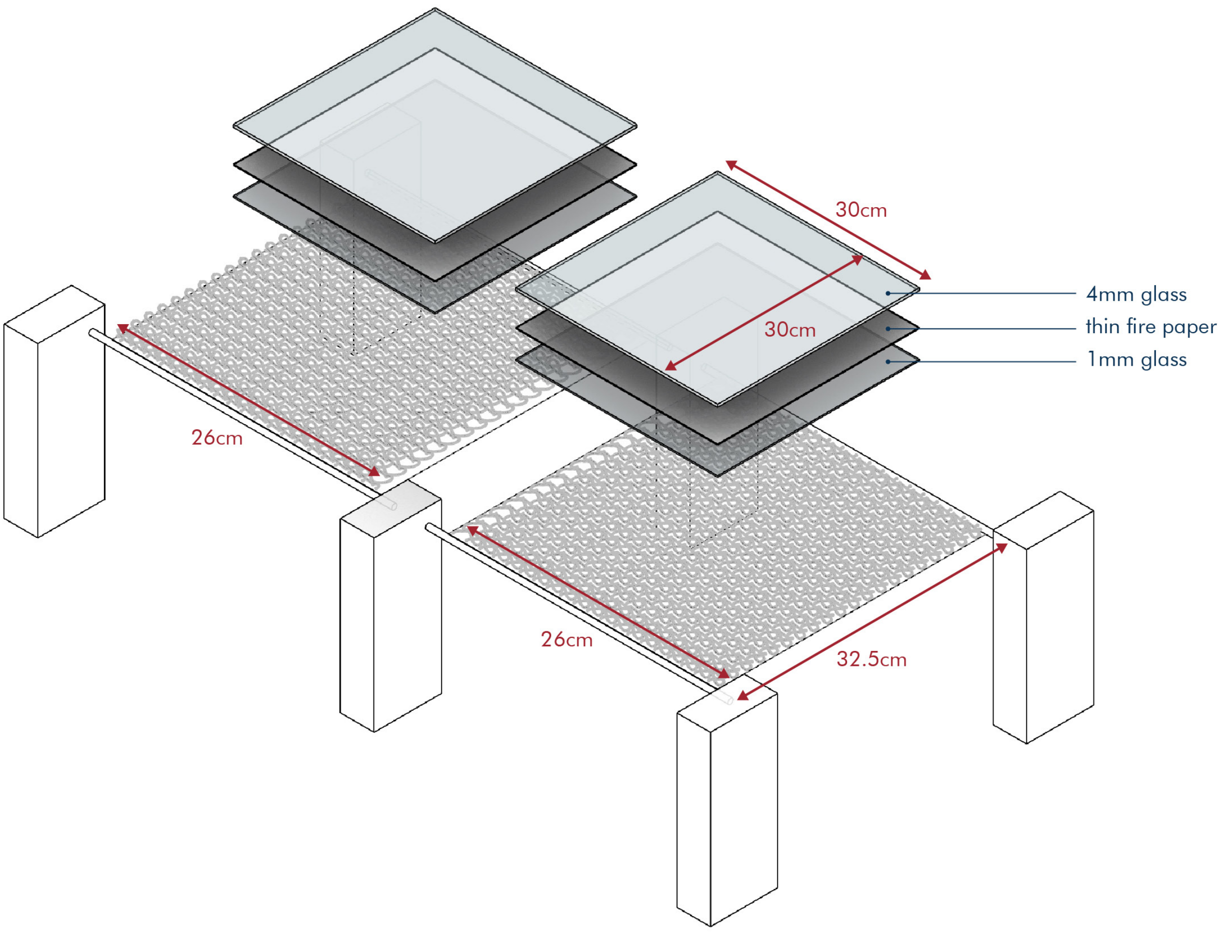


Figure 188: Diagram of prototype set-up.

Mould & set-up details

Figure 189: Basalt knitted mould; relaxed (left), with bars in the cannels (middle) and tensioned (right). Own images.

Figure 190: Clamps for maintaining the tensioned mould shape in a controlled position. Own image.

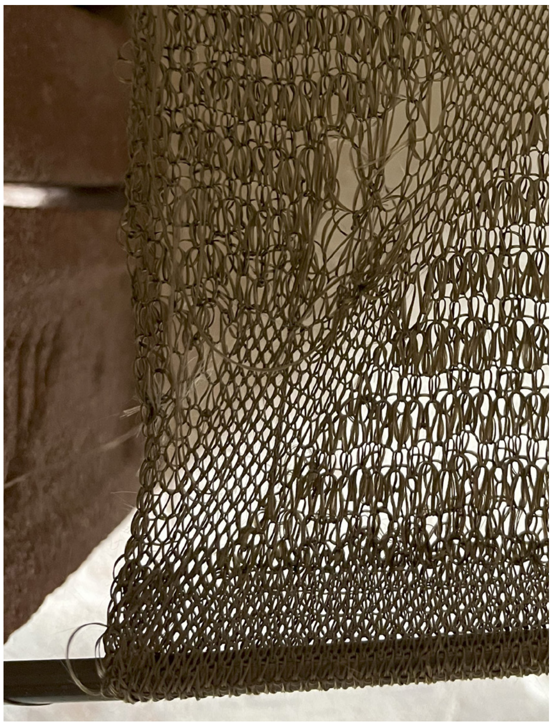


Figure 191: Holes caused by machine operations not tolerated by the basalt yarn. Own image.

Set-up in the oven

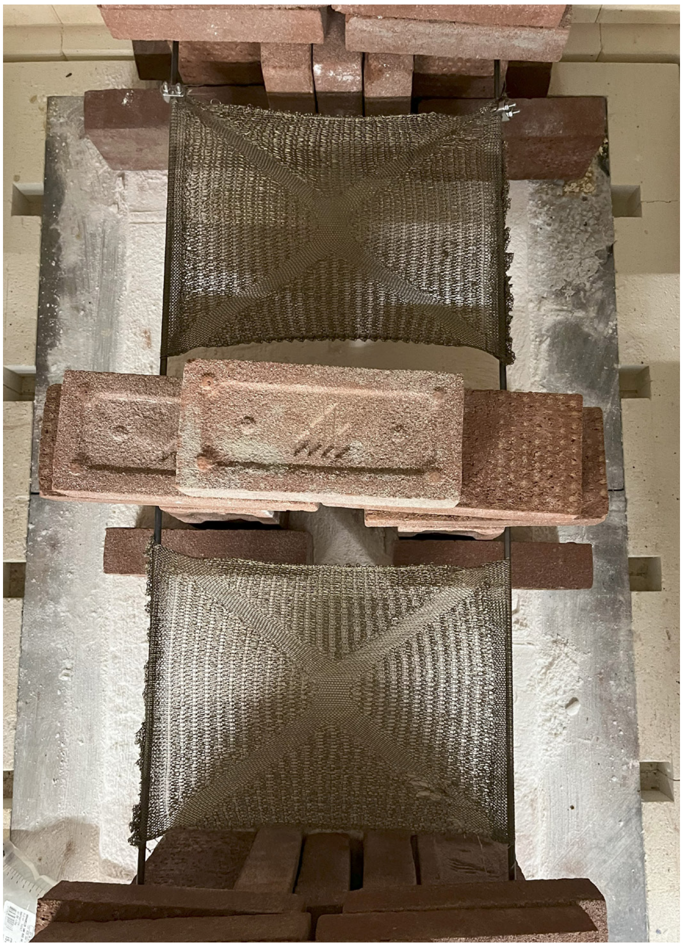
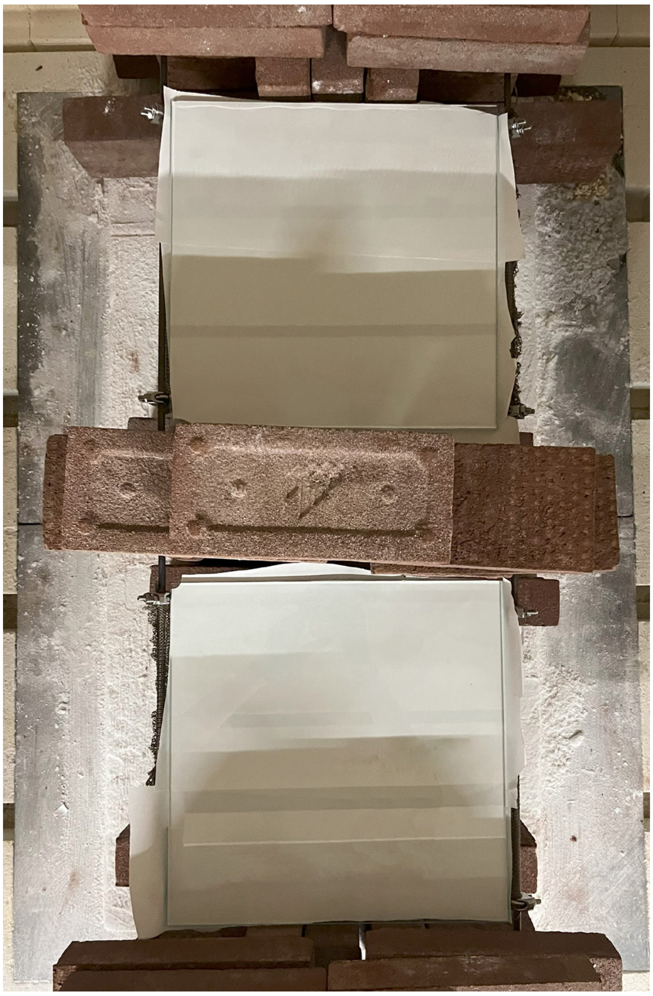
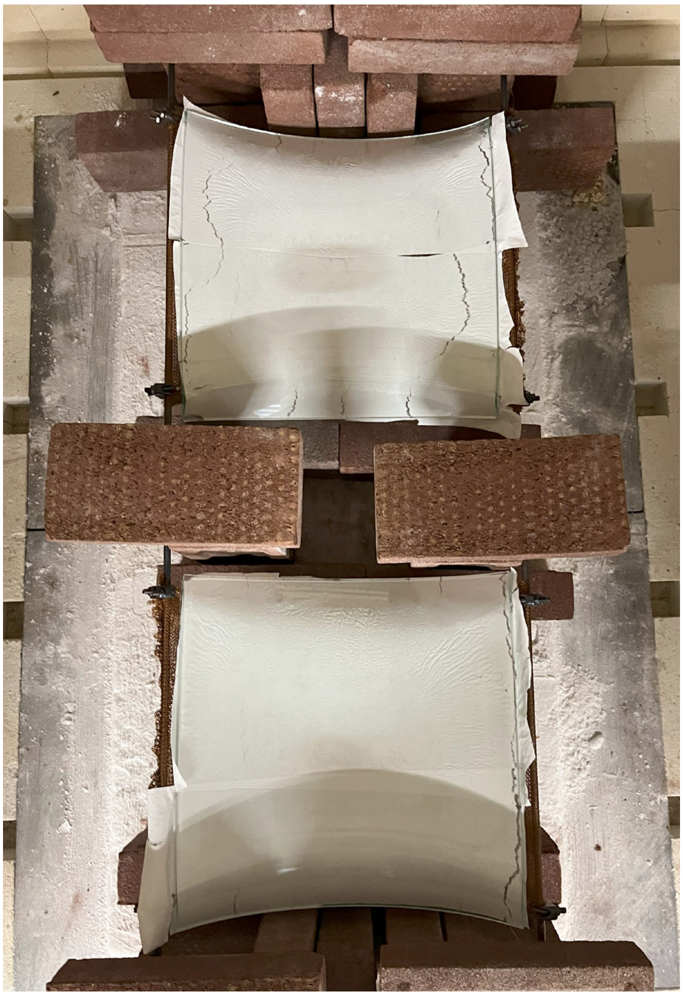


Figure 192: Set-up of prototype in the oven.
Up right: mould set up: above sample B and down sample A.
Down left: before slumping. Down right: After slumping.
Own images.





Results - geometry

The glass deformed into a double curved shape with multiple curvatures. The result seen in the images occurred since the entire surface of the glass was not supported on the mould and there were cantilevered parts, but also due to the fact that the supports of the mould were different between the sides (steel bars or no support). As expected, the unsupported sides deformed in larger curvatures than the rest of the mould. Had it been supported entirely on the mould, the geometry of the glass would still probably not have been a uniformly vaulted shape, however, the difference of the curvature of the sides would be significantly smaller. In fact, the change in the curvature from negative to positive to negative again happens at the very edge of the textile mould support at the free edges.

The sides supported with the steel bars appear flat until the point where the X pattern stops. Initially, the pattern was designed to have a very rigid part following the X shape and looser parts around it, allowing the glass to slump more at these parts while keeping the X part in a less deformed condition. The exact pattern has been tested with concrete [Flieger, 2024] in a larger scale (50x50cm) and proved to result in the described geometry. However, this was not the case for the glass samples of this prototype. Several factors might have influenced that expected result; the weight of the glass, the scale of the experiment, as well as the amount of tension in combination with the patterns chosen for designing the mould, where a bigger difference in knit density might have been a requirement to lead to the expected results.

