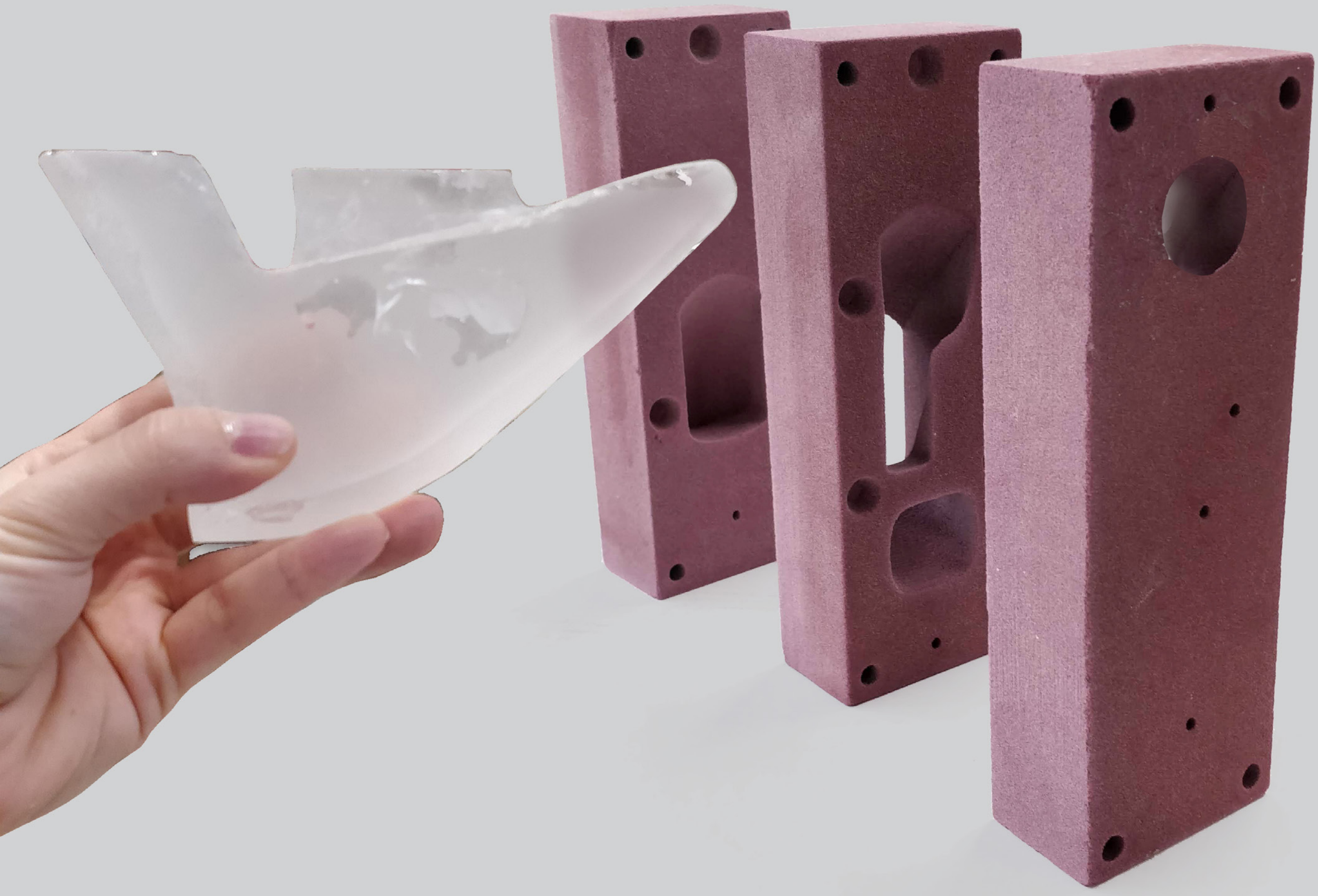
SHAPING TRANSPARENT SAND IN SAND

Fabricating topologically optimized cast glass column using sand moulds



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STUDIO SUSTAINABLE DESIGN GRADUATION STUDIO

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“Good design is obvious. Great design is transparent.”
-Joe Sparano

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ABSTRACT

Key words: cast glass, transparent, sand moulds, Additive manufacturing, 3D printing, 3D printed moulds, Binder jetting, Glass column, Column optimization, structural glass, topological optimization

This research investigates the potential of 3D printed sand moulds for casting structural glass column having optimized cross section. Conventionally, Glass, in architectural industry, has been used in form of sheets (Float glass) due to ease of fabrication of planar sheets, but in last few years, cast glass bricks have been used for creating structural wall/ envelope of few architectural projects namely, Atocha memorial (Spain), Optical house (Japan) and crystal house (Amsterdam) due to its high compressive strength. Cast glass offers many advantages over float glass, but, the reason for limited use of it, in the industry is due to annealing time. Thicker the section of glass, more time is required to anneal the element. To reduce this annealing time, one of the most promising solutions is to use an optimized geometry composed of thinner sections. These optimized geometries usually are based on stress and buckling load of the element; hence they have very dynamic geometry. In order to fabricate these optimized geometries, one has to take help from digital manufacturing tools involving additive manufacturing (3D printing). 3D printing of glass is still in very primitive stage and is currently used for creating artifacts rather than structural elements. Another alternative to fabricate these complex geometries is to print the moulds and then cast glass. 3D printed Sand moulds are being used in the industry to cast optimized concrete slabs and steel nodes. Hence this research explores the feasibility of 3D printed sand moulds for casting optimized structural glass geometries.

A column design as a case has been taken, for the experiment as glass having high compressive strength, comparable to steel, portrays as a perfect material for a compression only structure. The column is structurally optimized using topological optimization and sections of the complex challenging optimized geometry are fabricated using 3D printed sand moulds as different scale and results are drawn.

00

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01

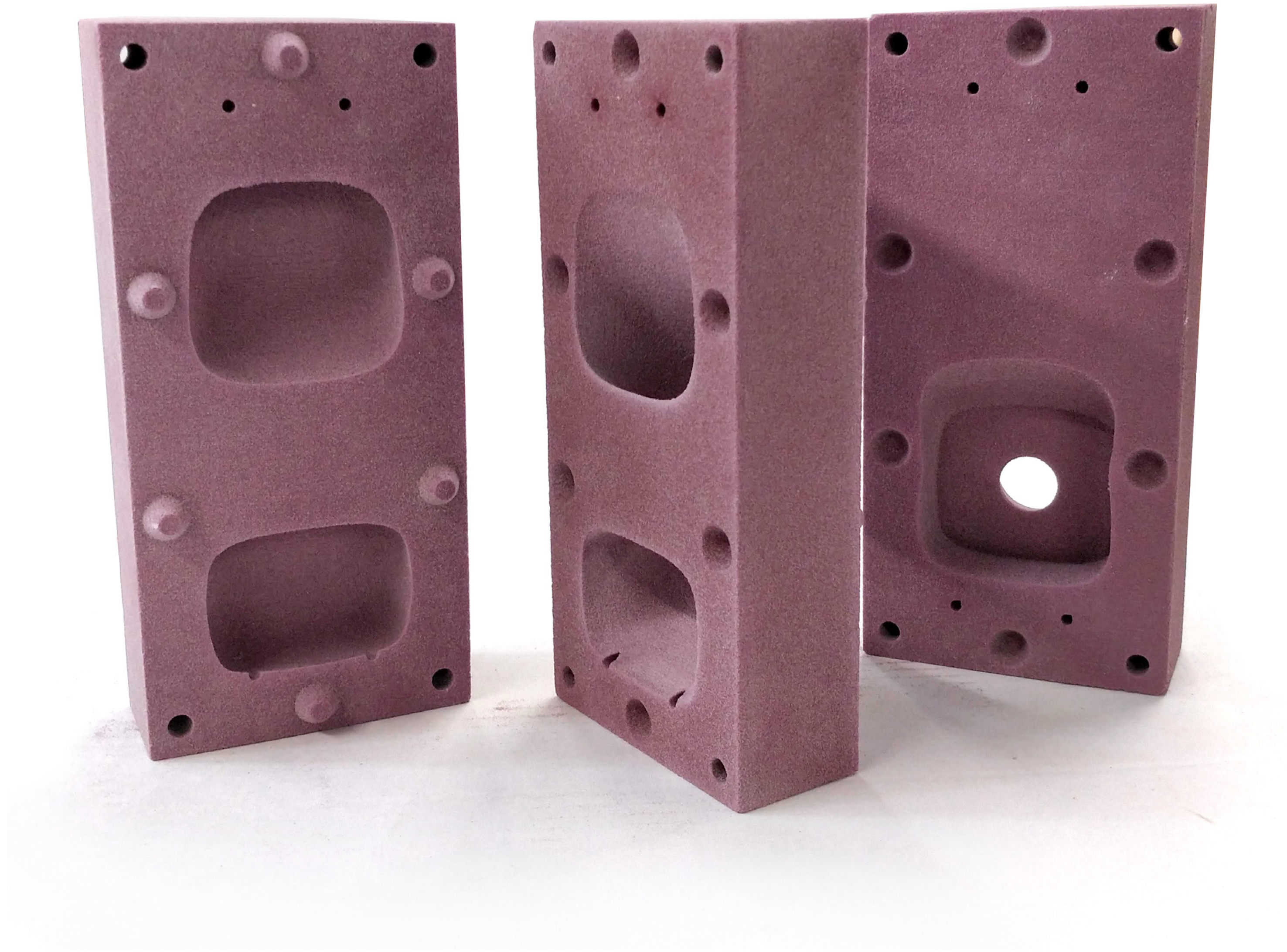
INTRODUCTION

Every day new inventions of materials are echoing around the world, but at the same time old materials are being developed and investigated further to achieve its full potential. Glass is one of those old materials which gained its popularity in Architecture during Roman time who inherited this art of glass making from Egyptians (O'Regan 2014) and since then it has been developing from a mere artifact to a structural element of a building. Some sources portray the invention of glass as man made but history even suggest the occurrence of natural glass during stone age where glass was used as a cutting tool. These glass pieces known as obsidian and tektites were found near the volcano made by the volcanic eruption on the rocks converting them into glass. (Pfaender 1996).

The inherent property of being transparent portray glass as a very unique material. This property of glass has fascinated architects to connect the exterior and interior spaces. Le Corbusier states that "Glass envelope is the minimum membrane between indoor and outdoor space". (Emami 2013) Glass industry has always been dependent on the fabrication process, hence the maximum developable size, quality and the quantity of glass enhanced with the advancement in the manufacturing process and post processing technologies. Hence, throughout the history, architect's vision of bridging the gap between interior and exterior space has developed. But architects are still not satisfied with the panoramic views of fully glazed envelope and desires a complete glass structure. This has resulted in pushing the boundaries of researchers and designers to investigate the structural capacity of glass. In this regards many structures and prototypes have been designed and built in 21st century. Some of the recent innovations include floor, columns, beams, bricks and even bridges made of glass.

The thesis introduces a new dimension to the production of complex and challenging geometries of glass structures with numerous potentials in architectural and construction industry. The thesis aims to overcome the limitation of the material by building over the current manufacturing traditions.

Fig. 01a : All glass structure at Apple store, Shanghai



02

RESEARCH FRAMEWORK

02.1

PROBLEM STATEMENT

While architects have a fascination of designing large obstruction free spaces, structural designers on the other hand have an ideology of creating load bearing elements in the design to transfer the load to the ground without any risk. This difference in ideology between the two professions generally results in expensive large span structures making the project unfeasible for the client. Transparent structural elements made of glass can be a solution to this acute problem in present times. Glass as a material has high compressive strength. Columns are designed to carry compressive forces along the axial direction and till date have proven in creating large spaces, eliminating the need for load bearing walls. Thus, glass columns have a potential to create a whole new possibility of realizing architect's visions.

Several glass columns have been envisioned and designed till date but involve very complex and time-consuming fabrication process. These realized columns are usually made of stacked laminated sheets (float glass) or casted monolithic pieces. Since float glass is easier to produce, majority of the columns have been realized by laminating planar sheets together. Due to brittle nature and spontaneous failure of glass as a material, safety cannot be guaranteed especially if the glass element is slender. Float glass planar sheets create a 2-dimensional geometry which makes the column more susceptible to buckling. Hence stacked laminated glass structures are highly unreliable.

Few columns have also been designed for cast glass but never realized due to high annealing time resulting in an extended labor, fabrication and costs. But, in theory, cast glass columns have 3-dimensional geometry, so, due to their monolithic nature, they are stronger than laminated glass columns offering resistance against buckling creating a more reliable structural element.

The annealing time of a cast glass element is exponentially proportional to the thickness of the glass structure. Designing a topologically optimized column based on stresses composed of interconnected thin sections can reduce the annealing time to a significant ratio thus rendering cast glass column more promising. But the major problem lies in fabricating these complex geometries.

Currently, customized geometries of high accuracy can only be made using expensive steel or graphite moulds. Labor intensive disposable moulds are another solution but they compromise on the accuracy and are non feasible due to time consuming and meticulous labor involved

Advancement in CAD (Computer Aided Design) & CAM (Computer Aided Manufacturing) has made it possible, manufacturing these complex geometries in many different materials. Challenging shapes of Steel and Concrete have earlier been casted in 3D printed sand moulds. Steel have a casting temperature much higher than glass makes it a viable option of casting complex and challenging geometries of glass.

02.2
RESEARCH QUESTION

According to the problem stated above, the main objective of the research is to contribute in the innovation of Glass structures by developing a new fabrication technique where structurally optimized glass geometries can be fabricated.

The main research question formulated is:

"How to fabricate a Topologically Optimized structural Glass Column using 3D printed sand moulds?"

The sub research questions formulated are:

1. How does Topological Optimization contribute to the feasibility of cast glass column?
2. What are the design criteria involved in designing a cast glass element?
3. What are the advantages and limitation of using 3D printed sand mould technology?
4. What are the constraints involved in 3D printing mould- size, thickness, edges/ corners etc?
5. Which binders and coatings are most promising?

02.3
RESEARCH METHODOLOGY

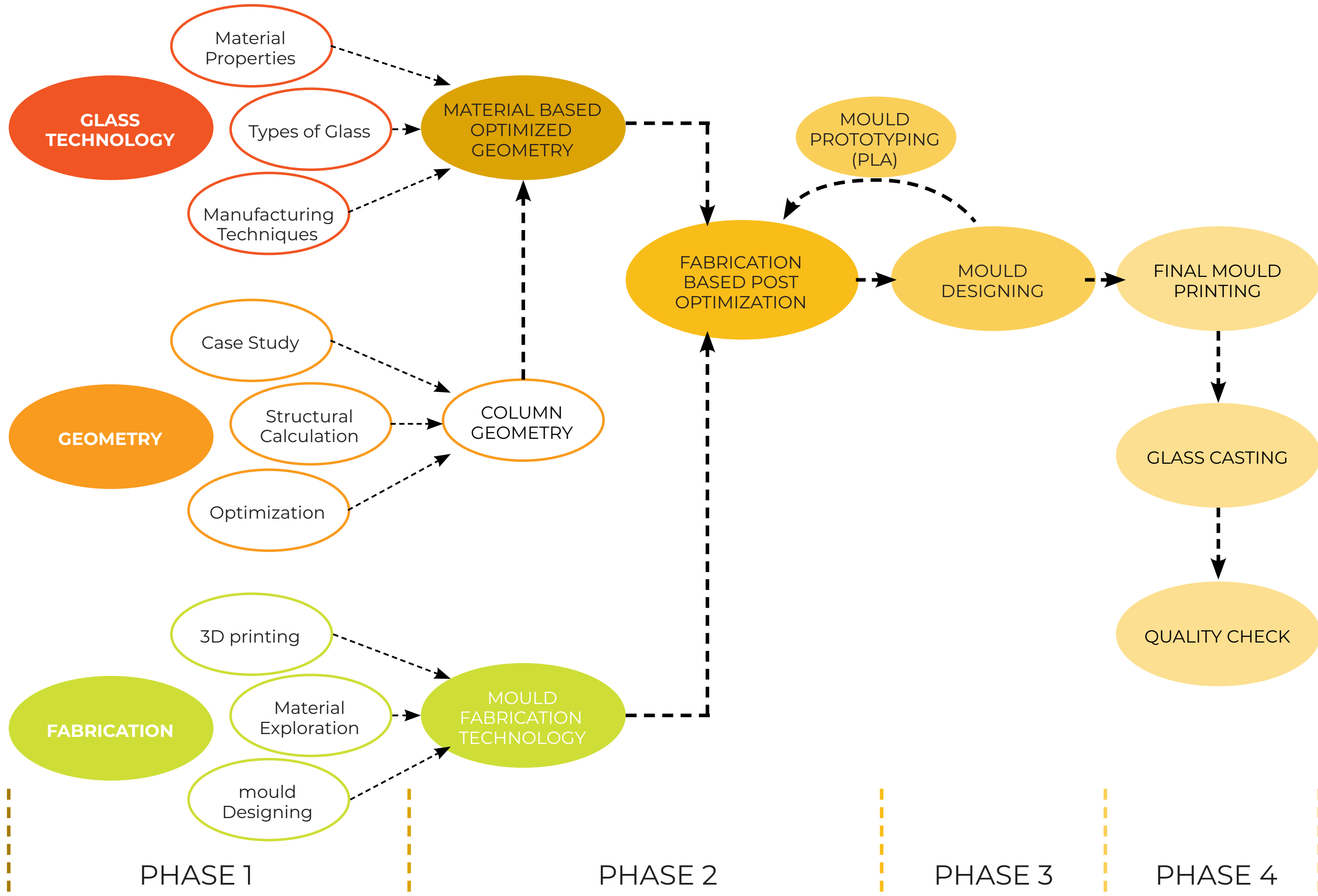
The structure of the research has been divided into 4 phases as shown in the figure below:

The 1st phase focuses on the literature study from different sources. Various books, journals, research papers, websites and few companies dealing with new upcoming technologies were consulted. This literature research provides a deep understanding of glass technology, from the material properties to the limitation and constraint offered by the material. Various digital manufacturing techniques have been investigated to understand the potential of using it for fabricating optimized glass structures.

2nd phase deals with designing an optimized geometry based on the parameters and constraints of the material. A case study of Kolumba museum has been selected to provide a realistic scenario in calculating load and exploring different geometries based on the constraints offered by material and fabrication technique.

3rd phase revolves around designing and materialization of the mould. Since the main focus of my research is the fabrication of the optimized geometry, major time of my research will be used in exploring the design of the moulds and investigating the material and technique suitable for manufacturing the mould and its exposure to higher temperature for a prolonged period of time. Prototypes of the moulds would be created using PLA first before fabricating it with actual material.

4th and the final stage focuses on casting of glass and creating a final prototype. The end product of this research is an optimized glass column. So, glass would be casted in the digitally fabricated sand mould and ways of demolding and finishing would be dealt with at the end.



02.4
RELEVANCE

The study of structural glass is at a premature stage in the architectural and construction industry. Also, there is an absence of official guidelines on the usability of glass at an international level. So, any development in the research will be a step forward for future reference for architects and structural designers both socially as well as scientifically.

Over the years, there has been a significant development in the way glass was manufactured in architecture field starting from the early roman technique of casting glass on table to the float process developed by Pilkington in mid-20th century. This research focuses in a method of casting glass elements by taking inspiration from the old traditional techniques and fusing them with the current trending digital fabrication methods. Hence fabrication of complicated/ challenging geometries will not be a challenge when it comes to glass as a material.

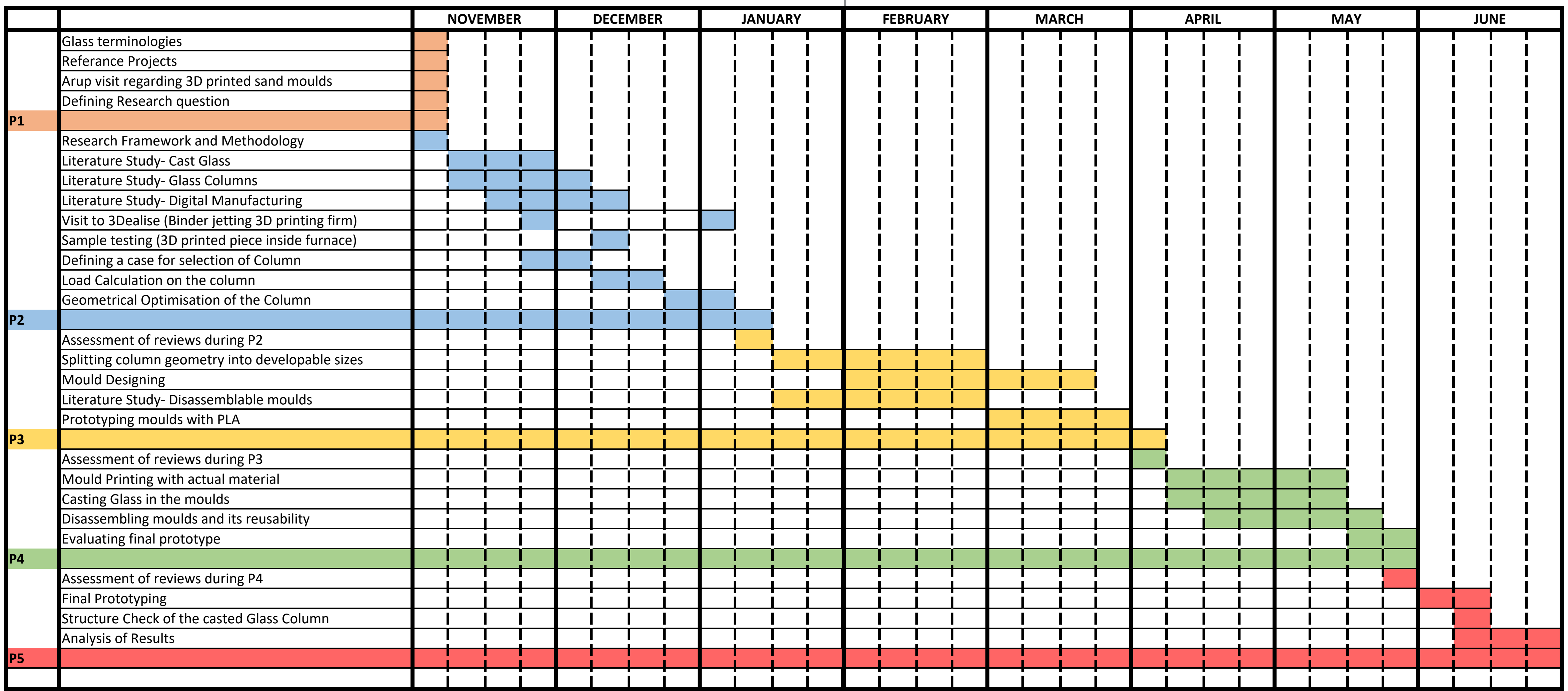
02.5
TIME PLANNING

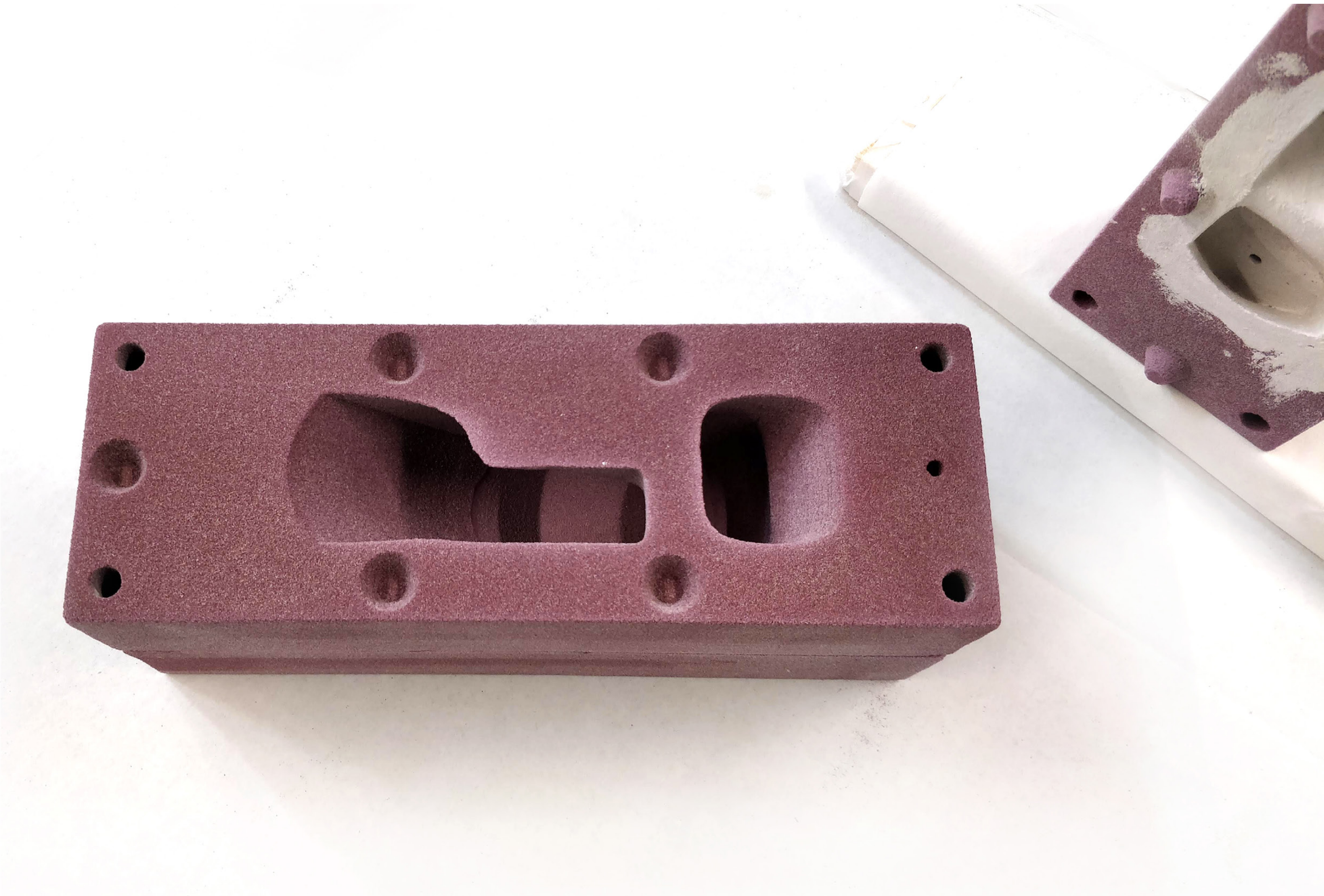
The development of the research has been strategically distributed on the basis of the 5 presentations. Fig. 1. explains the framework in more detailed manner.

The phase between P1 and P2 mainly focuses on the research and basic literature study required. A case study is selected and on basis of that a geometry of the column is optimised. Also, a sample of 3D printed sand mould is tested in the glass furnace to check the suitability of the binder and the mould inside the furnace at a very high temperature.
The next phase between P2 and P3 focuses more on the geometry and prototyping the moulds for the column.

After P3 sand moulds will be printed and casting of glass would be done to create a final geometry. Also demount ability and disassembly of the mould will be focused upon to get the finished product.

P4 to P5 is a phase marked for refinement of the research and a final report will be produced at the end.





03

LITERATURE STUDY

This chapter gives an overview on the current state of art of structural glass. Starting with the basic material properties, the first sub-chapter talks about the physical and mechanical properties of glass as a structural material. Second sub-chapter classify different glasses on basis of chemical composition and production processes and concludes casting method and borosilicate glass to be most efficient in fabricating an optimized geometry of glass column. The third sub-chapter briefs about the potential and limitation of casting glass. The forth sub-chapter describes the current techniques and moulds used for casting glass and introduces a new technique of cast glass using 3D printed sand moulds. Few examples of the application of 3D printed sand moulds for casting other structural materials is discussed in the next sub chapter. The last chapter gives a brief description of the various glass columns that have been realized in the construction industry and how the above discussed technique can be useful in developing an efficient, strong and cheap glass column.

03.1

GLASS AS STRUCTURAL MATERIAL

Glass being one of the oldest materials has been used in architecture for many years. But recently, Glass has moved from just being a facade element to a structural member and is being compared to the respectable load bearing materials in the construction industry like steel and concrete.

According to Pariafsai, in her review paper on design consideration in Glass buildings, the popularity of glass in the construction industry in 21st century is because of following reasons:

1. Very high compressive strength
2. Resistant to corrosion
3. Recyclable
4. Reduced energy consumption
5. Advancements in glass coating resulting in a sustainable envelope
6. Introduction of computer modeling software and Digital manufacturing tools, and
7. The growing demand of thinner and more transparent envelope.

(Pariafsai 2016)

But, psychologically, glass is still a very dangerous material in people's ideology as they associate the ease of breaking a drinking glass in their hand with the glass structures. The major challenge here is to control the brittle behavior of glass. With advancement in technology, safe solutions are being designed to overcome this issue by creating redundant structures. According R. Nijsse, a good structural system must produce warnings by yielding or deforming i.e. cracking noises or signals that an overload and fatal loss of integrity is imminent. So, adding redundancy to glass structures makes them more predictable, by giving a warning before breaking.

Many experiments and innovations regarding different structural elements are being designed and executed around the world to change the mindset of people. These structural elements include beams, columns, floor slabs, bricks and bridges. Famous examples of these elements are Yurakucho station canopy, Saint-Germain-en-Laye Town Hall, Atocha Memorial, Hongyagu glass suspension bridge, Casa de Musica in Porto and MAS museum in Antwerp .

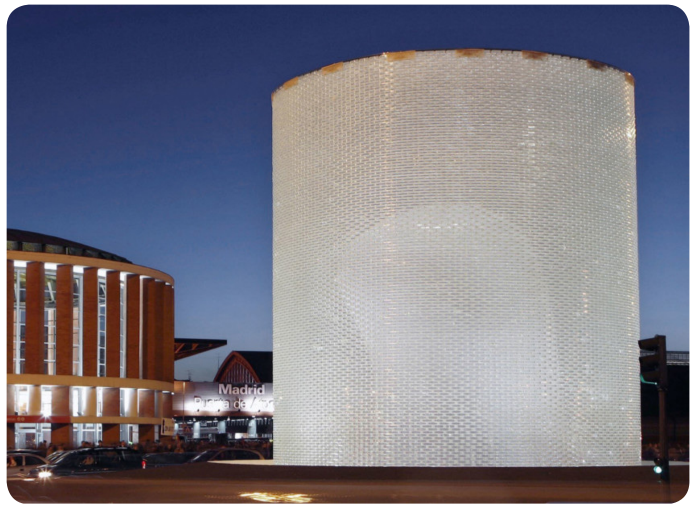


Fig. 03.1c : Atocha Memorial, Madrid, Spain
A 11m high shell structure made of 15,100 borosilicate glass bricks, glued together using a transparent acrylic adhesive (Goppert, et al. n.d.) (Pariafsai 2016)

Fig. 03.1a : Yurakucho Station Canopy, Japan
Cantilevered glass structure at Yurakucho station, this 10.6m long canopy having height apex of 4.8m is cantilevered at the entrance of an underground station (Emami 2013)

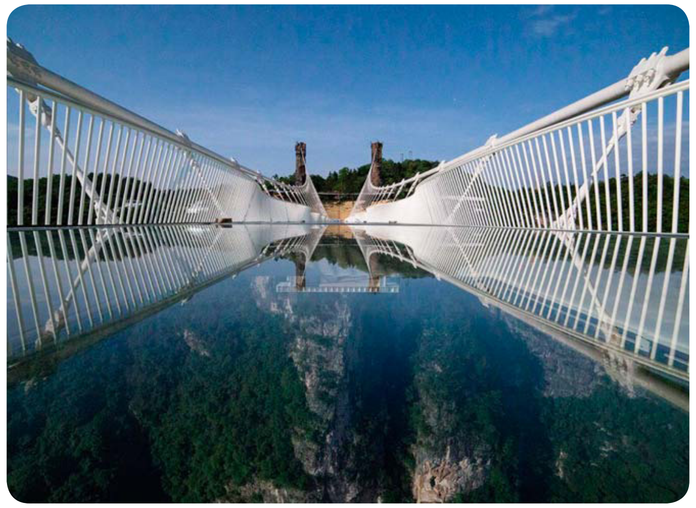


Fig. 03.1d : Hongyagu glass suspension bridge, Hebei, China
made of 1,077 panels of 4cm thick glass, this suspension bridge spanning between 2 cliffs can take a weight of 2000 people (Dezeen 2018)

Fig. 03.1b : Saint-Germain-en-Laye Town Hall, France
First set of glass columns ever built in 1994 carrying a load of 700m2 of glazed roof, where each column is capable of carrying 50 tons (Emami 2013)

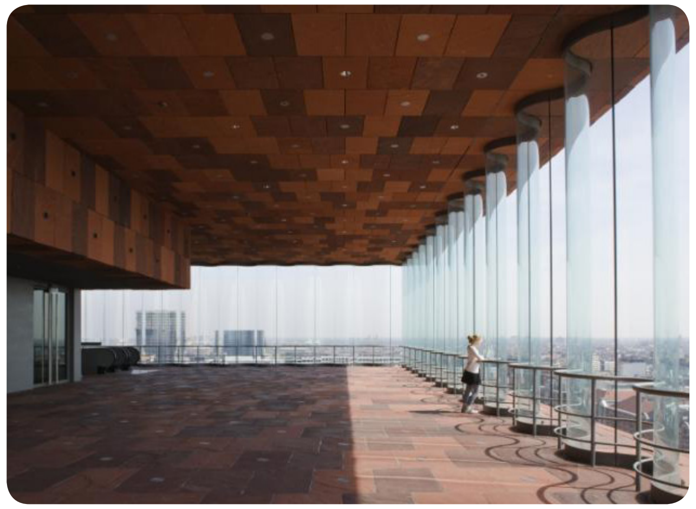


Fig. 03.1e : MAS museum, Antwerp, Belgium
5.5m high Corrugated glass panels have been used to create stiff and strong glass walls capable of tackling all the wind loads (Knaack and Klein 2009)

03.1.1 PROPERTIES OF GLASS

a. Mechanical Properties

STRENGTH

Owing to the strong atomic bonding forces, glass has a very high compressive strength of more than 1000MPa but this theoretical value can never be reached in practice. (Schittich, et al. 1999). Compared to the compressive strength, glass has a low tensile strength. The fracture behavior of glass is determined by many factors like surface, external environment and load applied. When a glass element is loaded in compression, peak stresses develop at points of impurities and surface flaws. These stresses are tensile is behavior and leads to failure of the structure. So, any attempt to measure the strength under compression develops tensile stresses, so an accurate value for allowable compressive stress can never be obtained. (Emami 2013)

The load bearing capacity of glass is also proportional to the time interval of applying the load and the surface area. (Weller, Unnewehr and Tasche, Glass in Building: Principles, Applications, Examples 2012)

MATERIAL	ULTIMATE STRENGTH (THEORETICAL)	
	Tension (MPa)	**Compression (MPa)**
Aluminum (2014-T6)	469	469
Structural Steel (A36)	400	400
Concrete	5	40
Glass	>1000	>1000

MATERIAL	ULTIMATE STRENGTH (PRACTICAL)	
	Tension (MPa)	**Compression (MPa)**
Aluminum (2014-T6)	414	414
Structural Steel (A36)	250	250
Concrete	1.5	25
Glass	6-80	120-200

Table 1: Theoretical and Practical Strength of Glass in comparison to other materials

BRITTLENESS

Glass being an amorphous material behaves in a very different manner as compared to other common structural materials. Mechanically, glass can have some elastic deformation but it doesn't yield plastically. (Emami 2013) The covalent bonds between atoms cannot repair themselves after being broken. (Veer 2009) This makes it hard to predict the failure of the material as it fractures immediately. So, glass is a very brittle material. (Emami 2013)

The failure occurs due to the presence of impurities or surface cracks leading to creation of local peak stresses. These stresses develop small crack which under continuous loading spread throughout the surface resulting in complete failure.

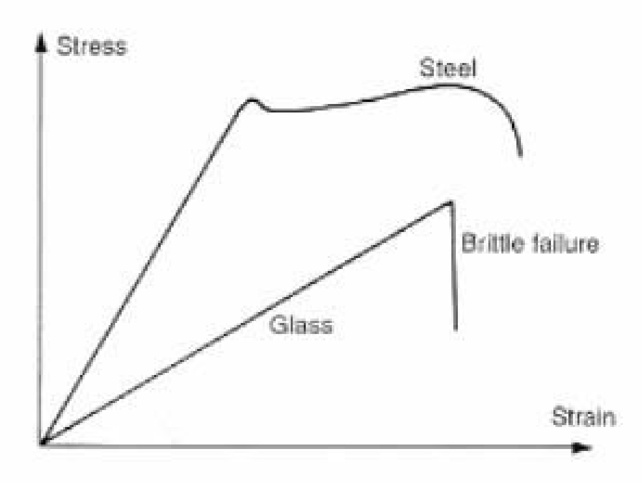


Fig 03.1 f: Stress and Strain curve of Glass V/S Steel
(sahol hamid 2007)

b. Physical Properties

MOLECULAR LEVEL

“In the scientific sense, the term glass refers to a frozen, supercooled liquid that has solidified without crystallization.” (Weller, Unnewehr and Tasche, Glass in Building: Principles, Applications, Examples 2012). At microscopic level, the molecules in glass are arranged in a complete random order creating multiple bonds. The molecular structure does not form any crystal lattice giving it the transparency. Since, it has multiple random bonds, glass doesn’t have any chemical formula. This makes glass an inorganic fusion of different elements. (Schittich, et al. 1999)

Glass has an amorphous chemical composition. Due to this amorphous composition, glass doesn’t have a melting point. (Pfaender 1996) When heated, it slowly changes its state from solid to a plastic-viscous and finally to liquid. The amorphous isotropy also makes the properties of material independent of any direction. (Schittich, et al. 1999)

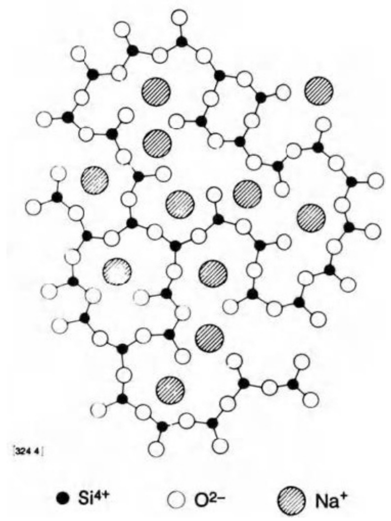


Fig 03.1 g: Molecular arrangement of Sodium Silicate Glass

OPTICAL PROPERTIES

It is important to realize that glass is transparent but not invisible. Glass being an amorphous solid, allows light to pass through it, but the amount of light depend on the profile, curvature, surface and type of glass used in the element. So, the remaining light is either absorbed by the material or reflected and scatter in the surrounding. Hence, glass is a reflective material as well. These properties make the glass still visible enough to human eye without disturbing the panoramic view of the space.

This transparency v/s reflection phenomena are more prominent along the edges. As seen in fig. 03.1 h, the facade of crystal house, made of several bricks is still transparent but the seams/ edges of each brick, makes the presence of a solid element more prominent.

Fig 03.1 h: Crystal House Facade showing the optical properties of glass bricks.
(Crystal Houses / MVRDV 2016)

DURABILITY

According to Nijsse, glass is a recyclable material and can be recycled endlessly without losing its quality. (Nijsse 2003) Also, glass is generally resistant to acids and alkaline solutions. (Schittich, et al. 1999) So, glass has a great resistance against most natural elements and chemicals. This makes the material non-corrodible, thus less or no maintenance cost.

TYPES OF GLASS

From the molecular composition of material to the fabrication technique, glass has evolved over centuries. Its use in the construction has always been dependent on these two factors as it affects the physical properties, surface finishes, maximum producible size etc.

So, glass can be classified into different categories on 2 bases:

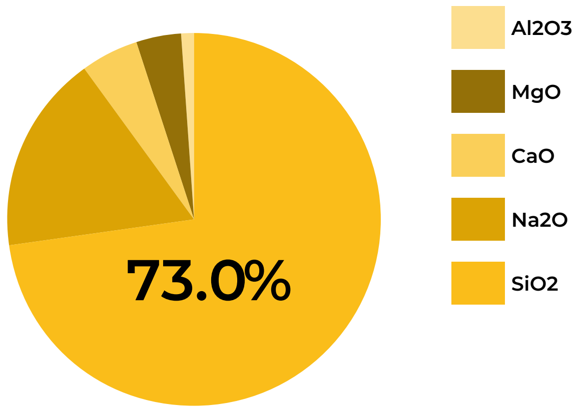
a. Chemical Composition
b. Fabrication Process

03.2.1 CHEMICAL COMPOSITION

The first glass recipe dates back to 5000 years ago, when Mesopotamians heated silicon, lime, sodium carbonate and metal oxide at 1400˚C, discovering a glassy object. But the first written records of glass composition dates back to 650 BC and the first glass pane was casted by Romans (Schittich, et al. 1999).