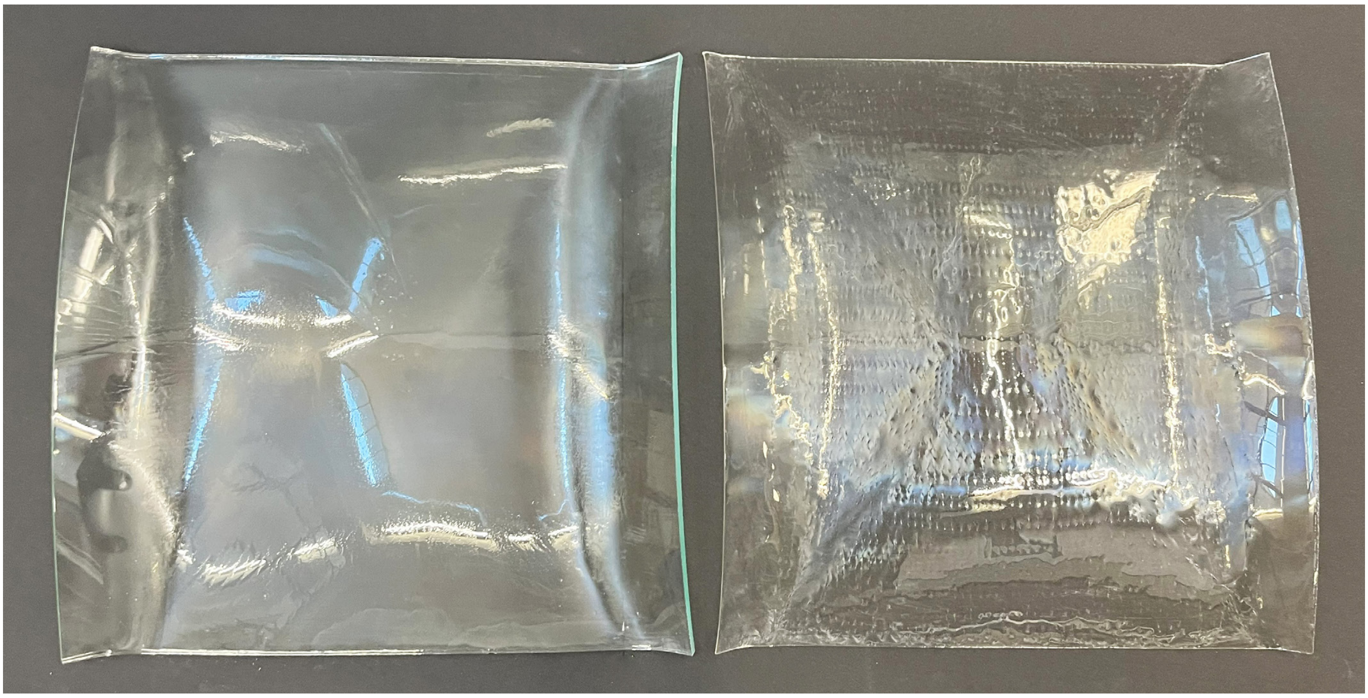


Figure 193: Sample A resulting glass pieces: 4mm(left) and 1mm(right). Own image.

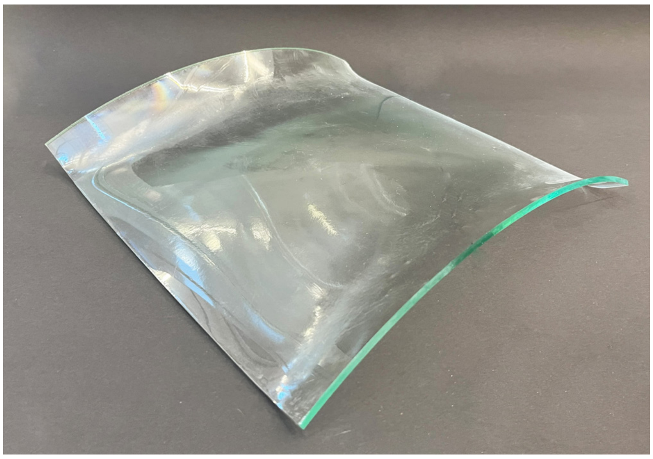


Figure 194: Multiple double curvatures of resulting geometry. Own image.

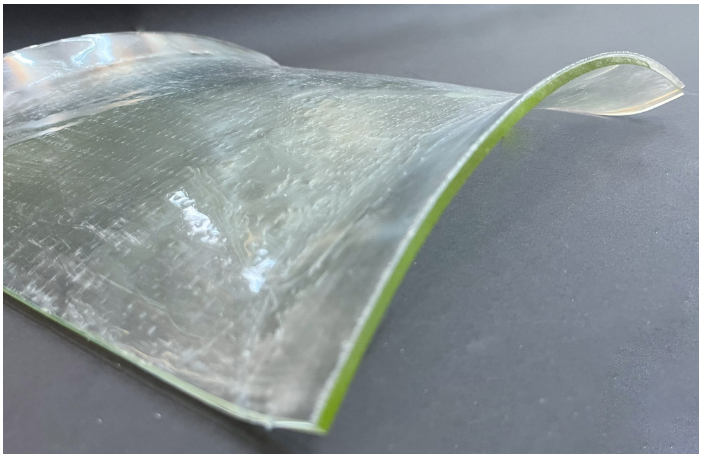


Figure 195: Aligned curvatures of 2 glasses - lamination possibility. Own image.

Another factor that most likely influenced the final geometry is the presence of the thin fire paper. Paper has different stiffness than the textile and thus, a different way of deforming. Slumping more than one glass simultaneously is not possible without an in-between layer. The reason for doing this is to achieve the required safety of the structure by having redundancy through lamination. As already observed from previous experiments, both glasses resulted in a completely aligned geometry allowing for possible lamination later, something that was not proved successful with separate slumping so far in the experimental work of the thesis. However, in order to be able to achieve both the geometry curvature resulting by the knit textile effect and the simultaneous slumping, a different material with similar properties as the knit should be investigated as an interlayer for the process.

Moreover, the amount of tension in the textile proved to be a crucial influencing factor for the overall geometry. It did not allow for a very big overall curvature, leading to a maximum deformation in the middle of the glass of span/15. Thus, proving that with the correct calculation of the tension of the mould, the desired curved geometry can be expected and designed from the beginning without the need of large tolerances.

Comparing the two samples

The resulting geometries of sample A and sample B appear to be very similar. By measuring the maximum deformations of the two samples it appears that the middle deformation of sample A is larger by 2mm than the middle deformation of sample B. There are two possible influencing factors to this difference that have to do with differences at the set-up; first might be the hole on the mould of sample A which was larger and closer to the X middle than the holes of sample B and the second might be the extra 1g weight of the glasses.

Regarding the non-supported side curvatures there were differences in the results. Sample A resulted in curvatures with maximum deformation difference of approximately 4mm between the 2 opposite sides. Sample B showcased similar curvature in both sides with a slight difference of <1mm at the maximum deformation. This deformation of sample B is the same amount of deformation as the side of sample A with the biggest deformation. A possible explanation for this difference in the curvatures of sample A is that the glass moved slightly more towards the side with the larger deformation while placing the in-between thin fire paper. Another explanation would be that the side exhibiting smaller curvature might have been tensioned more in the mould or supported slightly differently not allowing for larger curvature. The fact that the side deformation of sample A was smaller in one side might be an additional influencing factor that led to a larger middle deformation.

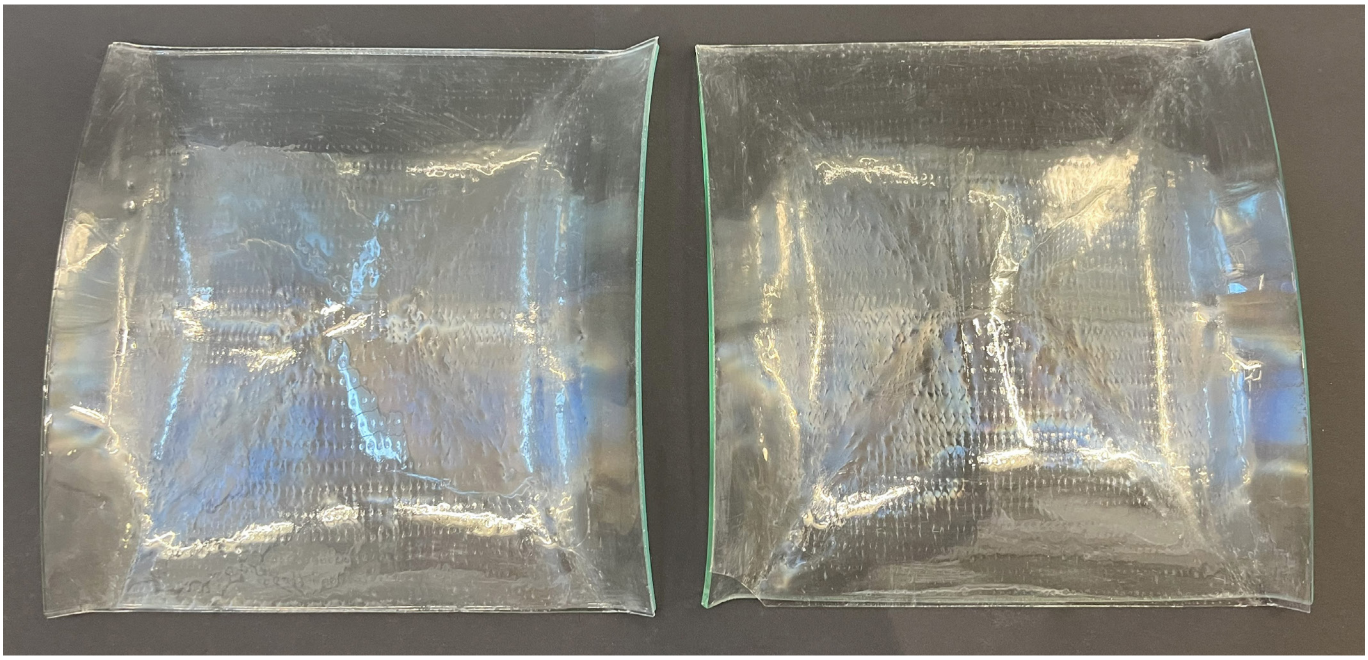


Figure 196: Sample A (left) and sample B (right) resulting glass pieces. Own image.

Swapping the pairs

Another way to check the geometrical difference between the 2 samples is to swap the top glass pieces and create the opposite combinations of glasses. It is quite evident that despite the differences mentioned before the matching is not completely unsuccessful. As seen in the image below, the samples can be combined with great overlap in the sides where the mould was supported. A small deviation of the matching point at the edge of the glasses reveals that there was indeed a small displacement of one of the samples from the initial measured position on the mould when the fire paper and top glass was placed. However, the geometry formed is similar and matching for a great part of the curved glass. The sides curved at the unsupported edges of the mould reveal that the combination on the left of the image the difference is greater than acceptable and on the right they match perfectly.

Moreover, when swapping the top glasses, it was observed that the glasses needed to be rotated to achieve better combinations. This means that the samples are not completely symmetrical. That result might derive from two things: the displacement of one of the samples causing a disruption of symmetry but also the possible difference in the heating of the glasses at the middle of the oven as discussed earlier.

Summarizing the differences between the two samples, it is obvious that a relatively high fabrication tolerance is required. The geometry results showcase big differences for the scale of the experiment (2mm in the middle deformation), however, the differences in the set-ups can justify these differences. Replicating the resulting curved glass proved to be possible and quite accurate for the conditions under which these experiments were performed. In the case of a professional set-up inside the oven and replicating the experiment by fabricating separately each piece it is safe to assume that the fabrication tolerance needed would be much smaller than exhibited here.

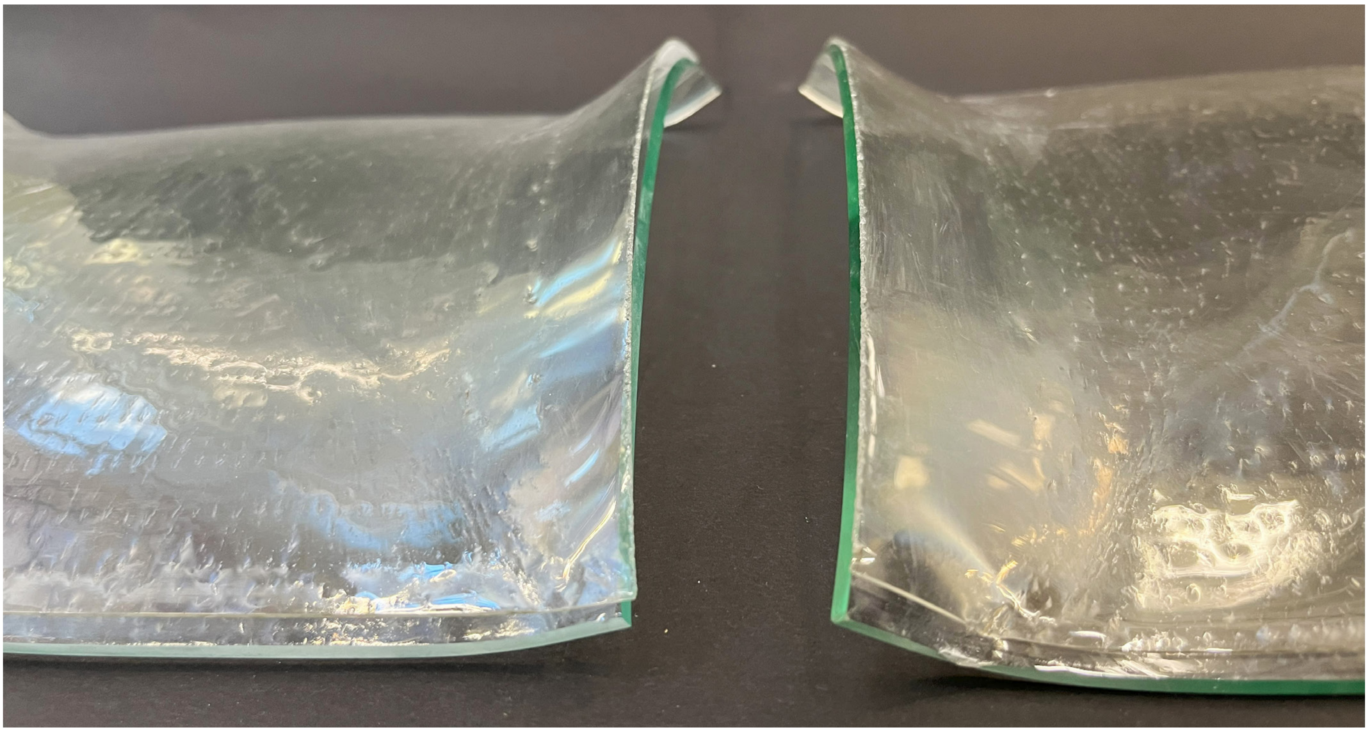


Figure 197: Swapped pair combinations. Own image.

Investigation of thin fire paper influence

As stated before, one of the possible influencing factors of the overall resulting geometry in the glass is the presence of the thin fire paper. To investigate if this is indeed a major influencing factor, the experiment was repeated with the use of the same set-up and a single layer of 4mm thick glass. While the weight is slightly different than before, in this set-up we can achieve similar initial conditions without risking the fusing of the 2 glasses.

The result of this experiment showed that the resulting geometry is very similar to the first samples. The middle deformation proved to be exactly the same as before while the max deformations of the side curvatures proved to be 0.4mm larger than before. These measurements show that thin fire paper did indeed influence the maximum deformations achieved, but in a rather small amount. The side curvatures were mostly infuenced by the presence of the paper but still not extremely. The overall geometry was not influenced as a whole at all, since even the small differences from the initial samples are very small.

Thus, it is safe to conclude that the thin fire paper does not have a major influence on the resulting geometry of the slumped glass, at least for the scale of this experiment. The density and pattern used to create the knitted textile are the influencing factors for the result in terms of geometry.

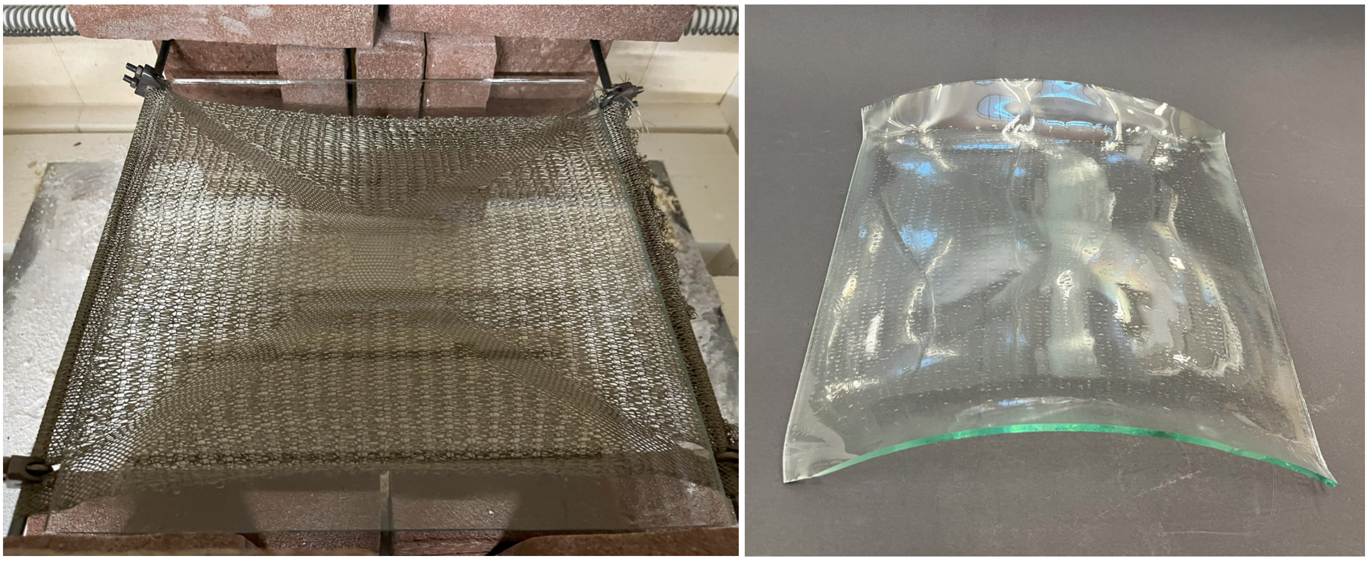


Figure 198: Repeating the experiment without fire paper and a single layer of glass. Left: set-up. Right: Resulting geometry. Own images.

Mould

Inspecting the mould after the slumping process we get similar results with all previous experiments: the mould appears in different color and the basalt fibers have lost part of their strength making the mould brittle. However, in this case the brittleness of the mould seems to be much smaller, the mould is permanently stretched in its tensioned dimensions and the mould appears to be capable of supporting the load of glass weight again. This result might be due to the dense patterns used and the amount of tension applied at the set-up. While previous experimental results concluded that the basalt moulds are not feasible to be reused with direct loading for slumping, these observations make it enticing to attempt reusing the mould.

Figure 199: Mould after slumping process. Own image.

Reuse of the mould

Since the mould used for the prototype experiment seemed to be in a better condition than the previous moulds with the looser patterns, a reuse of the mould was attempted to slump a single piece of 4mm glass under the same conditions. The experiment slumped the glass successfully, proving that basalt moulds can be used 2 times for slumping. However, after the second time the mould started to tear at the supports leading to a very fragile state of the mould indicating no more reuse possibility as a directly loaded mould. We can conclude that reuse of a basalt mould is possible at least once, however, that highly depends on the knitting pattern and density.

The resulting glass geometry was very close to the measurements of the previous prototype samples. The overall deformation in the middle was slightly bigger since the mould was "stretched" after the first fabrication process and the max side curvature was also bigger due to the stretched mould but also the non existence of the thin fire paper. In terms of surface, there is still imprinted texture from the mould, however with less intensity than the previous samples of the prototype experiment.

Figure 200: Left top: Mould reuse with single piece of glass after slumping.
Left bottom: resulting glass geometry similar to 1st time use of mould.
Right: Mould teared and stretched after 2nd slumping process. Own images.

Results - Surface

Focusing on the finishing surface of the resulting glasses, there are once again results regarding the finishing quality and the texture on both the 1mm and the 4mm glasses.

Regarding the finishing quality of the 4mm glass, we observe that the result is not optimal since there is crystallization. 1mm glass also has very light crystallization. Comparing the results of the experimental work described in the previous chapters, the most plausible explanation for the crystallization of the glass is the firing schedule. The difference between the amount of crystallization in the 2 glass thicknesses derives from the thickness itself and the cooling time needed for each glass. Crystallization appears in glass surface when the glass does not cool quickly enough, therefore, the 4mm glass is prone to exhibit more crystallization. Adjusting the firing schedule is the way to create the best surface quality in the glasses for the case of slumping with basalt moulds without the need of further use of coatings. The limited time of this thesis did not allow for further optimization of the oven schedule.

In terms of texture, there appears to be texture imprints on both 1mm and 4mm glasses. The texture on the thinner glasses in direct contact with the mould is strong, with basalt inclusions visible forming the whole pattern of the mould. This amount of texture and its pattern adds a very interesting aesthetic value to the resulting glass as well. However, as discussed earlier, pattern on glass is not always a desired quality in glass. Since avoiding texture is impossible with direct contact with knitted moulds, two possible solutions could be tested in the future: first could be to test porcelain coating on the knit, which may result in smooth texture if further processed, and second could be the use of a low-quality glass as a first layer in contact with the mould which will be discarded after slumping. However, both solutions lead to a certain amount of material waste which is unnecessary.

Figure 201: Finishing surface of 1mm glasses. Own images.

Moreover, there was also texture on the 4mm glasses. The texture resulted from the thin fire paper. As can be observed at the image below, the paper has wrinkled and shredded due to the stretching required by the glass and the loading. The fire paper which has influenced also the surface of the glass was a necessary measure to avoid fusing while simultaneously slumping glasses. In a further development of this fabrication method, different materials should be tested for in-between layers to avoid this type of texture imprints.

Figure 202: Up: Finishing surface of 4mm glasses. Down: Thin fire paper wrinkles and shreds resulting in glass texture. Own images.

11 Design

11.1 Façade design concept

Taking into account the rigid shape of the Casa da Musica in Porto and the contrast with the corrugated glass facades, the present thesis will try to envision a concept for an even more contrasting glass façade with a freeform curved surface. The function of the building as a music hall gives the inspiration to connect the concept with the architect and music composer Iannis Xenakis, famous for translating architecture into his music compositions. Trying to follow the reverse process, the concept derives from translating one of his music sheets into curves and then lofting these curves to fill the facade space of the corrugated window with dimensions of 22x12 m. In steps, the surface is simplified to achieve a geometry based on the geometrical limitations of the experimental work described in chapter 8.

Step 1: Translation of musical curves.

Step 2: Setting the side boundaries.

Step 3: Zooming in and using fewer curves to create the surface.

Step 4: Remapping the surface giving boundaries for curvature back and forth.

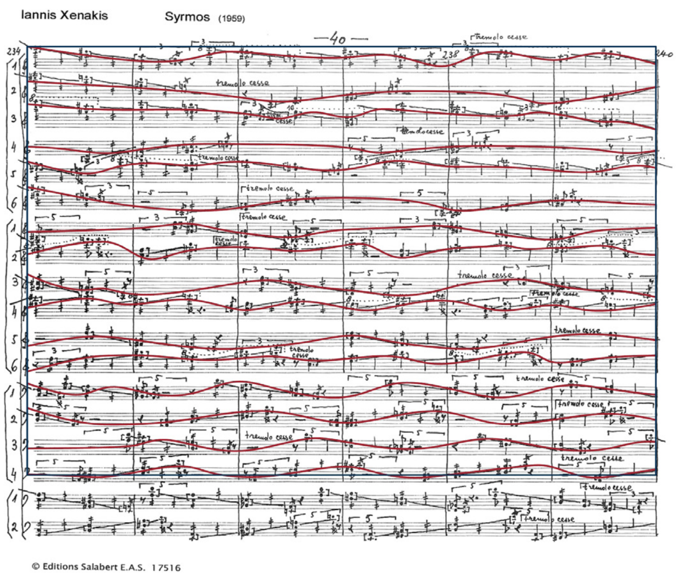


Figure 203: Curves drom music composition. Source: Own edit on music sheet from http://www.iannis-xenakis.org

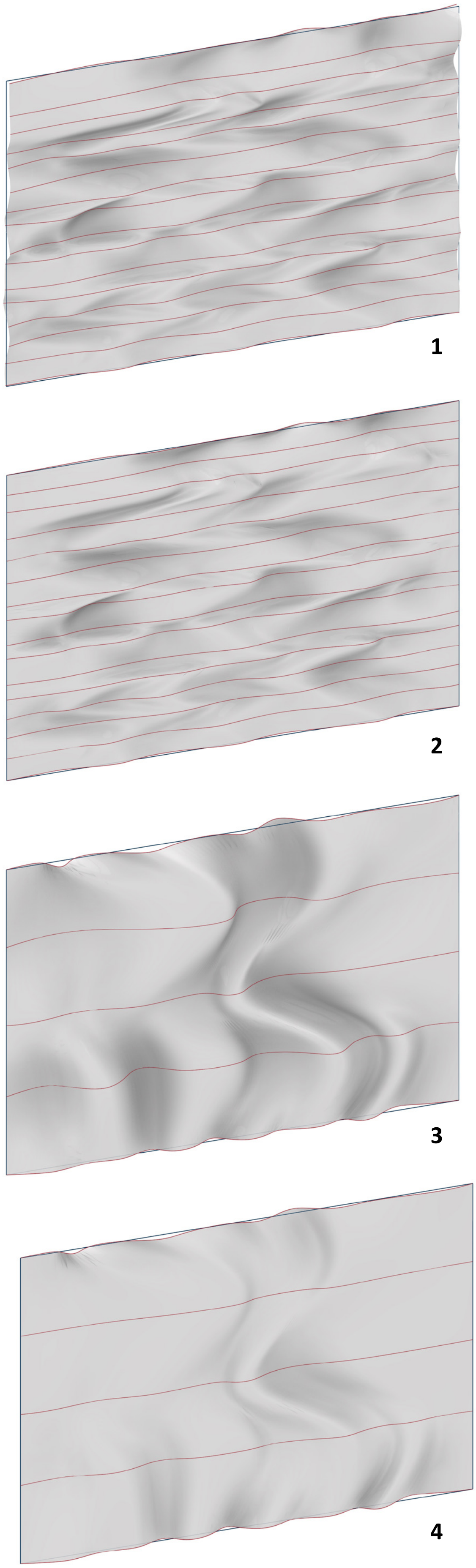


Figure 204: Evolution of the facade concept design : steps 1-4.