The typical composition of any glass is 70 % silicon dioxide (quartz sand), alkali oxide fluxes (lowers the melting temperature of quartz sand) and alkaline earth oxides (stabilizers). (Weller, Unnewehr and Tasche, Glass in Building: Principles, Applications, Examples 2012).
Today, glass can be classified into 6 main families based on the composition that are available commercially: Soda-lime, borosilicate, lead silicate, aluminosilicate, 96% silicate and fused silica glass. (F. Oikonomopoulou, et al. 2018). All these types have been explained briefly.

1. SODA LIME

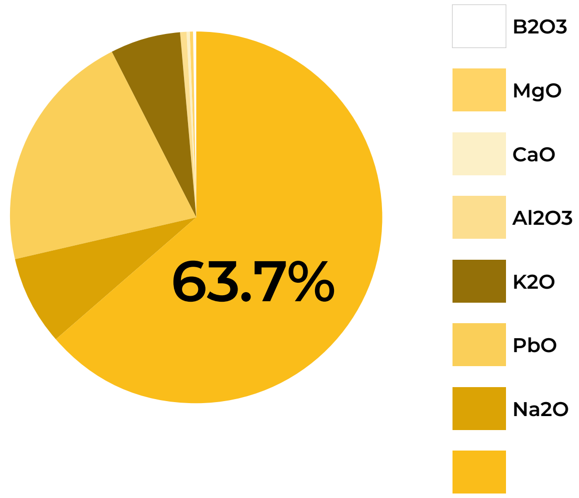


Soda Lime glass is the first type of glass invented and is still the most popular glass in the world.

Key Characteristics:
- Least expensive
- Most durable glass
- Poor resistance against thermal shocks
- Unacceptable resistance to strong alkali

Typical Applications:
- Window Panes
- Bottles
- Facade

2. BOROSILICATE

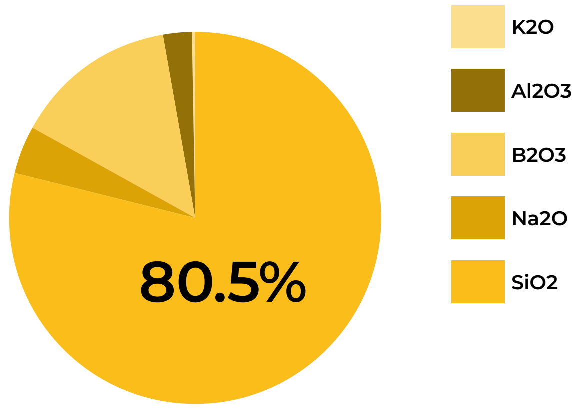


Borosilicate glass, also know as Pyrex, was invented by Corning Glass Works in 1915. It was developed to withstand high thermal shocks. The material has low thermal expansion coefficient. This makes it less prone to internal stress, hence would not fracture easily.

Key Characteristics:
- Resistant to high thermal shock
- Excellent Chemical resistant properties
- More expensive than soda-lime and lead glass
- Capable of transmitting UV at higher wavelengths

Typical Applications:
- Laboratory Glassware
- Household oven-ware
- Light bulbs
- Large telescopes
- Mirrors

3. LEAD SILICATE

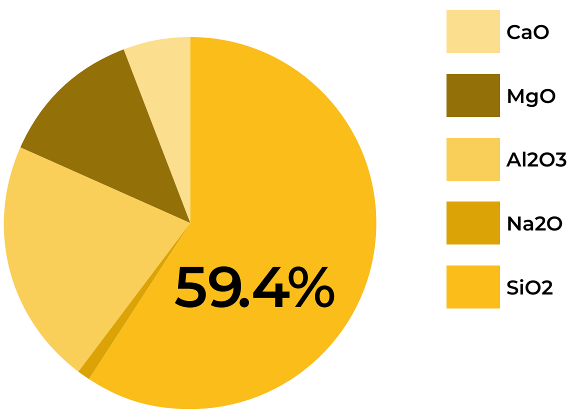


Lead-Silicate is a commonly used type for glass art. Due to its low working temperature and relatively soft surface, it is easier to grind and polish.

Key Characteristics:
- Second least expensive type of glass
- Softer glass in comparison to other
- Easy post processing (polishing and grinding)
- Poor thermal properties
- Good electrical insulating properties
- Susceptible to scratching
- Limited resistance to thermal shocks

Typical Applications:
- Artistic ware
- Neon- sign tubes
- Television screens
- Absorption of X-rays (high PbO %)

4. ALUMINOSILICATE



Aluminosilicate glasses have alumina (Al2O3) in their composition. This type of glass is very similar to Borosilicate type but offer better resistance to temperature fluctuations and chemicals.

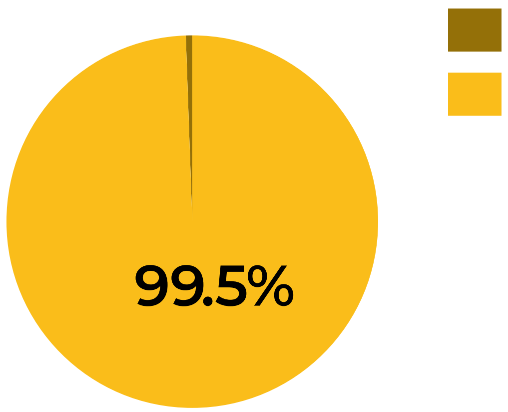
Key Characteristics:

- High melting point
- Resistant to high thermal shock
- Very good chemical resistant properties
- High manufacturing cost

Typical Applications:

- Mobile Phone Screens
- Fiber Glass
- High temperature thermometers
- Combustion tubes

5. FUSED-SILICA



As the name suggest, Fused Silica is almost 100 percent silica produced to withstand high atmospheric pressures. Silica has a very high melting temperature, so this type of glass is very difficult to manufacture.

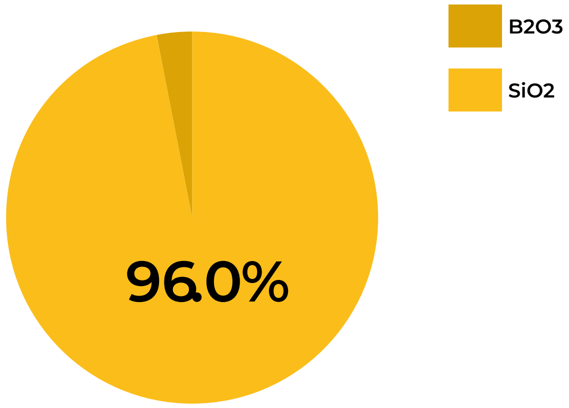
Key Characteristics:

- Highest thermal shock resistant
- Highest Chemical Resistant
- Highest melting point
- Toughest to work with
- High production cost

Typical Applications:

- Windows and windshield of Spacecrafts
- Astronomical Telescopes

6. 96% SILICA



96% silica is very similar to fused silica except 3% of boron oxide is added as stabilizer.

Key Characteristics:

- Very good thermal shock resistant
- Very good chemical resistant
- Meticulous manufacturing process
- High production cost

Typical Applications:

- Furnace Sight Glass
- Windows and windshield of Spacecrafts

Due to different composition of glass, the mechanical properties of every type differs. A comparison on different criteria has been formulated by F. Oikonomopoulou in the table below. (Table 2)

It was formulated that more the amount of silica, lighter the glass becomes and lower is the coefficient of expansion.

The melting and annealing point also depends on the ratio of silica content. Fused Silica and 96% Silica glasses are the toughest to work with.

On looking at the Physical properties and Mechanical Properties, borosilicate offers the best and most feasible characteristics in Architecture and Construction industry. The workable temperatures and reasonable optical qualities in comparison to the cheap ones makes it affordable to construct structural elements. Also, borosilicate glass has resistance to high thermal shocks making it a good candidate against fire resistant materials.

TYPES OF GLASS	SODA LIME	BORO SILICATE	LEAD SILICATE	ALUMINO SILICATE	FUSED SILICA	96% SILICA
Mean Melting Point at 10 Pa. s [°C]	1350-1400	1450-1550	1200-1300	1500-1600	>>2000	>>2000
Soft Point [°C]	730	780	626	915	1667	1500
Anneal. Point [°C]	548	525	435	715	1140	910
Strain Point [°C]	505	480	395	670	1070	820
Density [Kg/m³]	2460	2230	2850	2530	2200	2180
Coeff of Expan.0°C - 300°C [10-6/°C]	8.5	3.4	9.1	4.2	0.55	0.8
Young's Modulus [GPa]	69	63	62	87	69	67

Table 2: Comparison of Mechanical Properties of different types of Glass categorized on basis of Chemical Composition

03.2.2 FABRICATION PROCESS

Production of glass, for a very long time, has been dependent on the melting technique. Few people could only master this art of manufacturing glass. Slowly with the advancements in the technique and the advent of industrial revolution, mass production of glass became very easy and affordable. A brief description of the major break through in glass production for architectural industry are shown in the time line (fig. 03.2 a) based on the information from (Kingfisher Windows n.d.) and (O'Regan 2014)

But in 21st century, glass for architectural industry has evolved. As, described earlier, glass is not only used for facade panes but also for designing the structural aspect of any built mass. With that evolution, production process has also evolved. Currently there are 4 ways of manufacturing glass depending on the desired end product:

1. Float Glass
2. Extruded Glass
3. 3D Printed Glass
4. Cast Glass

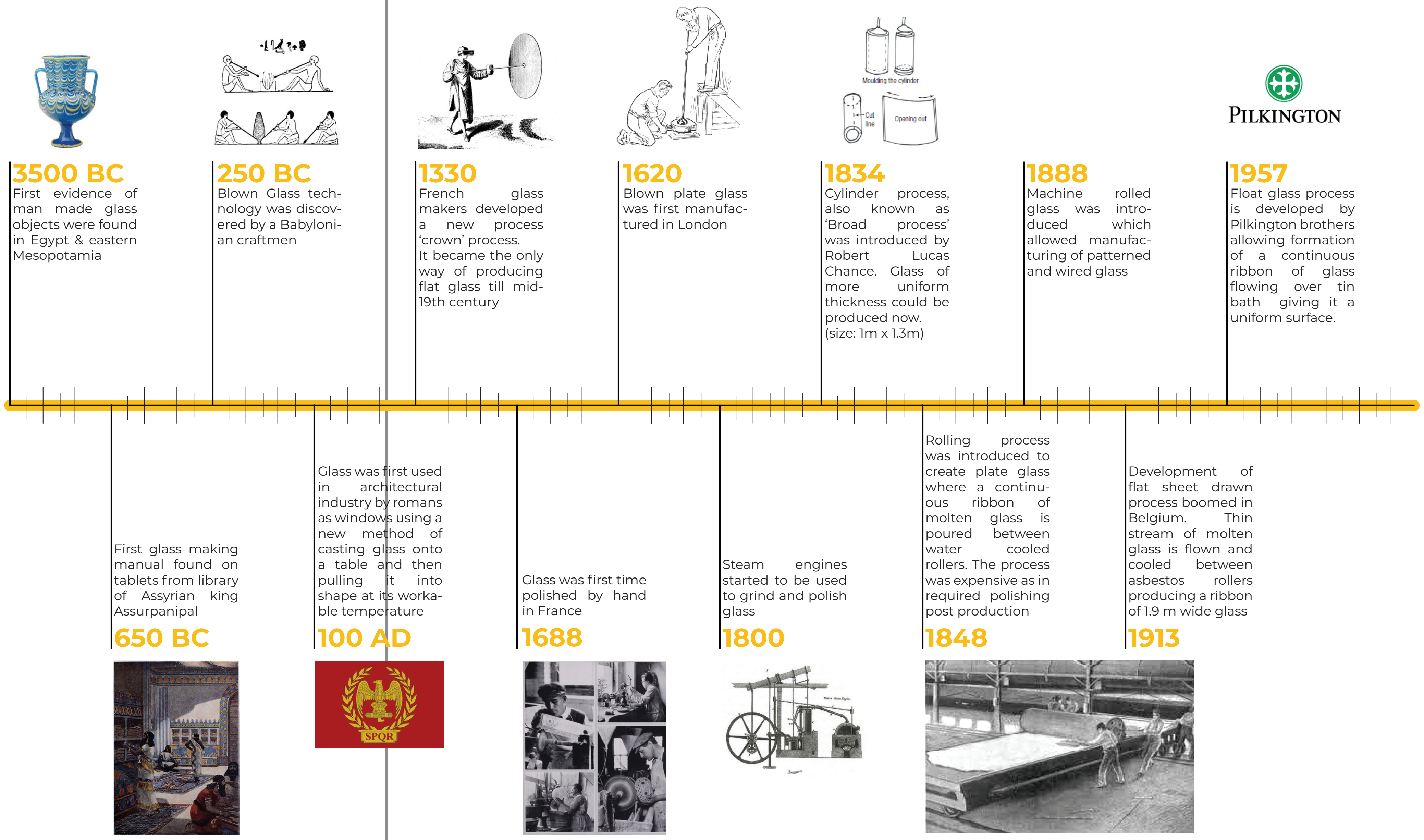


Fig 03.2 a : Historical evolution of Fabrication of Glass Techniques for Architectural and Construction industry.

1. FLOAT GLASS

Float glass is the most common technique used in architectural industry for creating flat glass sheets. Float glass process also known as ‘the Pilkington Process’ was developed by Sir Alastair Pilkington in 1957 in UK. The process still accounts for 90% of flat glass produced in the world.

The process of producing glass starts by melting all the ingredients in a melting tank at 1550°C as shown in the Fig. 03.2 b. The molten glass is then poured onto a large bed of molten metal, typically tin, at 1050°C where it slowly spreads to attain the required thickness. It exits the float bath at 600°C where it enters an annealing lehr. The glass is still soft at this temperature and is slowly cooled down to 100°C over a span of 150m. This slow cooling process helps to relieve the internal stresses. Glass is then brought to room temperature and then cut into pieces of 6m (typical length) (Pilkington n.d.)

The main advantages of producing glass using this technique are high optical quality, uniform thickness, flat surface, low cost and high production efficiency. This process still produces the largest size of glass panes in comparison to other techniques throughout the history.

Fig. 03.2 c: Apple Store, New York entrance made of Float Glass (Glassdoor n.d.)

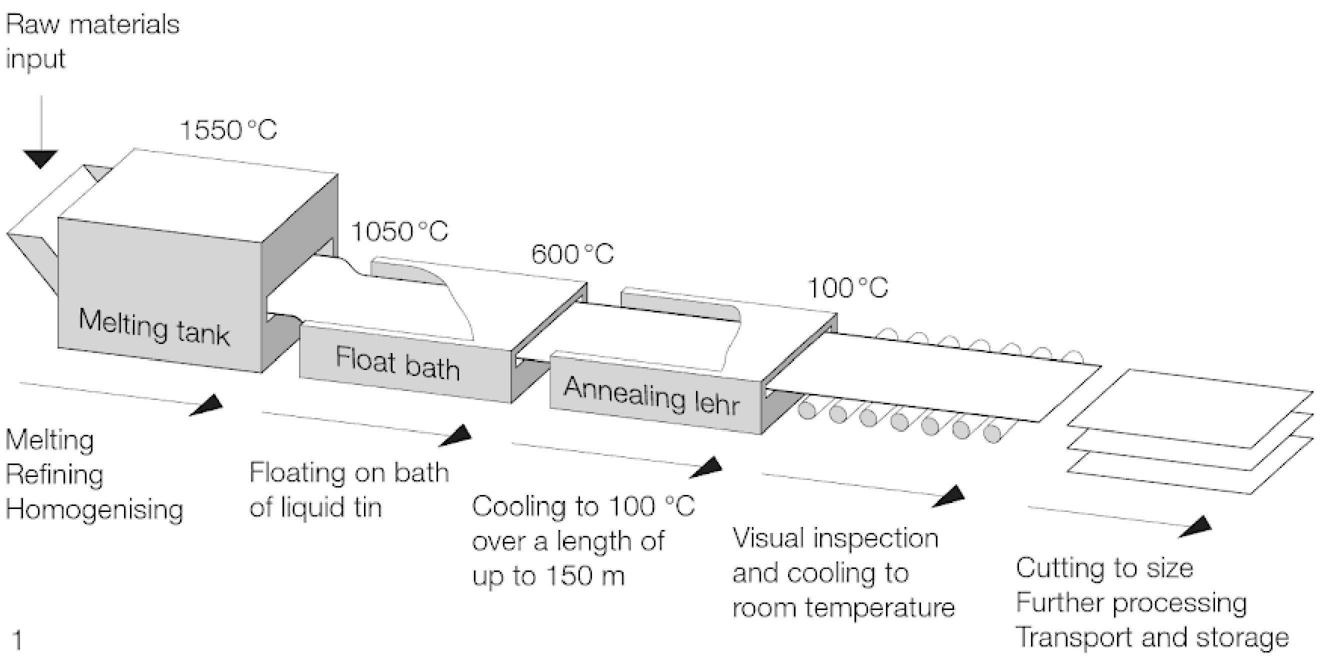


Fig 03.2 b : Float Glass Process from Melting to Annealing and finally post processing

2. EXTRUDED GLASS

An extrusion is a process of creating objects having a constant cross section throughout the profile. Extrusion is a suitable technique for glass elements for which typical manufacturing process like casting, blowing or drawing is not appropriate. The production process is used to manufacture hollow tubes, rods or profiles having non-circular cross section.

There are 2 types of extrusion process- Direct and Inverted extrusion. In direct extrusion process, billet is compressed with in the container and forced by ram to flow through the die. While, inverted extrusion process allows the ram to push the die from the opposite side against the billet. Fig. 03.2 e explains the 2 method graphically. The inverted process is advantageous as less pressure is required for extrusion. Also, flow pattern in inverted is simpler that direct one (Roeder 1971).

Extrusion is usually done for glasses with steep viscosity curve or glasses having a greater tendency to crystallize. (Pfaender 1996) Hence, borosilicate glass is usually used for creating glass billets in the process. The process is also useful for types of glasses having high melting point, as the extrusion can happen at a much lower workable temperature. E.g. Fused Silica or 96% silica glasses (Roeder 1971).
The final products of this production method have high thermal shock resistance, negligible tolerance and high optical quality

Limitation:
The process of extrusion mainly has 4 limitations:

- Firstly, the process depends highly on the die formation. If the negative of the shape can be casted as a die, then glass profiles can be extruded easily.
- Secondly, the size of profile cannot be bigger than the size of die.
- Thirdly, only profiles of same cross section throughout can be produced
- Fourthly, not all types of glasses can be used in this process

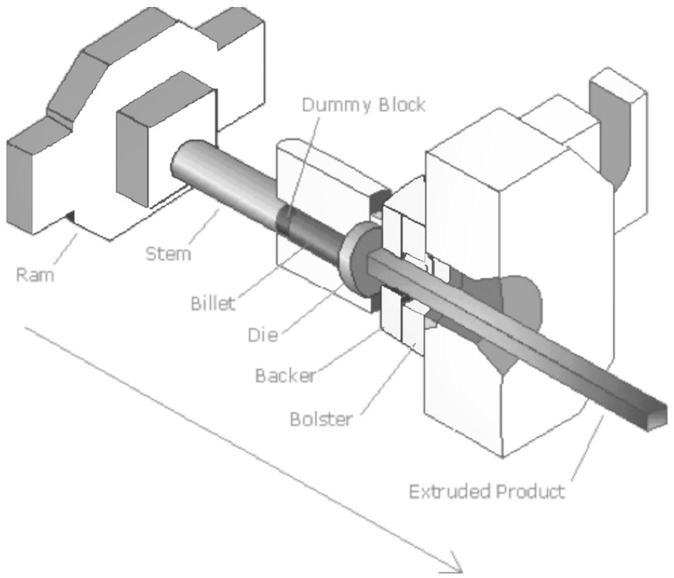


Fig 03.2 d : General process of Extrusion of any material

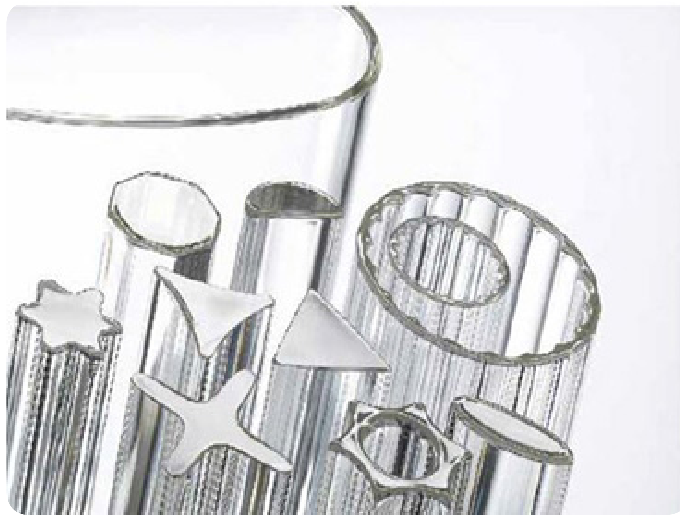


Fig 03.2 f : Extruded Glass Profiles

3. 3D PRINTED GLASS

3D printing in 21st century has become one of the revolutionary ways of producing geometries after industrial revolution. The possibility of creating detailed complex shapes with negligible tolerance is what sets it apart.
Manufacturing glass has always been a tricky process. Glass become liquid at a temperature above 800°C (soda lime glass) and after shaping, it requires annealing time to uniformly cool down the whole geometry else it will shatter if cooled rapidly under its own internal stress. So, technically, in order to 3D print glass, one needs to print inside a furnace at a temperature between 600- 800°C.

In 2015, an Israeli-based 3D printing company Micron3DP succeeded in printing glass for the first time. The glass was printed in a similar manner to thermoplastics, in molten form, on a Cartesian based gl5 machine, with a resolution (layer thickness) of 100 microns, layer after layer like a normal 3D printed piece. The company has printed many intricate forms with different colors. (Jackson 2016) (Krassenstein 2015) The printer is capable of printing an object up to 200mm x 200mm x 200 mm in size (Jackson 2016). Fig. 03.2 g shows a prototype of a printed geometry

Meanwhile MIT's Mediated Matter Group was able to develop a system known as G3DP. (Fig. 03.2 h). The printer has a dual heated chamber concept, drawing the molten glass at temperature of 1040°C from the upper part-kiln Cartridge and prints at a resolution of 4000 microns using a nozzle made of alumina-zircon-silica. This ceramic nozzle drizzles the molten glass into layers to slowly complete the desired geometry inside the lower part-annealing chamber. (Klein 2015) (Jackson 2016) This lower chamber is kept at a temperature between 480°C and 515°C with the help of propane torches. After the whole geometry is printed, it is moved to a proper annealing lehr (Vincent 2015) (Stultz 2015). Some of the printed prototypes are shown in Fig. 03.2 i.

Limitation:
Currently, 3D printing of glass is still in a beta stage and needs development. Limitation with this method of production are:

- The extruded glass sticks on the nozzle rather than the previous layer causing a deviation in the shape. This leads to uneven mass distribution creating problems in annealing of the final printed object.
- The major disadvantage of 3D printing glass is the speed of printing. It is 30 times slower than press manufacturing.
- The maximum size of the object depends on the lower chamber which is currently restricted to 20cm in height.
- The produced results have not been tested for their structural performance, so, its not a wise choice to use this method for making glass structural elements.

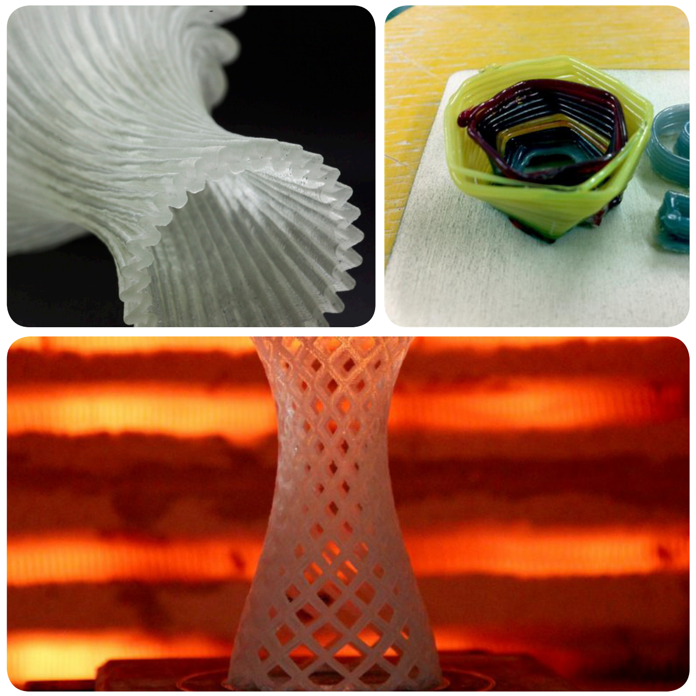


Fig. 03.2 g: 3D printed Glass prototypes by Micron 3DP (Micron3dp 2019) (Simon 2015)

4. CAST GLASS

Glass when in molten state, can be transferred to any shape or size. This shape or size is given by creating a stencil or a mould, where the molten state of glass can slowly solidify. So, glass casting is this process of pouring molten glass in a mould to give a desired shape. These shapes are usually large glass volumes having regular or organic geometry, perplex geometry, which cannot be produced by any other method of fabricating glass. The geometries created usually have high optical quality and strength as no cutting and least post processing is involved after casting.

Before fabrication starts, an integral part of casting glass is designing the mould of the desire shape. This mould can be made of any material which has low thermal expansion coefficient and can withstand high heat for a prolonged period of time. Some common materials used for designing moulds are steel, graphite, plaster, sand etc. A more in-depth knowledge about moulds is explained in sub chapter 5 of literature study.

The glass casting is then done by pouring molten glass at a very high temperature (800°C -1100°C) and quickly cooled to 700°C to avoid any molecular arrangement during crystallization zone which gives it high optical transparency. After this annealing is done where the temperature is slowly decreased to room temperature over a period of days or weeks to get the final product. Post processing is later done to make it optically sound. (F. Oikonomopoulou, et al. 2017)

According to F. Oikonomopoulou, there are 2 principal methods of pouring glass in the mould (F. Oikonomopoulou, et al. 2018):
a. Hot Forming
b. Kiln Casting

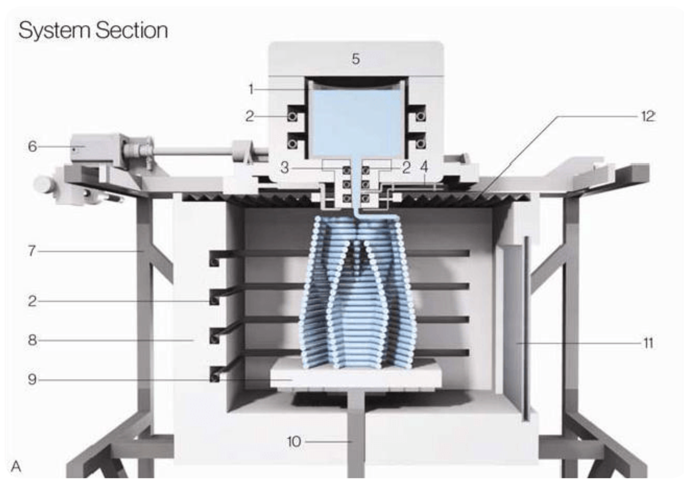


Fig. 03.2 h: G3DP dual heated chamber Glass printer by MIT
1. crucible, 2. heating elements, 3. nozzle, 4. thermocouple,
5. removable feed access lid, 6. stepper motors, 7. printer frame,
8. print annealer, 9. ceramic print plate, 10. z-driven train,
11. ceramic viewing window, & 12. insulating skirt

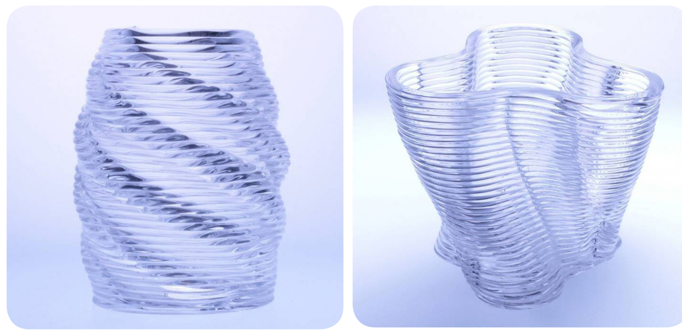


Fig. 03.2 i: Printed prototypes by MIT's Mediated Matter Group (Simon 2015)

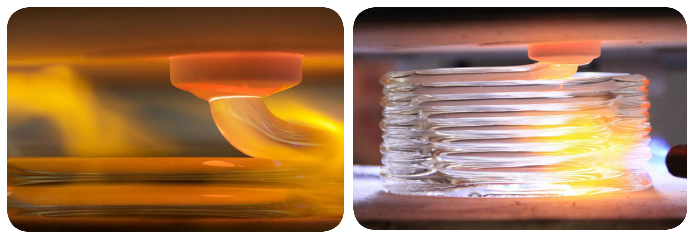


Fig. 03.2 j: View of the Kiln chamber while printing in G3DP. (Simon 2015)

HOT FORMING / MELT QUENCHING

- The process is suitable for mass production of an element.
- It involves 2 furnaces. The first one is used to mix raw ingredients to form the molten glass operating at a very high temperature around 1200°C and second one is for annealing the glass element from 600°C to room temperature over a span of days depending on the size of object.
- Molten glass from first furnace in poured into a preheated mould (850°C) and then the mould is placed inside the annealing furnace
- Moulds are usually made of steel for re usability

Fig. 03.2 k: Casting of Soda-lime glass bricks by Poesia Company

Fig. 03.2 l: Reusable Steel moulds for casting glass by Poesia Company

Fig. 03.2 m: Casting of molten Glass in a steel mould surrounded by sand to avoid expansion of mould due to pressure

KILN CASTING

- The process is suitable for prototyping or low batch of production such as art piece or mass customized one time object.
- The process involves usage of only one furnace oscillating between 800°C to room temperature. The raw material for the glass is broken pieces of existing glassware which are melted in the same furnace and later annealed by bringing the temperature down of the same furnace to room temperature
- The mould in this scenario is always present inside the furnace and preformed glass pieces melts and slowly poured down inside the mould.
- Moulds are usually made of gypsum using lost wax technique

Fig. 03.2 n: Kiln casting of glass objects at TU Delft glass lab

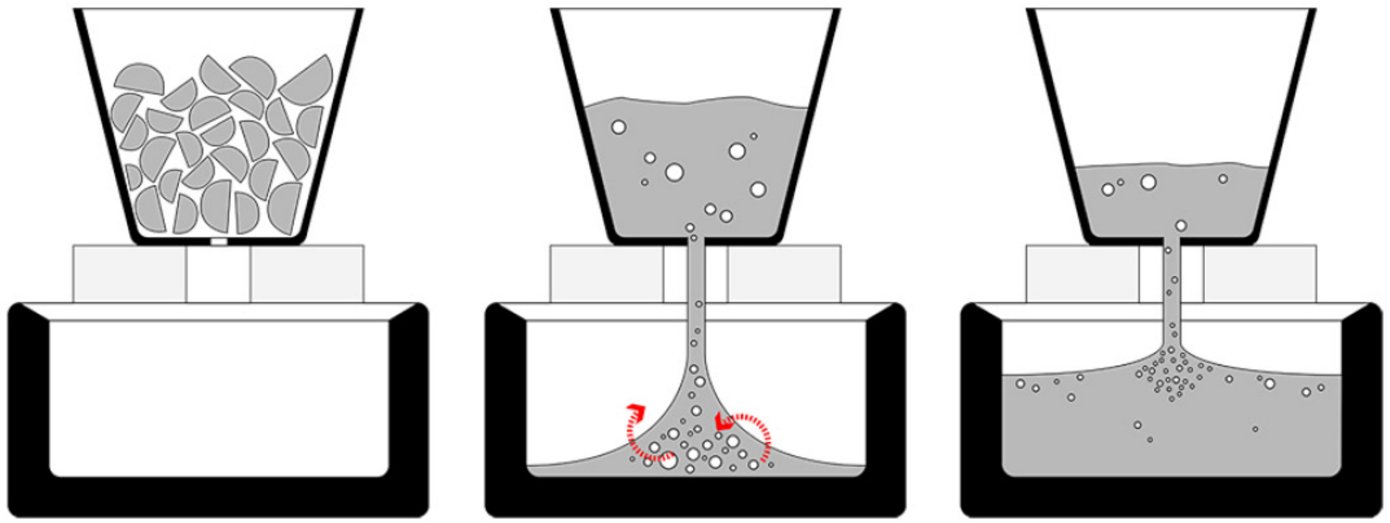


Fig. 03.2 o: Process of Kiln Casting using terracotta pots for melting the broken glass pieces which pours down in the mould

Cast glass has been used to create load bearing structural glass walls using cast glass bricks in architecture and construction industry. Optical House, Atocha Memorial and Crystal House are few examples. In other industries, cast glass is currently used in creating glass sculptures (Roni Horn) and Large telescope mirrors.

Limitation:

- Glass casting is not an easy process, rather it is the most laborious process.
- With all the benefits for creating large solid or perplex geometries, the main limitation of this method is the annealing time- the time required to homogeneously cool the whole geometry slowly to avoid creating internal stresses. Thicker the geometry, more is the time required to anneal the geometry. This phenomenon has been explained it detail in section 4 of literature study.
- It is difficult to handle heavy geometries.
- High manufacturing costs

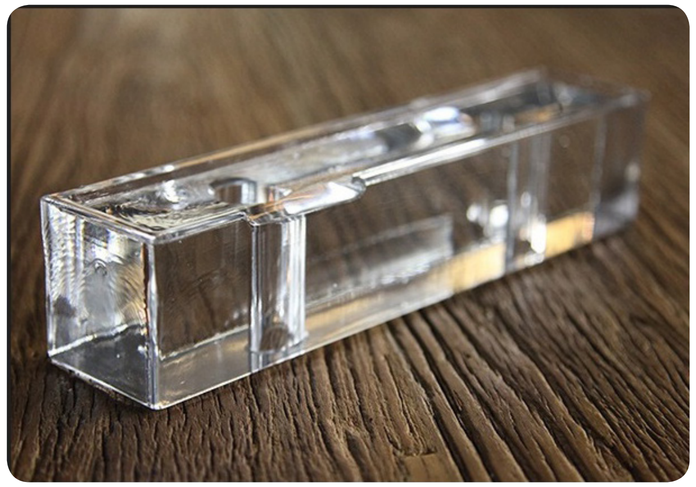


Fig. 03.2 q: Cast glass brick produced for Optical House, Japan

Fig. 03.2 p: Glass Sculpture by artist Roni Horn (Image Object Text 2012)

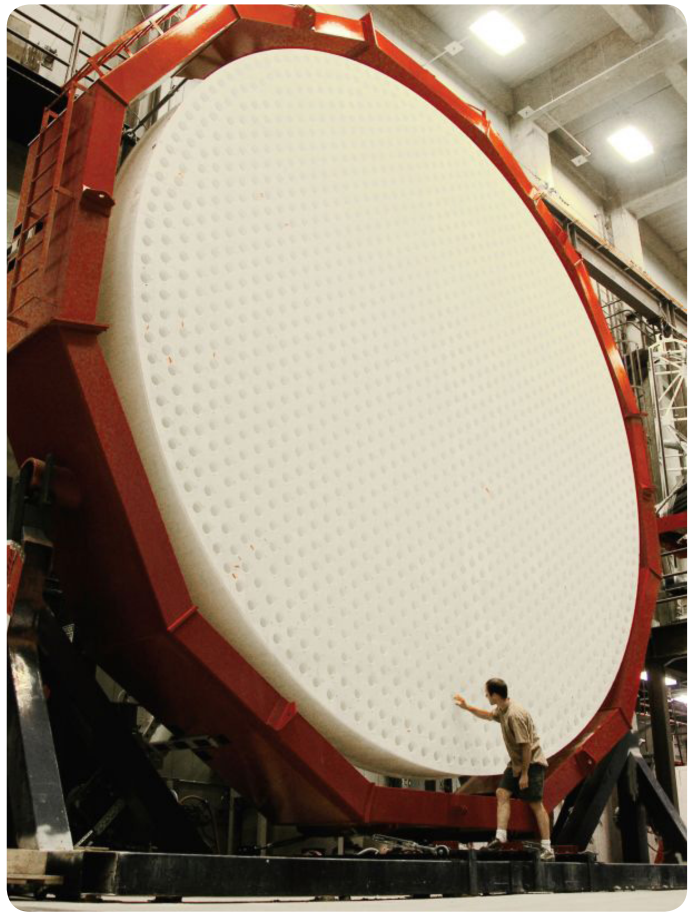


Fig. 03.2 r: Giant Magellan Telescope Mirror (Smithsonian Insider 2012)

03.3 GLASS COLUMNS

A column in architecture and structural engineering, as defined in Conservation wiki, is a structural element that transmits the load/ weight of structural elements from above to the foundation of the structure. In other words, a column is a compression only member. Usually, columns are round with a thick base known as pedestal and a thick capital. (Conservation wiki n.d.)

Columns throughout history have been designed with heavy masonry blocks of stone and marbles. Slowly, it evolved to materials like concrete, steel, timber etc. The only objective of choosing material was its strength in handling compressive load. Recently, it has been discovered that, glass has a compressive strength of 1000 N/mm2 , more than that of concrete, timber and even steel. Along with its transparent property and durability against corrosion, Glass is rendered as the most suitable material for designing a column.

03.3.1 EVOLUTION OF GLASS COLUMN

According to Heugten, the evolution of a glass column started from a stacked wall of planar glass sheets. As seen in Fig 03.3 a

This straight wall slowly evolved to a configured wall giving it a 3-Dimensional stability leading to a small section of boxes and finally deducing the shape of first glass column ever designed- the cruciform shaped profiled columns.

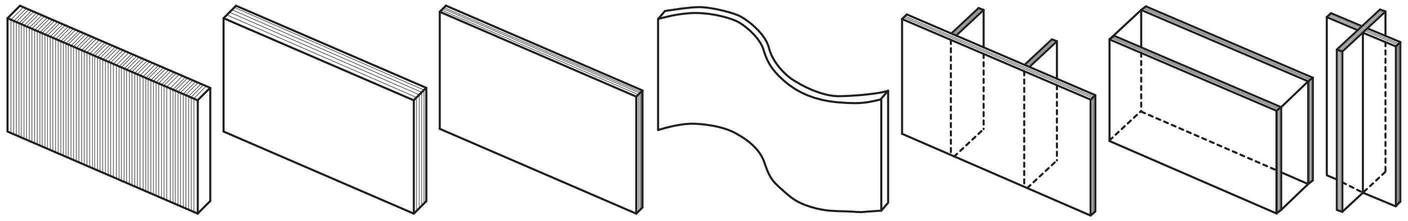


Fig 03.3 a: 1. Laminata Leerdam, Leerdam, Netherlands; 2. Mi Casa Es Su Casa, Leerdam, Netherlands; 3. Temple de L'Amour II, Noyers, France; 4. Museum aan de Stroom, Antwerp, Belgium; 5. Apple Glass Cube, New York, USA; 6. The Rheinbach Pavillion, Rheinbach, Germany; 7. Town Hall, Saint-Germain-en-Laye, France

03.3.2 DESIGN CRITERIA

Glass Columns are subjected to the same rules as the columns made of any other material. But the material properties of glass signify that the material fails under tension. When applying a compression only force axially on the column, this tension is originated due to surface cracks or peak stresses resulting into fracture of column. Another way of failure is by lateral forces which can cause instability of the column by buckling.

STABILITY

Stability is a relationship between load and deformation caused by the load. It is the case when a state of equilibrium is not attained under an applied load which creates problem. There are 3 states of equilibrium which can be defined according to Ball analogy- stable, instable and indifferent or neutral as shown in the fig 03.3 b (Roebroek 2009).