11.2 Connection details

The first step to making the façade concept into a realizable example is to divide the surface into glass panels and then design the connections between them. In order to design connections between the separate glass panels of the façade it is crucial to know if the glass façade is self-supported or not.

In the case of a self-supported façade, it is possible that the whole height of the façade (12m) can be produced as a single panel by the industry. The only limitation is the width of these panels. Based on the dimensions of the CNC knitting machine that produces the moulds for curving the glass and also the pattern that is used, panels of 1.2m width can be curved based on the current production process. A maximum width of 2.4m mould (and therefore glass) can be achieved in the condition that the pattern used for knitting is a single-bed pattern. Thus, in this design scenario, a width of 1.2m is assumed to be the width for the division of the glass façade. In future development of this fabrication method, wider panels of glass could be possible to be produced, and the limitation of their width then would be the float glass production standards.

An important factor in designing the connection between the panels of the self-supported façade is the angularity differences between the curved edges of the glass panels. Two scenarios are developed and presented in the following pages according to an expected angularity deviation of around 2mm of more than 2mm between the two edge curves.

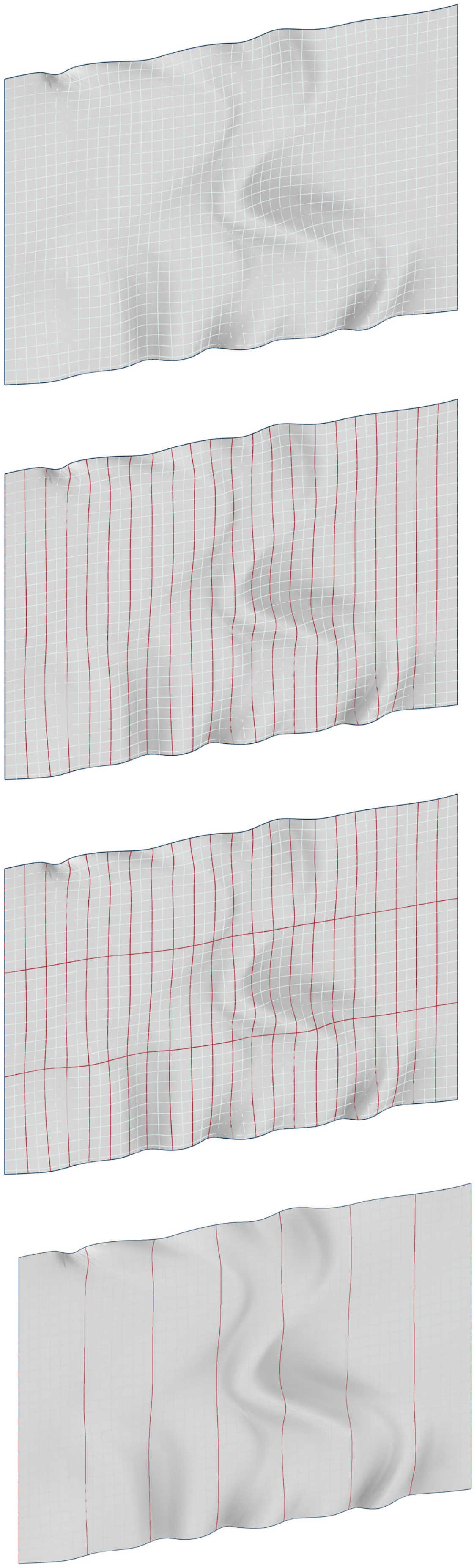


Figure 205: From up to down:
1.Final curved glass surface.
2.Division of self-supported facade in glass panels.
3.Division of non-self-supported facade.
4.Possibble future division in wide panels.

In the case of a non-self-supported façade, the glass surface must be divided horizontally. Following the existing division of 4 m in height due to the existing slabs and walkways behind these division lines, a similar division is decided to be followed here, as this would mean easy connection to the structure of the building. Inspiration for this connection detail is drawn from the MAS museum in Antwerp.

The top and bottom of the façade is connected to the rest of the building with a clamped detail in all possible scenarios that is inspired by the original existing detail.

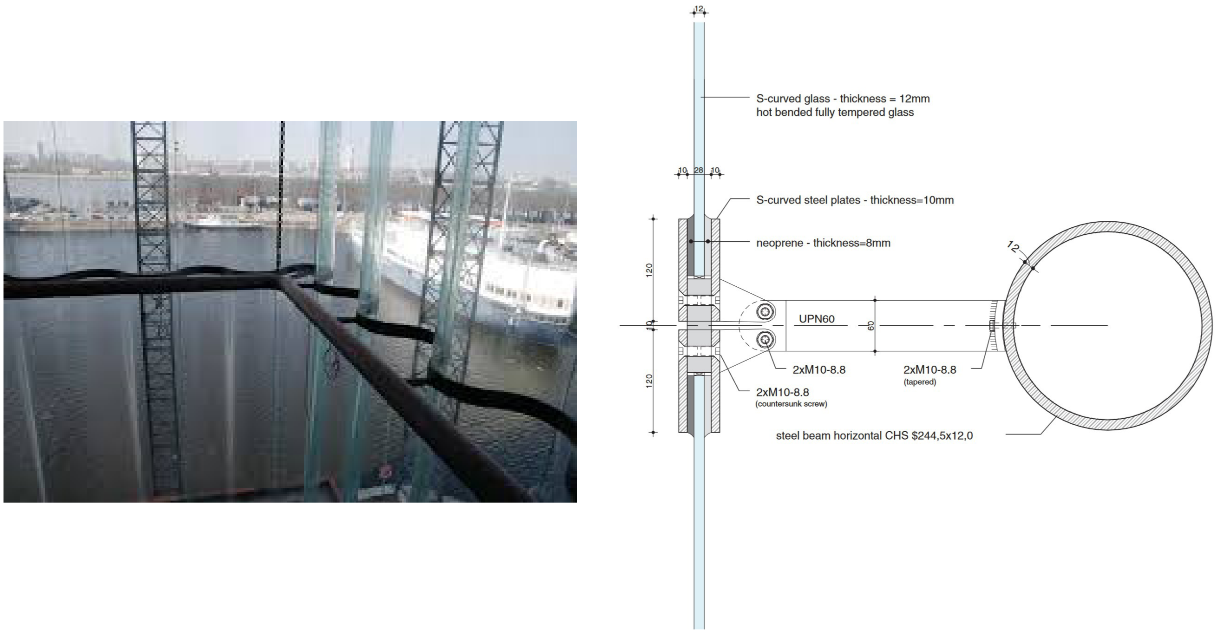


Figure 206: Horizontal facade detail MAS museum. Source: Nijsse & Wenting, 2014.

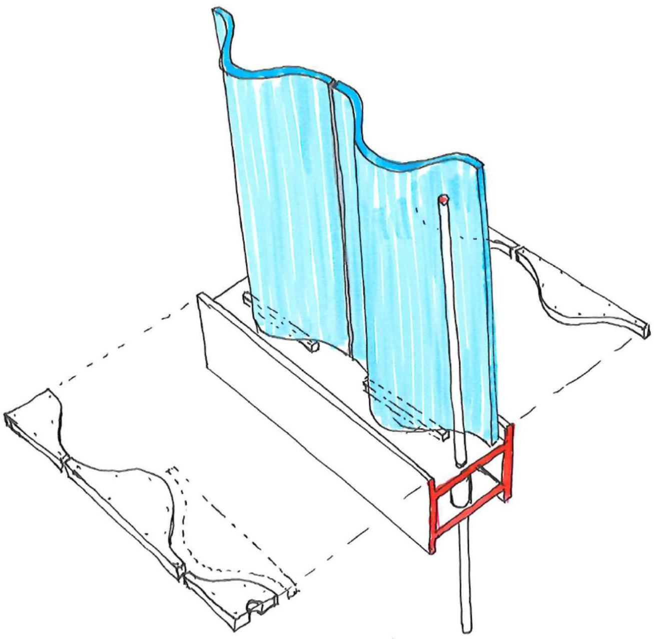


Figure 207: Casa da Musica facade clamping concept detail. Source: www.vs-a.group

Self-supported facade connection detail

Scenario 1: small agular deviation

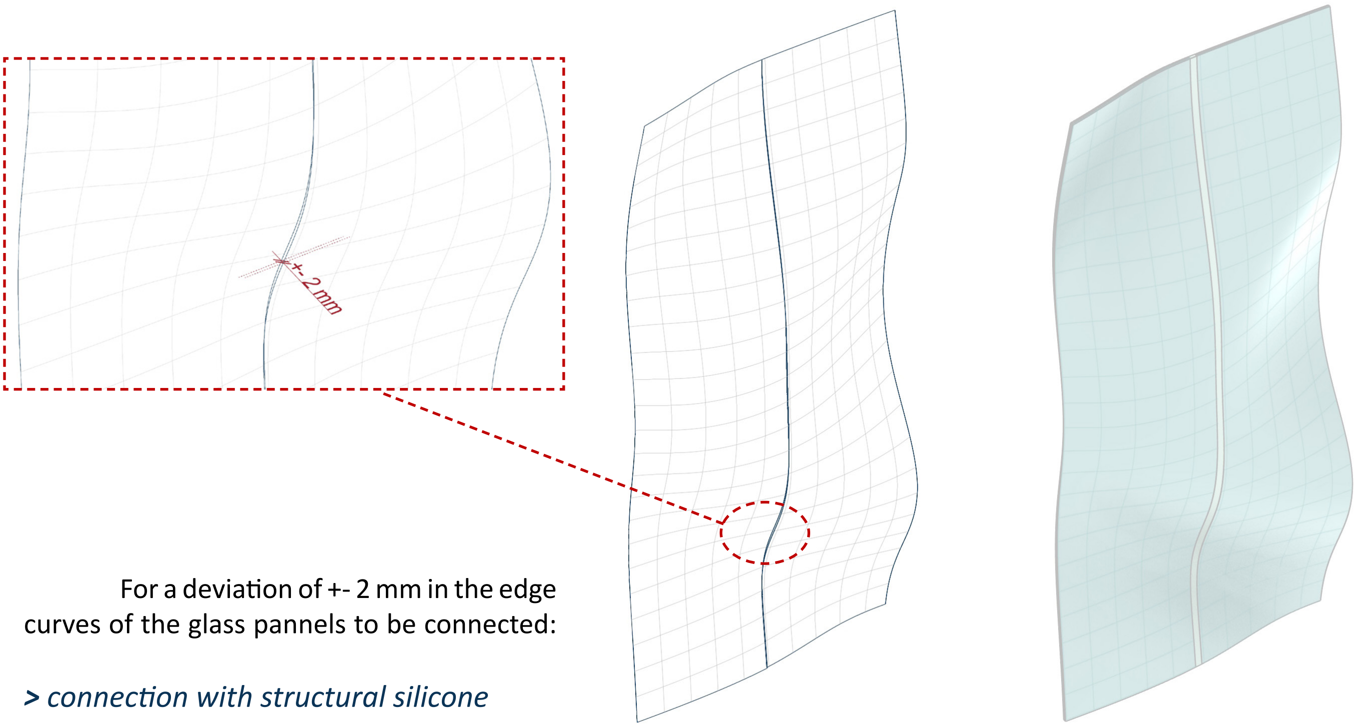


Figure 208: Small angular deviation between panels. Connection detail.