For a structural system, stable is the most desirable state, where any out of plane forces can easily be balanced keeping the column stable(Gambhir 2004). The second stage- indifferent stage usually doesn't exist due to the presence of imperfections on the surface of the material (Luible 2004). The third state is when a small disturbance in the column can result in complete failure of column. This problem usually can be solved using analytically or numerically (Vries 2018)

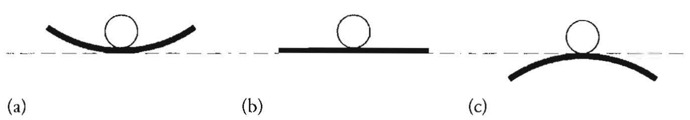


Fig. 03.3 b: Ball Analogy for different states of equilibrium
(a) Stable ; (b) Indifferent ; (c) Instable

BUCKLING

Due to slender geometry of a column, they have the tendency to bend under high load. This property of bending under pressure is known as Buckling. Euler's buckling formula is an expression derived to calculate the critical load at which a particular column will fail.

$$F_c = \frac{\pi^2 EI}{L_e^2}$$

Where, F_c is the critical failure load
E is the Young's modulus of the material
I is the second moment of area
L_e is the effective length based on the end supports

But in practice a glass column fails much before these values are reached due to imperfections present on the surface. It is very difficult to determine the exact value but the major factors affecting it are:

- Thickness of glass
- Initial Deformation
- Load eccentricity, and
- Degree of damage on the surface of glass

(Luible 2004)

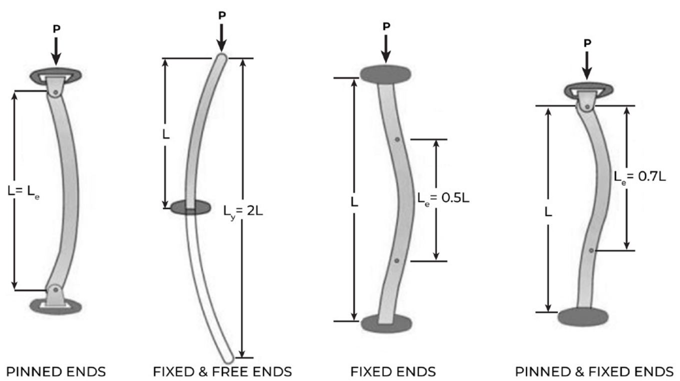


Fig. 03.3 c: Buckling of a column based on end supports
(Gharpedia n.d.)

THERMAL STRESSES

Thermal stresses occur due to sudden change in the temperature caused by different temperature at two areas in the same object at same time. This results in development of forces in the object. If these forces exceed the critical forces, the glass cracks and eventually fails.
There are 2 types of failure occurring due to thermal stresses- external and internal factor. The external occurs due to the temperature difference between outer most and innermost point of the glass column. This is based on the environment around the column and the effect is amplified in a closed shaped geometry. While, the internal factors are the temperature difference within the surface layer of the glass. This can originate due to the presence of impurities or defects in the glass.
In order to make to more susceptible to the thermal shocks, toughening of glass is done which increases the tolerance from 30 degrees to 200 degrees.

TORSIONAL BUCKLING

Torsional buckling is a sectional property and depends on the shape and size of the cross section. When the torsional rigidity is lower than the bending stiffness of the column, torsional buckling occurs leading to failure of column. Torsional Buckling results in the rotation of the horizontal plane but along the same axis due to the moments at the supports. A column having a circular profile is the strongest cross section against torsional buckling while cruciform section are the weakest against the property.

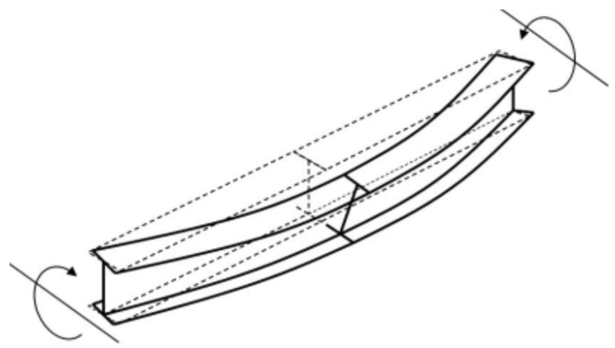


Fig. 03.3 d: Torsional Buckling of a column

03.3.3 CURRENT STATE OF ART

According to R. Nijsse & E. ten Brincke, 5 different possibilities of all glass column are possible till date- Profiled columns, Layered Tubular column, Stacked column (both horizontal & vertical stacking), Bundled column and Cast glass column as shown in Fig. 03.3 e.

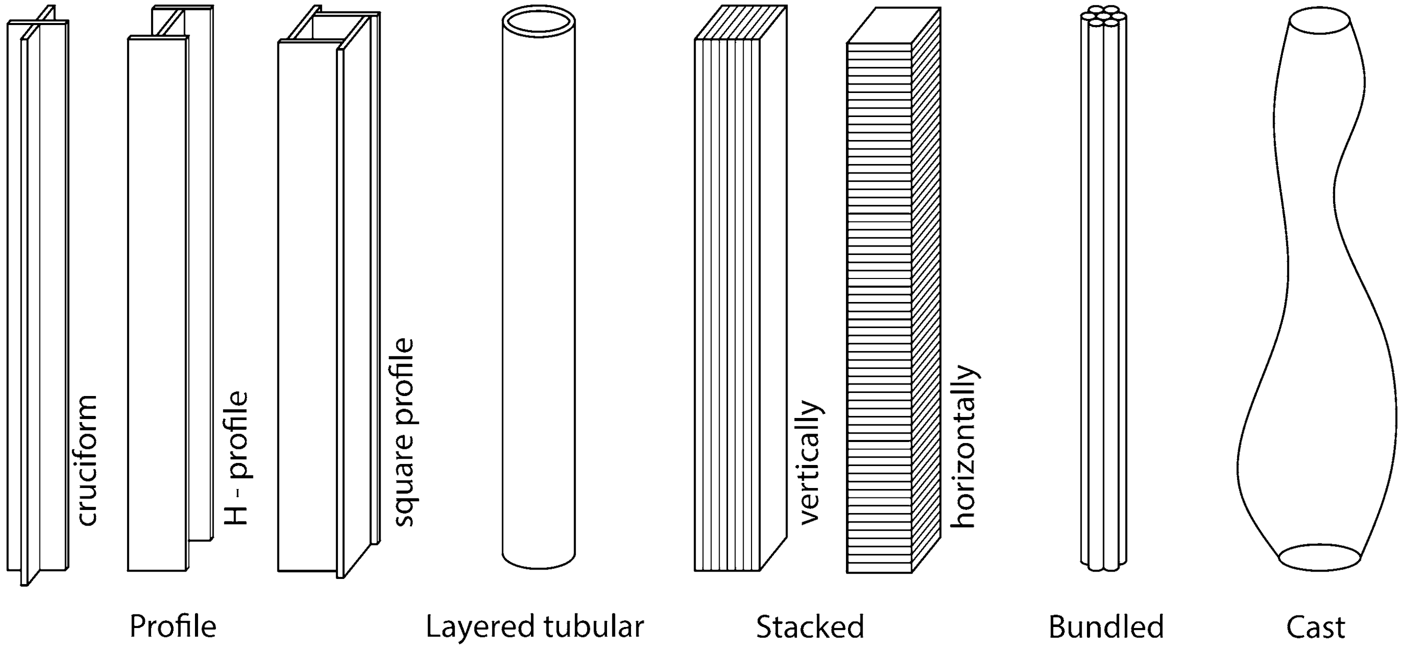


Fig. 03.3 e: 5 different types of columns defined by R. Nijsse & E. ten Brincke

These glass columns can be classified on basis of their production process as shown in Fig. 03.3f below :

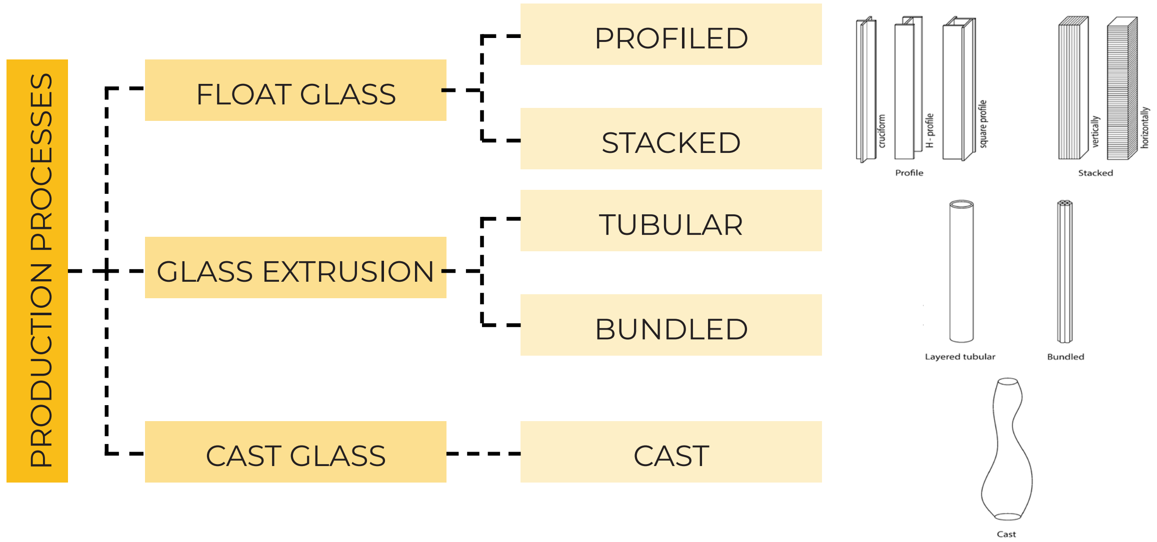


Fig. 03.3 f: Classification of columns based on production process

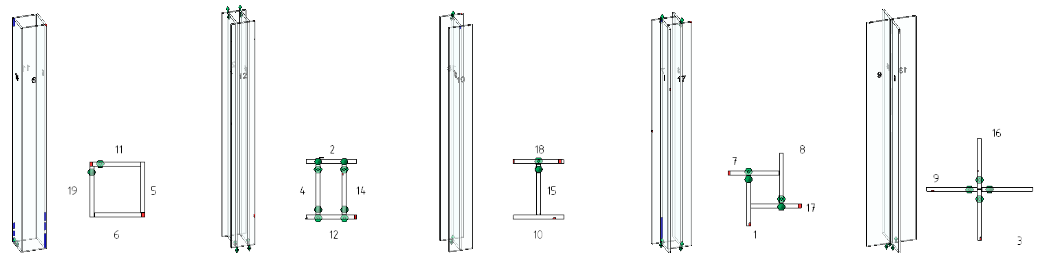
PROFILED COLUMN

Profiled Columns are made using flat sheets of glass. The sheets are cut and glued together to make different 3-Dimensional geometries offering more strength and stiffness to the column. The profiles vary from an X (cruciform), H or I shape to a closed geometry like a square or a triangular.

Cruciform profile is the only profile that has ever been realized. Out of all the columns, it is the only free-standing column, first executed in 1994 for a glass patio of St-Germain-en-Laye in France. The whole glass roof 700 m2 was supported by eight, 3.2-meter-high column (Schittich, Staib, et al., Glass Construction Manual 2012). These columns were designed 6 times stronger than the required load capacity. Same typology was used later for designing twelve 5.5 m high columns supporting the reception building of the headquarter of Danfoss in Denmark. On testing the column at 1:1 scale, it was deduced that after severe damage to the column, it can still carry more than twice the axial loads expected (Petersen and Bagger 2009).

In 2011, E. Ouwerkerk, a researcher in TU Delft conducted an experiment by testing various configurations of profiled columns and comparing them. 8mm thick sheets, 100mm wide were used in different configuration. Table 1 provides a brief comparison on the basis of the observation. Maximum compressive strength of 50.8 MPa was observed in H profile column before it buckled.

Fig. 03.3 g: Cruciform Profiled column at Danfoss Headquarters in Denmark (anne bagger 2009)



CONFIGURATIONS	SQUARE PROFILE	DOUBLE WEB PROFILE	H PROFILE	ZAPPI PROFILE	CRUCIFORM PROFILE
NO. OF PLATES	4	4	3	4	4
FAILURE LOAD (KN)	111.6	145.3	121.9	128.0	83.2
COMPRESSIVE STRENGTH AT FAILURE LOAD (MPA)	34.9	45.5	50.8	40.0	26.0
FAILURE MODE	crack	Crack & Buckling	Buckling	Buckling	Crack & Buckling

Table 3: Comparison of mechanical properties of different profiled glass columns (Ouwerkerk 2011)

STACKED COLUMN

Stacking offers a great flexibility in creating a free-form 3-Dimensional geometry using 2-Dimensional planar sheets. The stacking can happen both vertically as well as horizontally. Till date, no column of this typology has been realized, but many artists have used this idea for creating sculptures. The most famous ones are The Popano Park's water feature in Florida (Fig. 03.3 h) and De Glazen Engel (Archangel Michael) in Zwolle, Netherlands (Fig 03.3 i)

It is believed that the concept for this typology of column is influenced by The Laminata house, Netherlands. The walls of the house are made by stacking glass sheets creating a translucent facade allowing a diffused light inside the built mass. Through this case, it can be inferred that the column fabricated using this method creates an optically translucent surface due to the edges of the glass.

In 2013, a load bearing stacked column was prototyped and tested by Roy Van Heugten in Eindhoven University of Technology as a part of his Thesis (Fig 03.3 j). This is the only research that exist till date on stacked columns to the author's knowledge. (Heugten 2013)

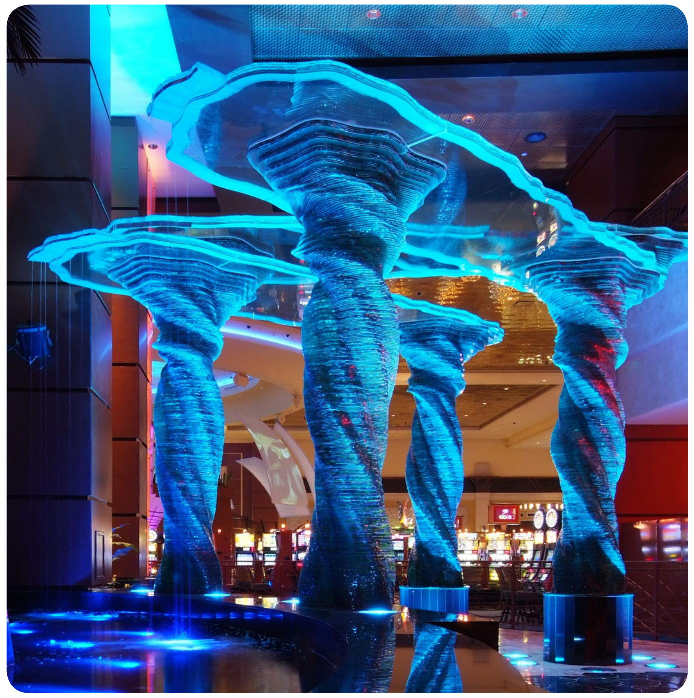


Fig. 03.3 h: Pompano's Park water feature, Florida (pinimg n.d.)

Fig. 03.3 i: De Glazen Engel (Archangel Michael) in Zwolle, Netherlands (plantagekerkzwolle n.d.)

Fig. 03.3 j: Vertically Stacked glass column

LAYERED TUBULAR COLUMN

Tubular Glass Columns are cylinders made either by extruding or by curving a flat sheet of glass. Since the column has a completely closed geometry having no edges on the surface except for top and bottom, it is the safest form of glass column. Also, circular form offers more stiffness making it better against buckling and torsion. (Heugten 2013) (Oikonomopoulou, Broek, et al. 2017)
Glass Tubes have been used as a structural member in practice but not for a column. Rather a compression only member has been designed and executed using 40 tubes on a glass atrium façade of Tower Place in London by Arup. These glass tubes are subjected to the wind load on the surface of atrium (Oikonomopoulou, Broek, et al. 2017). Steel cables were passed through these members to take up the tensile forces, subjecting the glass to compression forces only. (Akerboom 2016)
Another example that exist is a tree shaped glass structure where glass tubes are welded together using a sphere as a nodal point. The project was executed in Aachen, Germany for Glassbaum. (Akerboom 2016)

Fig. 03.3 k: Glass tubes used in facade structure of Tower Place, London

Fig. 03.3 l: Tree shaped structure in Glassbaum, Aachen (Glasbaum 2013)

BUNDLED COLUMN

Bundled Column is a collection or a bundle of extruded glass rods bonded together with a transparent adhesive to produce a unified strong cross section. The idea of bundling the rods was first conceived for ABT office in Arnhem, where 7 rods of 30mm dia were bundled together with one rod in the center and were glued together with a transparent adhesive. The column was never executed due to the limitation of bonding the tubes together. Almost two decades later, a prototype was finally built in 2017 by exploring 3 ways of bonding the tubes together as shown in fig (F. Oikonomopoulou, T. Bristogianni, et al., Developing the bundled glass column 2016)

Fig. 03.3 m: Final prototype of bundled glass column

Fig. 03.3 o: 1.5 m high column prototype

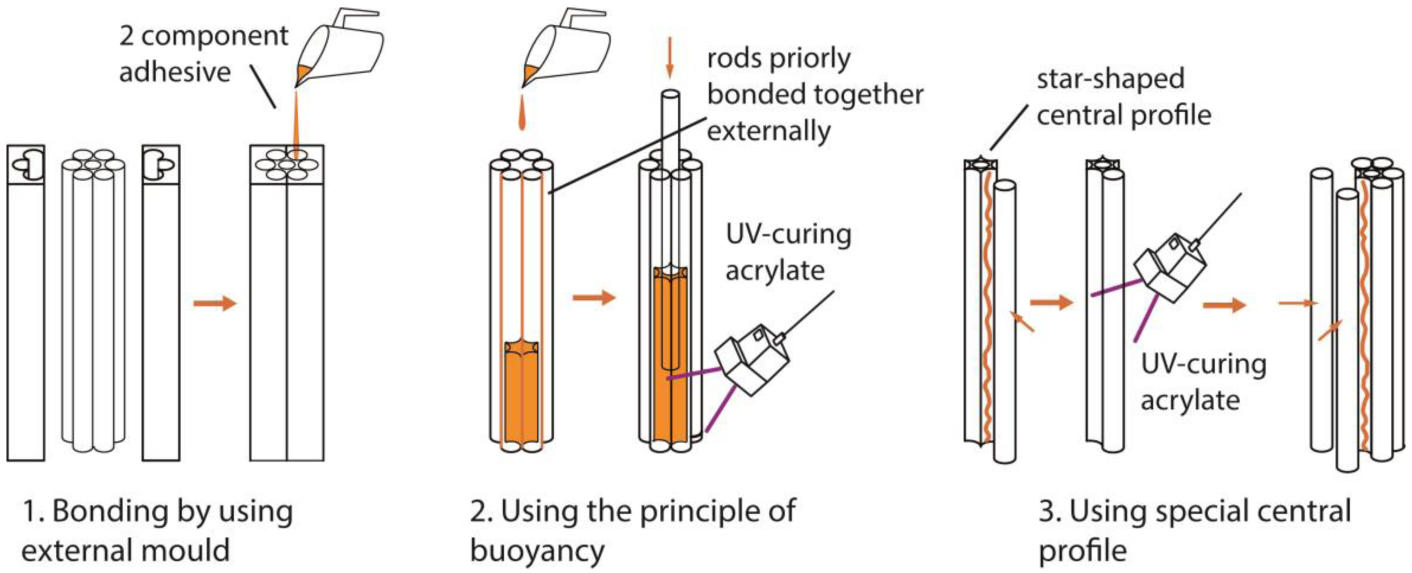


Fig. 03.3 n: Explored techniques for bonding rods together

CAST GLASS COLUMN

Though cast glass is the oldest form of fabrication in glass industry, still it's the least researched and executed. It is believed that a monolithic cast glass column is the most transparent and pure form of glass column, as it involves no adhesives, for sticking glass pieces. This typology of column allows a wide flexibility in creating complex perplex shapes giving a freedom in both shape and size.

The first design conceived for cast glass column was in 1942 for Danteum in Rome by G. Terragni and P. Lineri. These columns were never fabricated due to the limitation of cost and time involved in annealing the geometry.

Many cast glass brick have been realized for projects like Optical House, Atocha Memorial and Crystal House. Taking inspiration from them and historical columns, Akerboom, Felekou and de Vries created conceptual designs for stackable cast glass columns. Felekou created a stackable column which had pieces bonded by adhesive while Akerboom and De Vries created a dry assembly interlock able Cast Glass pieces which were stacked to create a column.

Fig. 03.3 q: Column design by (a) E. de Vries , (b) R. Akerboom

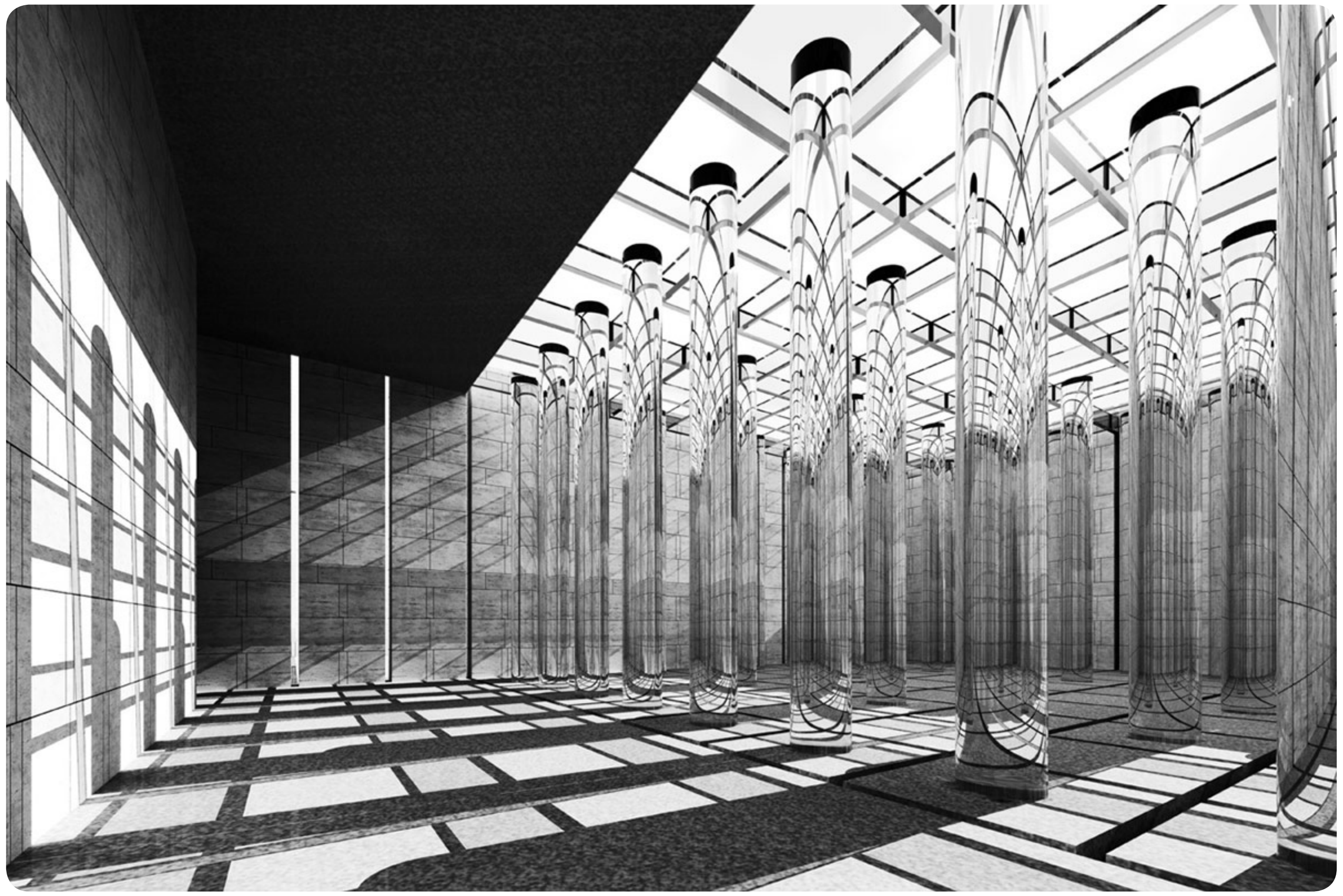


Fig. 03.3 p: Impression of Cast Glass column for Danteum in Rome (Archeyes 2016)

03.3.4 CONCLUSION

Cast glass renders a very strong potential as a material for structural columns. Many previous comparison and analysis have been done proving cast glass to be a potential candidate for a structural glass column. Some of the researches are discussed below.

F. Oikonomopoulou compared the mechanical properties of the characteristic example of all 5 types of columns in her research on Bundled columns. When loaded along axial direction, Cast glass column proved to be the strongest having a stress capacity of 128 MPa, while the second strongest was H profiled column. Table 4 provides a detailed description of the comparison.

COLUMN TYPE	X-PROFILE	X-PROFILE	H-PROFILE	TUBULAR	LAYERED TUBULAR	STACKED	CAST	BUNDLED
CROSS SECTION (mm)	449 x 449	400 x 400	116 x 100	150 diameters	120 (out) 95(interior) diameter	100 x 100	105 x 105	24
NO. OF GLASS LAYERS	3	3	1	1	2	50 horizontally	10 horizontally	3
LENGTH OF COLUMN (mm)	5500	3300	1000	4100	1500	615	650	1500
$F_{failure}$ IN AXIAL LOADING (kN)	575	430	212-255	221	137-196	525	1412	13.37
$\sigma_{failure}$ (MPa)	18.53	16.06	88.4 – 106.6	97.3	40.6- 57.9	52.5	128.0	26.4
APPLICATION	Danfoss Office	St-Germain-en-Laye	Academic Research	Academic Research	Academic Research	Academic Research	Academic Research	Academic Research

Table 4: Comparison of mechanical properties of the characteristic example of all 5 types of columns (Oikonomopoulou, Broek, et al. 2017)

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

Table 5: Comparison of all 5 column types on various aspects by (Vries 2018)

De Vries in her Master Thesis compared all the 5 types of column on various parameters of aesthetic, financial, mechanical properties and sustainability. She added a new class of column which was Cast Elements formed by stacked pieces of cast glass geometries. In her comparison, cast glass columns and cast elements columns have a more positive impact in Architectural, Mechanical and Sustainable aspect while least in Financial due to high Manufacturing cost and time. Table 5 depicts the comparison done by her.

Designing a glass column is very similar to designing a column with other materials. A normal column is designed for resistance against Buckling and Torsion by the virtue of its sectional properties and the shape of column. A thick circular section is the most favorable and optimal shape for designing a column. Glass column are also designed using same criteria. But due to the brittleness of material, peek stresses are the only extra consideration while designing them. These peak stresses could originate at the edges or connection points having asymmetrical loading. Thermal shocks like fire can also originate these localized stresses.

Profiled columns are the only columns that have been realized in practice due to the ease of manufacturing and stacking float glass sheets. But, looking at the analysis of F. Oikonomopoulou and De Vries, it is evident that Cast Glass Columns are strongest because of their solid geometry which makes its more resistant to buckling by making it stiffer. Also, the optical properties are way better in comparison to others typologies. Presence of no adhesive or glue makes it reusable and recyclable. Casting offers high flexibility in shape and size but the only limitation is the manufacturing cost and time. If the fabrication of casting is made easier and less time consuming Cast glass can offer a wide range of possibilities in Glass Columns.

STRESS RELEASE AND ANNEALING OF GLASS

Chapter 03.2 and 03.3 indicated the limited use of cast glass in the construction industry is linked to majorly two issues. The first being, the meticulous time-consuming annealing process and second is the skilled labor required. These issues correspond to high manufacturing cost. But the major question that arises is, "why do we require a time-consuming annealing/ cooling process and how can we reduce it". In order to understand, we have to first understand what is annealing.

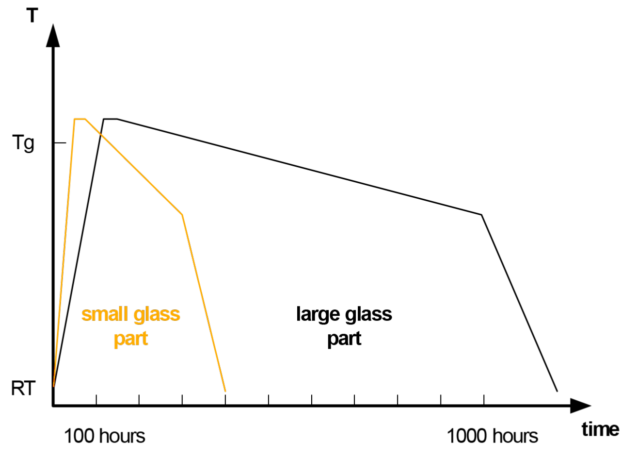


Fig. 03.4 b: Small v/s Large glass piece in regards to annealing time (SchottAG 2004)

03.4.1 WHAT IS ANNEALING?

As stated in Wikipedia, "Annealing of glass is a process of slowly cooling hot glass objects after they have been formed, to relieve residual internal stresses introduced during manufacture."
When glass cools from molten form to a solid, it contracts the exterior surface towards the hot interior. This contraction is a form of strain and this strain causes stresses to develop in it. Till the time the cooling is happening, strain is present leading to the development of more stress. (Sawyer n.d.) The magnitude of these stress and strain are highly determined by 3 main factors:

- Rate of cooling during the annealing range
- Coefficient of expansion of glass, and
- Thickness of the section being annealed

(Shand and Armistead 1958)

Since the property of glass and thickness of the section of geometry remains constant in a cooling process, the best way of avoiding these stresses becoming too high is by cooling as uniformly as possible in the region of annealing range. Fig 03.4 a depicts the most ideal or commercial way of cooling down a molten glass object.

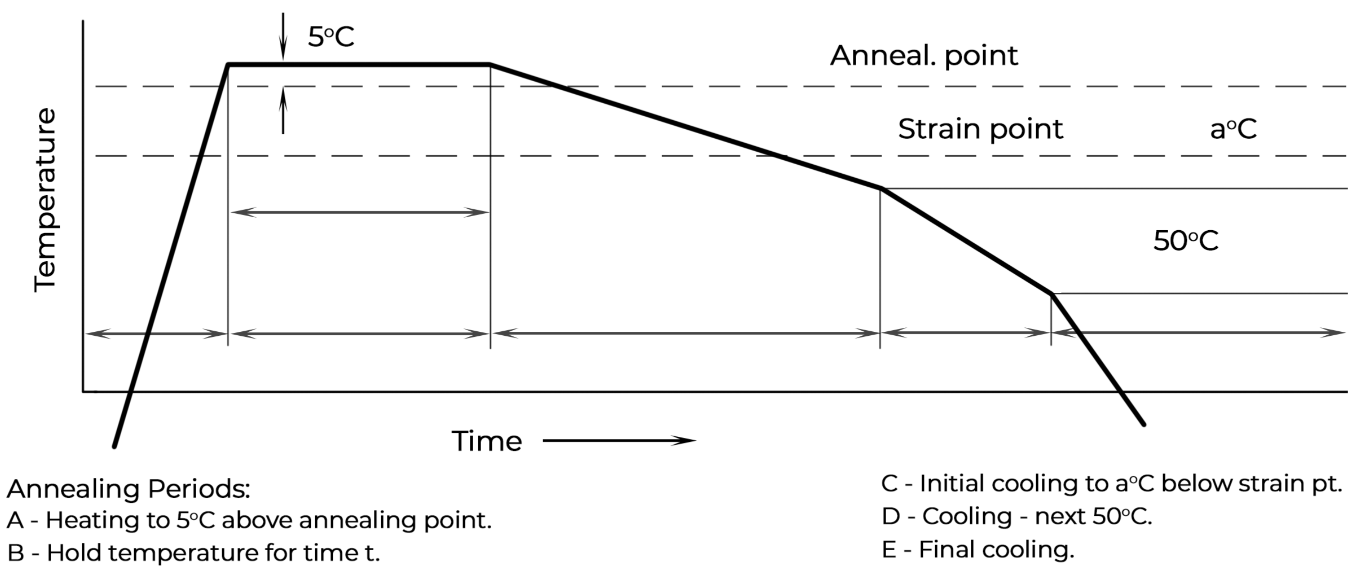


Fig. 03.4 a: Schedule (ideal) for commercial annealing- ordinary ware (Shand and Armistead 1958)

Fig 03.4 b illustrates the difference of time required for annealing a small and a large glass piece.

ANNEALING POINT

The temperature at which transition of glass occurs from plastic behavior to elastic behavior. (Sawyer n.d.) At this point the glass is viscous enough to relax any stresses induced in just few minutes. (Shelby 2005). Every family of glass based on composition has different annealing point and is inversely proportional to the viscosity of the glass. (Shand and Armistead 1958). Fig 03.4 c below shows the relation of viscosity as a function of temperature.

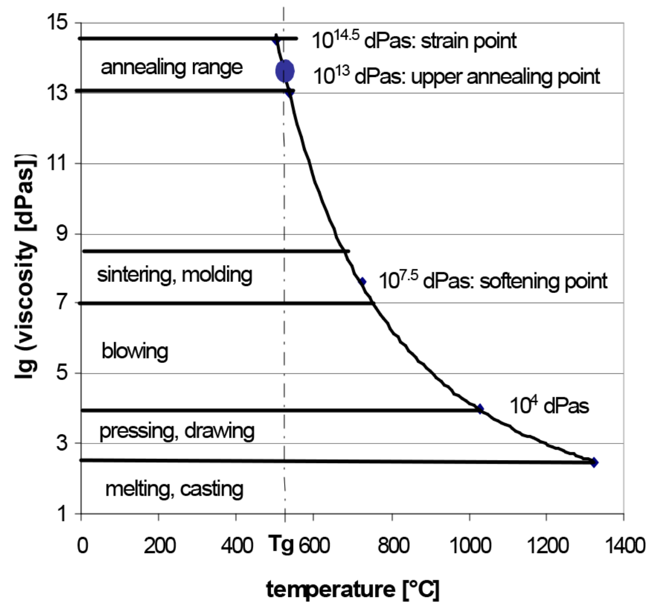


Fig. 03.4 c: Relation of Viscosity as a function of temperature (SchottAG 2004)

STRAIN POINT

The temperature at which the same stress present during anneal point is reduced to acceptable value in 4 hours is known at strain point
The most essential part of the process is the ability to achieve uniform temperature throughout the object at the anneal point and then cooling it down in a manner that the temperature difference throughout the object is not more than 10°F / 5°C. A very good annealing will leave a stress less than a 100psi while anything near 100psi or above can be considered dangerous. (Sawyer n.d.)

03.4.2 THICKNESS V/S ANNEALING TIME

In the parameters affecting the stress formation by Shand and Armistead, thickness of the object plays a very important role. But according to F. Oikonomopoulou, in practice, the heat flow required for establishing a desired temperature is influenced by various other factors as well- shape and mass distribution of geometry, sides exposed for cooling, presence of other thermal masses in the furnace and shape and characteristics of the furnace itself. (F. Oikonomopoulou, et al. 2017) There are many guides regarding the calculation of annealing cycle but all of them are very specific to a case. Considering that the heat transfer of avoiding stress formation is calculated on basis of above factors, still the annealing cycle of a 3-dimension geometry depends majorly on practical experience. Hence, creating a formula or expression would be illogical.

Bullseye Glass, a U.S. based company, has formulated an annealing chart for a flat slab of uniform thickness on the basis of theories of McLellan and Shand, and their practical experiences

03.4.3 HOW CAN WE REDUCE ANNEALING TIME?

Thick monolithic cast glass pieces weighing several tons have existed since Roman times. Objects were created by breaking the monolithic piece into small chunks and post production was done to create desired shapes. These monolithic pieces used to take hundreds of days to anneal and still takes the same amount of time. Over the years, only things that have changed is the development in chemical composition of the glass and better quality of furnace and equipment but the effect of the development is still not significant.

CORNING MIRROR OPTIMIZATION AND ANNEALING TIME

To reduce the time of annealing, one of the major breakthroughs in the world were illustrated by Corning. Corning has a history of 80 years in production of mirror blank for telescopes. Currently the company holds the record for producing the largest contemporary monolithic cast glass pieces of 8.4 m diameter weighing 16 tons (F. Oikonomopoulou, et al. 2018). They were able to anneal this big glass piece in only 3 months. The 2 major development that happened were the optimization of the shape of the mirror and the use of Spin casting Technology.

Until mid 1930's, telescope mirrors were made of solid glass disk and the largest one was 2.5m in diameter which took exactly a year to anneal. In 1936, first ever glass structure was structurally optimized for the Hale telescope in Mt. Palomar, having hexagonal cores, which was double the size (5m) of the largest glass blank until then. Pyrex glass was used to cast this glass piece and the mould was made of hexagonal shaped Silica firebricks (ceramics) bolted to a steel plate. The optimized shape was able to accommodate for 50% weight reduction and it took only 10 months to anneal this 15 tons of glass.

Further, in 1979, Corning was able to cast a 2.4m diameter glass blank in only 3 months. The mirror which earlier took a year. This blank was a mirror for Hubble Telescope and the optimization led to 80% weight reduction.

Currently, the company was able to cast the largest ever glass monolithic piece in the world of 8.4 m in diameter in just 3 months by further optimizing the shape and using spin casting technology for giving the curvature to the lens. 90% weight reduction was achieved for this Giant Magellan Telescope. (F. Oikonomopoulou, et al. 2018)

Thickness of slab (mm)	12	19	25	38	50	62	75	100	150	200
Anneal Soak Time @ 482°C (hours)	2	3	4	6	8	10	12	16	24	32
Total Min. Cooling Time (hours)	5	9	14	28	47	70	99	170	375	654

Table 6: Annealing time of a flat slab of uniform thickness on the basis of theories of McLellan and Shand (BullsEye Glass n.d.)

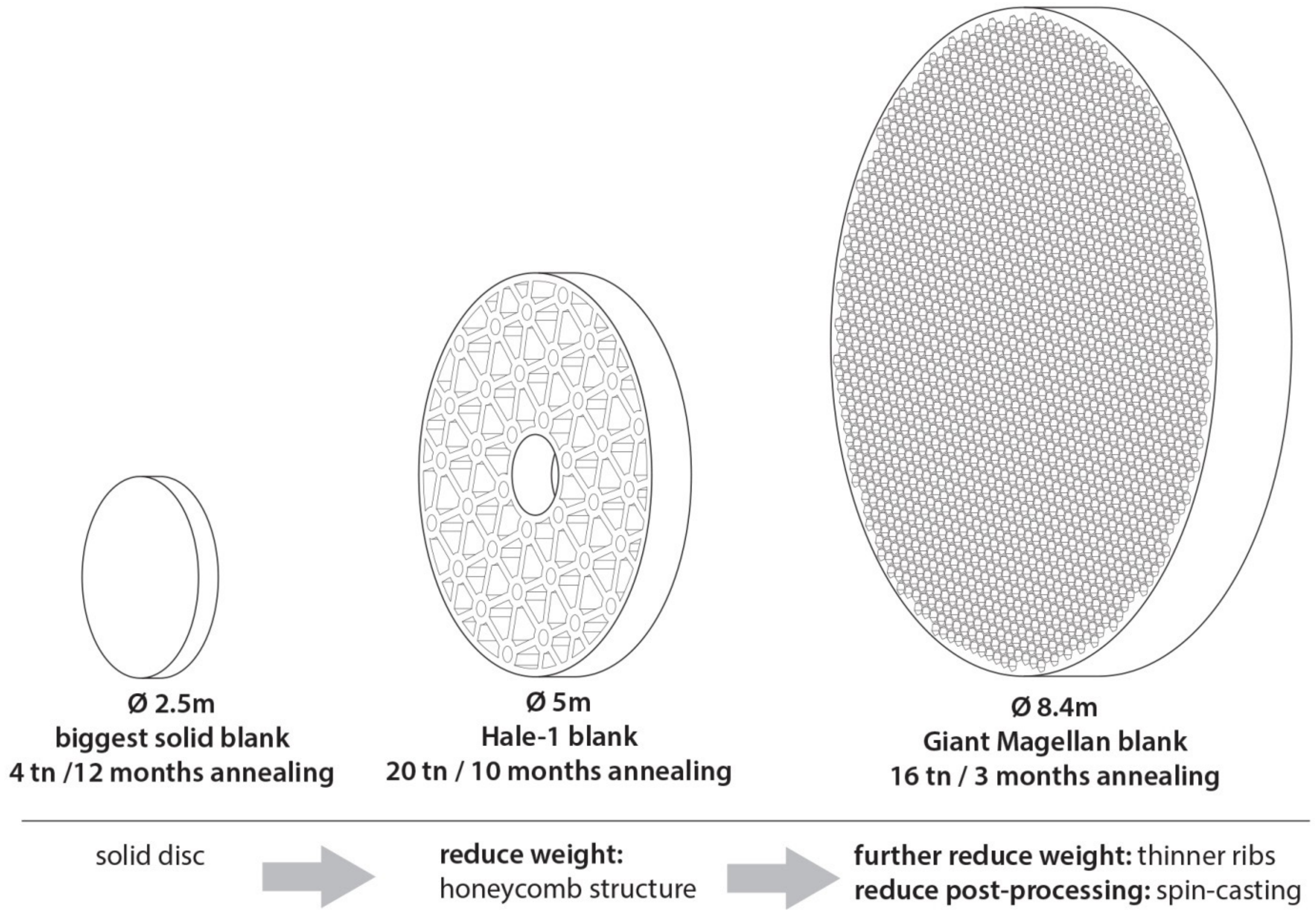


Fig. 03.4 d: Evolution of the cast mirror blanks in size due to smart geometry and manufacturing process (F. Oikonomopoulou, et al. 2018)

03.4.4 FUTURE OF SHAPE AND SIZE OPTIMIZATION IN CAST GLASS

Structural glass is currently in a very per-mature stage because of its dependency on the fabrication process. Glass structures usually exist out of float glass, majorly due to low/affordable cost and production time as compared to other fabrication methods. But it offers many challenges due to its planar geometry. While cast glass offers great potential in creating diaphanous structural elements of desired shape and cross-section that can overcome the limitations of float glass.

The integration of automated processes for forming glass has resulted in higher manufacturing speed and material processing for Float Glass, so standardizing production method and mass production can benefit cast glass industry as well. But shape and size also play an important role in reducing both time and cost. Currently, the realized structural elements in cast glass mimics the design language and details of old monuments made of stones where thick monolithic chunks were used. Idea of using improved optimized geometries like that of hexagonal ribbed glass mirrors can greatly influence the cast glass industry. These shape and size optimization can reduce the use of material making it light weight yet strong enough to create glass structures. Homogeneous sections of the mass can be optimized for even cooling of geometry. This can greatly influence the cost and fabrication time for using cast glass structural elements making it more practical to use in architectural industry. Geometry can also be used to cater to the aspect of circularity and sustainability by creating demountable, reusable interlocking structural elements. (F. Oikonomopoulou, et al. 2018)

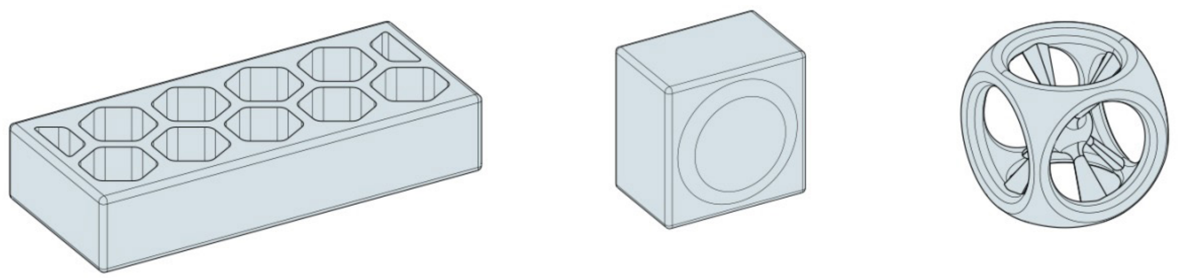


Fig. 03.4 e: Schematic illustration of new concepts for structural cast glass components by F. Oikonomopoulou (F. Oikonomopoulou, et al. 2018)

03.5 FABRICATION OF CAST GLASS (MOULDS)

In order to fabricate cast glass elements, molten glass is added to moulds. The material of these mould is dependent on the production size and the accuracy required for the casted glass object. This is driven by the cost and time as well.

03.5.1 CLASSIFICATION OF MOULD

There are two types of moulds based on the re usability and the cost or level of precision required:

1. Disposable Moulds
2. Permanent Moulds

DISPOSABLE MOULDS	PERMANENT MOULDS
1. These moulds are used for single use/ prototyping or small batch casting.	1. These moulds are used for large batch of production.
2. They are usually made of cheaper materials -Silica Plaster and Alumina-silica fiber.	2. They are made of more durable expensive material- steel or Stainless steel and Graphite
3. The finished product acquires a translucent rough skin and requires post processing for a finished transparent surface.	3. The moulds are coated with an easy release agent – boron nitride or graphite, which also helps in acquiring a clean transparent finished surface to the final product.
4. It is best suitable for Kiln casting due to brittle behavior of the material at high temperature. So, the moulds are not suitable for quenching, hence, hot forming is not recommended.	4. In order to be time efficient, Hot forming (Melt-quenching) is recommended process for casting.
5. These moulds have fixed geometry and doesn't require adjustability in the mould.	5. These moulds can have adjustable geometry to provide more flexibility in production process. Steel mould also can be of press mould type.
6. The level of precision in silica plaster is low or moderate but high in Alumina-silica fiber.	6. Level of precision is high in fixed moulds, very high is press mould and moderate/ high in adjustable moulds
7. Moulds are heated along with glass inside the furnace.	7. Moulds are preheated to avoid surface chills before pouring molten glass.
8. Complexity of the desired shape doesn't affect the cost of mould	8. Complexity of the desired shape increases the cost of the moulds.

(F. Oikonomopoulou, et al. 2018)

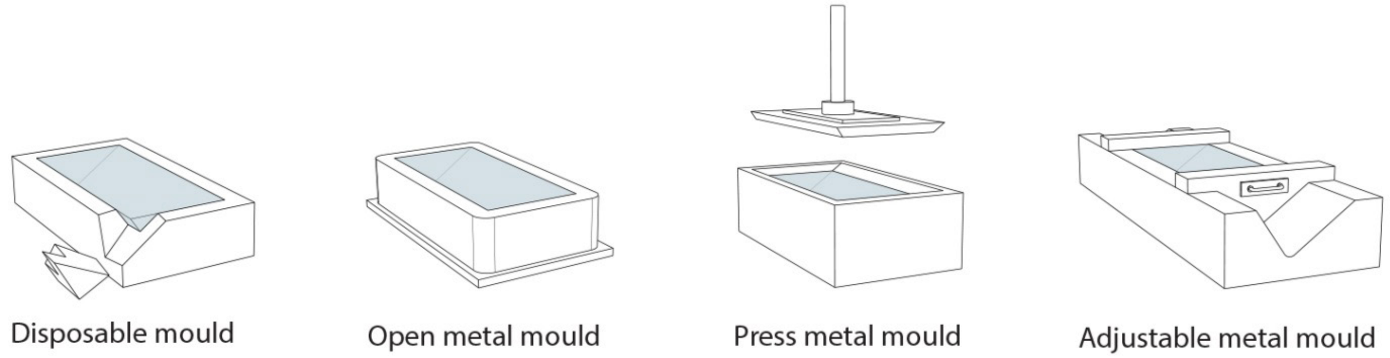


Fig. 03.5 a: Illustration of the most common mould types by F. Oikonomopoulou (F. Oikonomopoulou, et al. 2018)

03.5.2 CUSTOMIZED GEOMETRY AND ADDITIVE MANUFACTURING

From the above comparison between disposable and permanent mould it is clear that for complex shapes that require numerous different shape/sizes, disposable mould is more appropriate and for regular geometry disposable mould might work as well. Steel moulds or graphite moulds would be accurate/precise and would ease the production but are very expensive for one time use. Hence, steel moulds are not at all a feasible option. While disposable moulds- crystal cast moulds have a very laborious process of creating moulds (lost wax technique) and is not at all precise. Designing optimized structural geometries, discussed in last chapter, require a very precise/accurate method which is less laborious and time consuming and feasible in construction industry. Hence, conventional techniques cannot fulfill the required needs.

In past few decades, there has been a rise in fabrication of complex shapes designed and optimized using computational tools in many other material industries. Innovation in the field of Additive manufacturing has been useful is realizing these shapes. Using the technology for designing moulds can be useful in eliminating all the limitations and making the idea of customized geometry more feasible.

03.6 ADDITIVE MANUFACTURING

“Manufacturing complexity is free” is one the ten principles stated in the book Fabricated: The new world of 3D printing. (Lipson and Kurman 2013).
3D printing, also known as Additive Manufacturing, refers to various processes used to fabricate a 3-Dimensional geometry, by addition of successive layers using a machine robot, which collects electronic data produced by a 3D model in a computer.

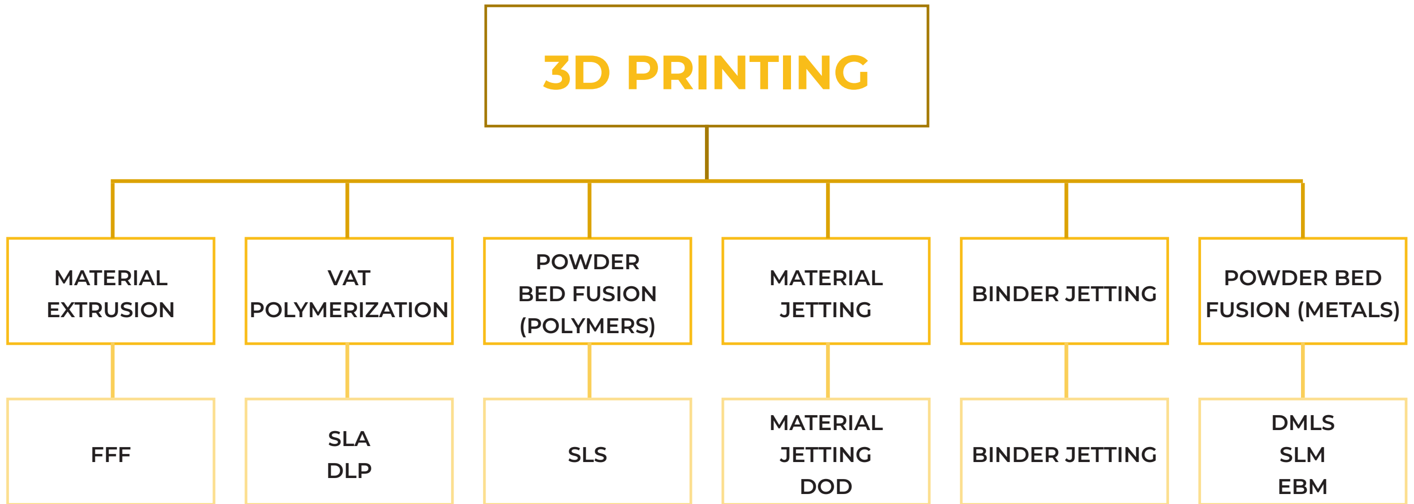
In its original sense, 3D printing referred to a process which sequentially deposit material onto a powder bed with inkjet printer heads. It is recently that the term has expanded to include a wide variety of processes like extrusion, sintering based processes etc.

Additive manufacturing enables a more flexible design approach in manufacturing industry. Objects can be produced having almost any geometry. The printed object requires least or no post processing. The process also doesn’t rely on any expensive tooling or trained human labor. But to all these advantages, there are downsides as well. The biggest limitation is its production capacity and speed of printing. In comparison to the traditional industry-based production techniques, additive manufacturing is good for prototyping and can never overcome mass production processes. Also, the process produces anisotropic objects, hence in many cases, the printed geometry doesn’t exhibits the property in terms of strength of the material(Redwood, et al. 2018).

The casting process of Arup's steel optimized node, discussed in this chapter, using 3D printing sand mould is considered to be the inspiration for this research. This chapter investigate sand printing (binder jetting technique) and compares with alternate additive manufacturing techniques and concluding with best method for this research.

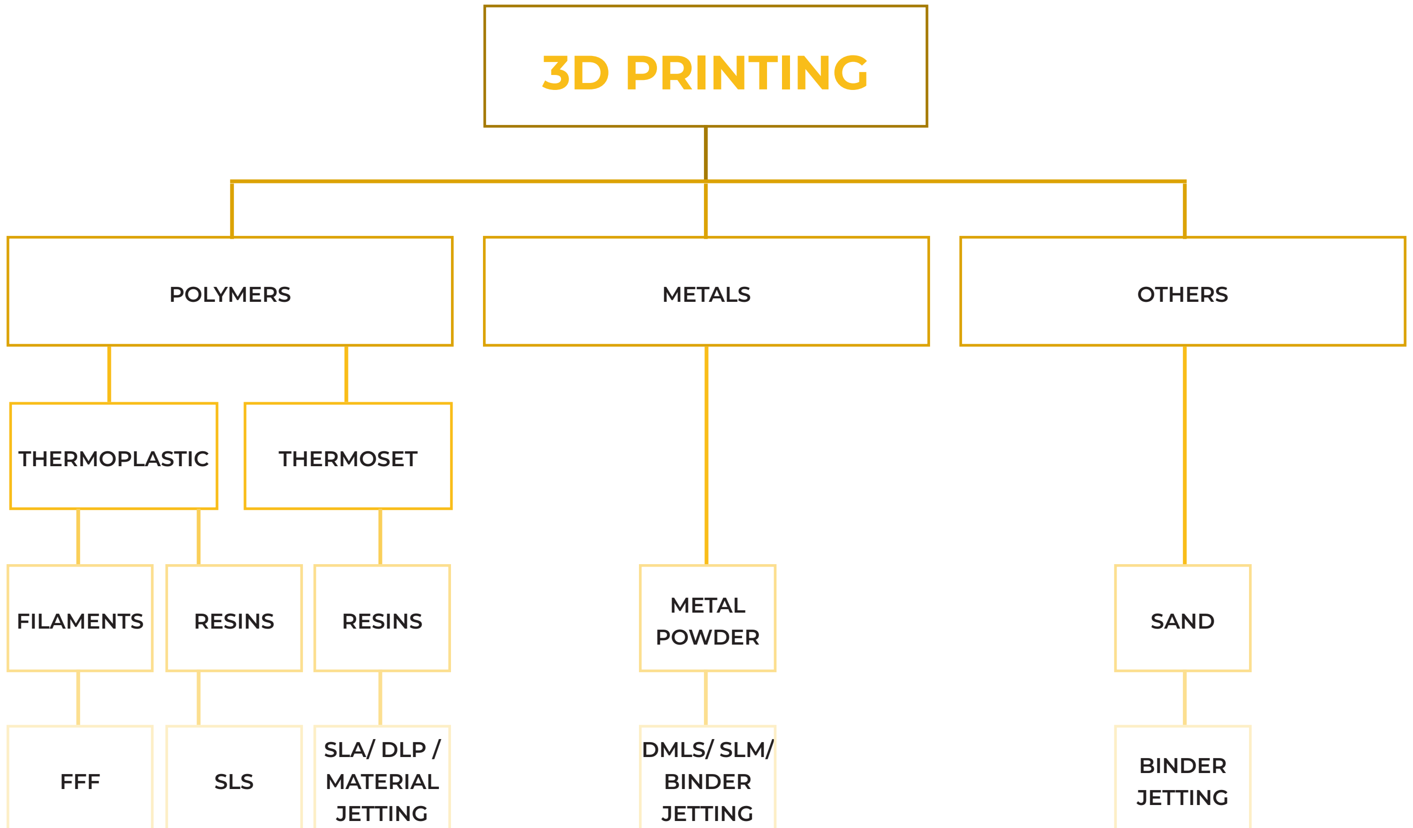
03.6.1 TYPES OF 3D PRINTING

According to the book “The 3D Printing Handbook”, Additive Manufacturing can be divided into 6 categories:

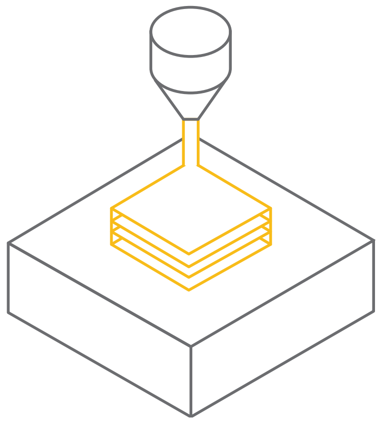


(Redwood, et al. 2018)

Additive manufacturing can also be classified on the basis of materials:



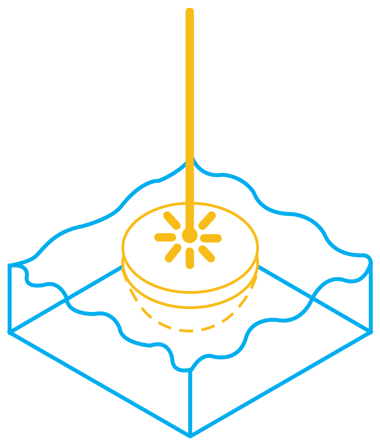
(Redwood, et al. 2018)



1. MATERIAL EXTRUSION

Description:
Additive Manufacturing process in which material is selectively dispensed through a nozzle or orifice

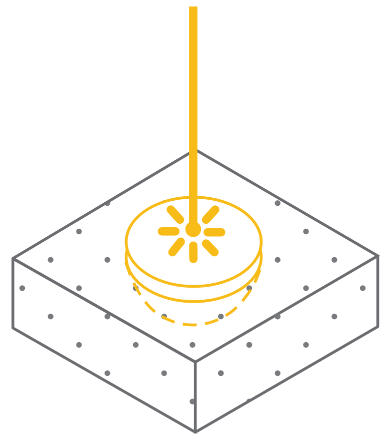
Technologies:
FFF: Fused Filament Fabrication, more commonly reffered to as Fused Deposition Modeling (FDM)



2. VAT POLYMERIZATION

Description:
Additive manufacturing process in which a liquid photopolymer in a vat is selectively cured by light-activated polymerization.

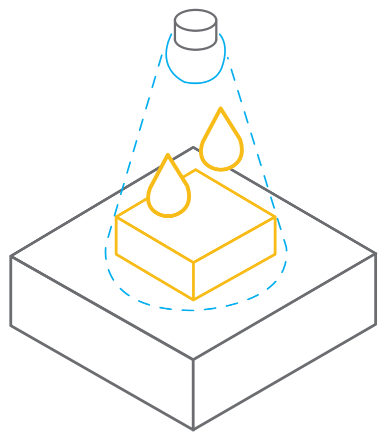
Technologies:
Stereolithography (SLA) ,
Direct Light PProcessing (DLP)



3. POWDER BED FUSION

Description:
Additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.

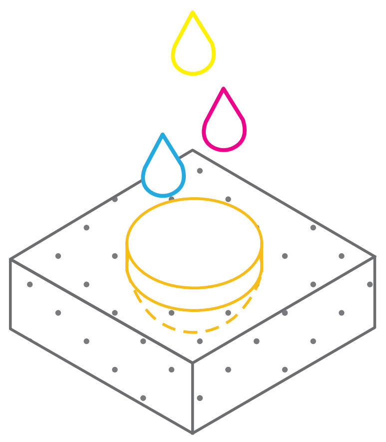
Technologies:
Selective Laser Sintering (SLS), Direct Metal Laser Sintering (DMLS),
Selective Laser Melting (SLM),
Electron Beam Melting (EBM)



4. MATERIAL JETTING

Description:
Additive manufacturing process in which droplets of material are selectively deposited and cured on a build plate.

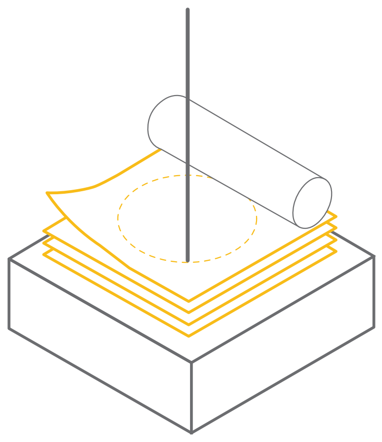
Technologies:
Material Jetting (MJ),
Drop On Demand (DOD)



5. BINDER JETTING

Description:
Additive manufacturing process in which a liquid bonding agent selectively binds regions of a powder bed.

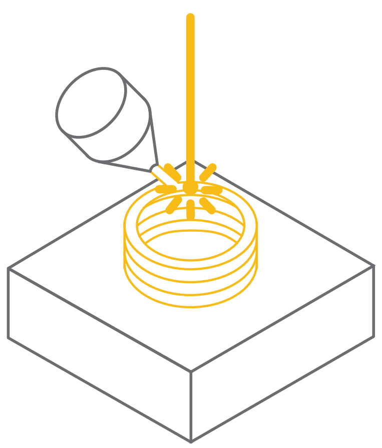
Technologies:
Binder Jetting (BJ)



7. SHEET LAMINATION

Description:
Additive manufacturing process in which sheets of material are bonded to form a part.

Technologies:
Ultrasonic Additive Manufacturing (UAM), Laminated Object Manufacturing (LOM)



6. DIRECT ENERGY DEPOSITION

Description:
Additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited.

Technologies:
Laser Engineering Net Shaping (LENS),
Laser Based Metal Deposition (LBMD)

03.6.2 COMPARITIVE ANALYSIS

PROCESS OF 3D PRINTING	MATERIAL EXTRUSION	VAT POLYMERIZATION	POWDER BED FUSION	MATERIAL JETTING	BINDER JETTING	POWDER BED FUSION
MATERIAL GROUP	Thermoplastic filaments	Photopolymer resin	Thermoplastic powder	Photopolymer resin	Sand or Metal powder	Metal Powder
COMMON MATERIALS	PLA ABS PEI TPU	Standard Castable Transparent High Temp.	Nylon 6 Nylon 11 Nylon 12	Standard Castable Transparent High Temp.	Stainless/ Bronze Silica (sand casting)	Aluminum Stainless Steel Titanium
DIMENSIONAL ACCURACY	+/- 0.5 mm	+/- 0.5 mm	+/- 0.3 mm	+/- 0.1 mm	+/- 0.2 mm (metal) +/- 0.3 mm (sand)	+/- 0.1 mm
SUPPORT MATERIAL	Dissolvable available	Support required	No support required	Dissolvable	No support required	Support required
STRENGTH	• Low cost • Non-commercial functional parts	• Smooth surface finish • Fine feature details	• Functional parts, good mechanical properties • Complex geometries	• Best surface finish • Full color and multi-material available	• Low Cost • Large Build volumes • Functional metal parts	• Strongest, functional parts • Complex geometries
WEAKNESS	• Limited dimensional accuracy for small parts • Visible print layers	• Brittle • Not suitable for mechanical parts	• Longer lead times • Higher cost than material extrusion for functional application	• Brittle, not suitable for mechanical parts • Higher cost compared to Vat Polymerization	• Mechanical properties not as good as metal powder bed fusion	• Small build sizes • Most expensive of all
COMMON APPLICATION	• Electrical/Housing enclosures • Prototyping • Jigs and fixtures • Investment Casting patterns	• Injection mold-like prototypes • Jewelry • Dental Application • Hearing aids	• Functional polymer parts • Complex ducting (hollow) • Low run part production	• Injection mold-like prototypes • Low run injection molds • Medical models	• Functional metal parts • Sand casting • Sand moulds for metal casting	• Automotive & Aerospace functional metal parts • Medical • Dental

Table 7: Comparative Analysis of all types of 3D printing technologies based on inferences from “The 3D Printing Handbook”

03.6.3 SELECTION CRITERIA

In order to cast a section of optimized geometry of a column designed on basis of stresses and loads following aspects need to be served:

- Precision of moulds
- Low cost
- 3D printed material should be able to sustain high temperatures for a prolonged period of time.
- No support or dissolvable supports
- Smooth surface or treatable surface

Looking at the comparative analysis above (Table. 7), Binder Jetting seems to be most promising. Both sand and Metal can take high temperatures, but sand is cheaper and widely available. Looking at the current industry applications of the process, sand printing is used to cast complex metal objects at temperature way higher than one required for glass. Also, the grainy texture of the sand mould can be treated by dipping the mould in any material. The process doesn't require any support for complex geometries as well.

Hence, Binder jetting process with sand as material will be further investigated in this research to produce moulds for casting glass.

03.6.4 3D PRINTED SAND MOULD PRODUCTION

Recently, the idea of hybrid casting has taken a leap in the market. Instead of directly printing the geometry from materials which are still unfeasible for being printed, negatives in form of moulds are being printed. Also, for sand foundries, which require a physical pattern to create a core or mould, now can economically design moulds directly from CAD data.

ExOne and Voxeljet are the 2 famous European companies that have recently started designing 3D printers based on Binder Jetting process specifically for the use of sand printing. Furan binder also know as furfural resin is the most commonly used binder to bind the sand particles. The printer comes in various sizes depending on the need. The largest monolithic piece that can be printed is 4000 x 2000 x 1000 (L x B x H) (Voxeljet 2018)

The process of printing starts with transferring the CAD data to the machine. Sand premixed with acid is applied to the build platform in the job box. Sand layer is smoothened by a leveler maintaining the layer thickness. A printing head applies furan binder on basis of CAD data. The build platform is lowered by a layer. The process of spreading sand and applying binder is repeated layer by layer until the geometry is completed.

The job box containing the sand is removed from the printer. The extra unbound sand is sucked and reused for future prints. Brushes and compressed air are further used to intensively clean the surface of the geometry to produce the final product.

The production technique can handle very complex geometries, including undercuts and thin walls. The main requirement for creating moulds is a path to easily extract all the loose sand from the cavities. The printed mould can achieve an accuracy of 0.1mm. (Voxeljet 2018)

TYPES OF BINDERS:

1. Furan Binder
2. Phenolic Binder
3. Silicate Binder
4. Aqueous-Based Binder

(3D Printing Binders n.d.)

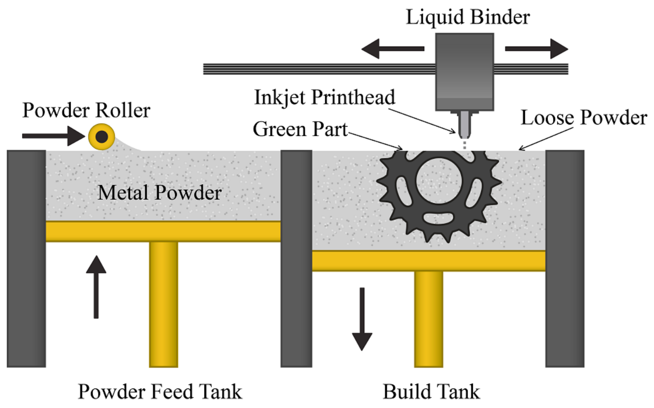


Fig. 03.6 b: Schematic diagram of Sand Mould 3D printing (Binder Jetting) (Sand 2017)

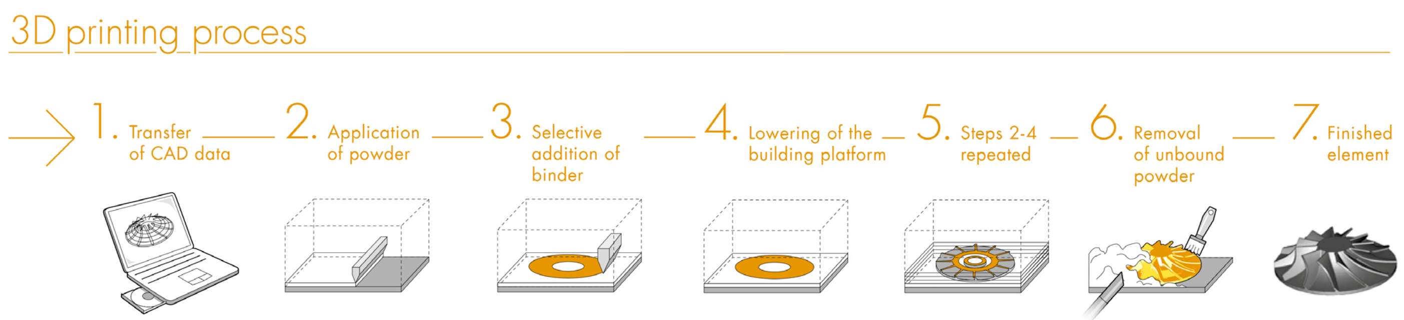


Fig. 03.6 a: Illustration of step by step procedure of sand casting of metal by (Voxeljet 2018).

03.6.5 APPLICATION OF SAND PRINTING IN ARCHITECTURE

1. ARUP – OPTIMIZED STEEL NODE

Arup recently in 2016 fabricated one of the steel nodes of a tensegrity structure housing 1600 nodes having 1200 design variation which were topologically optimized. The structural designer was able to achieve 75% weight reduction of the node by optimization. Since, each node was different in itself, mass customization and free form of the geometry led to exploration of unconventional fabrication technologies. The company created a prototype first using direct metal laser sintering also known as metal printing. But due to lack of certification, size limitation and relatively high cost, another fabrication technique was used. A satisfactory amalgamation of latest CAM technology and traditional industry proven casting process was used to cast this metal node in a 3D printed sand mould. 3Dealise was the company responsible for designing the moulds and printing it using ExOne printer. (Galjaard 2017)

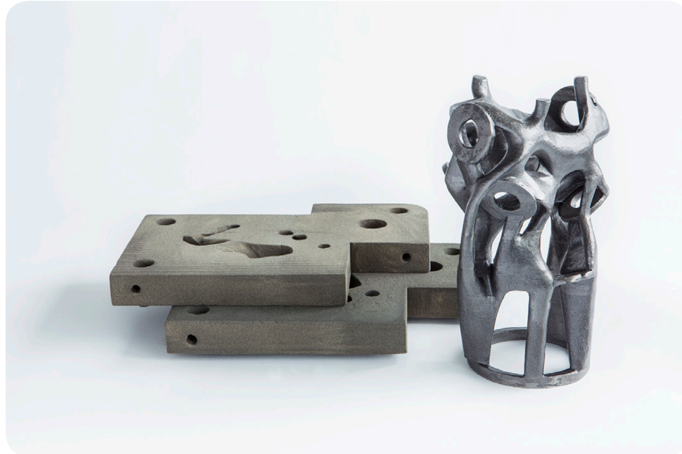


Fig. 03.6 c: Metal casted node in a 3D printed sand mould designed by Arup (Galjaard 2017)

Fig. 03.6 d: 3D printed sand mould designed and fabricated by 3Dealise for casting a metal node (Galjaard 2017)

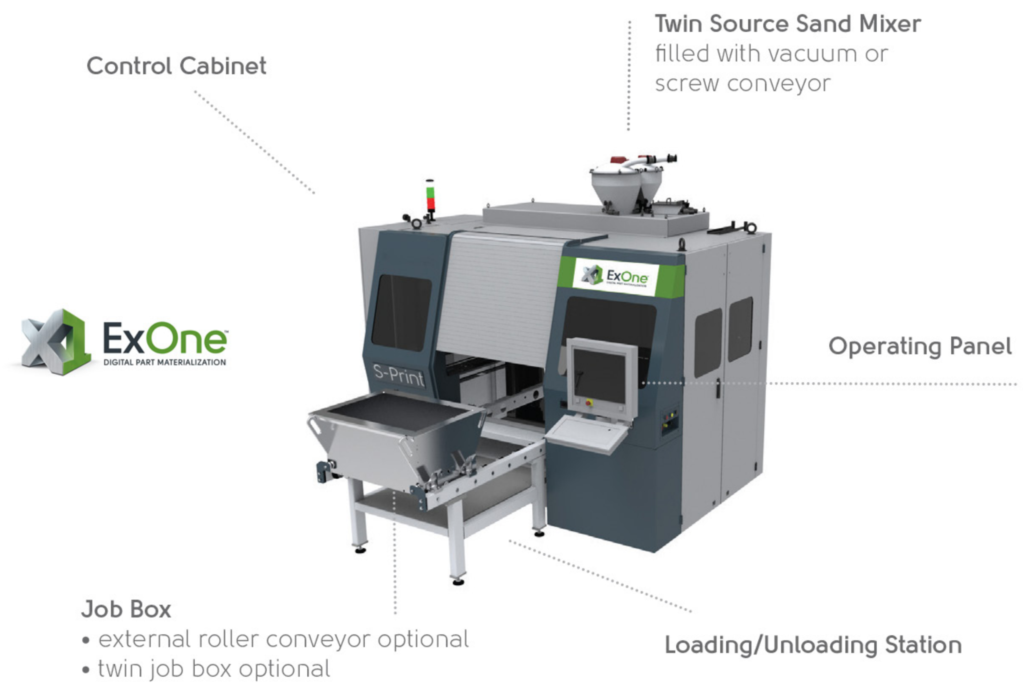


Fig. 03.6 e: ExOne printer- used for printing moulds by 3Dealise depicting different elements of the printer

2. EMERGING OBJECTS- QUAKE COLUMN & INVOLUTE WALL

In 2014, an earthquake resistant column was designed by Emerging Objects for a seismic zone like Peru. Masonry principles of traditional Incan ashlar were explored to design a dry-stone wall, where each stone piece is designed to interlock perfectly with its neighboring pieces. Since the geometry is challenging and all pieces are unique in itself, 3D printing was used to create these precise blocks of sand. Binder Jetting technology was used to print these 3-dimensional blocks.

Same technology was used to print the Involute wall, a prototype for the study of thermal mass and acoustic dampening in a massive 3D-printed sand structure (Rael 2018).

Fig. 03.6 g: Hollow inter lockable sand printed pieces for dry assembly (Rael 2018)

Fig. 03.6 f: Sand 3D printed Quake Column by Emerging Objects (Rael 2018)

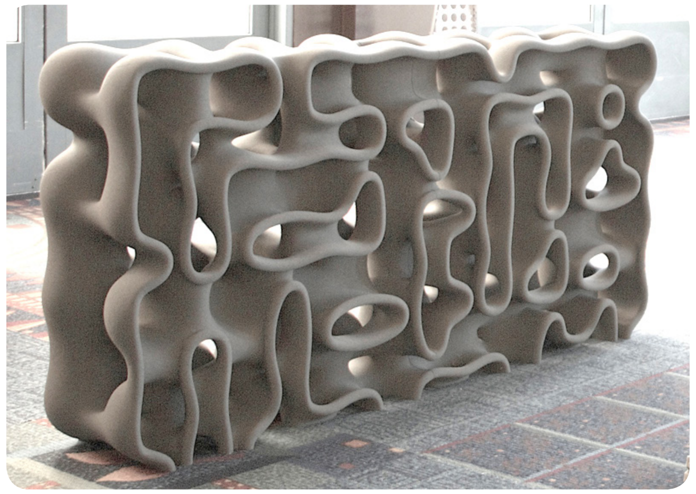


Fig. 03.6 h: Sand 3D printed Involute wall (Rael 2018)

3. DBT- SMART SLABS (ETH ZURICH)

On basis of the experiment conducted in 2016 for fabricating a small topology optimized concrete slab, Design Building Technology (DBT) was able to fabricate a smart slab for the DFAB HOUSE in 2018. The smart slab is a 78 sq. meter prestressed concrete slab discretized into 11 pieces, each piece 7.4 meter in length.
The geometry of the slab is structurally optimized for the challenging load case, having cantilevers of up to 4.5 meters. The material is distributed in a hierarchical grid of curved ribs varying from 60 cm in depth in center to 30 cm on the edge. The smart slab weighs 70% less in comparison to a conventional slab for the load case.
In order to produce this complex geometry, sand moulds were 3D printed using Binder Jetting technology for the underside form-work. Fused Filament deposition technique was used in between the slab to integrate building services. A laser cut plywood form-work was used on top for upstanding beams as shown in fig.03.6 j (The Smart Slab n.d.)

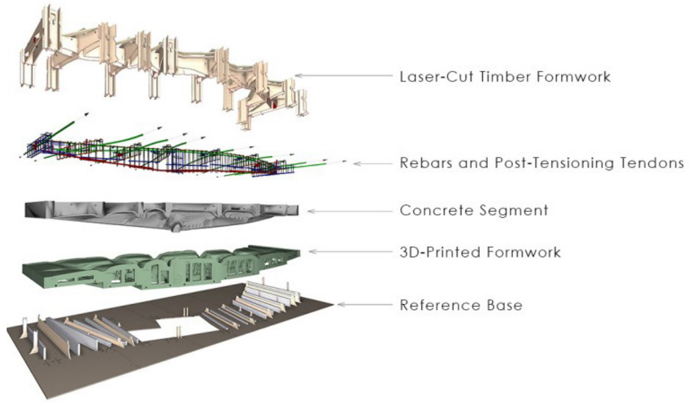


Fig. 03.6 j: Framework for casting concrete slab segment with provision for post-tensioning tendons.(The Smart Slab n.d.)

Fig. 03.6 k: Segments of 3D printed moulds stuck together to cast concrete slab and coated for finished surface and easy removal.(The Smart Slab n.d.)

Fig. 03.6 i: 7.4 m long optimized concrete slab casted in 3D printed sand mould. (The Smart Slab n.d.)

03.7
TOPOLOGY OPTIMIZATION

Chapter 03.4 explores the problem associated to annealing of glass geometries and discusses the solution lying in the optimization of the form/ geometry. To proceed further with the idea of optimization, this chapter provides a brief outline of optimization and its use in designing efficient structures.

Merriam-Webster dictionary defines Optimization as " an act, process, or methodology of making something (such as a design, system, or decision) as fully perfect, functional, or effective as possible."

Optimization is a mathematical solution aiming at finding the extremities (maxima and minima) in an equation. In simple terms, Optimization is a method of achieving best possible results under a given set of conditions. The initial idea of optimization can be traced back to ancient philosophers and mathematicians who defined optimum over several basic factors viz., numbers, geometrical shapes, optics, physics, astronomy, the quality of human life and government, etc. (Kiranyaz, Ince, & Gabbouj, 2014)

The concept of optimization, today, is being used in every sector involving mathematics to find the most optimal result. Architecture and Construction industry is one of these sectors, which is progressing on the idea of optimization for every step of innovation in the industry, in a hunt to create most sustainable structure which involves less material and high performance.

03.6.1 STRUCTURAL OPTIMIZATION

The demand for lightweight, low-cost and high-performance structures has gained popularity due to limited material resources, environmental impact and technological competition. Structural optimization is a way to find the best means to allocate and distribute the material within the domain of the physical volume while safely transmitting the loads to the support. Therefore, the use of structural optimization in designing these lightweight, low cost and high-performance structure is very crucial. The concept of structural optimization was earlier restricted to academic research but these days, it's a widely used by designers and engineers.

Structural optimization is based on a generic mathematical expression involving a function and 2 variables.

1. Objective Function (f): A function that is used to classify the design. For each possible design alternatives, f returns a number which indicates the performance of the design. Usually the optimization problem is defined as minimization problem, where the objective is to have a smaller value of f.
2. Design variable (x): A function or vector that describes the design as a parameter which can be changed during optimization. It may represent geometry or material properties.
3. State variable (y): For a given design x, y is a function or vector that represents the feedback of the structure. It may represent displacement, stress, strain, or force

$$(\mathbb{SO})\begin{cases}\text{minimize } f(x,y) \text{ with respect to } x \text{ and } y\\ \text{subject to }\begin{cases}\text{behavorial constraint on } y\\ \text{design constraints on } x\\ \text{equilibrium constraint.}\end{cases}\end{cases}$$

(Christensen & Klarbring, 2009)

Structural optimization is broadly divided into direct and indirect methods and categorised under three different methods of optimisation. These are: size, shape, and topology optimization (Querin, Victoria, Gordoa, Ansola, & Martí, 2017)

Size optimization: This method of optimization is usually used to determine the optimal cross-section area of elements of a beam in a frame or determining the optimal thickness of items in a plate, while the design criteria are satisfied.

Shape optimization: This method of optimization is usually used to formulate an optimal solution by considering the shape of the initial material layout confined within a design domain and providing alternatives to the shape boundaries.

Topology optimization: TO is a mathematical method which may or may not be gradient based which aims at determining the allocation of material within a given domain of design based on the loading condition and boundary constraints of the given object. The alternate solutions can possess any shape, size or connectivity.