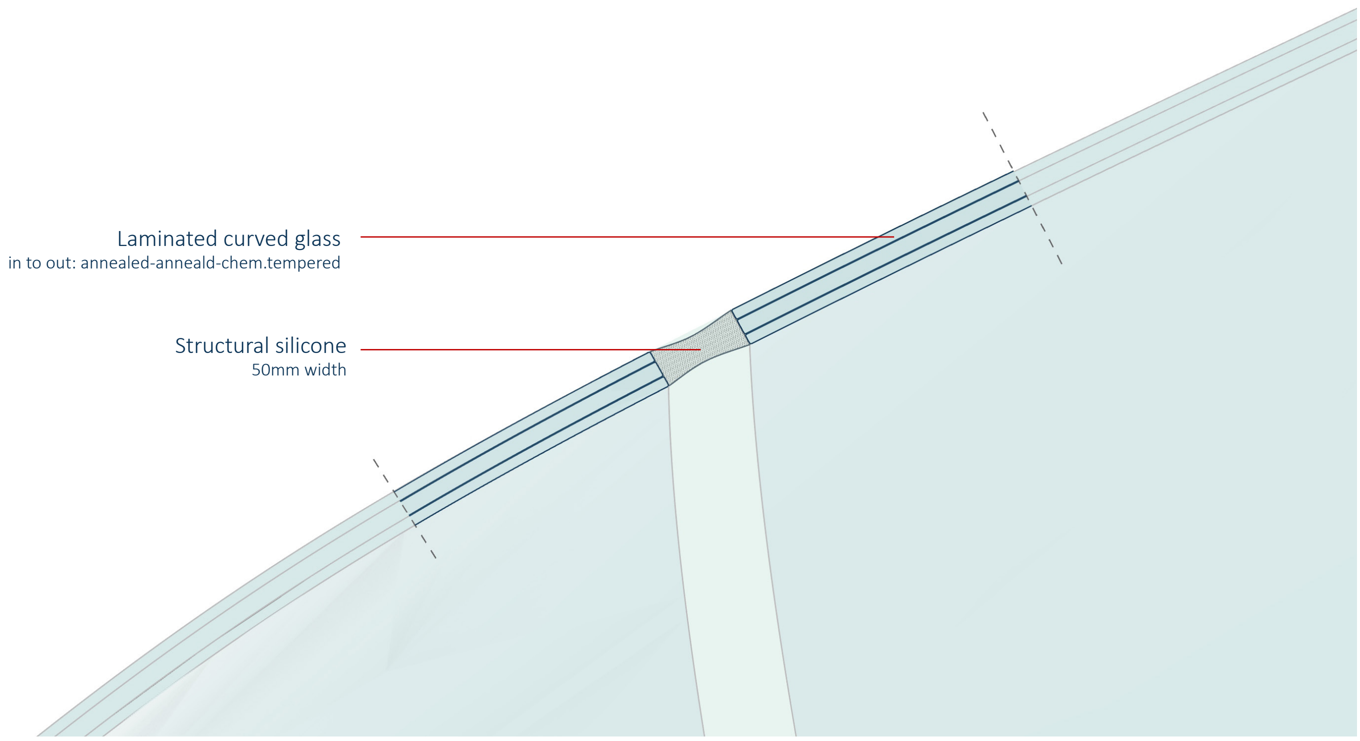
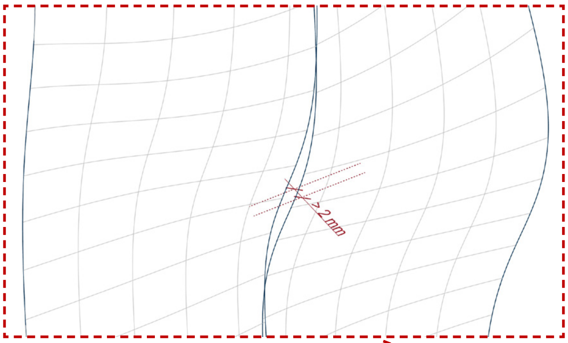
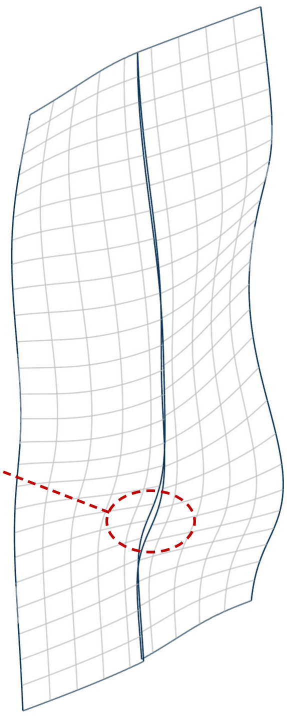


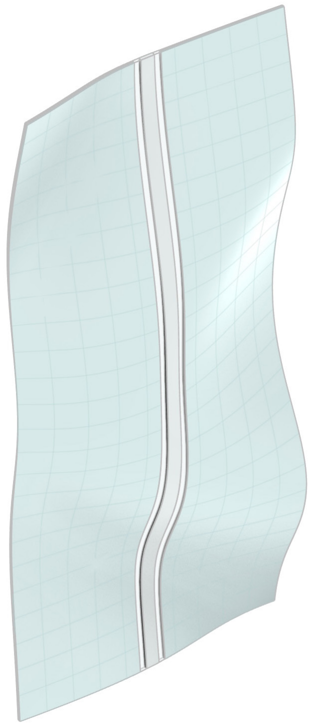
Figure 209: Connection detail scenario 1.

Self-supported facade connection detail

Scenario 2: big agular deviation







For a deviation of > 2 mm in the edge curves of the glass pannels to be connected:

> connection with specially formed cap to take the deviations

Figure 210: Big angular deviation between panels. Connection detail with cap.

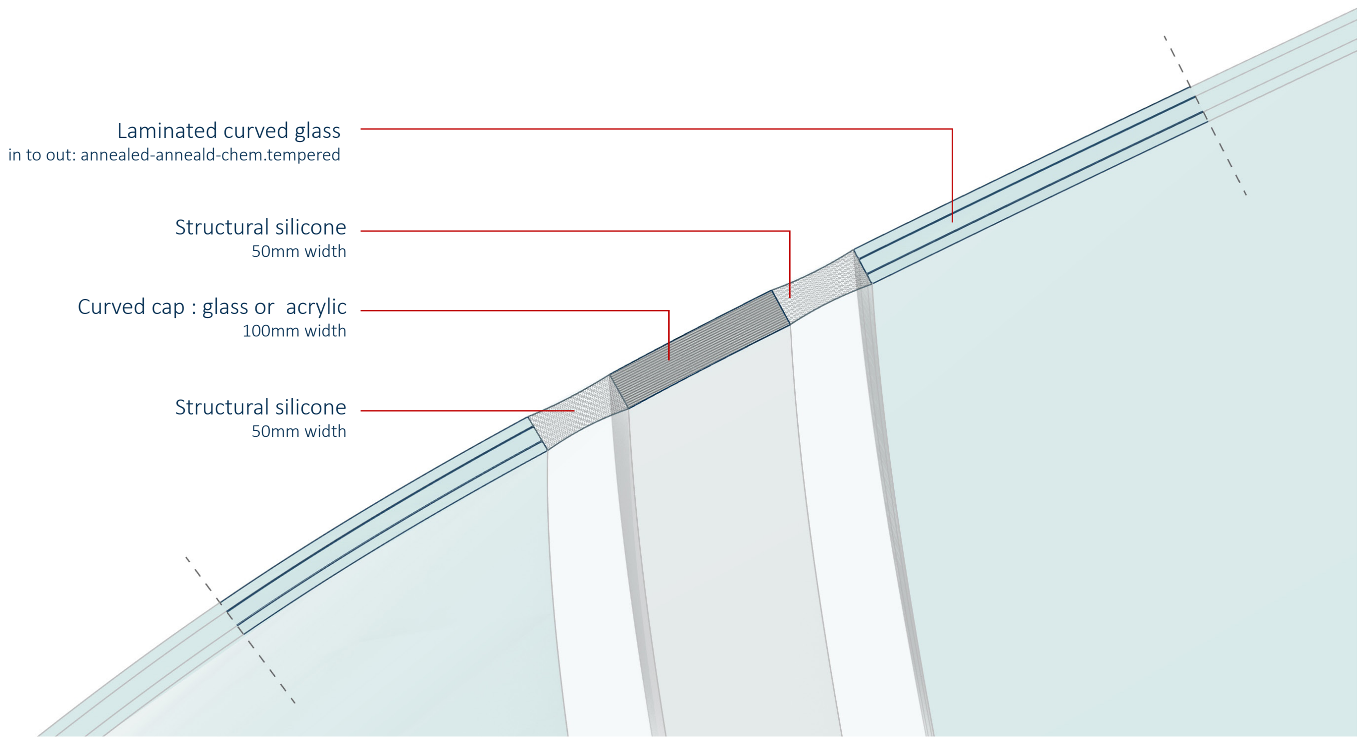


Figure 211: Connection detail scenario 2.

Non-self-supported facade connection detail

In the case of the non-self-supported facade, an adhesive connection is designed. In contrast to bolted conections, adhesive connections do not require holes in the glass and therefore, there is less stress concentrated locally in the glass as the loads are trasnfered in the hole area [Musgraves et al., 2019]. Creating holes in the curved slumped panels would also be difficult to execute, as cutting the holes before slumping would mean deformation of the holes and after slumping high risk of breaking the curved glass. An important drawback of using adhesive connections is that they are likely to exhibit creep and relaxation to some extent [Musgraves et al., 2019].

The connection is designed to have an adhesive bond between the glass panel and a prefabricated stailness steel component with a hinge which accommodates for the rotation and curvature of the glass by being able to rotate 180° in all directions. The steel component is then connected to a prefabricated spider component. The spider component has an extended 'arm' which ends with a steel ring that trasferes the loads to a steel tube. The tube, resembling the facade detail of the MAS museum, follows the curve of the facade at this height and supports it. The tube it self is then connected to the building steel structure of the inteior slabs for support.

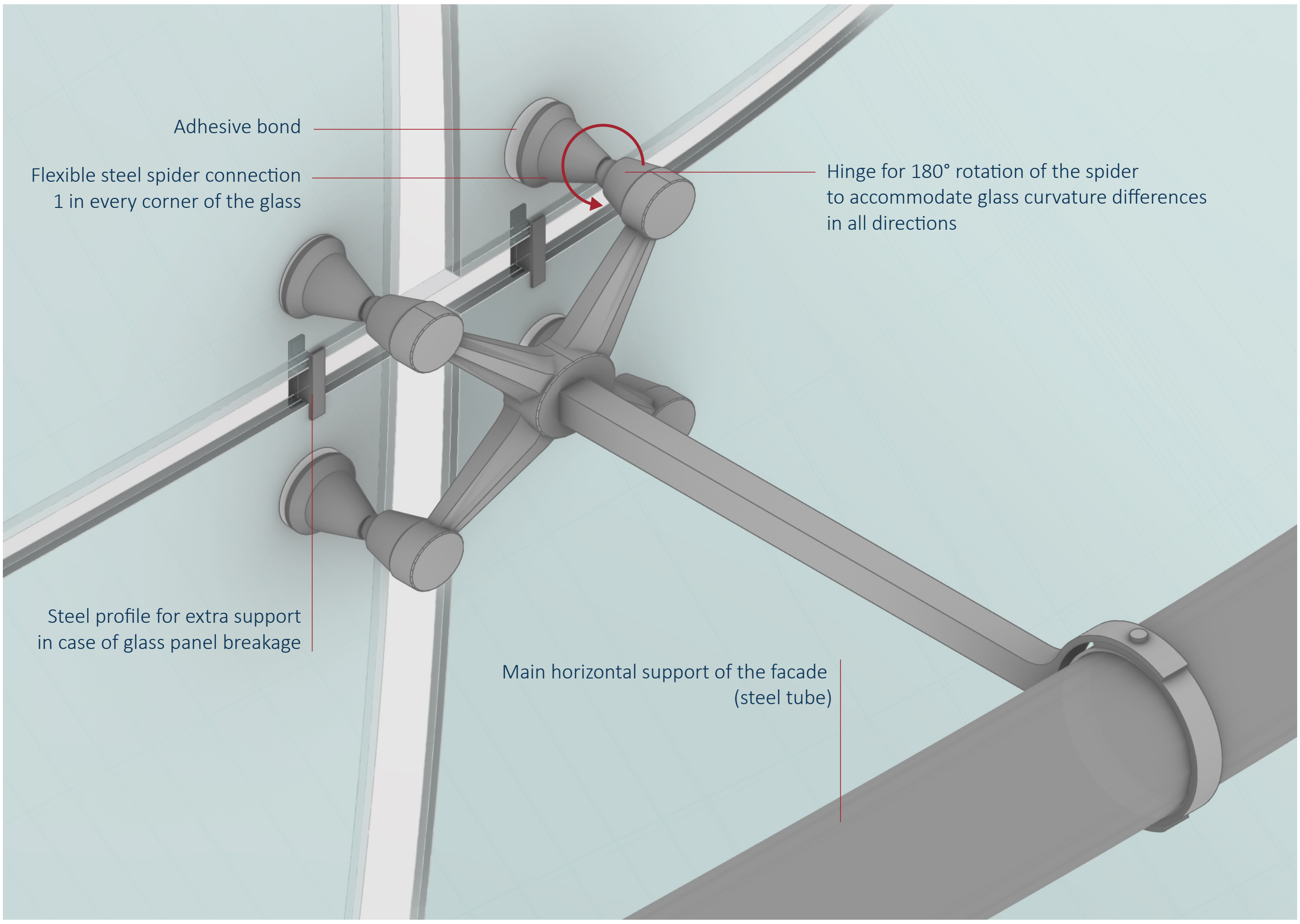


Figure 212: Non-self-supported facade. Glass panels connection detail.