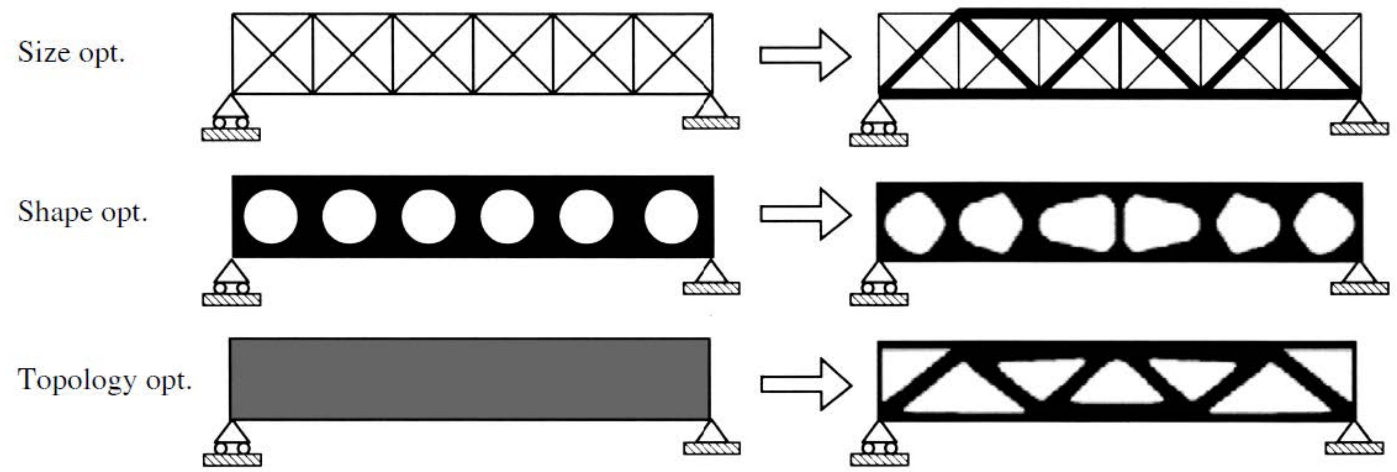


Fig. 03.7 a: Comparative illustration of size, shape and topology optimization (Gebisa & Lemu, 2017)

03.6.2 TOPOLOGY OPTIMIZATION

Topology optimization is one of the structural optimization techniques that optimizes the distribution of material within a specified design space for a given loading and boundary conditions while fulfilling the performance requirements of the product. In other words, topology optimization is performed to remove the areas of the part that are not sufficiently supporting the applied loads and not undergoing significant deformation and thus not contributing to the overall performance of the part.

Usually topology optimization works in a collaborative work flow between CAD (Computer Aided Design) and FEA (Finite Element Analysis). CAD is used in creating a rough/ initial model of the geometry to be optimized while FEA is used for analyzing the stress distribution and displacements throughout the geometry.

The design process involving optimization follows a specific approach. A CAD geometry is first analyzed using FEA for stresses and displacement. Using this analysis, different algorithms are used to minimize or maximize the optimization criteria. The produced result is then post processed for smooth and finished surface quality. At last a FEA validation is done to prove the structural efficiency of the design. Fig 03.7 b explains the process using a case.

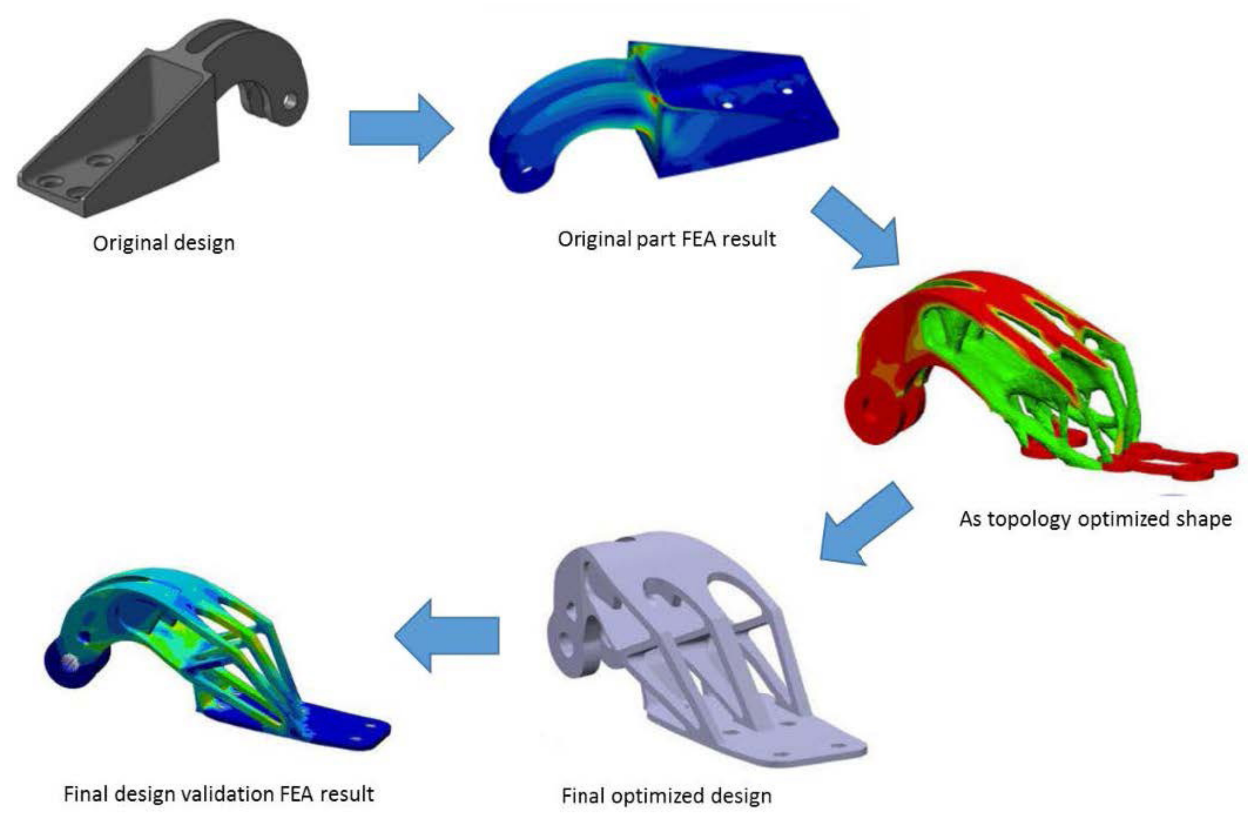


Fig. 03.7 b Topology Optimization process (Gebisa & Lemu, 2017)

Topology Optimization uses different algorithms to process the optimized geometry. These algorithms vary amongst different softwares. Following are the main optimization algorithms used in the industry.

- Solid Isotropic Microstructure with Penalization (SIMP) method
- Evolutionary Structural Optimization (ESO) method
- Bi-directional Evolutionary Structural Optimization (BESO) method
- Homogenization method
- Level set method

According to Gebisa and Lemu, in there paper on "a case study on topology optimized design for additive manufacturing", topology optimization has a huge potential in product development process. Following benefits can be achieved by using topology optimization for design process:

- Lightweight structures
- Fabrication ready design
- Reduction of time to market
- Material reduction
- Less physical test required
- Saving large amount of processing energy
- Reduction of physical prototype building

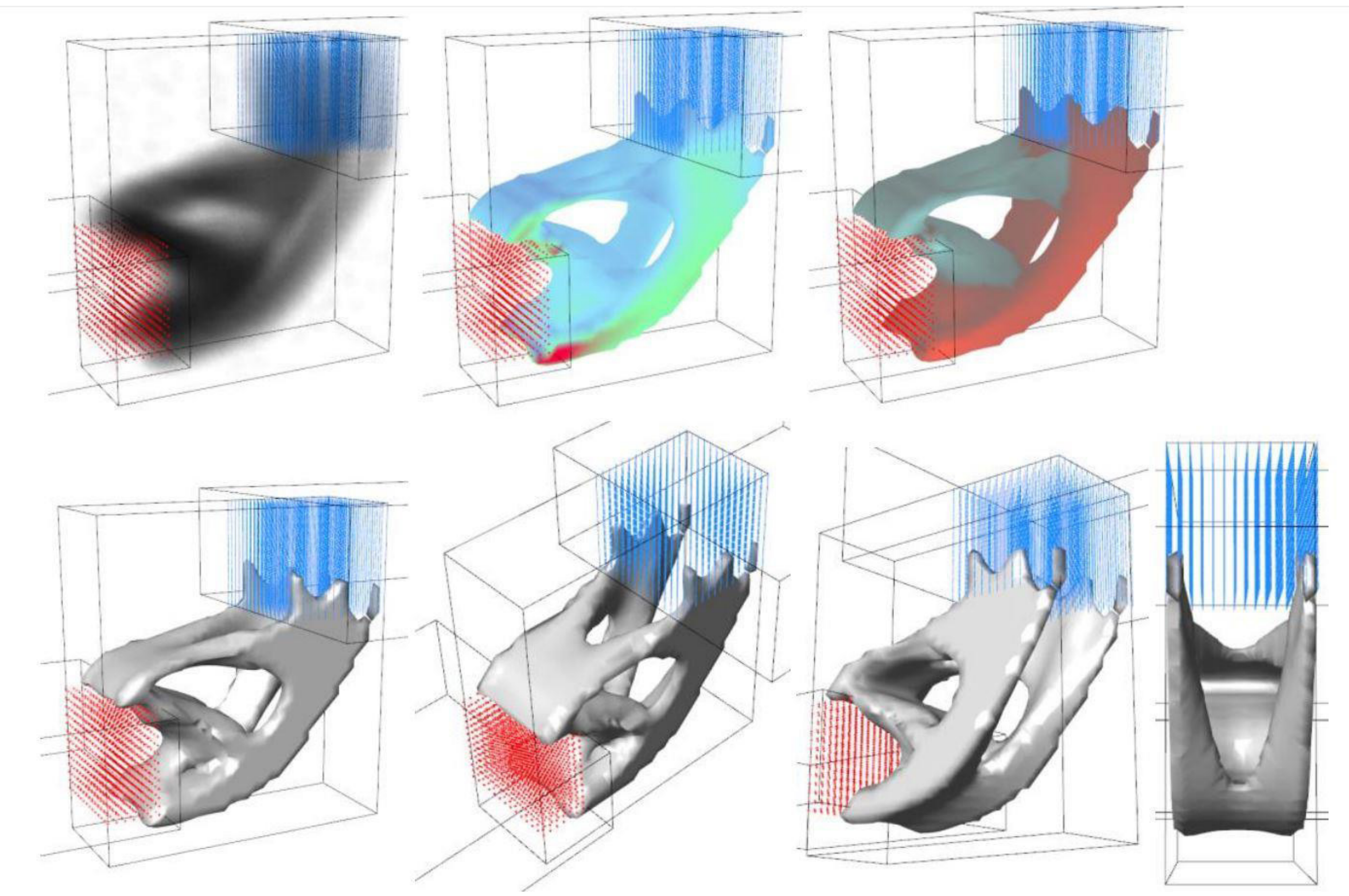


Fig. 03.7 c 3 Dimensional topology optimization using millipede (Michalatos & Kaijima, n.d.)

03.6.3 AVAILABLE SOFTWARES

1. MILLIPEDE

Millipede is homogenization method-based optimization software. The software is available as a plug-in for rhino-grasshopper environment. The component uses a very fast structural analysis algorithms for linear elastic system. It is available free of cost for academics with non-commercial license.

2. AMEBA

Ameba, earlier known as BESO 3D, is a program developed by researchers of RMIT, Australia. The software comes as a Rhino-Grasshopper plug-in. Ameba works on BESO algorithm for topology optimization. The tool can be used to minimize either the mises stresses or the displacement while performing a mass reduction. The major advantage of the software is that it provides a support of cloud computing and doesn't require a high specification system to run. The optimization takes into account material properties like Young's modulus and Poisson's ratio of the material having an advantage over millipede plug-in in rhino-Grasshopper environment. Also, the software has extra components for post processing the optimized geometry.

Thought the software is available free of cost currently but due to its developmental stage, the software offers many restrictions.

3. ANSYS

Ansys is a software package designed for mechanical engineers and building physics industry. It offers an extensive structural design and analysis package. Topology Optimization is a small part of the static structure analysis and provides 2 methods of optimizing a geometry – Sequential Convex Programming & SIMP based Optimality criteria method. The software provides a detailed control over material properties for optimization. The software allows user to set manufacturing constraints like member size, symmetry etc.
The software has an educational version which comes with a lot of restriction. The educational version allows a limit of 32000 nodes for static structure analysis.

4. OPTISTRUCT

The software is a product of Altair Hyper Works engineering software package and is widely used for industrial application. The structural analysis solver of the software is a state of the art and provides the user an option between SIMP or Level set method for optimization. The software offers diverse options regarding manufacturing constraints e.g. Extrusion constraint, pattern repetition and symmetry constraints. Unfortunately, the software is not available for academic or non-commercial license.

The popularity of Optimization method in the industry has attracted many software developers and companies to develop their own topology optimization software. The above-mentioned softwares are the most famous amongst all and have been earlier used in architecture and construction industry. The most commonly optimized materials in the industry are concrete and metals like steel and aluminum. Glass is a very new material in the structural industry and offers unique properties. Comparing the aforementioned software, Ameba and Ansys are the only 2 software that are available for academic use and offers customization in material properties. Hence only these 2 softwares will be explored in this project.

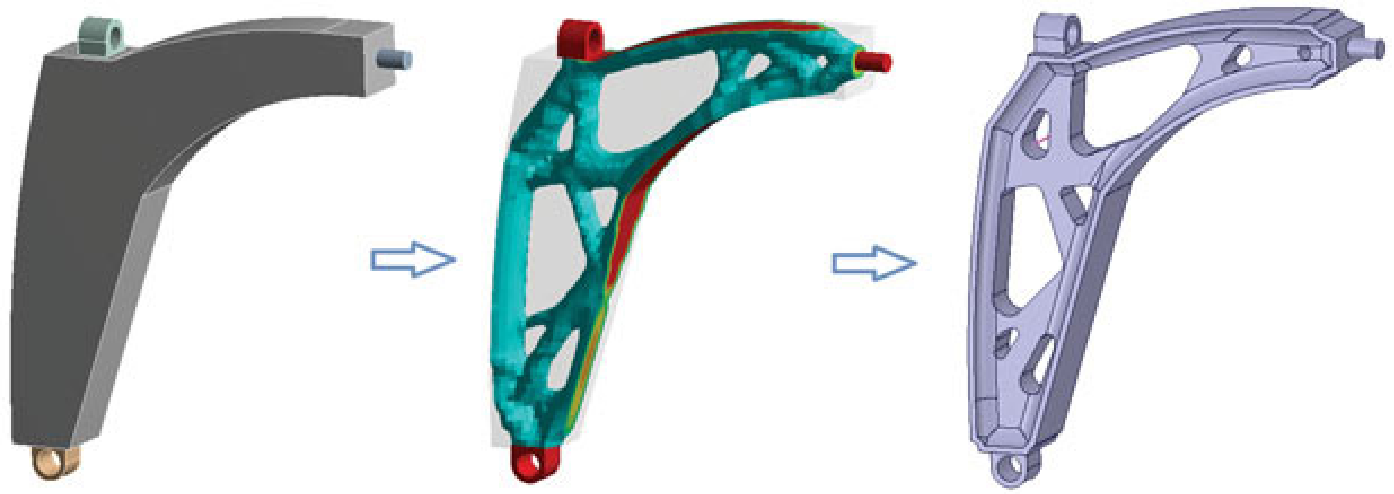


Fig. 03.7 d Topology Optimization of a Automotive part done using Ansys
https://www.digitalengineering247.com/article/simulate-to-shed-weight-sooner/

03.8
TYPES OF GLASS CONNECTIONS

Based on the industrial use of glass, there are three classification in which cast glass elements can be connected to either another glass element or other materials. All connection typologies had their own merits and limitations.

03.7.1 MECHANICAL CONNECTION

Mechanical connections are the most popular amongst all connections. An additional substructure is used to transfer the tensile forces

Characteristics:

1. The introduction of metal compromises transparency.
2. Peak stresses develop around the connection which can lead to cracking of glass.
3. Dry assembly connections which are easy to assemble
4. The connections are reversible creating a demountable structure or easy replace-ability

03.7.2 ADHESIVE CONNECTION

Adhesive connections are glued connection which transfer the load by adhesive forces developed at an atomic level.

Characteristics:

1. It allows homogeneous load transfer. Hence no peak stress are developed.
2. The process is meticulous and labor intensive
3. The adhesive layer needs to have right thickness to ensure optimum strength.
4. The connection is highly transparent
5. It is a non-reversible process..

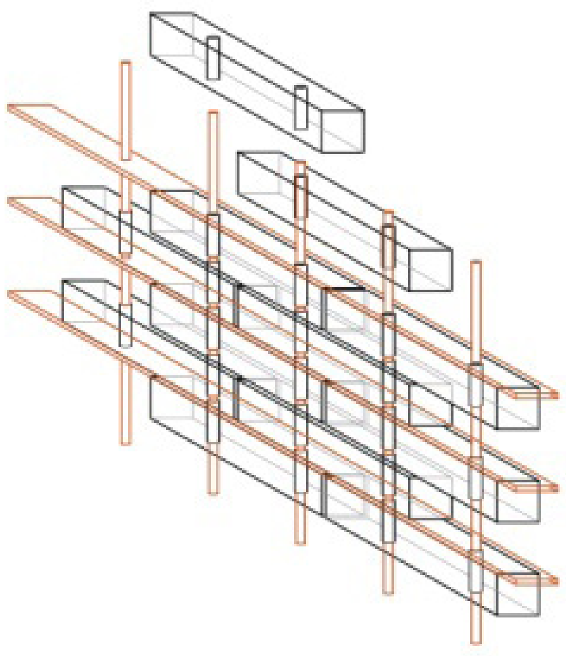


Fig. 03.8 a Optical House facade illustration showing the substructure (F. Oikonomopoulou, T. Bristogianni, et al., Interlocking cast glass components, Exploring a demountable dry-assembly structural glass system 2018)

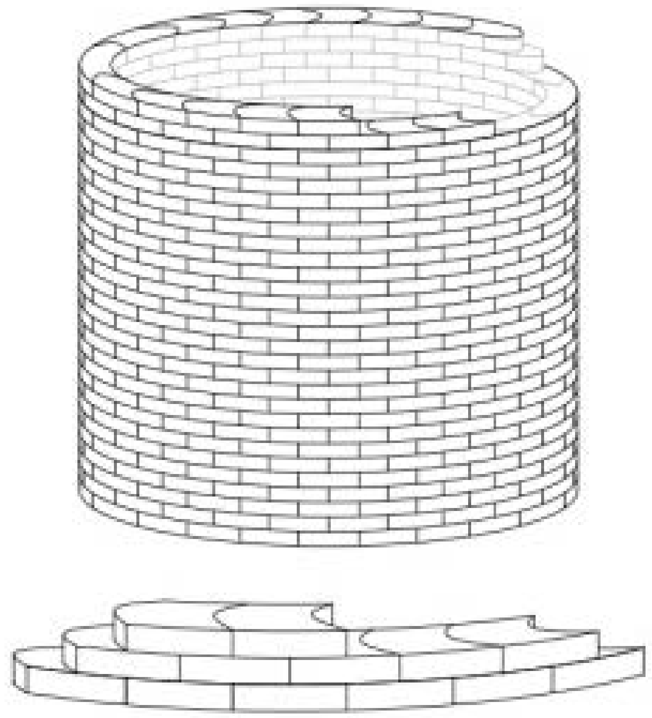


Fig. 03.8 b Atocha memorial adhesively bonded facade system (F. Oikonomopoulou, T. Bristogianni, et al., Interlocking cast glass components, Exploring a demountable dry-assembly structural glass system 2018)

03.7.3 INTERLOCKING GEOMETRY

The interlocking geometries are lego inspired construction technique typically designed for cast glass structures. The application of this particular connection is still restricted to research and scientific field and hasn't been executed in any practical scenario

Characteristics:

1. The construction technique's biggest advantage is that it caters to the aspect of circularity
2. It is a dry assembly connection which are reversible
3. An interlayer between the glass pieces accommodates for tolerances
4. High transparency is offered by this construction technique.

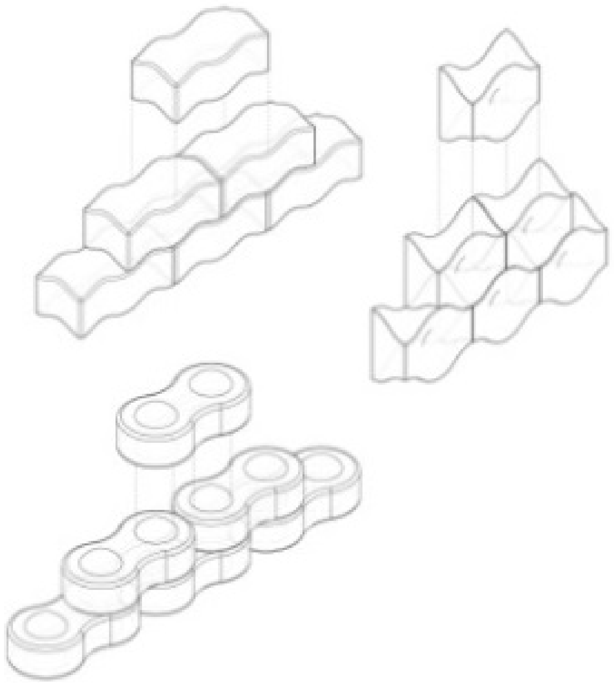


Fig. 03.8 c Interlocking geometries
(F. Oikonomopoulou, T. Bristogianni, et al., Interlocking cast glass components, Exploring a demountable dry-assembly structural glass system 2018)

03.7.4 CONCLUSION

The design of a cast glass optimized column requires homogeneous load transfer and should offer complete transparency.
Comparing all the 3 types of connection techniques, Adhesively bonded glass structures offer the most transparency and allow homogeneous transfer of load. Hence adhesively bonded connections will be used between different glass geometries.

While the connection from slab to column and from column to foundation cannot be connected via adhesive to allow easy replacibility on breakage. Also, the transparency aspect need not be addressed at these junctions, hence, mechanical connections will be used for holding the complete column between slab and foundation.

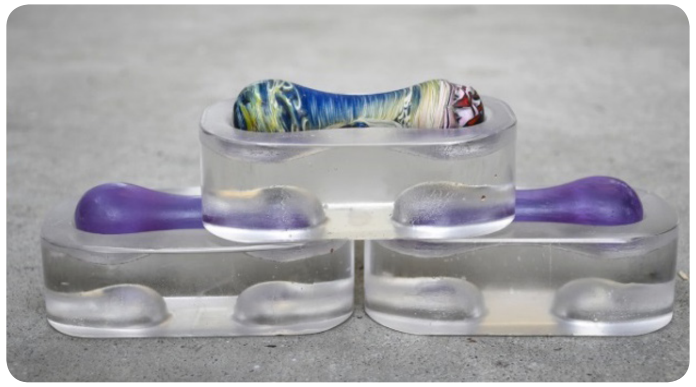


Fig. 03.8 d Interlocking geometry units
(F. Oikonomopoulou, T. Bristogianni, et al., Interlocking cast glass components, Exploring a demountable dry-assembly structural glass system 2018)

04

CASE STUDY

Scientific researches happen in different fields worldwide but many fail to get implemented in the practical environment due to their inefficient and non-realistic approach. This chapter revolves around selection of a space that finds the relevance and applicability of a cast glass column and how the fabrication process can significantly help in improving the quality of the space by realizing the vision of the architect.
An analysis is later done on the existing structure and a column is selected from the space carrying the highest load which acts as the case for designing, optimizing and further fabricating.

04.1
SELECTION OF A CASE STUDY - KOLUMBA MUSEUM

Building contractor	Archbishopric of Cologne / Vicariate General
Achitect	Peter Zumthor, CH - Haldenstein
Project Management	Rainer Weitschies, Atelier Zumthor
Project supervision	Atelier Zumthor & Stein Architekten,Cologne
Structural Designers	Jürg Buchli, Haldenstein, with Ottmar Schwab / Reiner Lemke, Cologne
Architectural Height	12 m
Year of Proposal	1997
Initiation of Construction	2003
Year of Completion	2007
No. of Floors	2
Built Area	6200 m^2

(Kolumba Museum, Cologne), (Kolumba, n.d.)

Fig. 04.1: Street view of Kolumba museum depicting the fusion of old remains with new architecture. (https://www.nrw-tourism.com/a-kolumba-museum-cologne)

Designed by swiss architect, Peter Zumthor, Kolumba museum is situated in Cologne, Germany, a city that was almost destroyed during world war II. The museum is famous for its location having history associated to it since Roman settlements and its Roman Catholic Archdiocese's collection of art which spans more than a thousand years.
Peter Zumthor won the competition in 1997 with his unique design and it took 10 years to realize the project. The museum has won several awards for its architecture since then. (Kolumba Museum in Cologne, n.d.)

04.1.1 HISTORY

Sarah McFadden aptly termed the Kolumba museum as " a museum of contemplation in which there is an ongoing dialogue between past and present". (Kolumba, n.d.)
The site where the museum stands today has been a place of worship since 11th century. It all started with a small temple which had an expansion in the 12 th century and later in the 16th century was replaced by a gothic styled architecture which became the most famous of all during the medieval period. (Hybel, 2013)
This church known as Saint Kolumba parish was the largest in the city at that time and was used to demonstrate the powers of parish.
The church stood until 1943, when an air-strike destroyed the church along with the whole city during world war II.
The ruins of the church were left untouched after that and in remembrance of the devastating bombing an octagonal shaped chapel was built in 1949 by the local architect Gottfried Böhm.
The chapel still stand till date and is not a part of museum experience. It has a separate entrance but serves as a very important part of the museum(Kolumba, n.d.)
Fig 04.2 depicts the historical development over the years on the site.

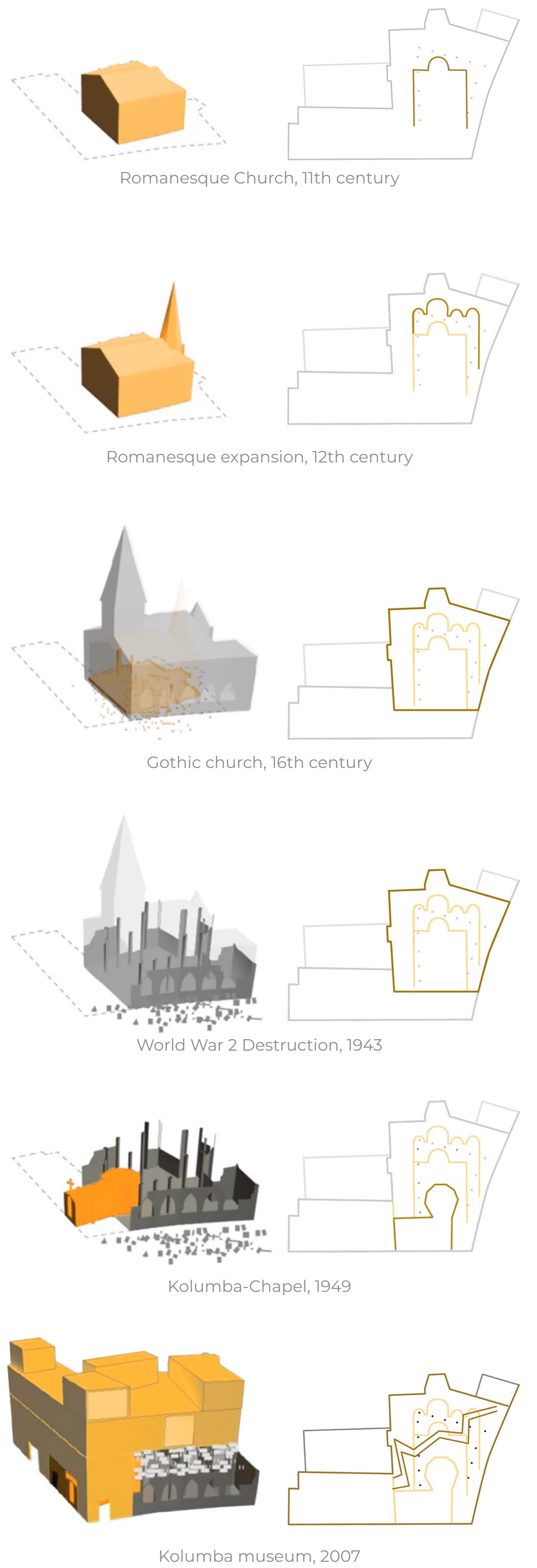


Fig. 04.2: Historical evolution of different structures built on the site over the years.

04.1.2 ARCHITECTURAL CONCEPT

The contextual complexity of the site throughout the ages was a challenge for the architect but he managed to reconcile different chapters of history with the new proposed museum by keeping and embracing the per-existing fragments.
The building on the outside is a very subtle structure which merges with the surrounding street scape. The building doesn't reveal a lot from outside but carries a mysterious feel to it. The facade of the building is composed of two layers- the historical ruins of previous structures and a subtle modernistic facade, merging together. This modernistic part of the facade has been made of a special hand made brick and thick horizontal mortar which seamlessly merges with the ruins. The brick size has also been altered and resembled dimensions of a roman brick. The bricks have a warm gray color to it and the whole wall contrasts with the ruins marking it as an important focus. The modern part of the facade also carries small punctures after a certain height.
These punctures are basically holes in the wall allowing filtered light and ventilation to the double height space on the ground floor of the museum housing archaeological excavations. A zigzagging path guides a tourist from the main foyer through this historical space.
At the end of this massive space, an octagonal shaped structure is the only standing thing.
The architect wanted to depict and make the user feel the post world war II scenario. Standing on the elevated wooden path, the tourist could feel the serene calmness and coldness in the space. The space was designed for the people to go back in time to feel the misery associated with the site.
Amongst all this, are thin slender concrete columns holding the floor above, which

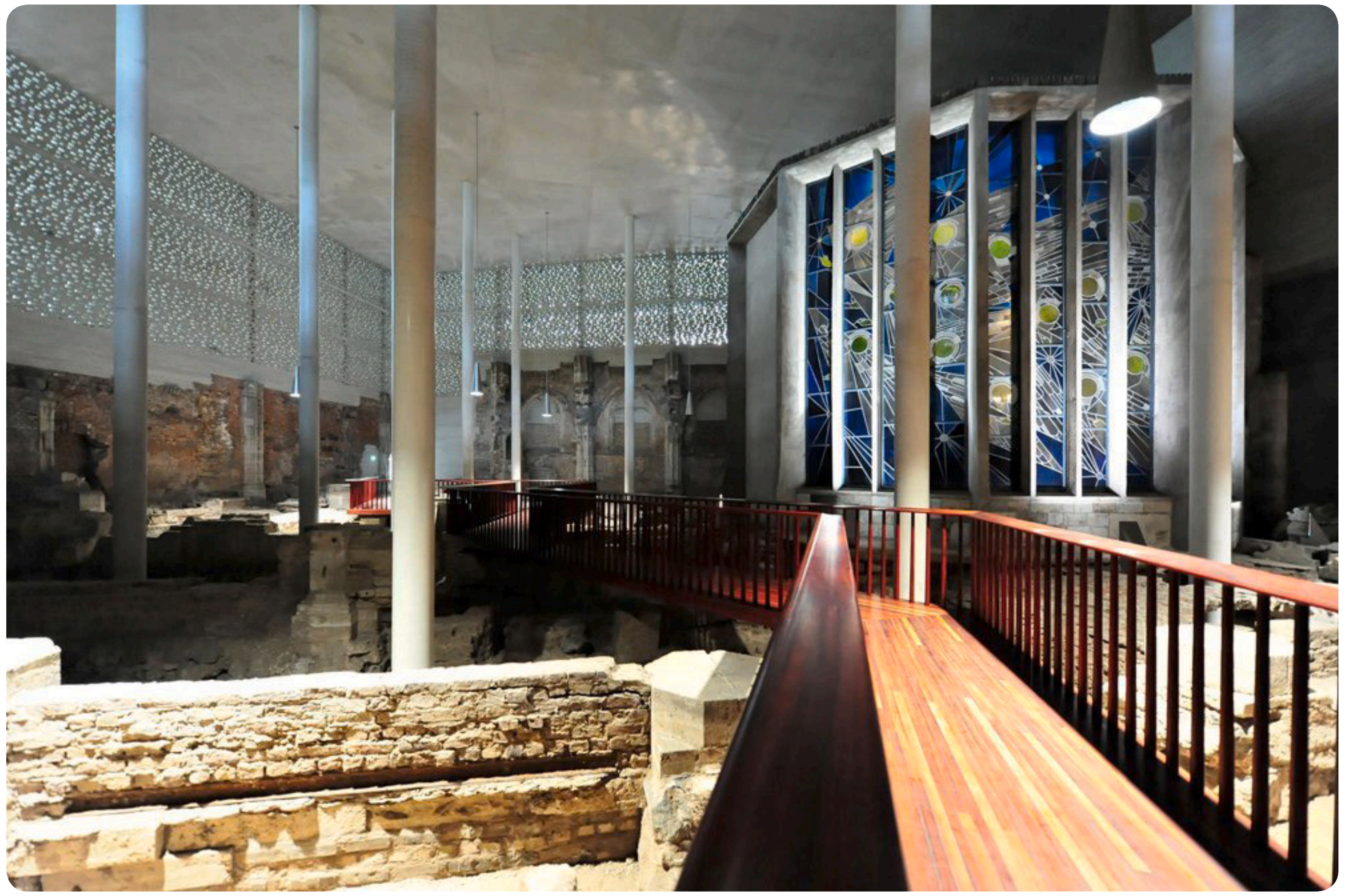


Fig. 04.3: The archaeological excavation area of the museum having the zigzagged path going through the space
(http://architecturalmoleskine.blogspot.com/2012/04/peter-zumthor-kolumba-museum-cologne.html)

houses the exhibition. Figure 04.3 and 04.6 clearly depicts the scenario of the space on the ground floor. These columns are not positioned according to any grid rather are aligned to the historical remains to preserve them hence creating a bit randomize grid. The drawings of the museum illustrates the same clearly shown on the next page.
The upper floor is accessed through a single narrow staircase from the entrance foyer. The exhibition of the archdiocese, who commissioned the museum is distributed in few rooms partitioned along walls continuing the columns below as can be seen in the drawings shown on the next page and the circulation is very random. There are very few openings on the floor but those openings are very massive and span full height of the room allowing natural light to flood the space inside.

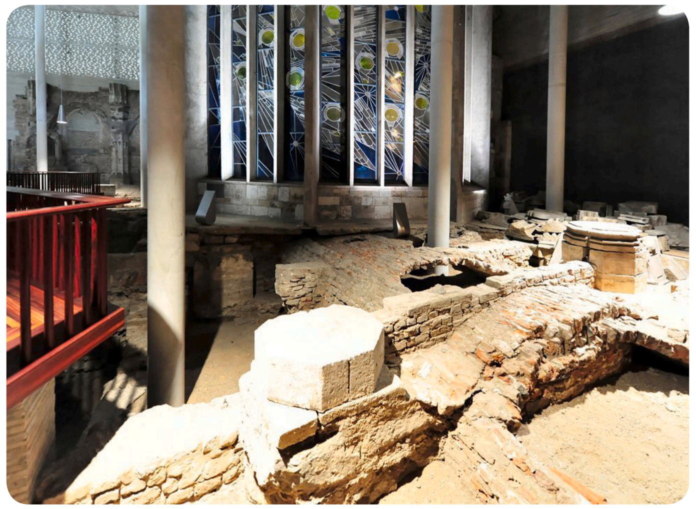


Fig. 04.4: Archaeological remains of the previous built structures.
(https://www.archdaily.com/72192/kolumba-musuem-peter-zumthor/30-custom)

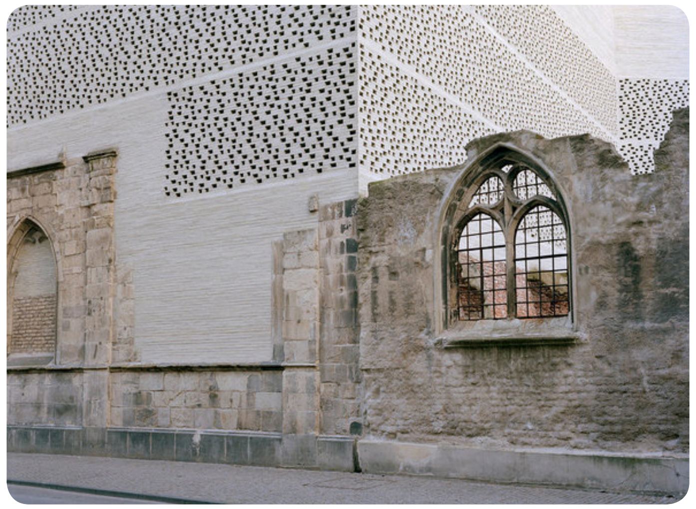


Fig. 04.5: The fusion of the new facade with the ruins
(https://proyectos4etsa.wordpress.com/2014/07/03/museo-kolumba-colonia-1997-2007-peter-zumthor/)

Fig. 04.6: Wide angle view of the ground floor archaeological excavation area.
(https://nl.m.wikipedia.org/wiki/Bestand:St._Kolumba_K%C3%B6ln_-_Di%C3%B6zesanmuseum_-_Ausgrabungen_1.jpg)

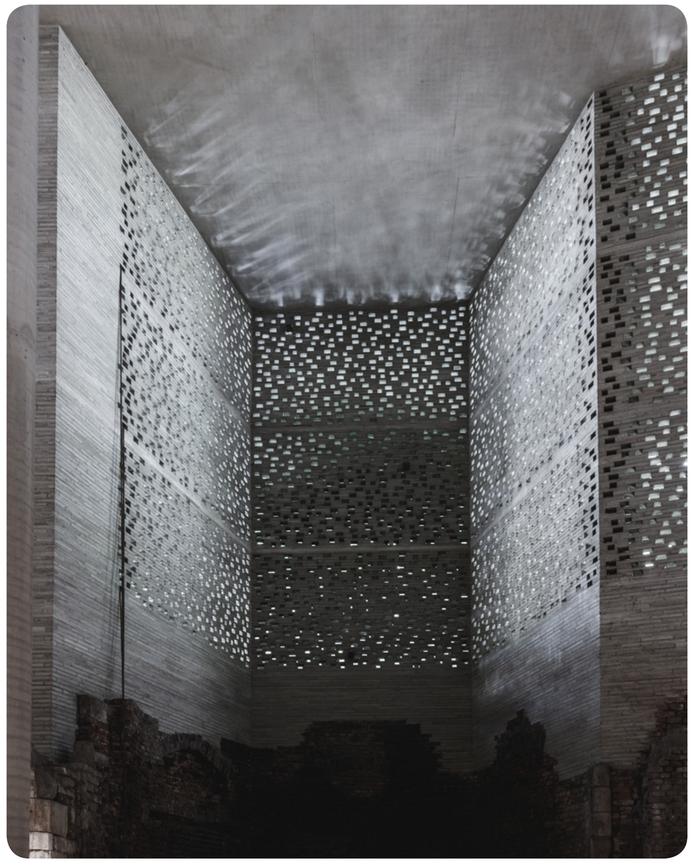


Fig. 04.7: Punctures in the wall to allow diffused light and ventilation inside the space to provide a more natural environment (https://www.archdaily.com/877432/peter-zumthors-kolumba-museum-through-the-lens-of-rasmus-hjortshoj)

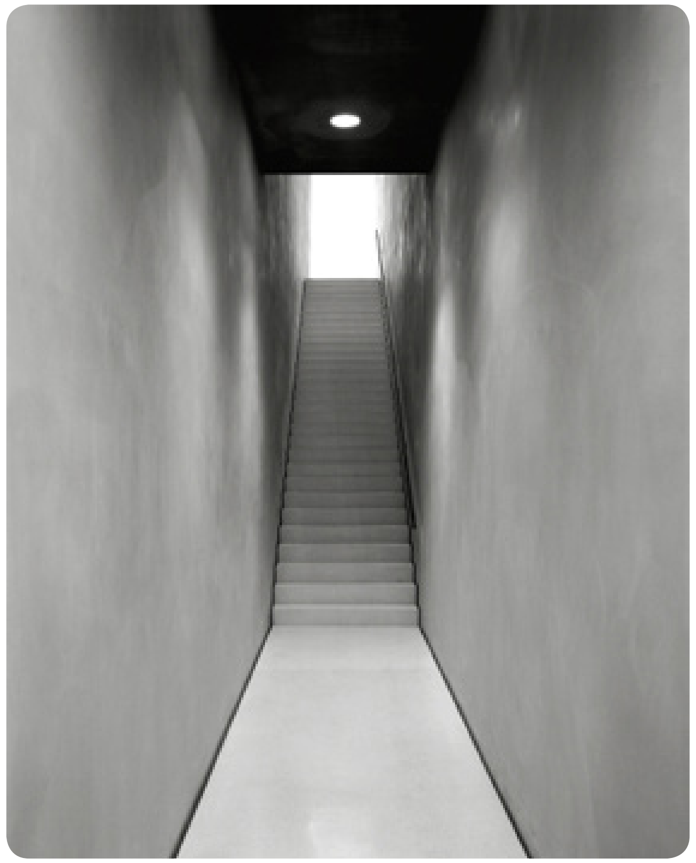


Fig. 04.8: Elegant staircase connected to the entrance foyer guiding the tourist to the museum on upper floor (https://www.kolumba.com/?language=eng&cat_select=1&category=14&artikle=61&preview=)

04.1.3 NEED FOR INTERVENTION

Every designer or an architect desires of a column free large space to have a continuous uninterrupted vision throughout the space which offers high flexibility in terms of movement and provides connectivity inside the space. But when these spaces are realized in practice, column being an essential aspect of any structure, cannot be removed out of the space and act as a thick mass standing in between breaking the continuity of the space.