Base and top clamped connection detail

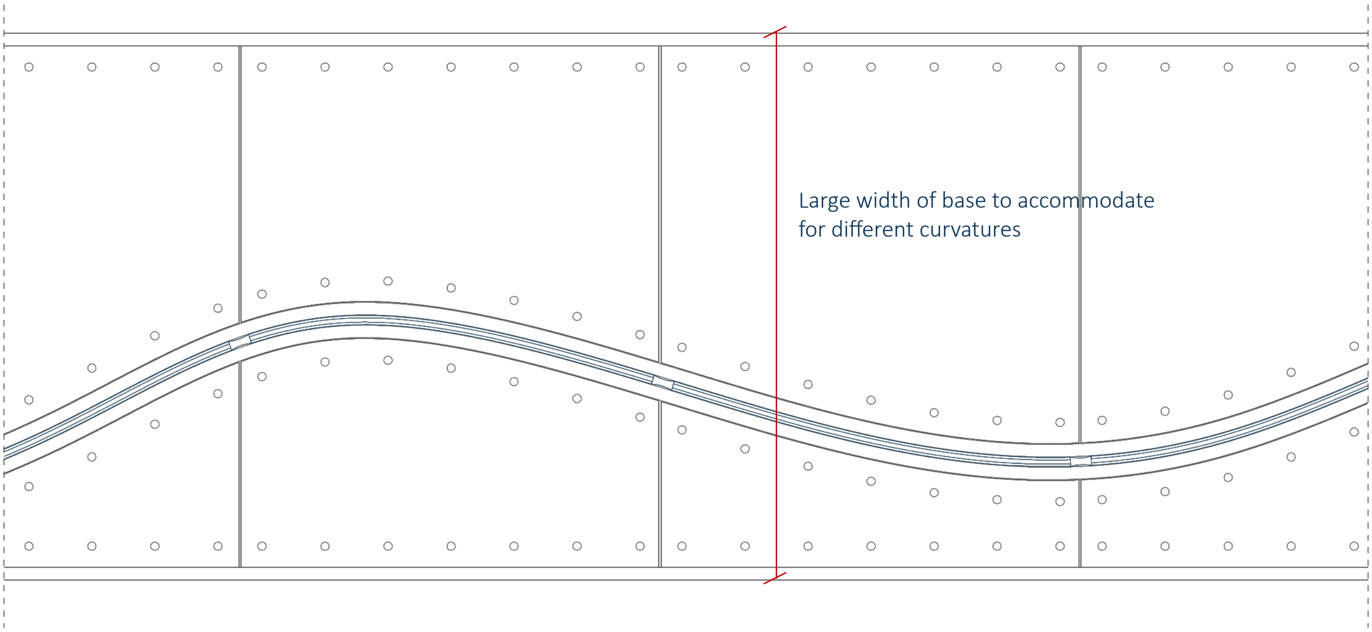


Figure 213: Base clamped connection detail : plan view.

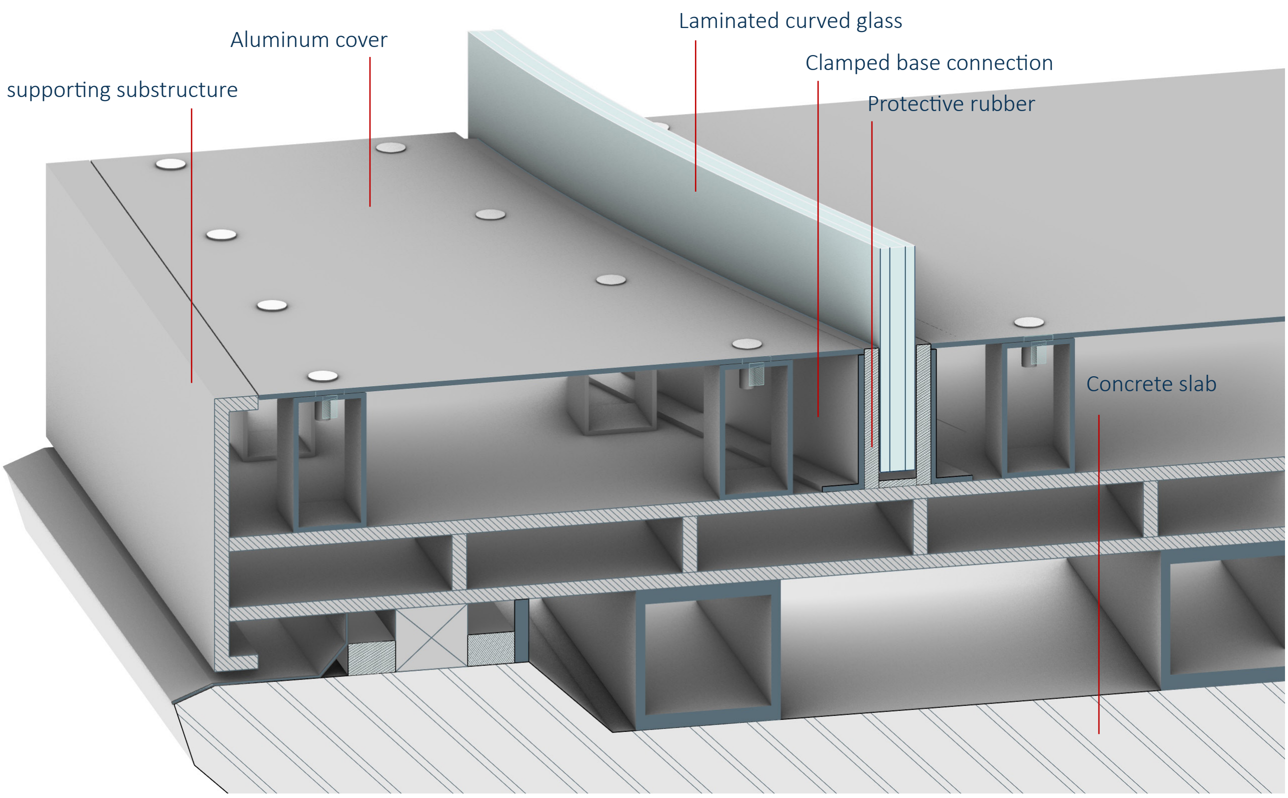


Figure 214: Base clamped connection detail : axonometric section.

11.3 Façade visualization

Figure 215: Possible freeform facade variations of the Casa da Musica.

11.4 Proposed fabrication

In order to fabricate such a façade in real life with the proposed method of this thesis there are several aspects that need to be taken into consideration. At the moment, while there are several realized examples of glass panels big enough to cover the whole height of the façade, a more realistic scenario for glass slumping on knitted moulds would be to start with a smaller scale, such as the proposed 1,2x4m panels. A major factor for this is the glass weight. Since slumped glass needs to be laminated to have the required structural redundancy for the façade, multiple glass pieces need to be placed simultaneously on top of the mould. Therefore, the exact weight of them needs to be calculated from the beginning and this will also influence the pattern design of the knit.

The produced textile needs to be tensioned in place with the help of rods at its perimeter forming the edges shape. These rods help secure the edges control of the slumped glass to be formed similarly to adjacent glass panels of the façade. The pretension added to the textile at each support point tensioning the rods inside the specially formed channels in the textile need to take into consideration the glass weight and the type of curvature needed. The pattern of the knit needs to be formed with multiple densities to allow for more or less deformation, or very rigid areas. Underneath the textile, extra "mushroom" supports need to be placed where the positive curvatures need to be formed, so that the textile does not sag under the glass weight.

In several cases it is more convenient to slump the glass upside-down to form the correct shape. This needs to be decided for each panel separately, depending on the main curvatures.

The following graphs show the fabrication process of a freeform curved panel of the designed façade. The panel chosen has multiple curvatures and needs to be fabricated in a reverse upside-down way to achieve them.

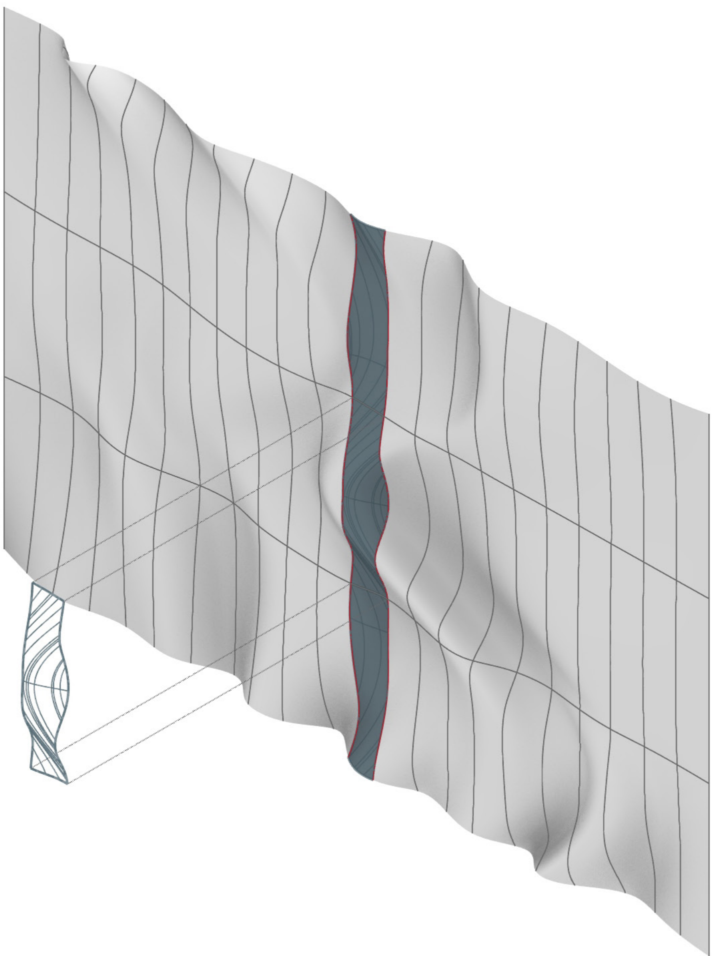
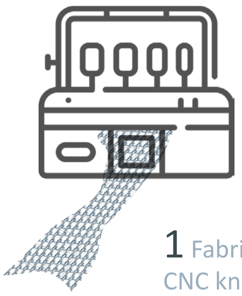
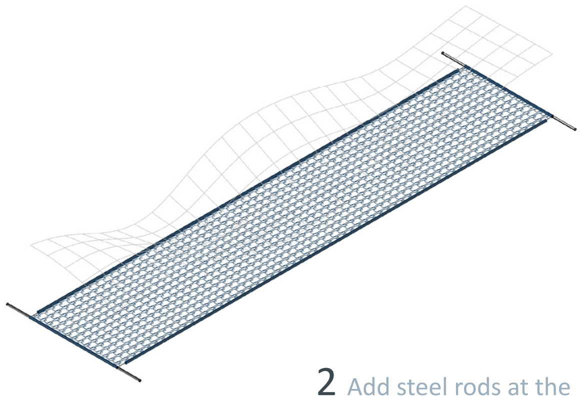


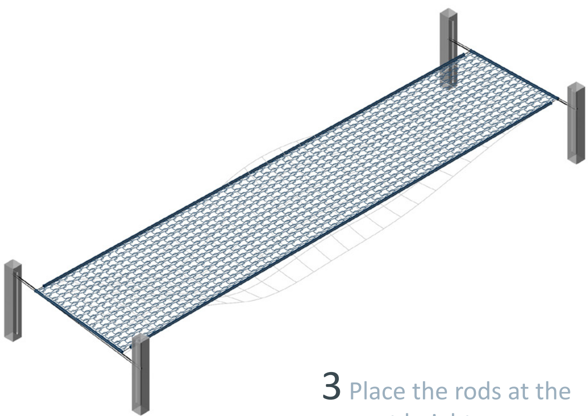
Figure 216: Facade panel selected to showcase the fabrication process.