Same complexity exist in the above case study. The area surrounding the tourist with archaeological remains have a sense of feeling attached to it. The concept of depicting the misery, post world war 2 destruction, is not fully conveyed by the space. The discontinuity in the vision of the space due to many concrete columns loose the essence of the architect's thought.

Architects and structural designers when designing a structure always think about the most conventional materials in the market. Concrete has been the most used material in designing a column for decades now but the need for a new material that could solve the issue of discontinuity in the space can revolutionize the thinking process of architects and help in realizing their visions.
Glass being transparent in nature and having high compressive strength can be an alternate to the current problem. Replacing the current concrete column with the glass column wont offer full transparency but the space will have a continuous flow and feel to it.

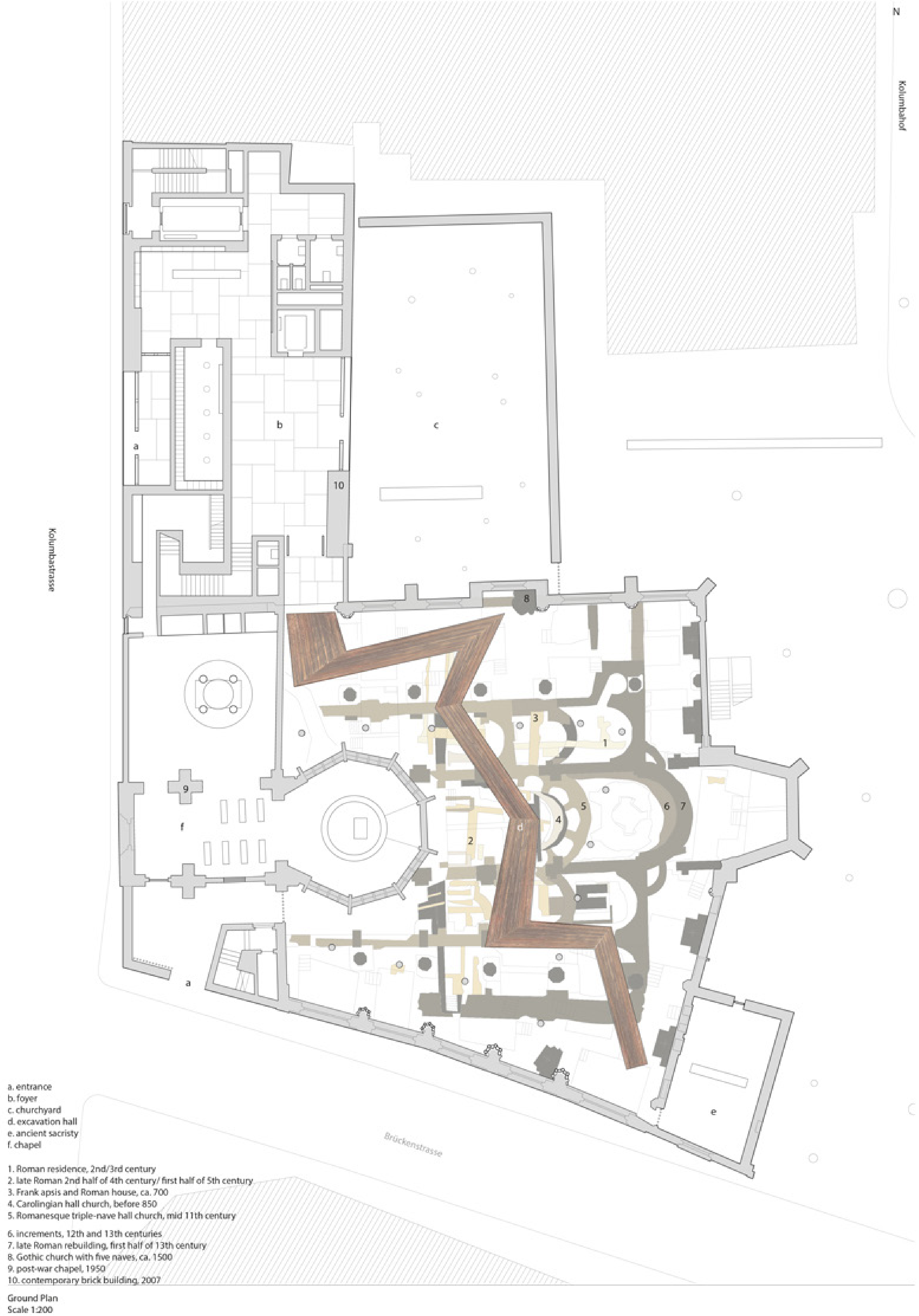
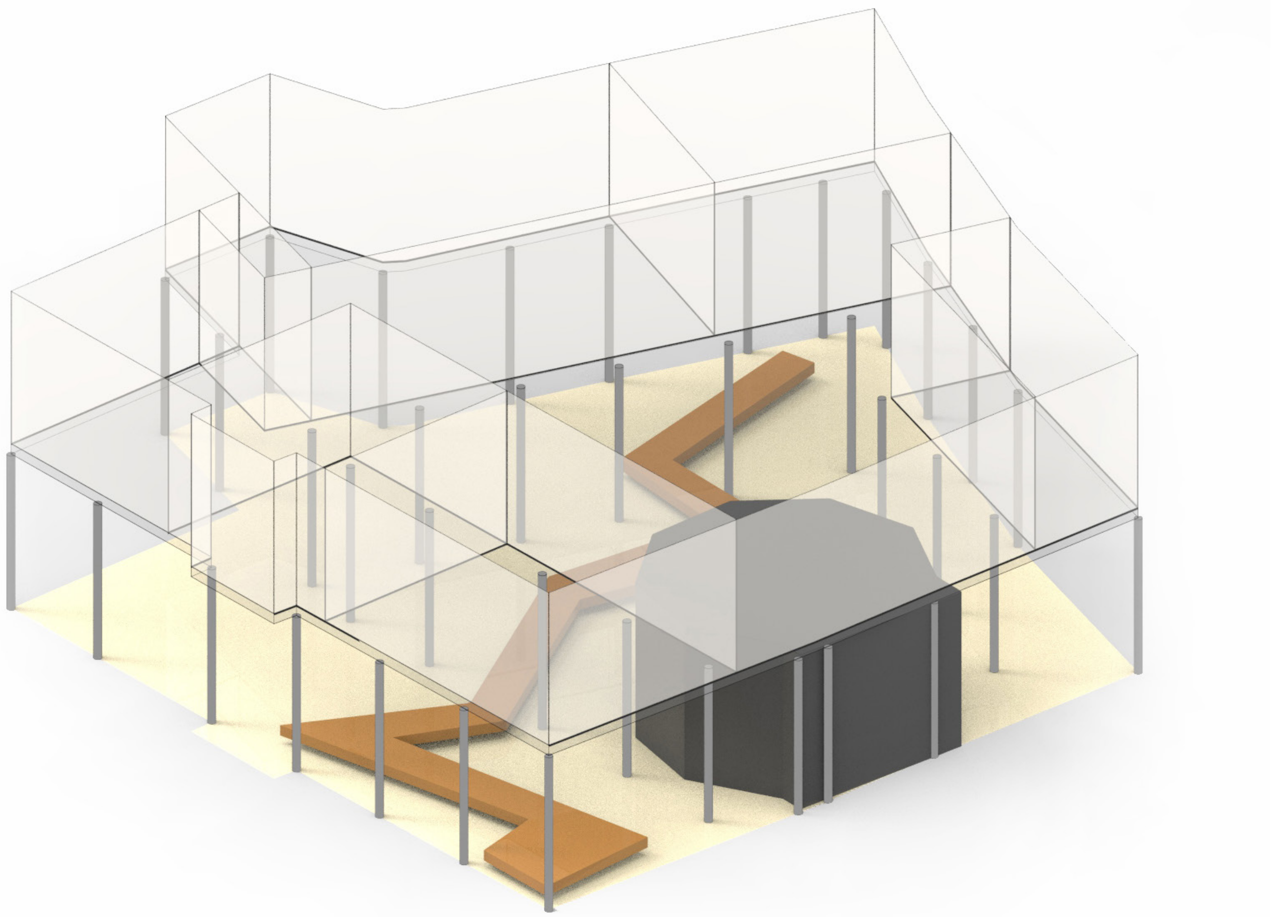


Fig. 04.9: Ground Floor plan depicting various layers of history together.
(https://www.kolumba.com/?language=eng&cat_select=1&category=14&artikle=61&preview=)

ARCHITECTURAL DRAWINGS



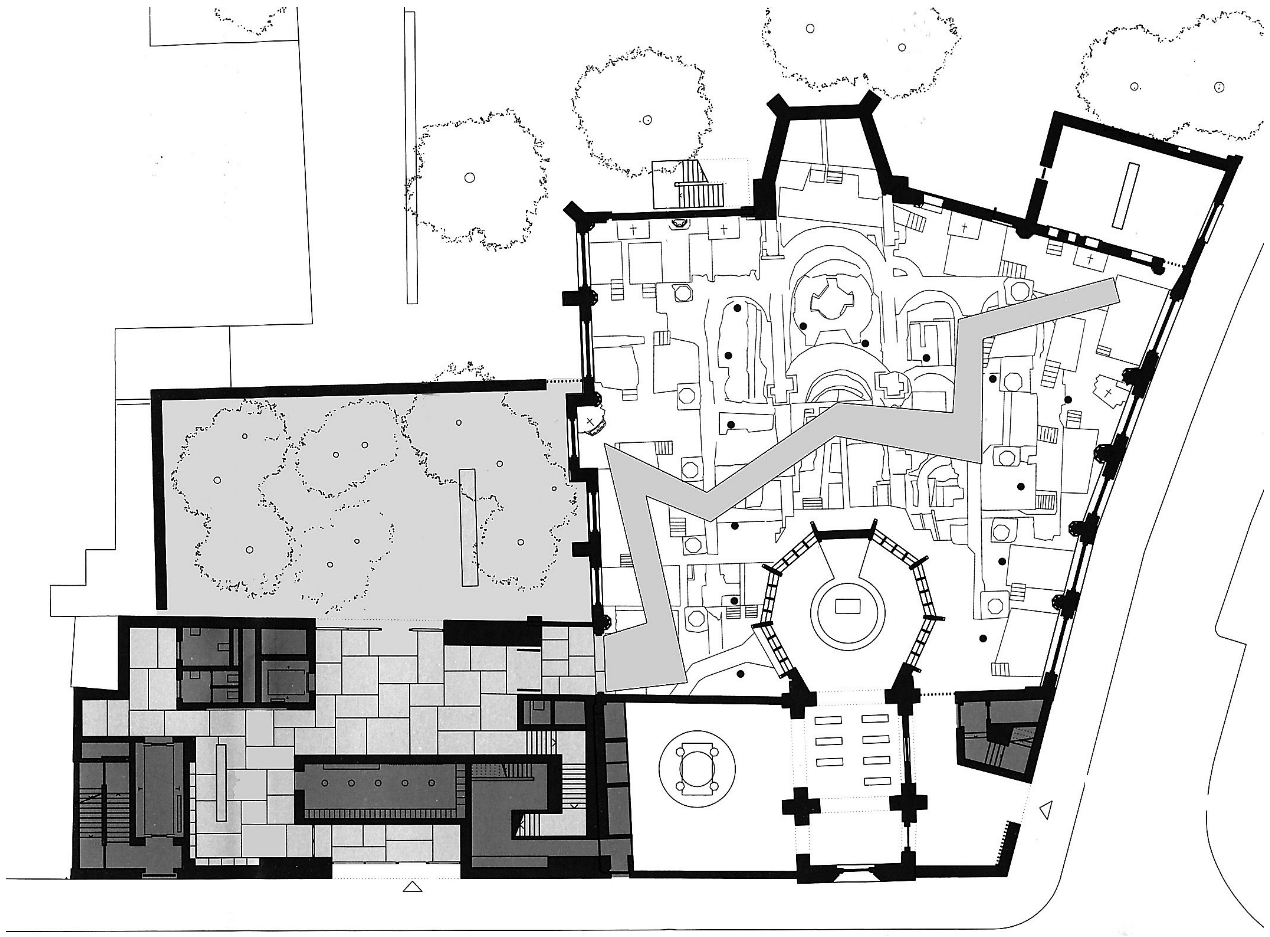


Fig. 04.11: Ground Floor plan of the museum
(https://www.kolumba.com/?language=eng&cat_select=1&category=14&artikle=61&preview=)

Fig. 04.12: First Floor plan of the museum
(https://www.kolumba.com/?language=eng&cat_select=1&category=14&artikle=61&preview=)

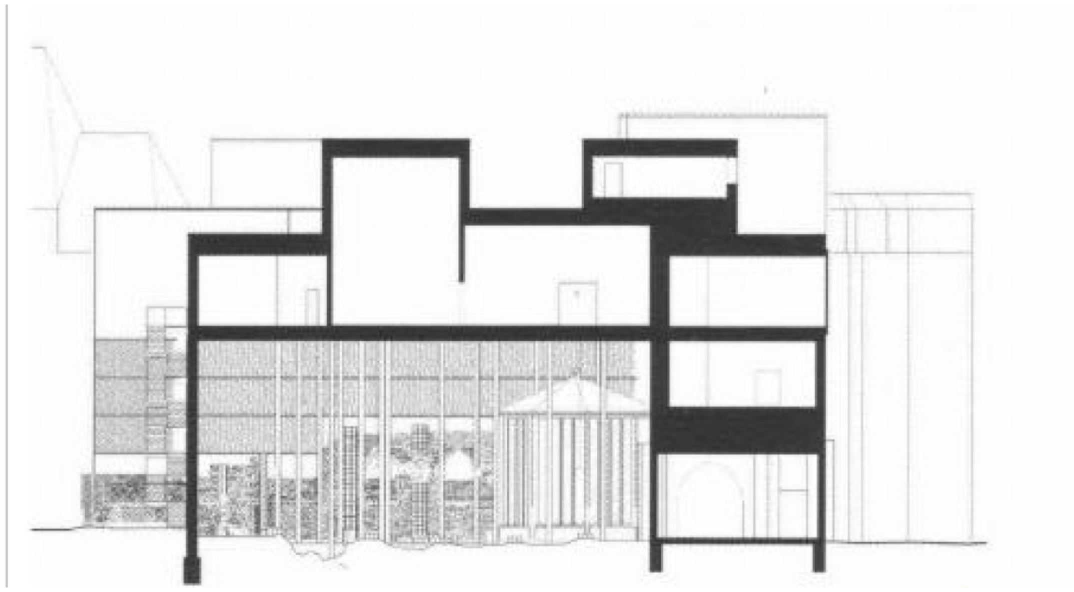


Fig. 04.13: Section AA depicting the relation of height of the column and the space
(https://www.kolumba.com/?language=eng&cat_select=1&category=14&artikle=61&preview=)

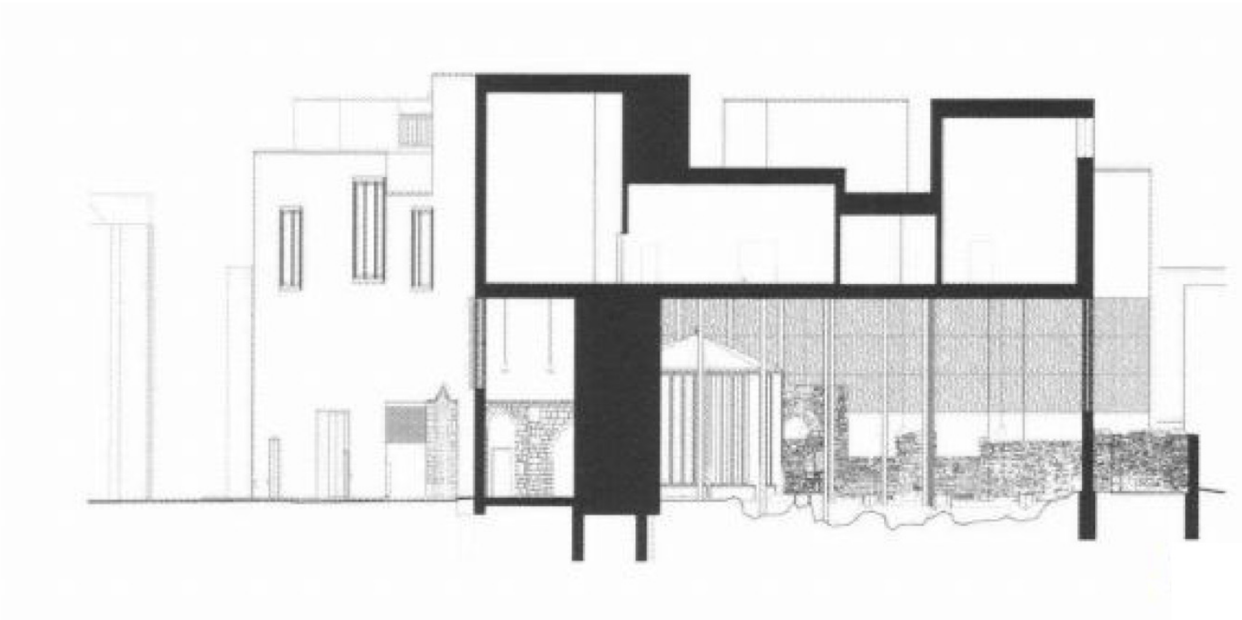


Fig. 04.14: Section BB
(https://www.kolumba.com/?language=eng&cat_select=1&category=14&artikle=61&preview=)

04.3
LOAD CALCULATION ON A COLUMN

Designing a column requires load that needs to be transmitted. To calculate the load, only the structure associated to the space having archaeological remains were taken into consideration. Figure __ illustrates the selected region.

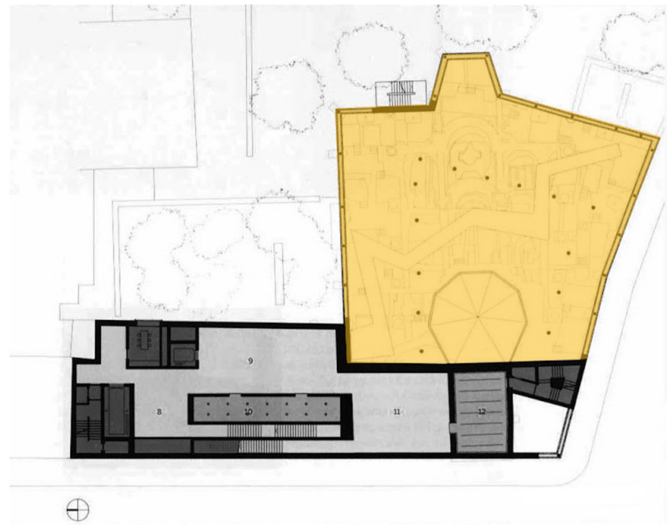
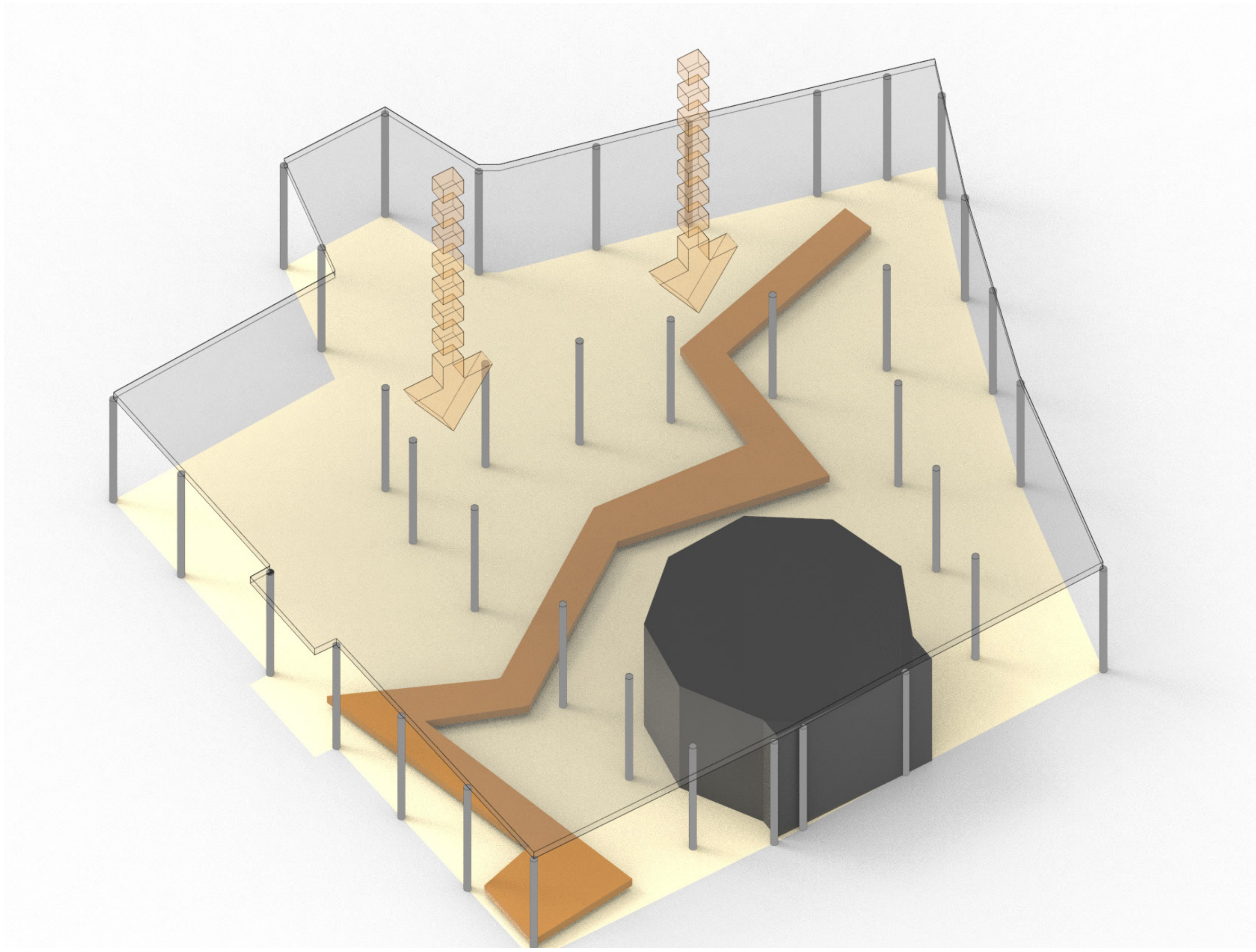


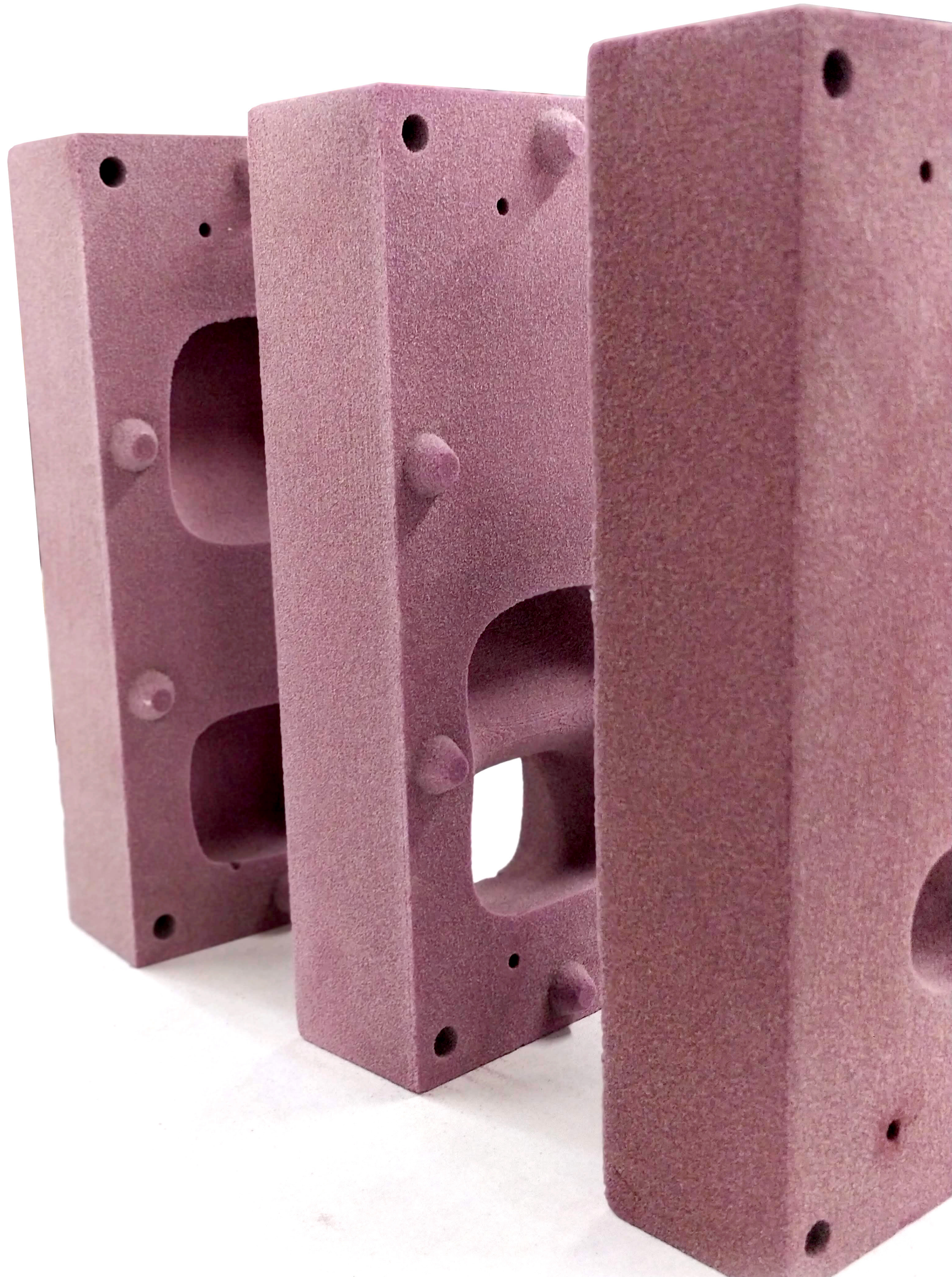
Fig. 04.15: Key plan highlighting the region selected

Following load cases were taken for calculation:
Wind Load: 0.32 KN/m^2
Snow Load: 0.65 KN/m^2
Live Load for museum: 5KN/m^2
Live Load of roof: 1KN/m^2

Total load on the slab calculated is 15216 KN.
Total number of columns are 34
(Appendix 1)

Load on one column is 447.54 KN
With a safety factor of 1.7, critical load for a column is 760.8 KN





05

DESIGN DEVELOPMENT

Previous chapter focused on understanding the context for which the column was being designed and on basis of some conversational design theories listed, design criteria will be discussed in this chapter.
On basis of these design criteria, a final column geometry would be proposed having a rationalized thought behind the evolution of design. The design developed would then be optimized, resulting in an efficient structural column.

DESIGN PRINCIPLES & CHALLENGES

1. MATERIAL FABRICATION

As studied during literature study, glass offers many constraints in terms of fabrication. To make the casting process easier and efficient following limits were set.

a. Homogeneous Mass Distribution

To estimate a proper annealing time and to avoid excessive annealing of certain regions of the glass piece, it is recommended to have homogeneous distribution of mass. Excessive annealing can result in explosion of thinner regions in the geometry.

b. Limited annealing time

Section 03.4, Stress Release and Annealing of Glass, depicts how annealing time is proportional to the thickness of geometry. The major objective is to reduce the annealing duration of the geometry. So, a limit to the thickness on the basis of practical experience has been set to have a reasonable duration of annealing time.
Thickness: 100 mm to 200 mm

2. LIMITATION OF SAND MOULDS

The material for the fabrication of glass is sand, printed using an ExOne Binder Jetting printer. Use of these 3D printed sand moulds in steel and aluminum foundries have allowed the designers to formulate some guidelines.

a. Wall Thickness

The molten metal or liquified state of glass when entering the mould would exert a pressure on the walls. Considering the strength of the binder, a minimum thickness has been advised by the company to prevent it from destroying during the cooling process. Table 8 showcase the thickness for different metals formulated by 3Dealise. On comparing these materials (Table 8) on basis of densities, it was deduced that aluminum being lighter, exerts less force on the walls and vice versa for steel.
Borosilicate glass has a density of 2230 kg/m3, which is almost similar to that of aluminum. So, wall thickness for the mould or the gap between any 2 elements of the column geometry must have a distance more than 3 to 4 mm.

b. No sharp corners

Glass in liquefied form is a very viscous material. To allow smooth flow of the material in the mould, it is recommended to have no sharp corners. A minimum of 3mm of fillet is recommended by the 3Dealise company for casting steel. Same radius of fillet would also be used in case of glass.

MATERIAL	THICKNESS (mm)	DENSITY (kg/m³)
Aluminum	3 - 4	2700
Cast Steel (carbon steel)	6	6800-7800
Steel	8	7850-8000

Table 8: Establishing a relation of thickness to the density of the material.

3. TRANSPORTATION & LOGISTICS

The design and fabrication of the column needs to consider the fact that the fabricated pieces need to be transported to the site and assembled in position by humans.
The maximum permissible dimension of lorry in Germany is 12m (length) X 2.55m (width) X 4m (height). Considering that the whole column can be produced in one single piece in a specially designed autoclave, it should still be under these dimensions for logistic reasons.

4. VISUAL PERFORMANCE

The use of glass as a material for column is to allow maximum transparency in the context. But glass offers optical illusion. Layers of glass can totally destroy the image on the other side. So, to provide a clear image of the archaeological remains, the region of the column aligned with the human perspective should be made as solid as possible. This can result in a better continuity in the vision of the person walking along the elevated path.

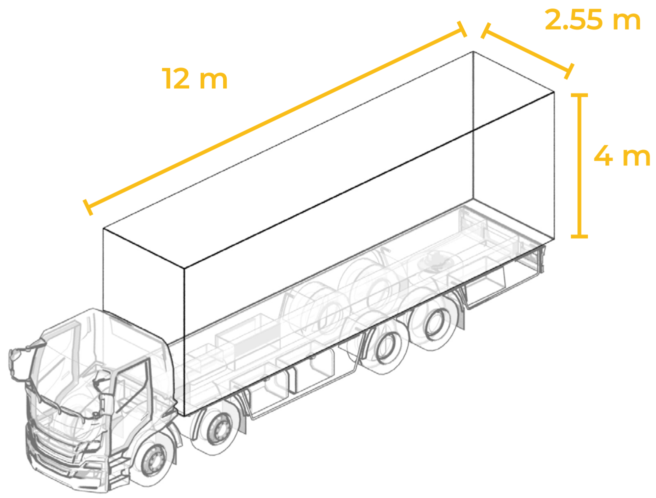


Fig. 05.1 a: Maximum permissible dimension of a truck on German roads

Fig. 05.1 b: Better optical quality by complete infill of geometry

05.2
DESIGN DEVELOPMENT

05.2.1 OPTIMIZATION PARAMETERS & CONSTRAINTS

a. Material Properties

Chapter 3.2 concluded borosilicate glass to be the most optimal material to be used for the column design due to its high thermal shock resistance and reasonable optical quality. For the foundation and the roof connection, structural steel has been used as can been seen in the illustration (Fig. 05.2 a)

The material properties of both Borosilicate glass and structural steel can be found in the table 9.

b. Support & Loading Condition

1. Load Condition:

The column was loaded with 2 forces acting along the axial direction of the column.

- Dead and Live load of the structure: 1521 KN (inclusive safety factor: 1.7)
- Self-Weight

2. Support Condition: Fixed Support

3. Displacement:

Since the beam transferring the load to the column is connected to a grid of beams and columns and practically cannot displace in any lateral direction (x and y axis) without a lateral load, so a displacement constrain was added to the beam allowing it to only deform in axial direction only (z axis).

	BOROSILICATE GLASS	STRUCTURAL STEEL
Density (kg/m³)	2250	
Coefficient of Thermal Expansion (/degree C)	3.7×10^{-6}	1.2×10^{-5}
Young's Modulus (Pa)	6.2×10^{10}	2×10^{11}
Poisson's Ratio	0.2	0.3
Tensile Strength (Pa)	9×10^{6}	2.5×10^{8}
Compressive Strength (Pa)	100×10^{6}	2.5×10^{8}

Table 9: Material properties used for calculation

c. Geometry & Optimization Parameters

The form development and optimization calculation for the column geometry was done using Ansys 19.0. Static Structure feature of workbench was used to first structurally analyze the stresses in the geometry and topology optimization feature was then further used to optimize it. The software functions on basis of mesh elements. Smaller and uniform the size of the mesh elements, more accurate and precise is the optimized geometry.

The student version of the software allows to statically analyze the structure until 32000 nodes/ elements. These nodes correspond to the size of the element the software can analyze for a geometry. Bigger the geometry, bigger is the size of the mesh and less accurate is the final optimized result.

Following parameters were selected for optimizing the geometry

- Mesh Type: Uniform
- Mesh size: Varies
- Maximum number of iterations: 500
- Minimum normalized Density: 0.001
- Optimization Objective: Minimize compliance (Maximize stiffness)
- Mass Retention Percentage: 10 – 50 %

05.2.2 OPTIMIZATION OF A STRAIGHT COLUMN

Chapter 03.7 explains 3 ways of optimizing a structure. Following a rationalized approach for creating the geometry, it was decided to use the third way of optimization- Topological Optimization.

The shape and size of the column used in currently in the Kolumba museum is a cylinder having a radius of 150mm. So, the same column was used for first optimization. 2 different software were used- Ameba (a BESO algorithm-based optimization software) and Ansys. Fig 05.2 b shows the result for both optimization software.

The principal of topological optimization works on the removal of material based on stress line generated in a geometry. On analyzing the geometry in Karamba- a finite element structural analysis software, stress lines of a cylindrical column loaded under compression were deduced. The two principal directions of stress lines can be seen in the last sequence of Fig. 05.2 b.

It is evident from the fig that the removal of any part in the geometry would result in interference in stress line. Topologically optimizing the geometry would create a discontinuous column as seen in earlier optimization results.

Fig. 05.2 b: Optimization of a straight column & Stress lines

05.2.3 OPTIMIZATION OF A TRIANGULAR COLUMN

To find a solution to the above problem, design criteria for developing the column were glanced through again. The substitute of the original geometry should respect the context and at the same time should not be banal. So, the case study was read through again. The idea of the architect to intervene the least on the original site and foundation ignited an idea of removing all the supports in the middle of the archaeological remains. A slanted column was proposed where the load in the middle of the slab was directed to the foundation of the periphery columns. The Fig 05.2 d illustrates the new conceptual idea of the column. The next stage involved merging the slanted and the straight column on the periphery together. This evolved into a triangular shaped geometry as seen in Fig 05.e

The evolved form of the column not only respects the archaeological remains but also deals with the issue of user experience which was a major aspect in the design criteria. So, this new form of the column was analyzed structurally and optimized.

The diameter of 1 column currently in Kolumba museum (Fig05.2 c) is 300 mm and since this newly formed triangular column is transferring the load of 2 columns, the total thickness of the column was extruded to double the width.

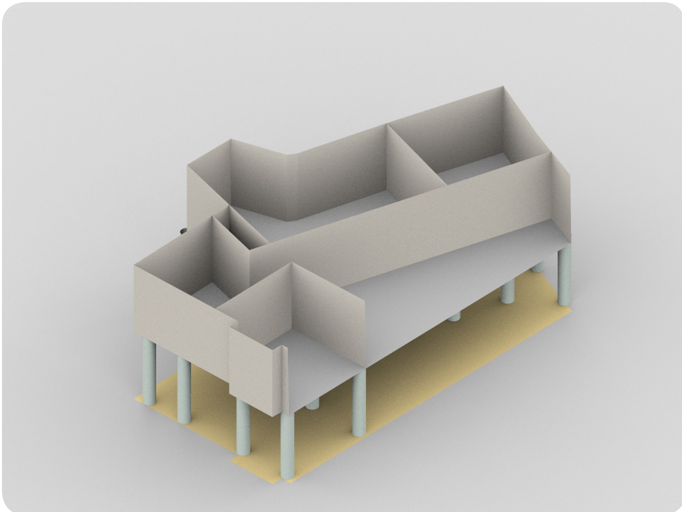


Fig. 05.2 c: Current column design at site

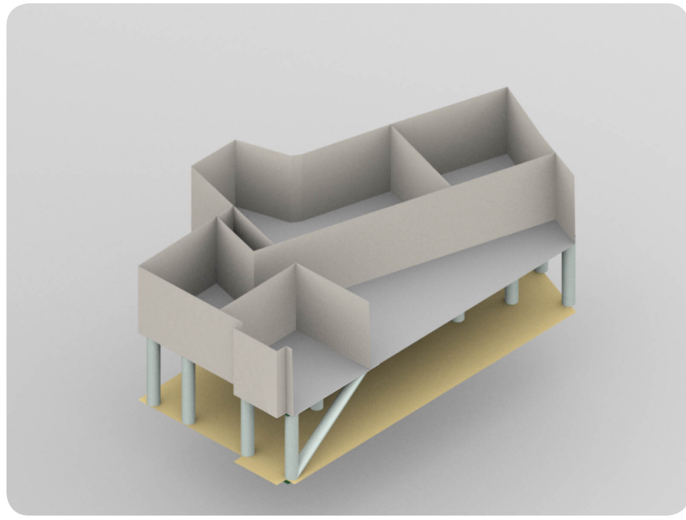


Fig. 05.2 d: Slanted column transferring the load to the periphery

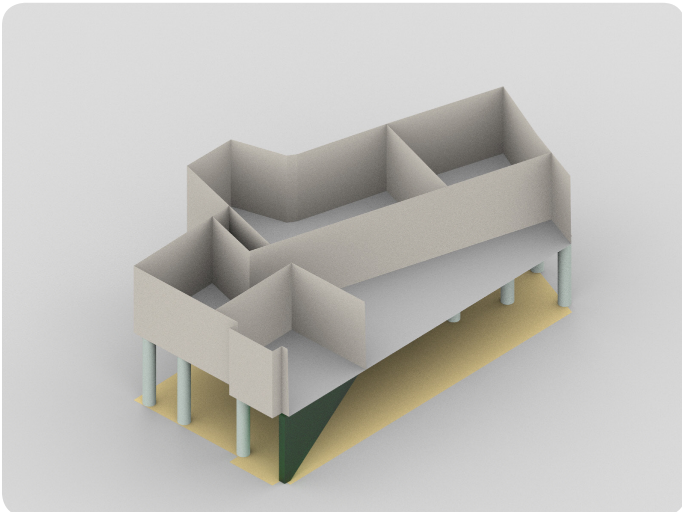


Fig. 05.2 e: Triangular shaped column as an input for Optimization

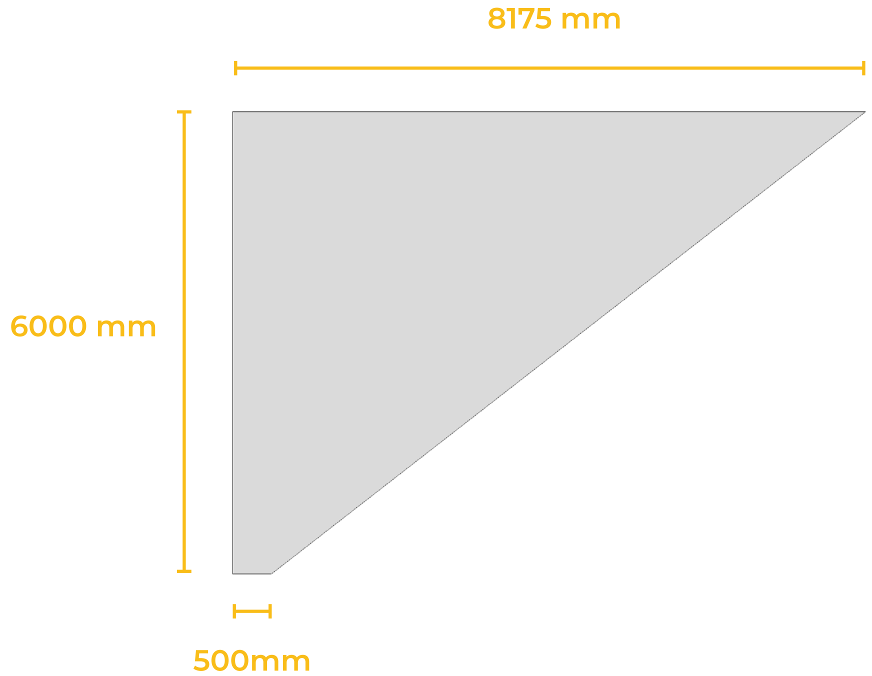


Fig. 05.2 f: Dimension of the new column to be optimized

Thickness: 600 mm

Minimum achievable mesh size: 71 mm

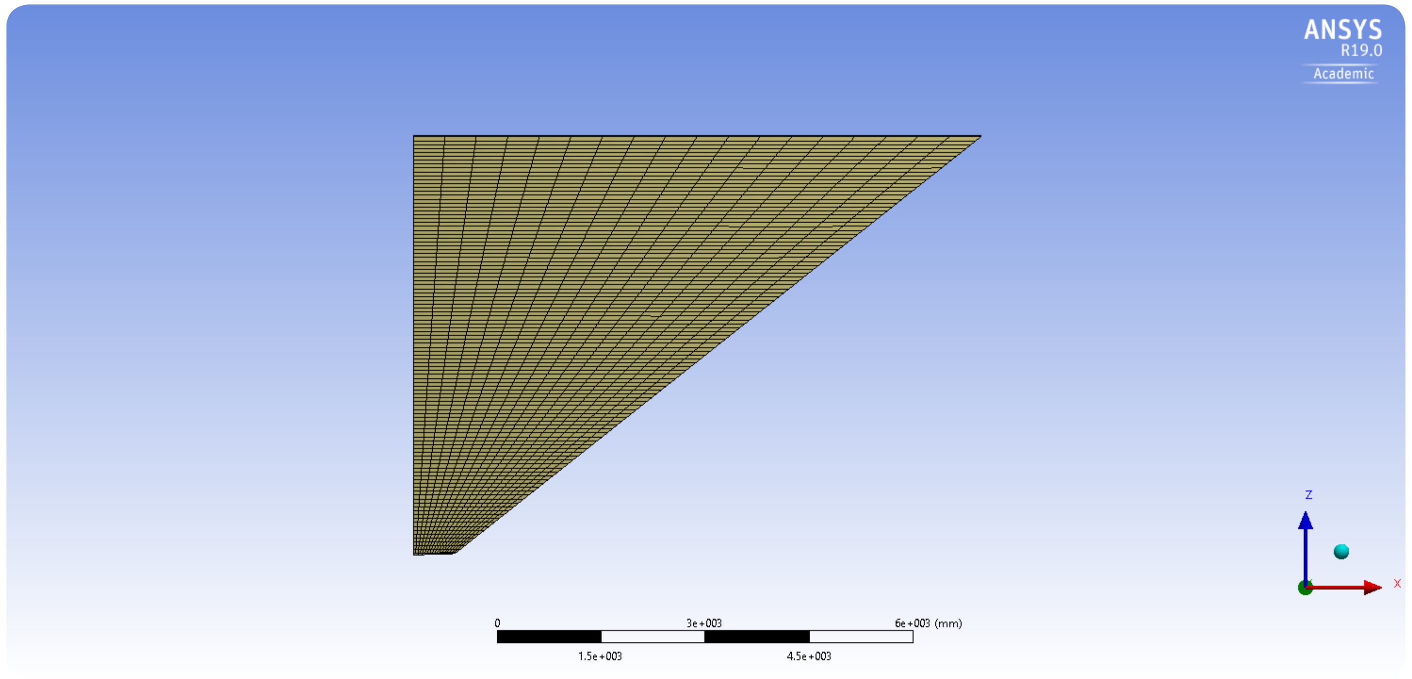


Fig. 05.2 g: Mesh size and distribution of the geometry

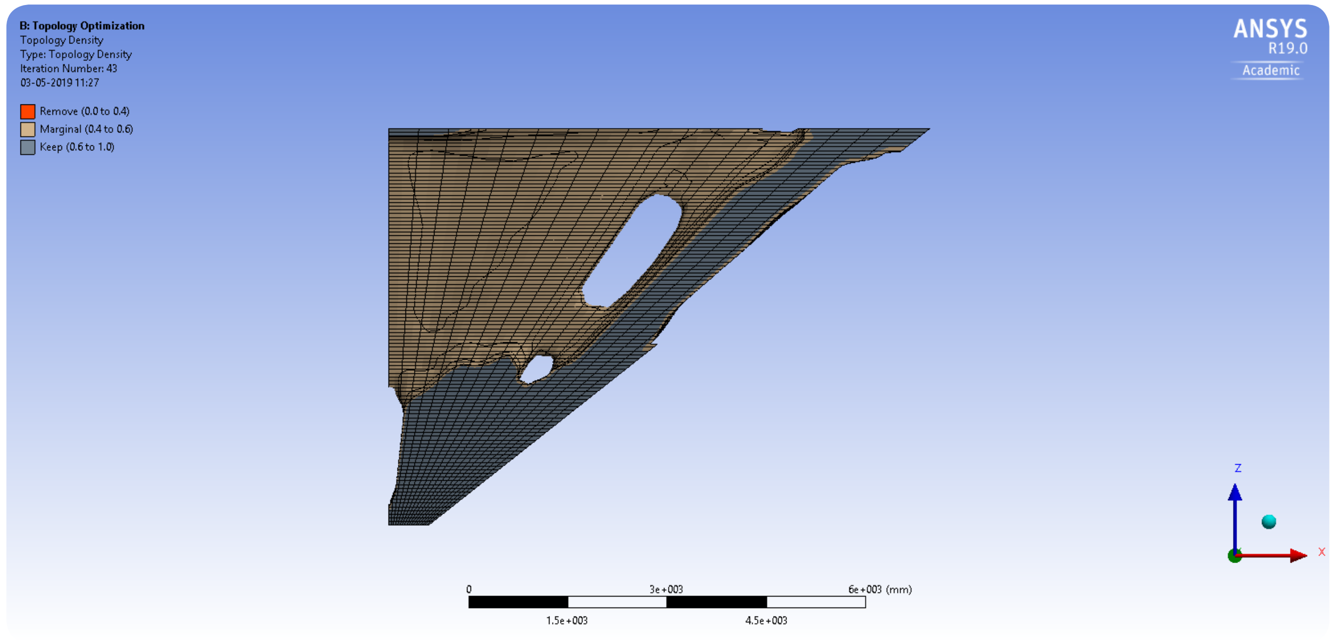


Fig. 05.2 h: Front view of the Optimized Geometry

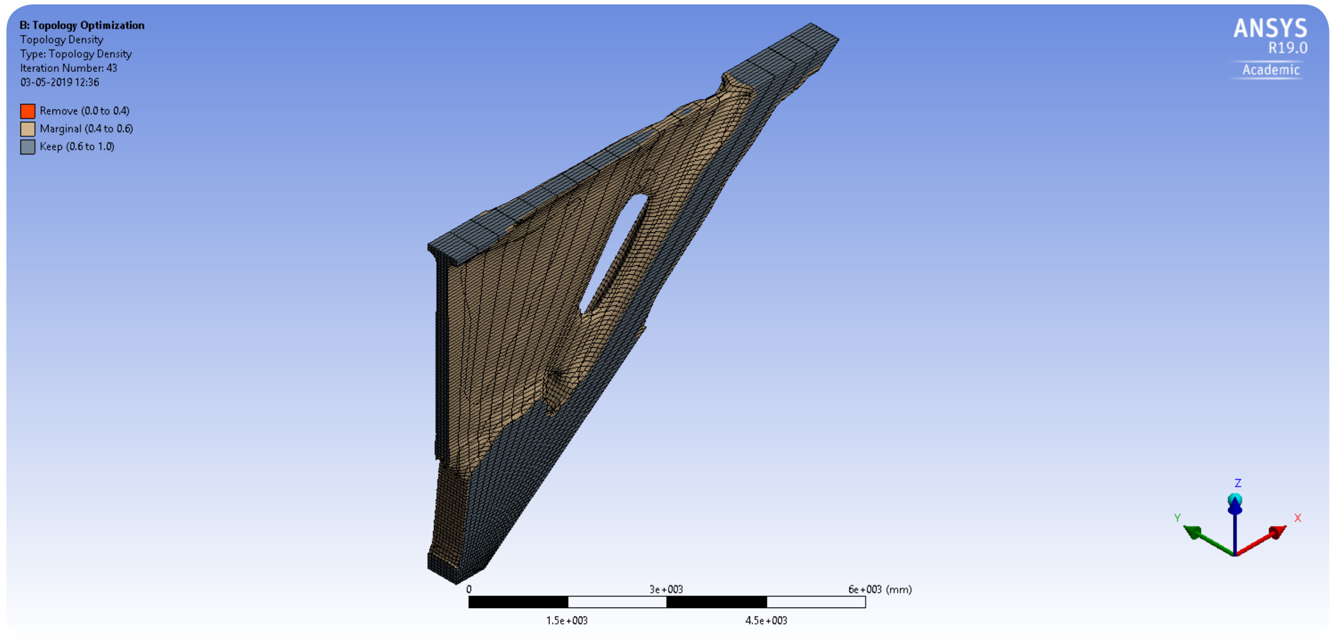


Fig. 05.2 i: Isometric view of the optimized geometry

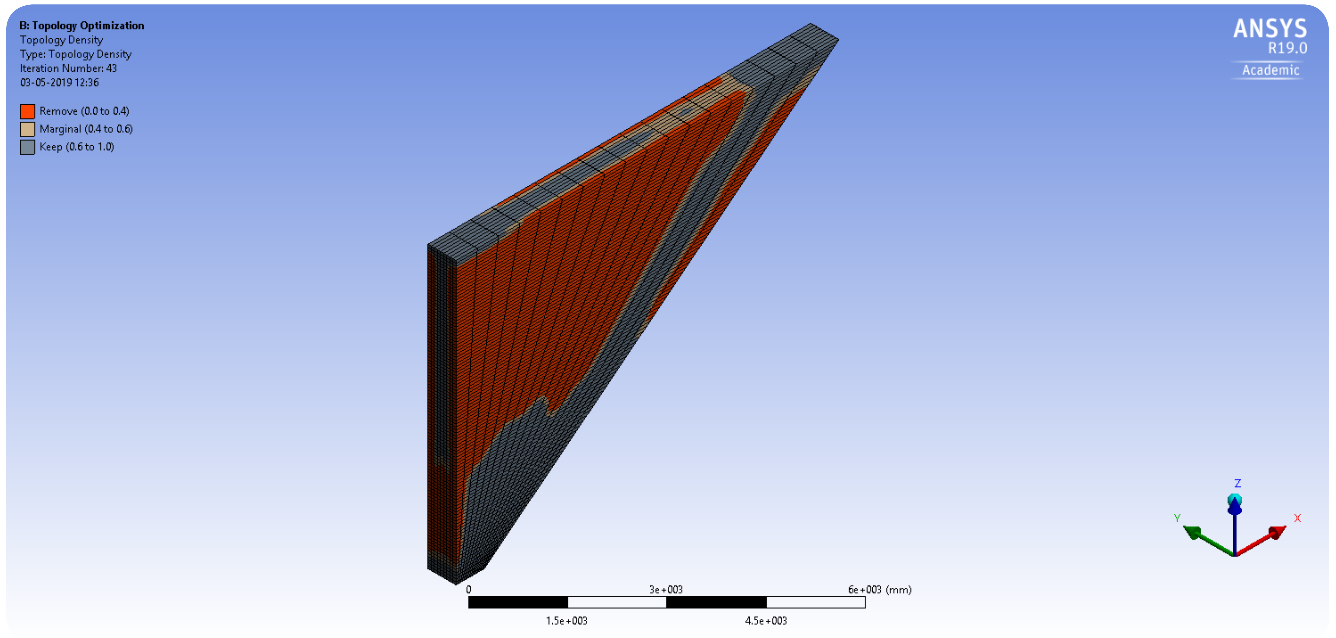


Fig. 05.2 j: Isometric view illustrating the material that is completely removed in red.

Optimization Results:
Iteration number: 43
Percent mass of Original: 51.32 %

Inference:
The geometry was too big, resulting in bigger mesh faces. The optimization was successful in removal of almost 50% of mass but still looks bulky. The angular overhang part , the hypotenuse part, is the thickest and has been unaltered by the optimization processes. The force acting at the extreme cantilevered point is the highest resulting in direct transfer of that load to the base resulting in the thick cross section along the hypotenuse.

05.2.3 DESIGN EVOLUTION

To reduce the number of mesh size, the initial volume of the column needed to be reduced. On reevaluating the design consideration decided before designing of the column, one realized, the column is too bulky and doesn't fits the environment being designed for. The crude state of the column was so bold in its presence for the context that it required further redesigning. Also, the straight angular part could act as a hindrance in the visual connection of the visitors. At the human eye level, the column takes up more space than required as seen in the Fig 05.2 k. So, due to ergonomic and aesthetic reasons, the column's form needed a remodeling.

Inspired from the load distribution and design of arches, the straight angular part of the column was converted to a semi arch shaped as seen in the Fig 05.2 l. The new shape offered more obstruction less space.

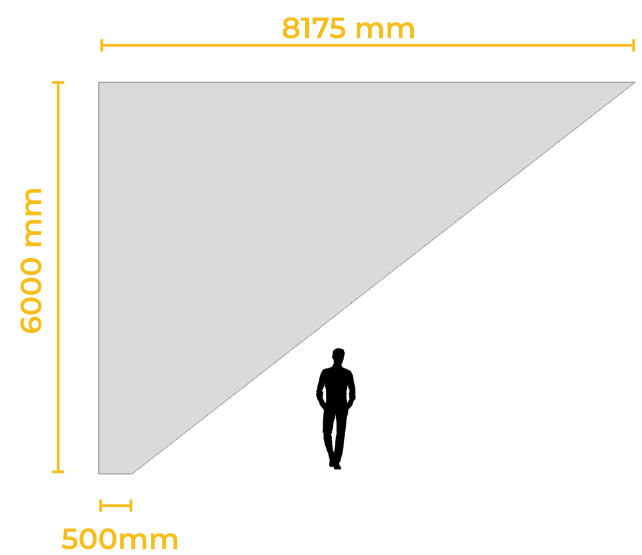


Fig. 05.2 k: Non- ergonomic design

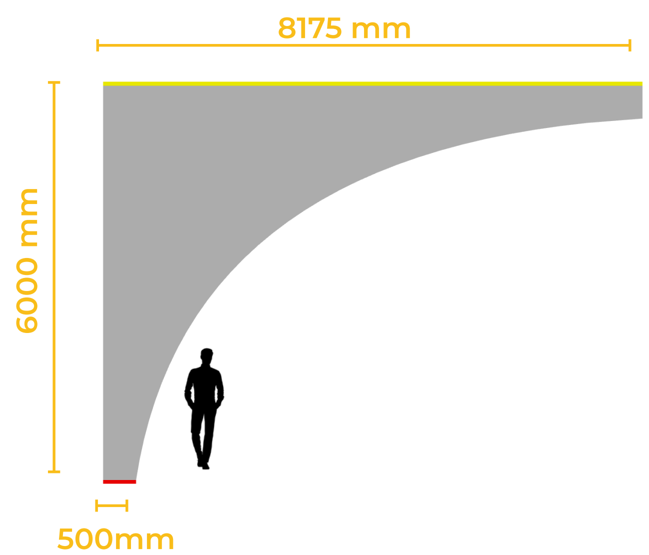


Fig. 05.2 l: Ergonomic design inspired by an arch

The redesigned column was tested for 3 thickness structurally before optimizing 250mm, 500mm and 750mm

The stresses and deformation were the criteria used for comparison. The analysis for each thickness can be found in the appendix. But a comparison has been drawn in table 10.

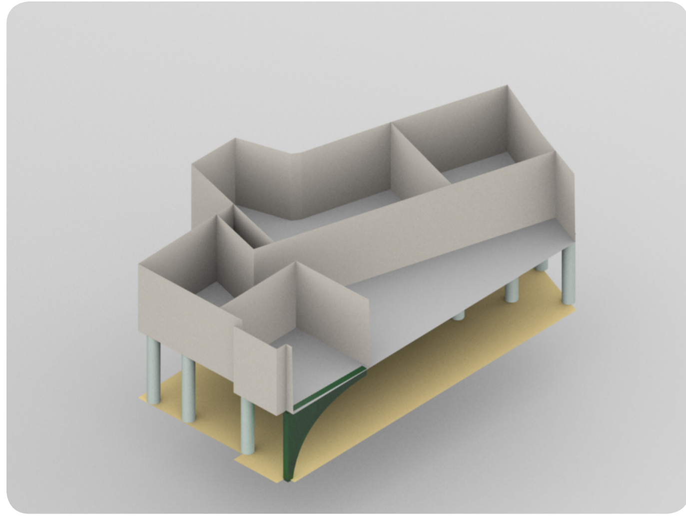


Fig. 05.2 m: Arch shaped column 500 thk as an input for Optimization

Thickness of Geometry	**250 mm**	**500mm**	**750mm**
Maximum Principal Stress (Tensile stress) (MPa)	46.12	28.8	5.7
Minimum Principal Stress (Compressive stress) (MPa)	-52.06	-35.5	-94.9
Total Deformation (mm)	4.86	4.3	4.5
Maximum Shear stress	25.63	19.62	34.9

Table 10: Comparative structural analyses of 3 different thickness of the arch shaped column

Allowable stress in tension for borosilicate glass ranges from 22 MPa to 32 MPa and in compression from 264 MPa to 348 MPa. 750 thick column was expected to outperform others but the increase in self-weight added to more compressive and shear stress.
It can be evidently seen, thickness of 500mm works the best amongst all in terms of stresses as well as deformation. Hence this 500mm thick semi arch shaped column was chosen for optimization.

Thickness: 500 mm
Minimum achievable mesh size: 60 mm

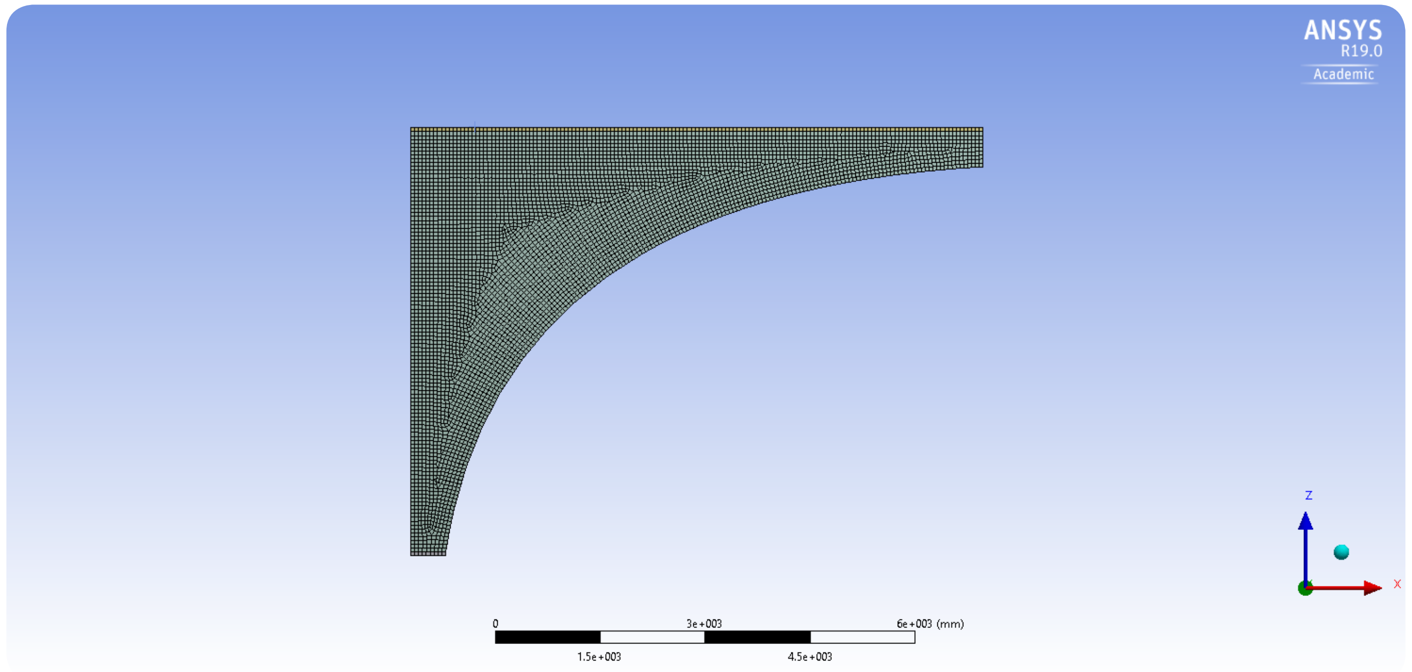


Fig. 05.2 n: Mesh size and distribution of the geometry

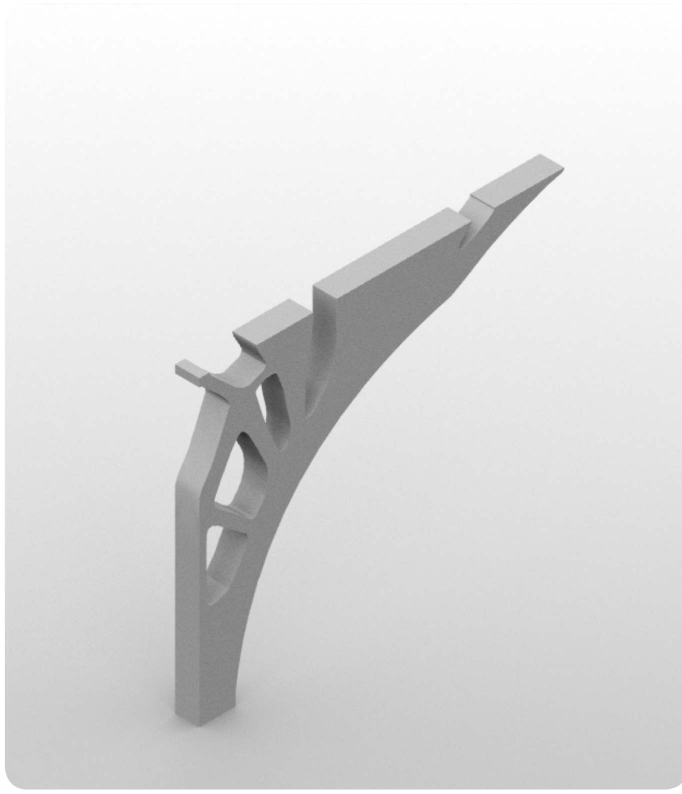


Fig. 05.2 o: First Optimization of the 500 thk geometry

Optimization Results:
Iteration number: 31
Percent mass of Original: 51.50 %

The geometry was structurally checked after optimization and resulted in the same stresses and displacement. But looking at the design criteria, the optimized geometry is too thick to be used for fabricating glass column.

Inference:
It is inferred that the mesh size used for structural optimization the geometry is too big to create a result having thin member sizes. Since, the limitation of the educational version of the software doesn't allow us to reduce the mesh size, a new approach for reducing the mesh size need to be explored.

The optimization result has less volume as compared to the initial geometry. This means that the mesh would result in a finer quality due to its small size. Hence, the optimization would result in thinner cross sections.

On inserting the optimized geometry directly for re- optimization, due to the curvatures on the surface of geometry, the mesh size achieved for even bigger that the original geometry. So, a silhouette of the optimization was created and same thickness of 500mm was given to the geometry as seen in the fig.05.2 p

This geometry on re-meshing gave a better result in comparison to the original geometry.
The mesh size achieved was 52mm.
Fig 05.2 q shows the optimized result.

Optimization Results:
Iteration number: 82
Percent mass of Original: 56.6 %

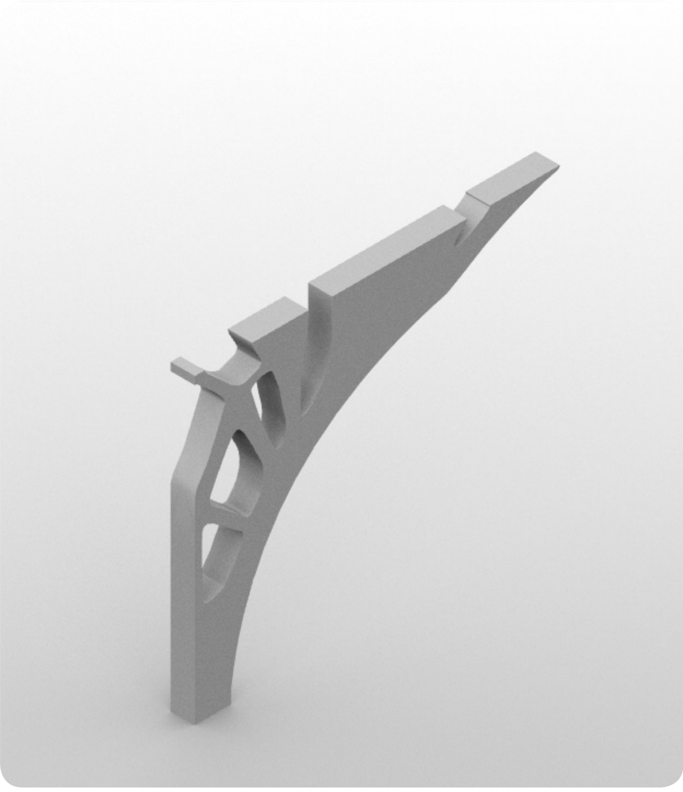


Fig. 05.2 p: Extrusion of silhouette of 1st optimized geometry

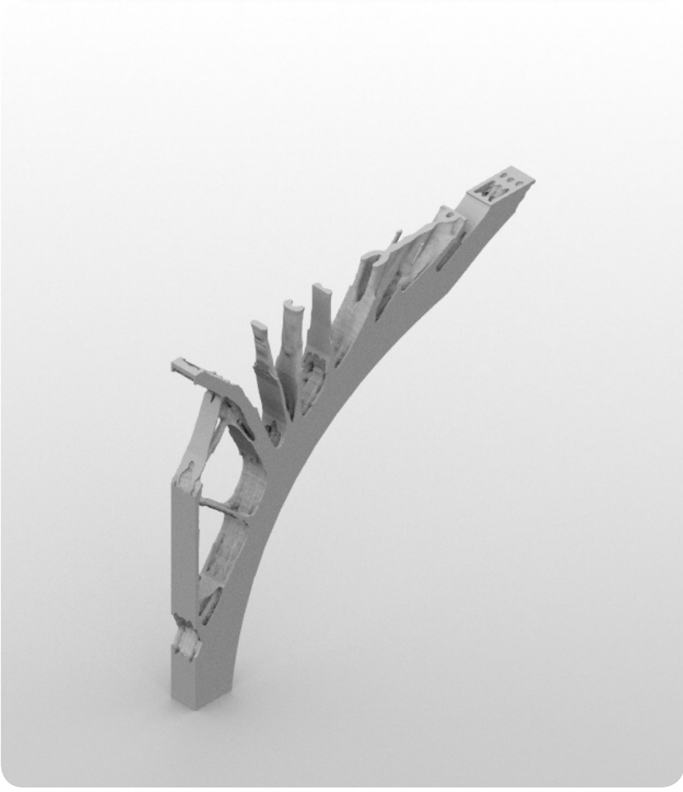


Fig. 05.2 q: Second optimization

Same procedure was repeated again and again till the time the mesh size stopped reducing. A planar version of the new optimized geometry- 2nd optimized geometry, was created with same thickness. (Fig 05.2 r)
The mesh size achieved for 3rd optimization was 49mm. Fig 05.2 s shows the optimized result.

Optimization Results:
Iteration number: 47
Percent mass of Original: 71.9 %

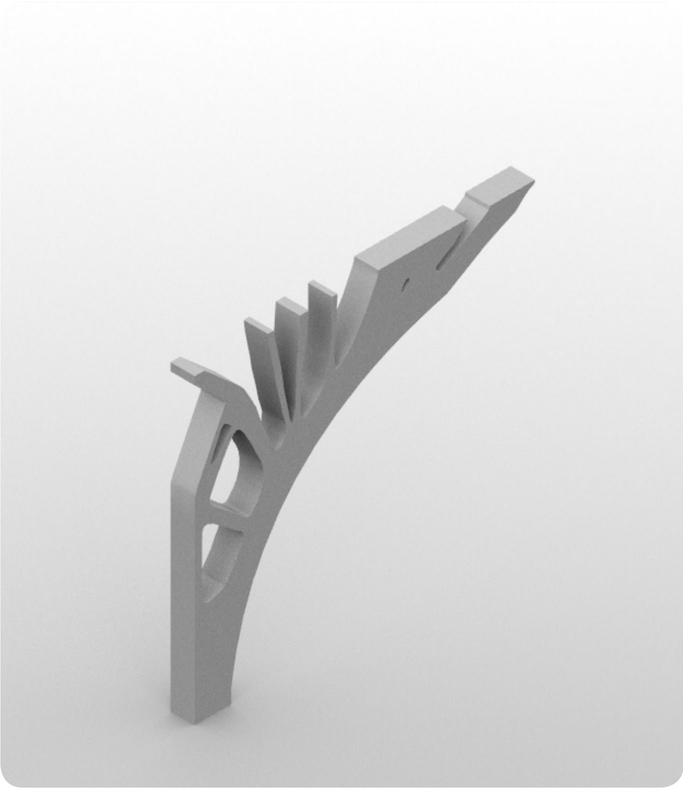


Fig. 05.2 r: Extrusion of silhouette of 2nd optimized geometry

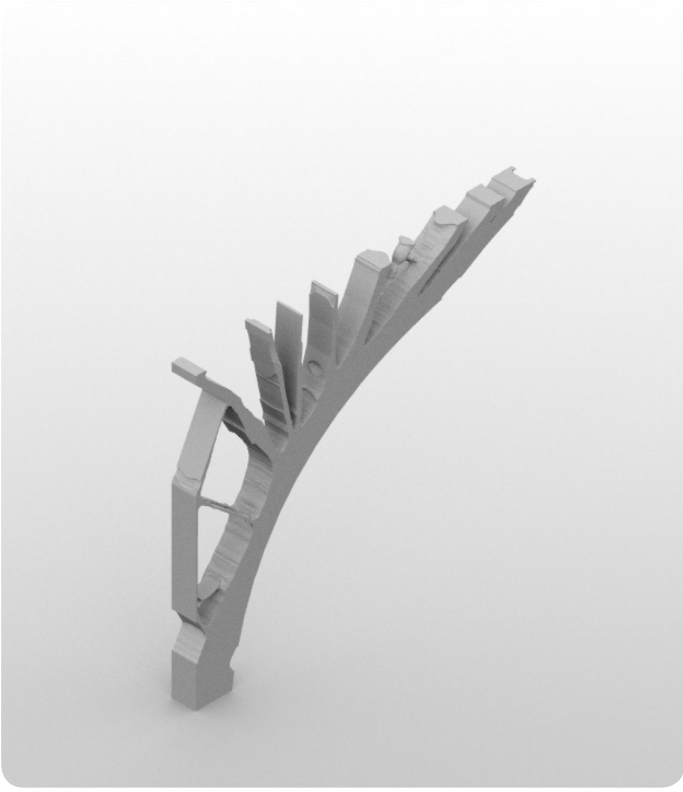


Fig. 05.2 s: Third optimization

The mesh size stopped reducing after the third optimization. On comparing the mass of the third optimized result to the initial geometry, where,
Mass of original geometry is 20369 kg,
Mass of optimized geometry is 8221.6 kg,

A 40.3 % of mass retention was achieved in comparison to original geometry.

With the help of various post processing tools offered in rhino- grasshopper environment, the geometry was further post processed to achieve a smooth finish. Fig 05.2 t shows the smoothened geometry.

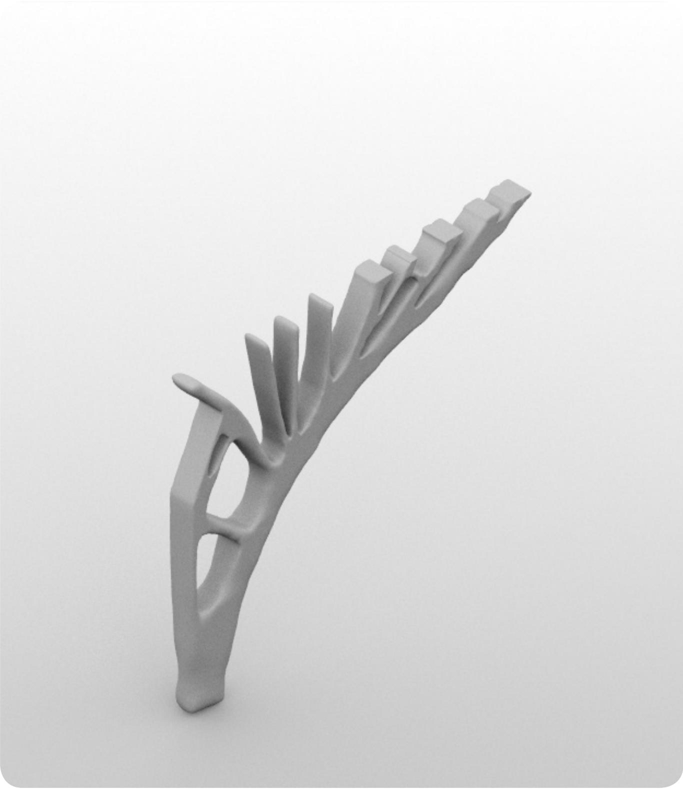


Fig. 05.2 t: Post processing of the optimized geometry

Inference:
The column geometry produced after 3 consecutive optimizations, resulted in a geometry which has a mass of 8221.6 kg and a uniform thickness of 500 mm. The design criteria formulated in the beginning of this chapter, doesn't satisfy with the currently produced geometry. In chapter 03.4, time estimated by bulls eye glass for a 200mm thick slab with uniform thickness is around 28 days, almost a month. In accordance to the table, the geometry would take almost 3 months to anneal in the furnace which would result in an inefficient design. The whole idea of using optimization would be doubted upon. A new design scheme needs to be sought to, for finding the solution.

05.2.4 SPLIT COLUMN

The incapability of the software to further optimize the geometry due to student license constraints has resulted in seeking of solution in other domains of design. A new design scheme was formulated, where the column is split in two halves as shown in fig 05.2 u. In other words, two thin geometries 200 thk each are placed next to each other with a small gap of 100 mm between them for safety reasons.

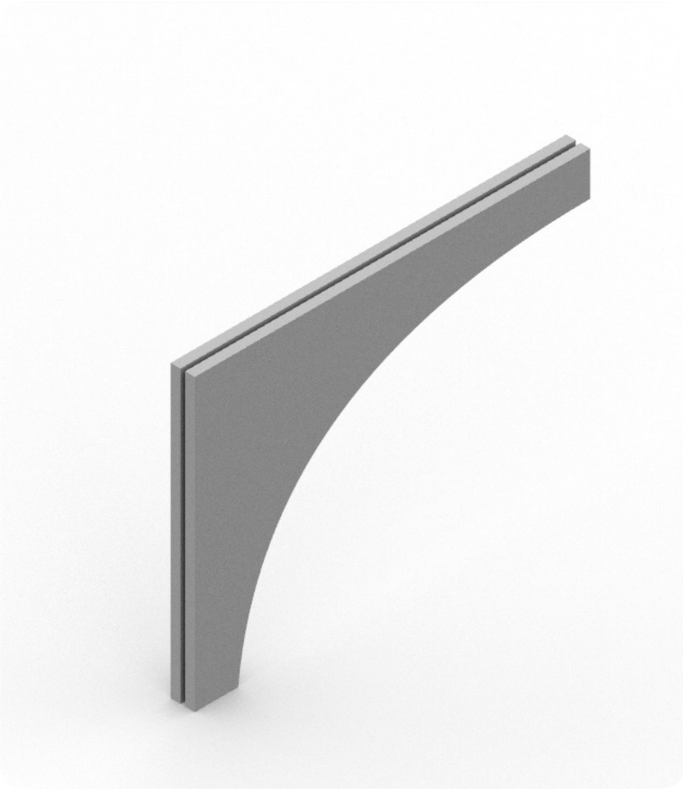


Fig. 05.2 u: New split geometry with 200 thk member and 100 thk gap in between the 2 geometries

The purpose here is to reduce the annealing time of the geometry. So, an achievable thickness in glass of 200mm is chosen representing one piece of the column and a distance of 100mm between the 2 pieces. The design was then tested for structural stability. Following were the results on analyzing the geometry in ansys.

On comparing the results of the current design scheme with the previous, it can be observed that the split geometry performs better than the earlier design. There is a significant difference in the tensile forces being developed in the column. Glass as a material being poor at the tensile part makes the current design much more effective.

To proceed with the whole design by optimization, similar ideology of re-optimizing again and again, as in the previous case, was used and the results achieved are discussed on next page.

GEOMETRY	SPLIT GEOMETRY	500mm
Maximum Principal Stress (Tensile stress) (MPa)	15.38	28.8
Minimum Principal Stress (Compressive stress) (MPa)	-29.39	-35.5
Total Deformation (mm)	3.25	4.3
Maximum Shear stress	19.47	19.62

Table 11: Comparative structural analyses of previous and the new splitted geometry

FIRST OPTIMIZATION:
Mesh size: 55 mm

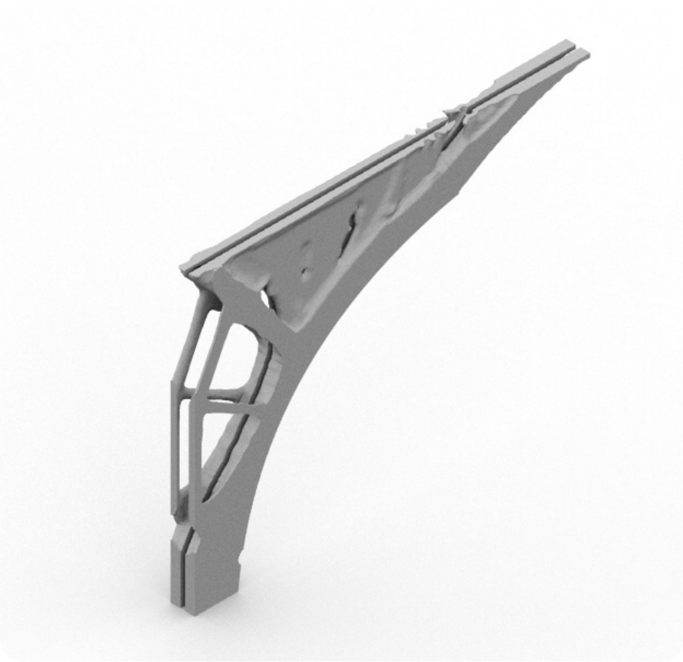


Fig. 05.2 v: First Optimization of split geometry

No. of iterations: 51
Percentage of mass retention: 52.4 %

SECOND OPTIMIZATION:
Mesh size: 50 mm

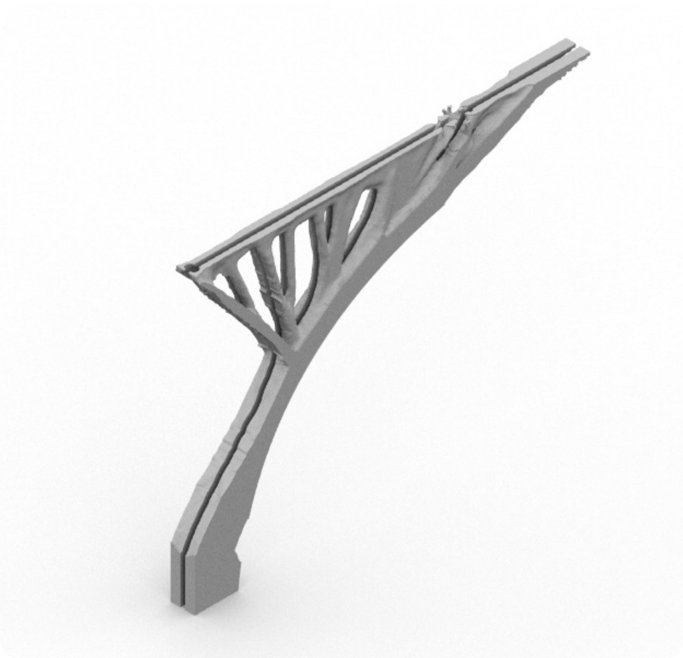


Fig. 05.2 w: Second Optimization of split geometry

No. of iterations: 41
Percentage of mass retention: 50.81 %

THIRD OPTIMIZATION:
Mesh size: 47 mm

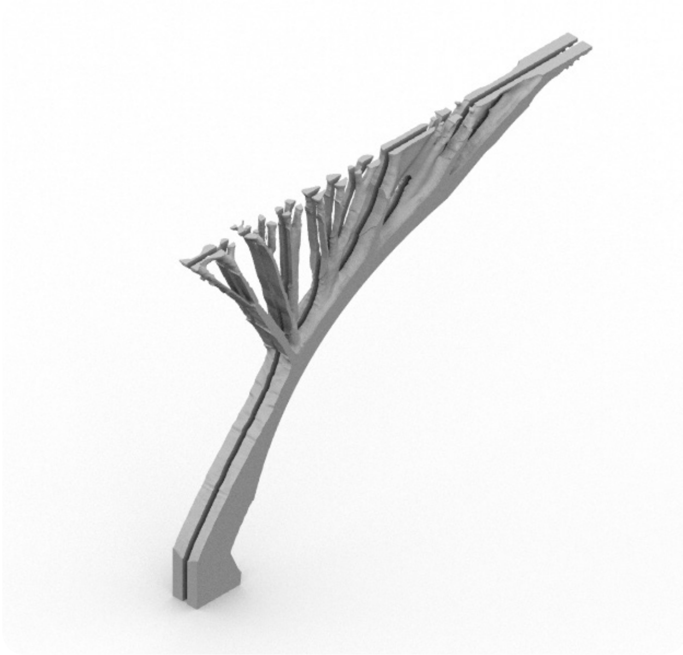


Fig. 05.2 x: Third Optimization of split geometry

No. of iterations: 28
Percentage of mass retention: 50.22 %

FORTH OPTIMIZATION:
Mesh size: 45 mm

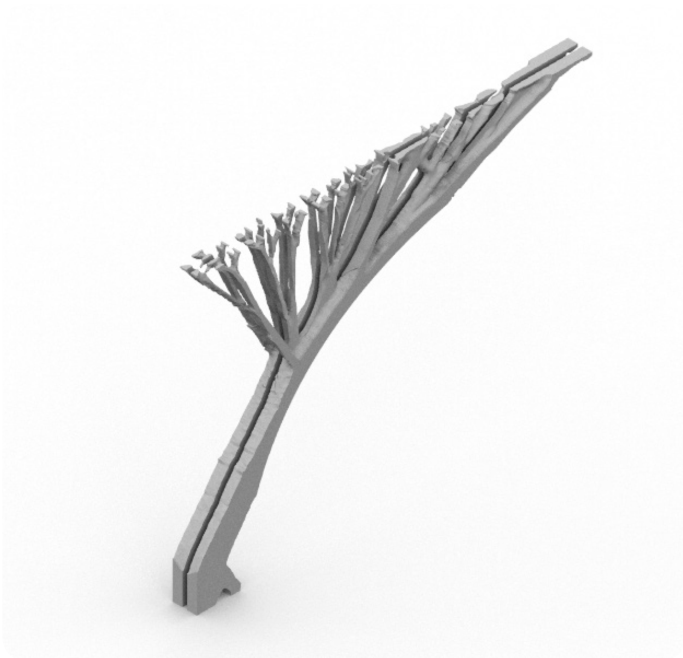


Fig. 05.2 y: Forth Optimization of split geometry

No. of iterations: 33
Percentage of mass retention: 51.22 %

After 4th optimization, the mesh size stopped reducing and the result was similar to the 4th optimization. Hence, the optimization process was terminated at this point. The mass of the original geometry, 2 neighboring elements combined, was 17146 kg and the mass for the final optimized geometry achieved after 4th optimization, 2 neighboring elements combined, was 4404.4 kg. So, one single piece of glass column would weigh around 2202.2 kg.