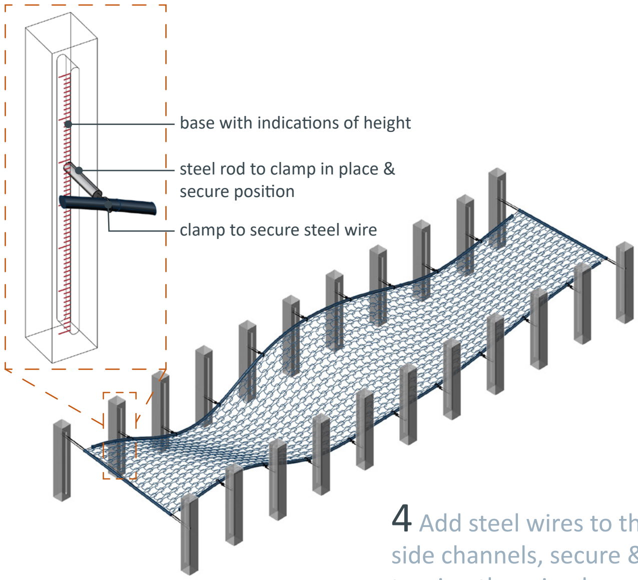
1 Fabrication of the CNC knitted mould



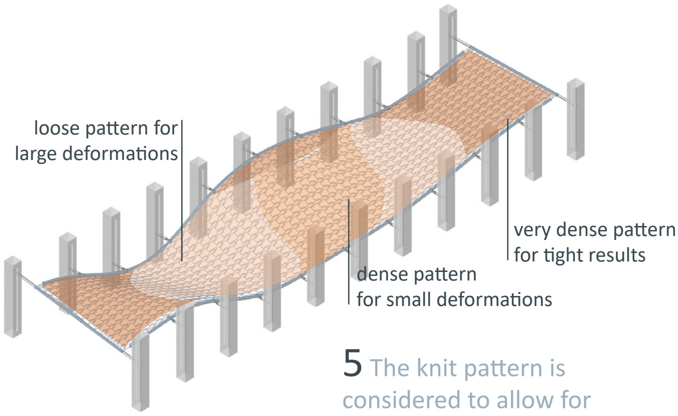
2 Add steel rods at the short sides' channels



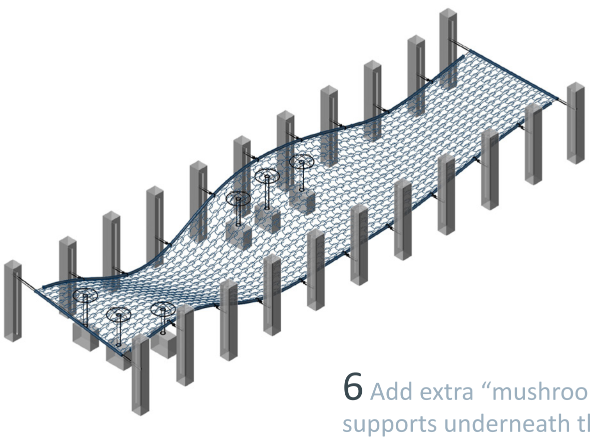
3 Place the rods at the correct heights, secure the position & tension the textile



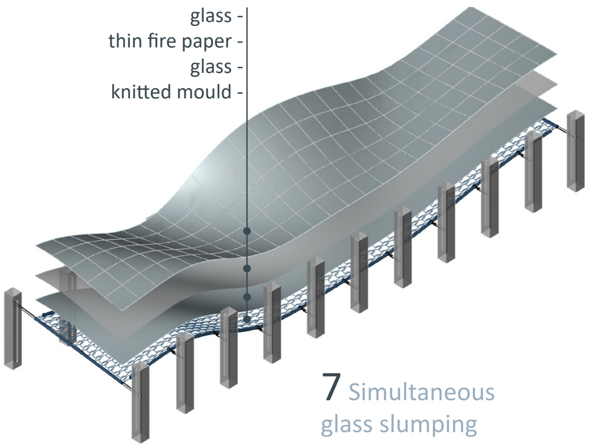
4 Add steel wires to the long side channels, secure & tension them in place



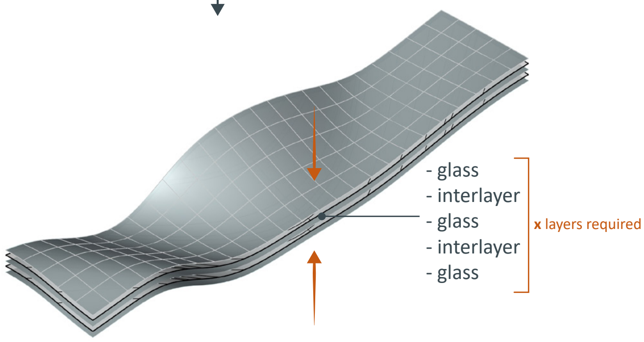
5 The knit pattern is considered to allow for more or less deformation



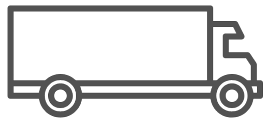
6 Add extra "mushroom" supports underneath the textile to ensure textile staying up despite glass



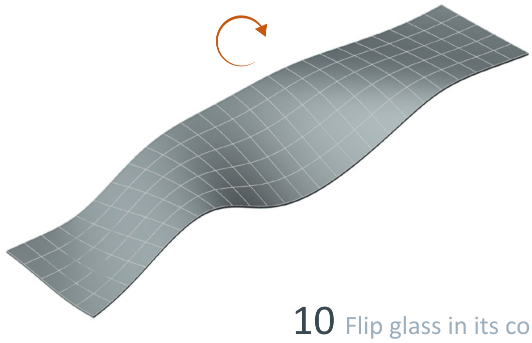
7 Simultaneous glass slumping



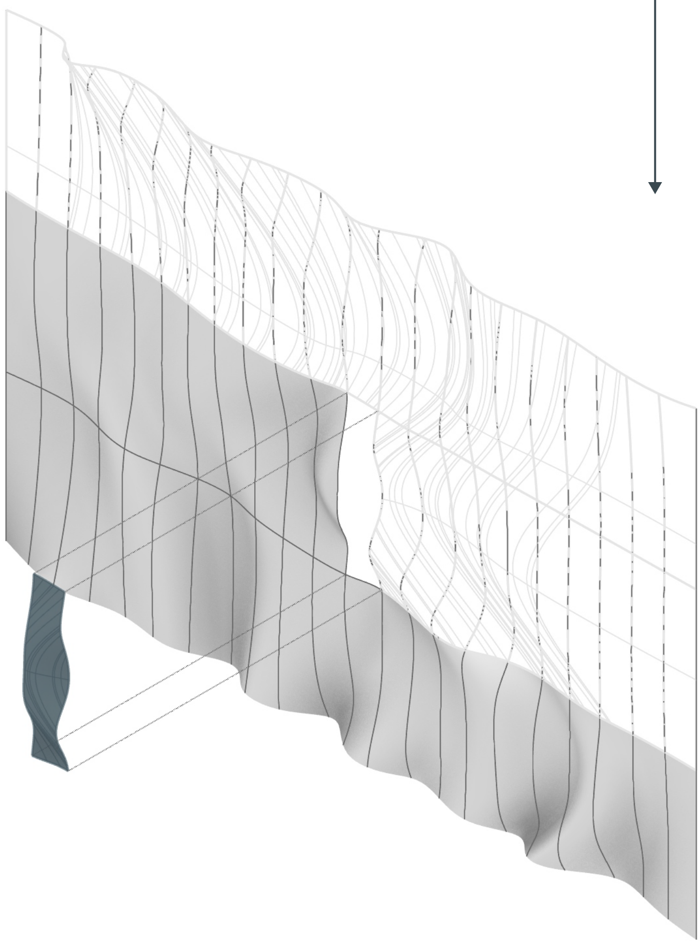
8 Glass lamination & possible chem. tempering of panes



9 Tranport to site



10 Flip glass in its correct position



11 Place on facade & connect with other panels & supporting substructure

The steps of the fabrication process shown in the previous graphs are the following:

Step 1: Design and fabricate the CNC knitted mould. Embed channels at the edges of the textile for geometry manipulation.

Step 2: Insert stainless steel rods at the short side's channels. Bare in mind that based on the curvatures of the design, the glass piece might need to be curved in the reverse way.

Step 3: Place the rods at the correct height, connect to the base set-ups and secure the position in place. Clamp the edges of the fabric to tension in place.

Step 4: Add steel wires to the long side's channels and curve the wire to start forming the curved edge's geometry. Clamp the wire on special steel rods. Then, connect the rods to the base and secure them at the correct height each time based on the indications of the base to tension the textile according to the designed curvatures.

Step 5: The knit pattern of the produced textile is also considered to create the correct curvatures. The density of the knit and the pattern used may allow for different deformations under the glass weight. Use denser patterns for results with less deformation and loose knit patterns to allow for bigger curvatures.

Step 6: Add extra "mushroom" supports underneath the textile. The mushroom shape will create a smoother curved surface for the textile. The extra supports are placed where the designed curved panel has positive curvatures. In that way they will ensure that the textile will not sag under the glass weight.

Step 7: Place the first glass piece on top of the mould. Then, place thin fire paper layer or other in-between layer to avoid glass fusing. Place the next glass piece on top. Repeat as many times as necessary to simultaneously slump all glasses necessary for the calculated safety of the final panel. Fire inside the oven at the decided firing schedule.

Step 8: Laminate the curved glass pieces by placing interlayers in between them. If needed for increased redundancy, chemically temper the glass piece to be placed on the inside of the building before laminating.

Step 9: Place in the truck for transportation to site.

Step 10: Flip the reversely curved glass panel to be ready in its correct position.

Step 11: Lift by crane and place on the façade. Connect with the chosen way of detail connection to the adjacent panels.

12 Discussion

12.1 Conclusions

The present thesis was developed taking into consideration all previous work and knowledge of the Glass & Transparency Research Group at TU Delft, that focuses on innovative glass solutions for building structures using cast glass, but also glass recycling. No previous master's thesis or research has ever dealt with glass slumping with the novel fabrication technique proposed in this thesis, therefore, a lot of ground needed to be covered. A lot of experimental research on different objectives needed to be done in order to cover a wide range of unknown sides of this fabrication method and give an overview of the possibilities and limitations in the limited timeframe of a master's thesis.

Summarizing everything learned throughout this thesis, conclusions are reached, and the research question posed at the start of this work may be addressed:

What is the potential and limitations of utilizing knitted basalt moulds for the creation of customizable, freeform curved float glass components?

As early as the first experiments conducted in the scope of this thesis, it became evident that using a lightweight textile mould made of continuous basalt fibers yarn is a feasible and promising fabrication method for curving glass by slumping. Throughout the experimental research, both woven and knitted textile moulds were produced and tested, proving that there are many possibilities in the development of such a technique for creating freeform glass geometries, but also, they entail several constraints and limitations. The experimental work conducted within the framework of this thesis proved that this novel fabrication method enables the easy customization of freeform curved glass, showing the great potential of using such flexible moulds to enrich the potential of a fluid architectural language using glass. The potential of using knitted moulds thus, lies in creating forms with multiple curvatures and forming complex geometries but also introducing the dimension of texture on glass which can be used towards increasing the aesthetic value of the result. Several limitations, however, were encountered while experimenting with basalt knitted moulds regarding the achieved deformations but also the sustainability aspect of using basalt fibers for this method.

To fully answer the main research question, the sub-questions posed at the beginning must be discussed.

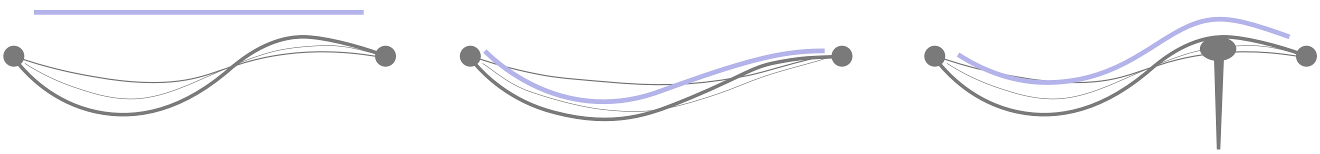
Which are the geometrical limitations of this method?

Summing up the results of the experimental work of this thesis, as discussed in chapter 9, there are strengths and limitations in producing curved glass geometries using basalt textile moulds. To understand better what the geometrical limitations are it is necessary to divide them into single or double curved geometries, but also examine the properties of the mould and the initial state of the set-up before the slumping process, as well as the firing schedule used.

For single curved geometries, it is clear that for wide spans of more than 30cm, the glass can deform and shape into the form of the mould with great accuracy, however, that appears to be the case of a loose mould set-up. A loose set-up is considered a mould that is not pre-tensioned or in a flat position at the beginning of the experiment. The moulds tested in this condition were woven moulds, which meant that there was no flexibility of the mould itself to stretch into a geometry with bigger deformation, and therefore the glass itself followed the exact shape. This is not an indicating factor of what would happen with a similar span and a tensioned mould, since this type of set-up is equivalent to free slumping of glass under its own weight without any resistance. In the case of knitted moulds however, with an initial slightly pre-tensioned set-up and different thicknesses we can see slight differences in deformation, depending on the thickness of the glass. Therefore, the pattern of the knit should be examined thoroughly to calculate the possible deformation before the experiment as the knitted textiles are able to stretch differently according to their pattern. In the case of slumping in spans less than 10cm, there is a high limitation in the achieved deformation in the middle of the glass. That is due to the maximum temperature of the firing schedule used, which if higher, would give different geometry results.

For double curved geometries, a major limitation factor is the support type of the moulds in combination with the desired geometry. For vaulted geometries, the support system by edges or corners of the mould has been proven (and would be proven if not failed for different reasons) to work. The results of this, however, do not give very large middle deformations for pre-tensioned moulds, which is a factor that again depends on the knitting pattern and could be affected by the maximum temperature of the firing schedule. The attempt to achieve a geometry that is double curved by setting different heights in its corners proved to be unsuccessful by supporting the mould in 4 corners. An assumption would be that by supporting all 4 edges would make it feasible to create such geometries by tensioning the textile in place and having calculated the precamber of it under the weight of the glass to get the exact geometry of the textile, otherwise an uncontrolled geometry would result due to stretching and sagging of the knitted fabric under the weight of the glass. Finally, the extreme achieved geometries with knitted formworks and concrete are not feasible to be replicated with glass due to the different nature of the material and its initial state when placed on the mould. Float glass is a solid plate that needs to be placed and stabilized on the mould since no clamping is possible inside the glass oven, while concrete is cast in place and can attach to the textile immediately. This factor of supporting glass at the starting position of the slumping is a major limitation in creating extreme double curved panels with supports on different heights since it might not be able to be supported at the position needed.

Another limitation to the final geometry depends on the general setup of the knitted mould. Creating a double curved or freeform glass piece with alternating curvatures in opposite directions – going from positive to negative – as seen in the graphs, is impossible only by using the draped textile mould surface between supports. The weight of the glass will force the textile to sag everywhere. As seen in experiment 6 which resulted in alternating curvatures, the only reason for this happening was the non-stretchable nature of the woven mould in combination with glass slumping between the mould and large unsupported areas of its surface, as well as collapse leading to supports from other elements. The rest of the experiments attempting to introduce multiple curvatures succeeded in doing so, however, resulting in an overall negative curvature. In order to achieve a controlled geometry in that sense, separate supports pushing the textile from underneath should be used in a predesigned and calculated manner.



a) initial design of textile mould for multiply-curved geometry

b) change in curvature: not possible to create the positive (going up) curvature just by textile tensioning; a flat result is feasible by adjusting the density & the knitting pattern

c) change in curvature: possible to create the positive (going up) curvature by adding extra supports under the mould.

Figure 217: Achieving multiple curvatures with the mould set-up.

Which is the best combination of materials for the mould in terms of glass surface quality, coatings/release agents for de-moulding, final achieved geometry, and possibility of texture on glass?

Experiments using no coating on the basalt moulds showcased that there is no need for coatings on the mould in order to be able to remove the glass after the slumping process. Two experiments dealt with the use of coatings in combination with moulds to achieve complex geometrical shapes. The combination of a Crystalcast dipped woven basalt mould proved to be unsuccessful and the basalt got significantly weakened as a fiber, leading to a completely brittle behavior of the mould after slumping. The use of heat-resistant cement on a knitted textile to produce a complex shape and then use the hardened cement as a mould for glass slumping proved quite successful. The full complex shape achieved by the cement was not replicated with glass. This was impossible due to the very narrow tip drop in the middle of the funnel geometry as well as the maximum temperature used in the firing schedule, which if higher, would probably lead to a more accurate replication of the original geometry of the cement.

The glass surface quality was influenced by the mould itself as well as the used coating layers. Glass appeared to exhibit light or great crystallization on the surface depending on the density of the moulds' weaving or knitting supports when the glass was in contact with the basalt mould without coating. The crystallization was addressed by testing the use of a combination of biosoluble and fire paper between the contact surfaces and clearcoat overglaze devitrification spray. Both tests proved to create a slightly better finish surface on the glass, however, still not achieving a completely transparent result. The crystalcast and cement coatings used achieved a quite transparent surface on the glass without the need for any other coating. Surface crystallization was also visible at the experiment that did not use any mould for slumping. Thus, to create an optimized finishing surface on the glass the firing schedule should be altered.

In terms of texture, basalt moulds have a possibility of creating light or strong imprints on the glass surface. The imprints pattern or intensity is in relation to the density of the support points of the glass from the mould but also the glass thickness; the denser the supports or the thinner the glass the less the intensity of the imprints. The texture imprinted on the glass also resembled the forms of the weave or the knit loops. By examining the resulting glasses under the microscope, it is also evident that in all cases there are inclusions of basalt in the glass surface, which in glasses with fewer supports are more visible, creating a colorful interesting effect on the glass. The crystalcast and cement coated moulds give out different textures, in the form of strong dotted particle inclusions which look like accidental surface bumps.

Structurally, the microscope does not show any concentrated stresses in the glass, only a few negligible stresses around the inclusions. While the basalt inclusions do not seem to pose a threat on the future breakage of the glass and its structural integrity, the inclusions caused by the coated moulds seem to be deeper and more prone to cause microcracks that will propagate over time. Thus, coating of the moulds is not an optimal solution in terms of texture either.

How can this fabrication method be improved in terms of visual & aesthetic quality, structural redundancy & sustainability?

There are a few possible scenarios to improve the fabrication of curved glass using lightweight knitted moulds. These can be categorized in terms of visual, structural and sustainability criteria.

The visual and aesthetic quality of the resulting curved float glass is inextricably linked to the use of coatings, firing schedule and also the knitting pattern of the mould itself. The first improvement would be to test different application methods of the coatings or different coatings on the glass surface to remove all crystallization, fogginess, and iridescent patterns. Moreover, modifications of the firing schedule should be tested which might be the only cause of these imperfections. Aesthetically, the imprinting of texture is a matter that might be wanted or unwanted. If unwanted, to remove all possible textures from the glass, a replication of the method using the biosoluble and fire paper combination could lead to a perfectly smooth texture by adding another layer of fire paper to not have imprints of the biosoluble paper. This would also be possible by using the cement coated moulds, however, by smoothing their texture before placing the glass on top. If wanted, the patterns used for knitting the mould should be selected accordingly and multiple tests like experiment 8 (bubble knit) could be performed to determine the possibility of having specific texture in specific parts of the glass.

Structurally, since simultaneous slumping is a possibility, future lamination of the glasses automatically means redundancy for the glass. Chemical tempering of one of these resulting curved glasses would be a further improvement of the overall redundancy of a designed glass panel that consists of multiple glass layers.

In terms of sustainability, the basalt moulds may only be used once, since the basalt becomes very brittle after firing at such high temperatures. Different heat-resistant fibers could be tested to check the possibility of multiple reuses of the moulds. As examined in one of the quick tests performed for examining certain parameters in the microscope, reuse of the once used basalt mould is possible not for supporting and curving the glass, but for creating different patterns and textures to the glass surface. This would be useful in a possible scenario of desired texture on multiple glass surfaces. The use of coatings which is not necessary to produce the curved glass parts is a positive aspect in terms of using less materials for the fabrication method.

12.2 Future research

There are several next steps that can be taken in researching this topic since it is at its very beginning. Some of them are the following.

Geometry

Researching the possibilities in geometry, a very important step is to align the experimental work results with **FEM simulations** in order to be able to compare the resulting curved panels according to the designed geometry. This will later lead to controlling the factors that influence the final results to achieve the closest possible results to the computer designed geometries. Also, **experimenting** with even more **extreme geometries** would enrich the knowledge in terms of geometrical limitations of this method.

Moreover, the testing of **different knitting patterns** is crucial to understand the **different deformations** that are possible with glass by using those patterns. A great starting point would be the research that has been conducted in the master's thesis of Flieger [2024], who has created a database of knitting patterns and concrete sample deformations. It is crucial to take into consideration the difference in the fibers used in the knitting process. Different materials of yarn lead to very different results in the resulted knit textile in terms of dimensions. Thus, a proper calibration should be designed to ensure that the design results in the final desired shape of a mould. This factor influences the amount of tension needed in the set-up.

Another step would be to **calculate the pre-tension needed** in the moulds initial set-up in order to produce a fully controlled geometry, but also the precamber that needs to be introduced by taking into account the weight of the glass. **Other types of supports** should be examined as well (e.g. "mushroom" supports under textile) to ensure that multiple geometries can be produced in a controlled manner for a result as close to the initially designed geometry as possible.

Finishing surface quality

Regarding the finishing surface quality of the glasses, further **investigation of finishing quality** in comparison to the thickness of glass is required and testing more coatings for **optimizing the surface results** are interesting topics to dive into. In this area of research, **calibration of the firing schedules** used and cooling times in the oven are crucial to optimize the results.

Structural

Structurally, **mechanical testing** of the curved glass components is needed to determine whether self-supported glass panels are a possible application or not, but also which might be the limits to the curved geometry itself. This involves evaluating factors such as load-bearing capacity, resistance to impact and thermal stresses, and overall durability under various environmental conditions. By thoroughly understanding these properties, designers can optimize the possible final shape and curvatures of the glass, but also the thickness of the glass required to ensure both aesthetic appeal and structural integrity.

Sustainability

In terms of sustainability, future research could include the **testing of different fibers** for the moulds. As seen by the experimental research, basalt moulds lead to single-use moulds and it would be an opportunity to discover if there is another heat-resistant fiber that could withstand **multiple-uses**. Additionally, investigating the mechanical properties and heat resistance of alternative fibers could reveal more sustainable and cost-effective options in terms of overall fabrication. Finally, a **possible reuse and recycling strategy for the basalt** or other moulds that are not reusable should be investigated. Developing such strategies could minimize waste and reduce the environmental impact of the manufacturing process.

12.3 Reflection

What is the relation between your graduation project topic, your master track (A, U, BT, LA, MBE), and your master programme (MSc AUBS)?

The Master of Science in Architecture, Urbanism, and Building Sciences program employs an interdisciplinary approach to provide innovative solutions for the built environment. By bridging the gap between the track's emphasis on sustainable practices and my specific focus on innovative glass fabrication, my project contributes to the broader objectives of the Building Technology (BT) master track. My graduation project topic is based on a novel curved float glass fabrication method, utilizing lightweight knitted moulds, which is consistent with the objective of the BT master program, which stresses advanced technology and new approaches to building design. My investigation into cutting-edge fabrication processes for curved glass is linked to the BT studio's larger focus on digital manufacturing.

How did your research influence your design/recommendations and how did the design/recommendations influence your research?

The topic's complexity required a multi-method approach. The thesis is divided into three parts: literature study, laboratory experiments, and prototyping.

Literature reviews served as a methodology for research of existing glass curving methods, as well as moulds utilized within these techniques. A comparative study of all methods and moulds with specific criteria led me to select the most promising and appropriate techniques to what I was trying to achieve for this project and put it to the test with the experimental work at the lab.

Since the proposed fabrication method of my thesis hypothesis has not been tested before, as far as the literature review of state-of-the-art papers and articles in the field of glass innovation, the second part of my graduation project, the experimental work, was the most crucial in determining which elements I should research further and how I should design my final prototype.

How do you assess the value of your way of working (your approach, your used methods, used methodology)?

The selected way of working during this thesis is a methodical research by design and design by research approach. Qualitative comparison between all researched fabrication techniques and set assessment criteria helped determine the most promising technique for curving glass based on research examples. Following that, qualitative assessment of the moulds used for each of the aforementioned techniques but also used for different materials dictated that the use of knitted moulds could be suitable for this project. Further research on specific yarns in order to create the knitted textile based on the fabrication technique chosen and criteria such as temperature resistance, led to the initial choice of material for the experiments.

Initial testing at the lab already showcased that the use of hand-woven basalt moulds is a viable option for creating curved glass, proving the feasibility of the method proposed. Accidental testing of a simple double curved geometry led to a freeform shaped glass plate and proved my thesis hypothesis to be correct, that a knitted mould can be used for glass freeform shaping.

Next step was to discover by experimental testing the geometrical limitations for freeform geometries by investigating the limits of curving glass by slumping by comparing it to findings in literature and trying to recreate and exceed these experiments.

Decision making after examining each experiment's results was crucial in my workflow. It led to strategically designing the next experiment, to figure out how to solve issues that occurred and improve the fabrication method.

How do you assess the academic and societal value, scope and implication of your graduation project, including ethical aspects?

My graduation work has a broader social, professional, and scientific context, making it relevant outside academia. Socially, my study on a novel fabrication technology for curved glass corresponds to the growing need for sustainable and aesthetically pleasing building solutions. My work contributes to the larger societal goals of resource efficiency and environmental responsibility by presenting a method that provides lightweight moulding options for making non-standardized components of geometric complexity. As the industry embraces technology innovations, my study offers a practical and forward-thinking approach to meeting the changing needs of fluid architecture.

Scientifically, my graduation work contributes to the growing body of knowledge in the field of building technology. It introduces a new perspective on fabrication methods for curved glass, adding valuable insights to the ongoing discussion on sustainable construction practices. This research has the potential to inspire further studies and advancements in the broader scientific community, fostering innovation and pushing the boundaries of what is achievable in architectural design and construction with glass.

How do you assess the value of the transferability of your project results?

My project serves both as a database for existing fabrication methods and moulds for glass curving but also as a documentation of various experiments utilizing the knitted basalt textile as a mould for curving float glass. The workflow and details of the experimental work of this thesis can be further developed and improved by future researchers aiming to develop a lightweight mould for glass.

Furthermore, the workflow could be improved in the future to explore the possibility of reusing or recycling the used moulds. Also, another aspect would be to further explore the detailing of connections between the produced freeform glass panels. By reading through the detailed description of the performed experiments, their designed set-up, documentation and discussion of the resulting geometries, a future researcher would be at a position to continue the project itself or focus on a specific issue.

How are your project results transferred to the built environment? Are the results applicable in practice?

Freeform curved glass is a research field with very few real-life applications. The main reason for this is that, despite the rising demand for fluid architecture in recent years, the fabrication is extremely expensive, especially due to the moulds needed to produce the panels. These moulds are usually made of steel and are very bulky, not flexible and not reusable. The transferability of my project results in the glass industry would be the introduction of a novel fabrication technique that attempts to solve the problem of the mould by testing a new flexible and lightweight method.

The stage of development of the method proposed, in combination with the short time of this thesis, does not make this novel technique directly applicable in practice. However, with further research it has potential to be a revolutionary method for curving float glass in the future, enriching the architectural language that may be used from designers.

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