On calculating the percent retention of mass to the original geometry, a 25.68 percent of optimization by mass was achieved.

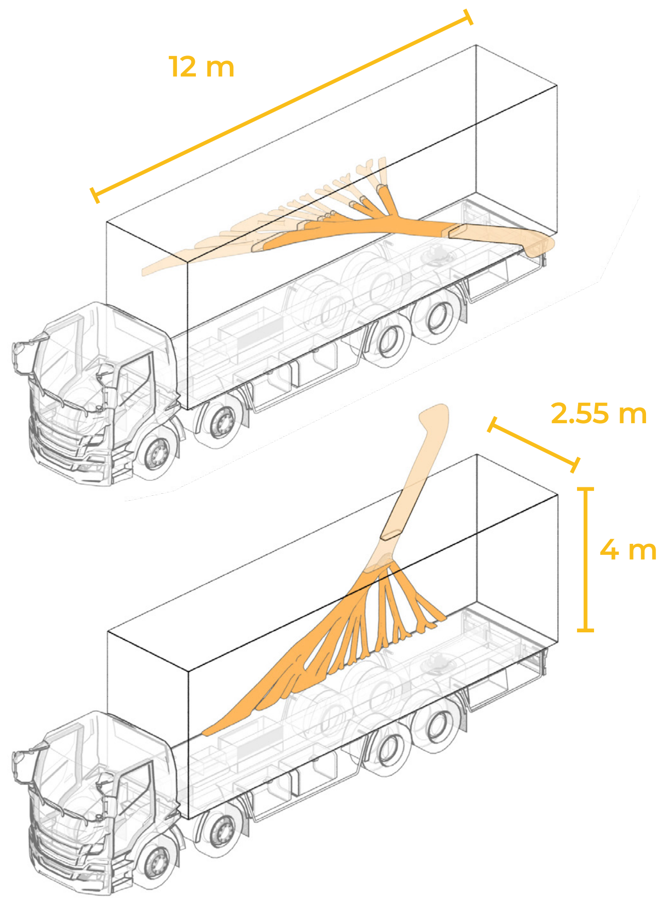


Fig. 05.1 z: Transportation concerns of the optimized column

05.2.5 CRITERIA CHECK

The column was designed according to many criteria listed in the beginning of this chapter. Cross checking our final design scheme with the criteria:

1. **Material Fabrication**

- Annealing Time: Design corresponds to the criteria by influencing the thickness
- Homogeneous mass distribution: Design doesn't correspond to the criteria. Column design looks similar to a tree structure having a thick trunk and small branches.

2. **Limitation of Sand Moulds:**

- No sharp corners: The geometry has some irregular surface having sharp pointy corners. So, design doesn't correspond to the criteria
- Wall thickness of mould: The geometry corresponds to the criteria

3. **Transportation & Logistics:**

The Eurocode mentions that the biggest size of the vehicle (truck with a lorry) that can carry goods in Germany has a dimension of 12m (length) X 2.55m (width) X 4m (height). Dimensions of the column are 8.2 m (length) X 0.2 m (thickness) X 6m (height) as shown in figure.
Clearly, the geometry doesn't seem to fit in a truck (lorry/trailer). So, the geometry doesn't correspond with the criteria.

4. **Visual Performance:**

The geometry corresponds with the criteria set. No obstruction or intervention is being done by the column to the archaeological site. Also, there is no hindrance in the vision or continuity of the space.

05.2.6 STRUCTURAL VALIDATION

The optimized column needs to be verified for buckling before further proceeding. Ansys was again used for buckling analysis. Fig 05.2 za and Fig 05.2 zb shows the same.

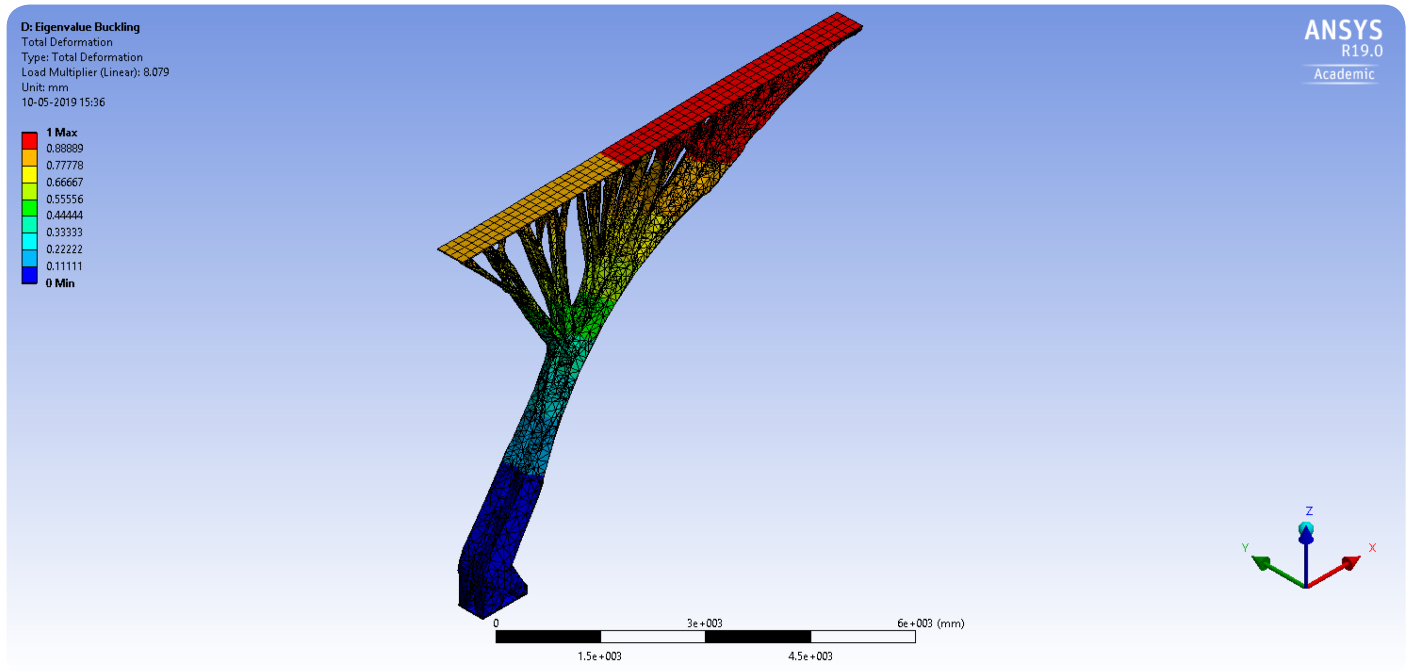


Fig. 05.2 za: Buckling Analysis along y axis.

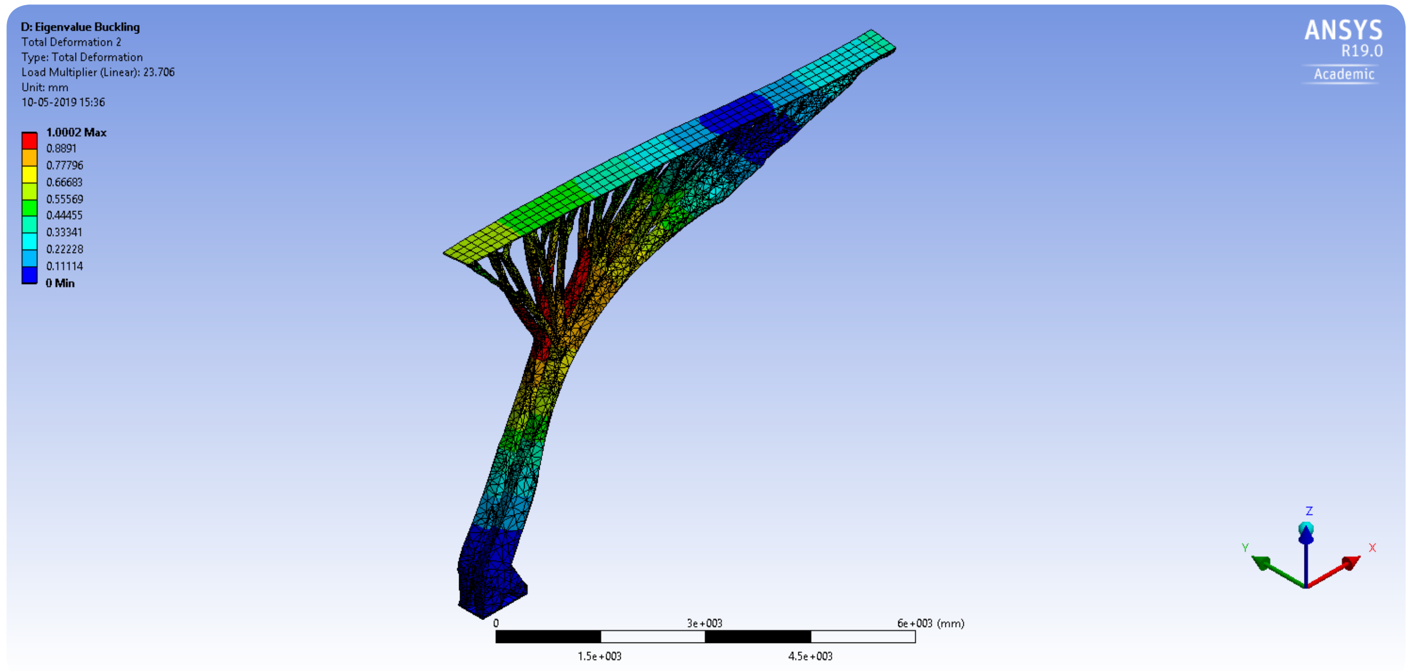


Fig. 05.2 zb: Buckling Analysis along x axis.

The results show only 1mm of deformation along x and y axis. Allowable deformation criteria for a column according to eurocodes is usually span/ 250.So, a deformation of 24 mm is allowable. 1mm is way under the allowable deformation criteria. So, the column is cross checked for structural stability.

INFERENCE:

The new design scheme developed taking the material property into account, results in a structure that performs better than the nominal design scheme. The reduction of tensile stresses and displacement makes it better for the performance and durability of the column. The mass of the optimized geometry is 4404.4 kg, almost half of the previous design scheme. Considering the fabrication and logistics, splitting this mass into 2 pieces, 2202.2 kg, the column would be easier and cheaper to manufacture. Also, the geometry would be more efficiently handled by the labor for transportation and assembly on site.

05.2.7 HOMOGENISATION & POST PROCESSING

The geometry doesn't satisfy the criteria of homogeneous mass distribution and sharp corners category. So, the geometry was post processed to satisfy these criteria.

On analyzing the geometry 2 different generalized thicknesses can be observed as depicted in fig 05.2 zc. The first one is the thick cross section- tree trunk, spanning from the ground to the cantilevered corner and the second is the small branches growing from this thick section to the top beam.

Fig. 05.2 zc: Generalization of thickness of the optimized geometry

A silhouette of the geometry was first created in rhino. The 2 generalized thickness were used to generate a uniform geometry having a homogeneous mass distribution using t spline- a plug in for rhino-grasshopper environment. The use of t spline ensures a fluidic design having no corners. Fig 05.2 zd illustrates the final result.

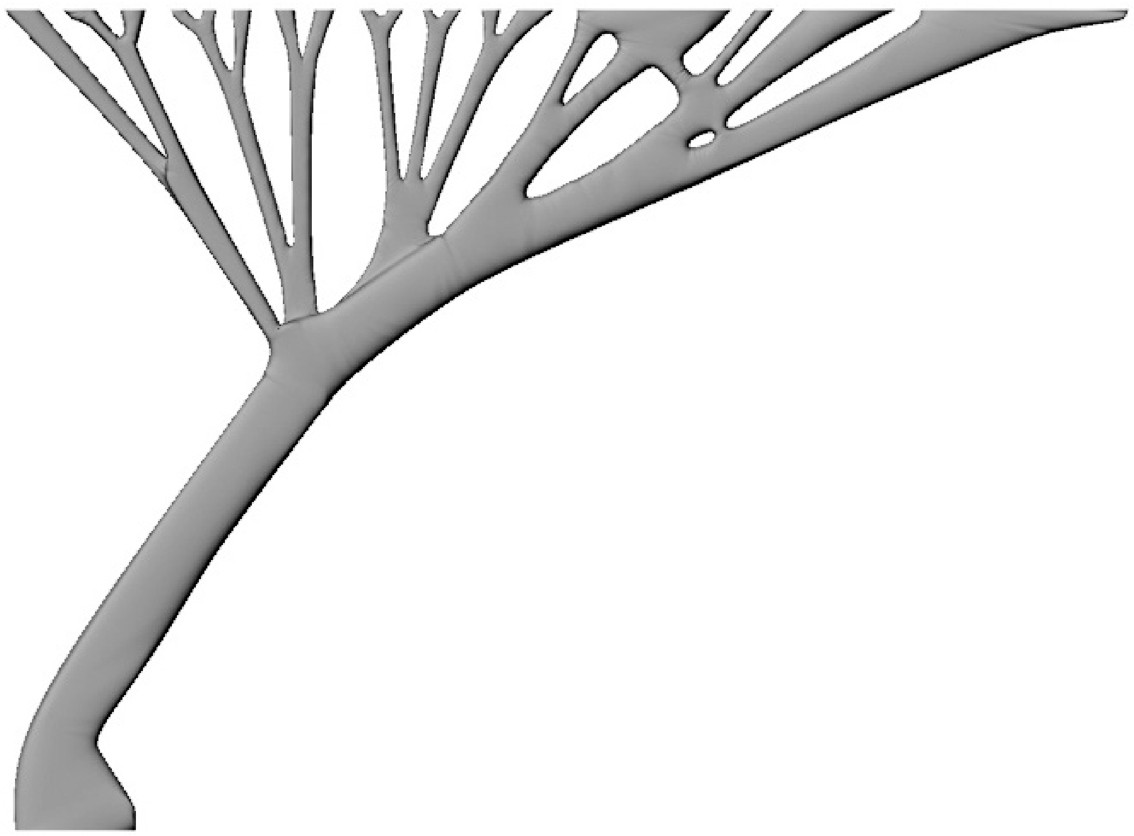


Fig. 05.2 zd: Final Optimized Geometry for fabrication

The weight of the new post processed geometry is 3375 kg.

05.2.8 SPLITTING OF GEOMETRY

The post processed geometry now needs to be fabricated and transported to the site. But the dimensions of the column doesn't fit the maximum size of lorry permitted on German roads. Also, the column posses different thickness which can lead to problems during annealing of the geometry.
For these reasons, the geometry needs to be splitted into pieces, which makes it easier for the fabrication (annealing) as well as transportation of the column.
Before splitting the geometry, certain norms needs to be formalized because of the unique qualities of glass material. These are:

- The geometry should have similar thickness throughout the cross section of the piece.
- The splitted geometry when assembled on site and put under compression, should be able to resist the shear forces developed between the pieces.
- Splitting of geometry should not create areas having thin section. This can result in peek stresses and hence development of crack fracturing of the glass column.

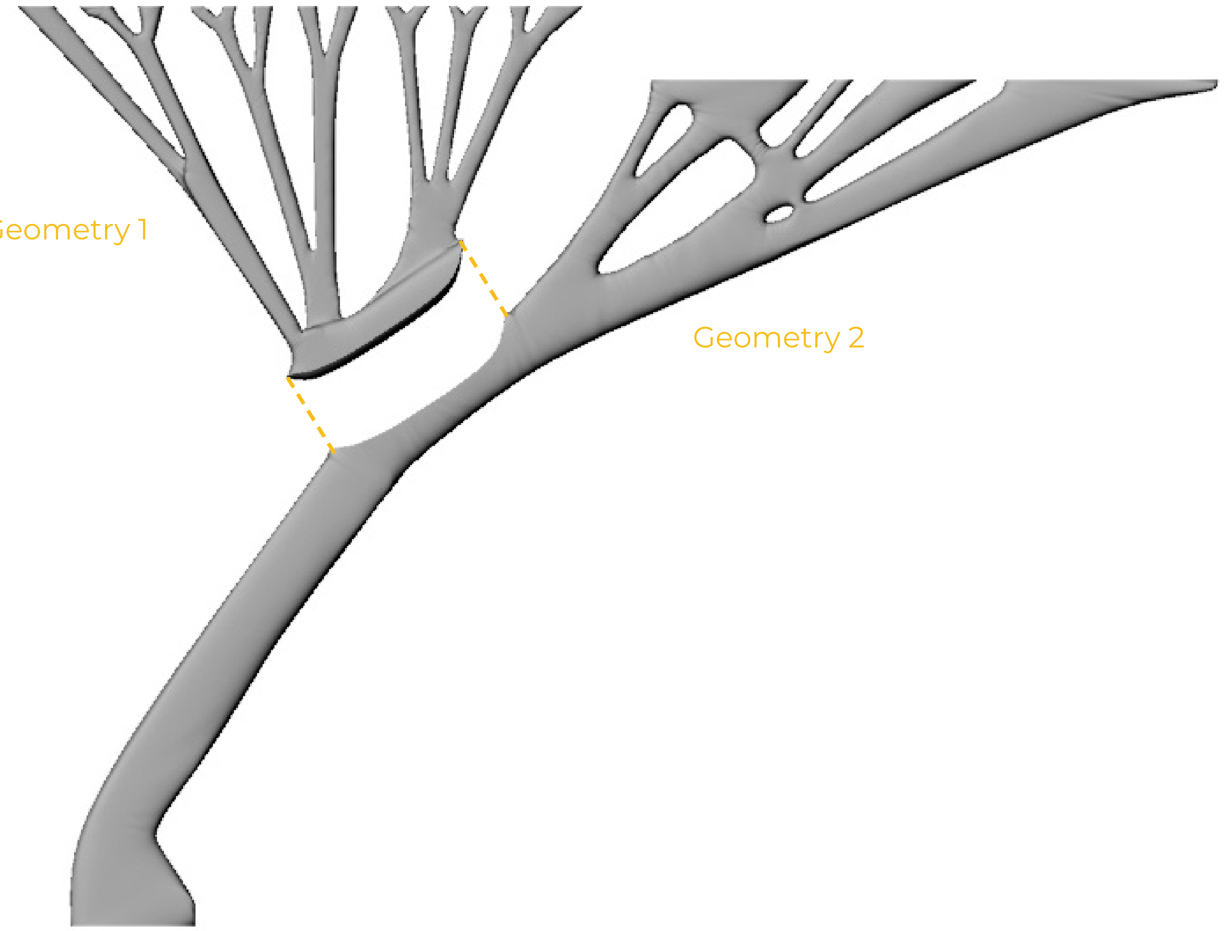
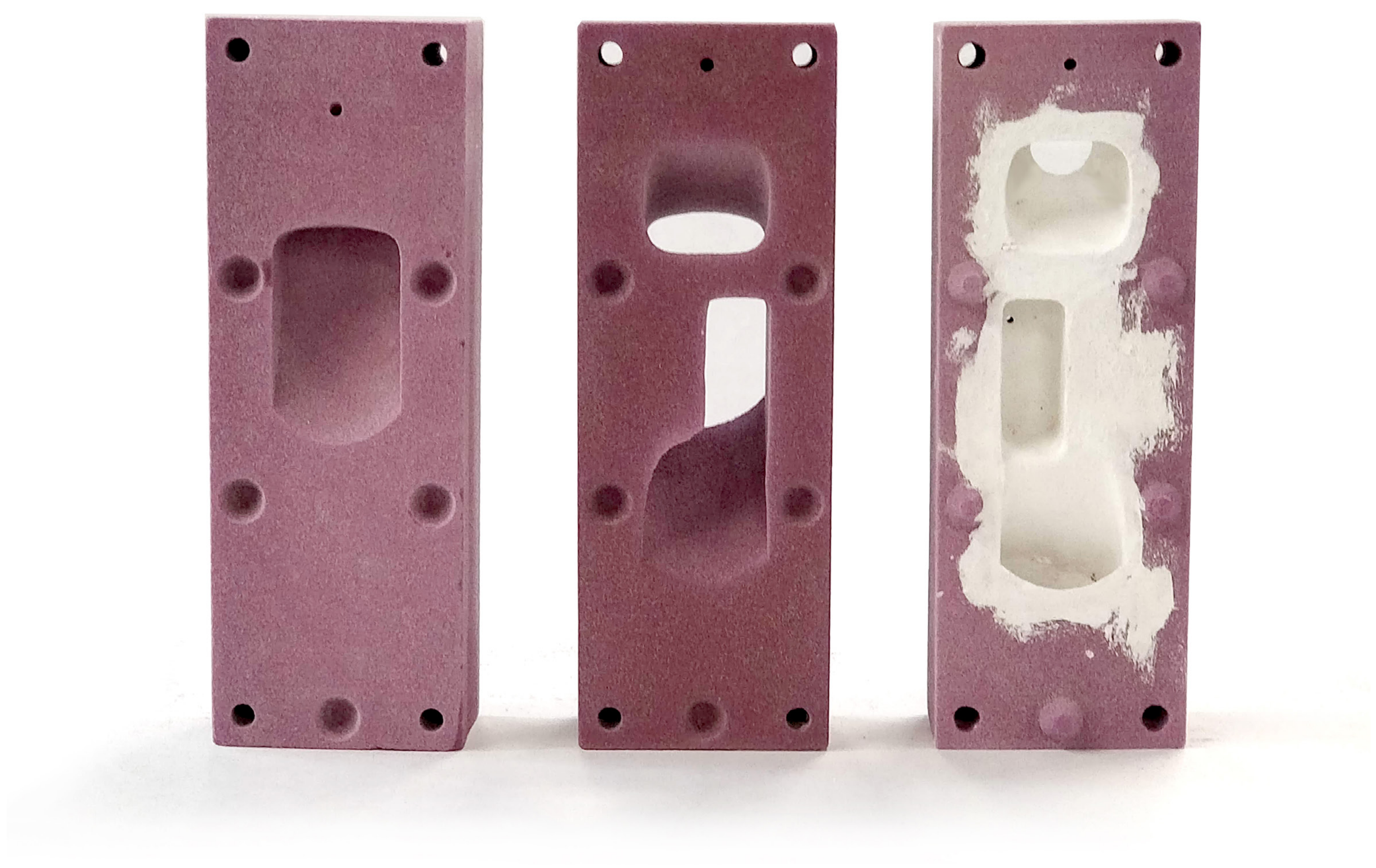


Fig. 05.2 ze: Final splitted Geometry for fabrication

	LENGTH (m)	WIDTH (m)	WEIGHT (kg)
Geometry 1	4.1	2.65	810
Geometry 2	10	2.58	2565



06

FABRICATION & EXPERIMENTS

The main aim of this project is to explore a new fabrication technique for casting glass structures. Chapter 03.5 depicts the traditional way of fabricating moulds for casting structural glass elements and it was concluded that the laborious and time-consuming process of creating moulds for challenging geometries requires help from the additive manufacturing sector. Chapter 03.6 portrays how digital manufacturing and 3D printing can totally revolutionize the industry's approach in fabricating customized and complex shapes easily.

This chapter illustrates various experiments and how each experiment leads to the next, progressing further to achieve the major aim of producing cast glass using 3D printed sand moulds.

06.1 EXPERIMENT 1

Unaware of the binder properties inside the sand mould and its reaction to high temperatures, the first experiment involved hot pouring of molten glass at room temperature in controlled environment to avoid any hazards in the lab.

Objective: Hot pouring of molten glass directly into the mould.

Specimen: 3D printed sand mould with furan binder having impressions carved inside them

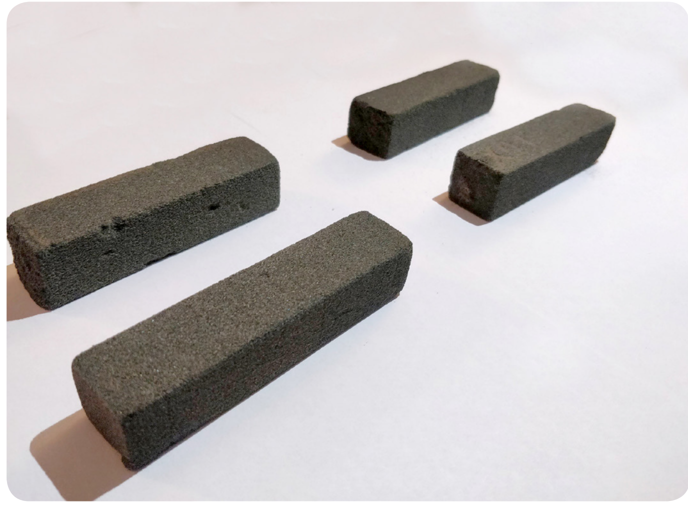


Fig. 06.1 a: 3D printed sand mould with furan binder system

- Sand type- silica sand
- Binder- furan (furfural resin)
- Casting method: Hot pouring
- Kiln type: Carbolite HTF 1700

Procedure:
A cavity was created manually in the 3D printed test bars as shown in fig 06.1 e using stone carving tools. Bigger glass pieces of soda lime were crushed and kept in a high alumina crucible (fig 06.1 d) to melt the glass as shown in fig 06.1 e

Fig. 06.1 b: Carbolite HTF 1700 kiln used for first experiment

Fig. 06.1 c: High alumina crucible

Fig. 06.1 d: Broken pieces of glass in crucible

Fig. 06.1 e: Hot pouring of glass on top of first specimen

Fig. 06.1 f: Glass hot poured in the cavity of first specimen

The alumina crucible was kept inside the kiln at 1100 degree Celsius. When the temperature was reached, the molten glass was poured into the test bars. Fig 06.1 e and fig 06.1 f illustrates the process.

Same was done for the second specimen.

Fig. 06.1 g: Hot pouring of glass for second specimen

Observation:
After the cooling of the glass piece, it was removed from the sand mould. There were 2 major observations.

- Surface chill on the glass: When the molten glass (1100 degree) was poured into the mould at room temperature (20 degree), the surface of the glass which came in contact with the mould developed surface chills on the surface as seen in fig. 06.1 h.

- White powder on top of mould: A white colored powder started to develop in the regions where the molten glass came in contact with the mould. (fig 06.1 i & fig 06.1 j)

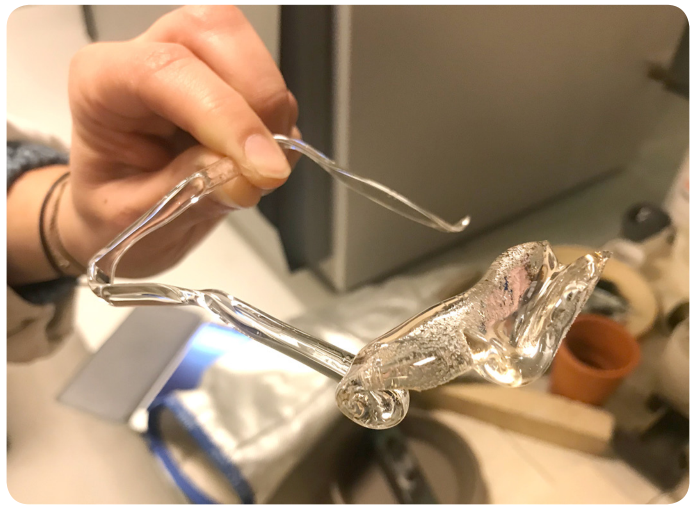


Fig. 06.1 h: Casted glass piece, Specimen 1

Fig. 06.1 i: Surface chills observed on the contact area

Fig. 06.1 j: Casted glass piece, specimen 2

Conclusion:

- The main aim of casting should be first to check quality of glass. Since in the above experiment we could observe surface chills which results in disruption of optical vision of the glass, hence, it is recommended to preheat the mould to avoid the surface chills.
- The second observation regarding the white powder which is basically sand and the dark green color which corresponds to the binder evaporated resulting in disintegration of the mould

06.2 EXPERIMENT 2

The last experiment concluded that the sand moulds need to be preheated before hot pouring. Also, the mould started to disintegrate. So, this experiment aims at observing the sand mould inside the kiln at varied temperatures.

Objective: Understanding the behavior of the sand mould at different temperature inside the kiln.

Specimen: Small piece of 3D printed sand mould with furan binder

Fig. 06.2 a: Specimen tested for direct exposure to heat

Fig. 06.2 b: Specimen failure against heat in first 10 minutes

- Sand type- silica sand
- Binder- furan (furfural resin)
- Casting method: Hot pouring
- Kiln type: Carbolite HTF 1700

Procedure: The annealing of glass is usually done between 500 to 600 degree Celsius. So, to initiate with learning the behavior of the mould to the heat, the kiln was heated to 500 degree Celsius and the specimen was kept on a terracotta tray inside the kiln. After 12 degree raise, the kiln was opened again to check and was stopped at 570 degree.

Results:

It was observed that the mould started to disintegrate after 12 degree of raise (1 degree raise / minute) as seen in the fig 06.2 c

Fig. 06.2 c: Disintegration of binder resulting in loose sand around

When the kiln was opened again at 570 degree, the mould had already disintegrated completely as seen in the fig 06.2 d

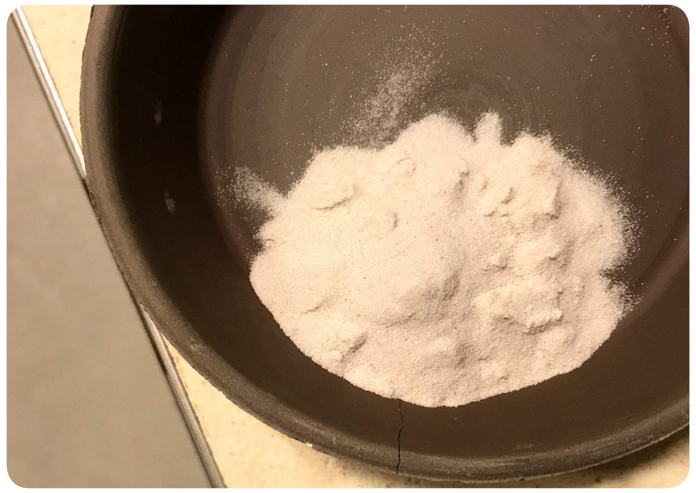


Fig. 06.2 d: Total disintegration of binder leaving a heap of sand

Conclusion:

It is evident from the above research that the binder vaporises on direct contact with the heat. The residual left is pure sand.

06.3 EXPERIMENT 3

Last experiment concluded with the binder vaporising on exposure to direct heat. This experiment involves forming an envelope around the mould with crystal cast (gypsum) to avoid the direct exposure.

Objective: Understanding the behavior of sand mould coated with a layer of crystal cast

Specimen: Crystal cast coated/ slip casted 3D printed sand mould with furan binder having impressions manually carved in it.

Coatings with different consistency were made and slip casting of moulds were done to achieve a perfect sample. Fig 06.3 a shows the wet version and fig 06.3 b, the dried version of the slip casting. The moulds were let dry in the room temperature for almost a day. 7 different iterations were created with few being coated twice and thrice.

7 different types of slip casting done were:

1. Dipping the mould in a thick consistency of crystal cast which is about to solidify
2. Dipping the mould once only in a liquidy crystal cast
3. Dipping the mould once only in a semi consistent crystal cast.
4. Applying a semi consistent crystal cast using a wooden stick on top of mould
5. Dipping the mould twice in a liquidy crystal cast in a gap of 15 minutes
6. Dipping the mould in a semi consistent crystal cast twice in a gap of 10 minutes
7. Dipping the mould thrice in a liquidy crystal cast in a gap of 15 mins each.

Fig. 06.3 a: Different consistancies of crystal cast tested on top of 3D printed test bar

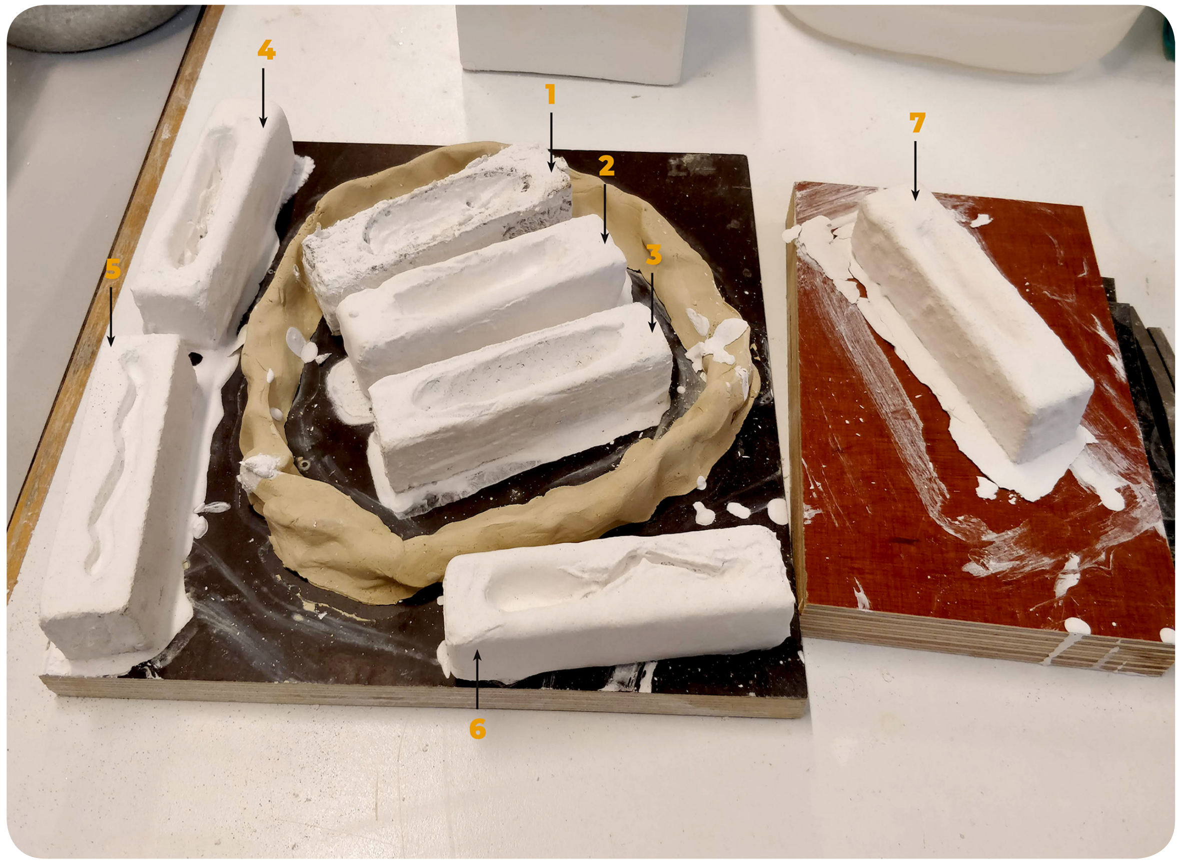


Fig. 06.3 b: After 24hrs of drying of crystal cast coating

2nd and the 7th iteration seemed most promising out of all the 7. Hence, they were selected as the specimen for this experiment.

The specimens were placed on a sand bed (sand particle size 0 to 4 mm) to avoid any hazard inside the kiln as shown in the fig. 06.3 c

Fig. 06.3 c: Experiment setup- precautional measures taken to avoid damage to owen

- Sand type- silica sand
- Binder- furan (furfural resin)
- Casting method: Hot pouring
- Kiln type: Carbolite HTF 1700

Procedure:

Old glass bottles were broken into smaller pieces and were placed on top of the mould inside the cavity as seen in fig

The 2 specimens were placed inside the kiln as seen in the fig and the kiln was programmed to function according to the following description:

1. A rise of 1 degree per minute till 780 degree Celsius. (melting point of the soda lime glass)
2. A dwell of 90 minutes at 780 degree Celsius (dwell in this context means maintaining the same temperature) to allow complete melting of glass and escape of air bubbles.
3. Followed by quenching at -2.7 degree per minute till 430 degree Celsius.

4. A dwell of 60 minutes at 430 degrees to allow the glass piece to anneal.
5. The kiln is allowed to turn off and allow automatic cooling.

Fig. 06.3 d: Setting up of specimens inside the owen

Fig. 06.3 e: Carbolite 1700 kiln

After 5 hours of the initiation of the kiln, the specimen was checked as a cautious measure. The whole experiment took 24 hours to finish and the kiln was opened again only after completion.

Fig. 06.3 f: Casted glass piece in specimen 1

Fig. 06.3 g: Casted glass piece in specimen 2

Observation:
The experiment was successful in casting the glass in the mould. The color on the glass is red and black because of the use of old glass pieces. The color pigment in the molten got segregated and gave the result as shown in fig 06.3 h

Fig. 06.3 h: Result of Specimen 2

The main observation was regarding the mould. On removal of glass piece from the mould, it was observed that the mould disintegrates on just touching it. Fig 06.3 i & 06.3 j illustrates how fragile the mould was and the sand inside was being held by the thin outer layer of crystal

Fig. 06.3 i: Lose of strength by the mould after casting process

Fig. 06.3 j: Lose of strength by the mould after casting process

cast.

Conclusion:
It can be concluded from the above experiment that the furan binder vaporises because of heat and the mould was just being kept intact by the thin outer layer which under excessive load of glass for casting bigger piece would disintegrate within 10 minutes of exposure to higher temperatures.

A layer of structural concrete instead of crystal cast can be a way forward for casting smaller pieces but won't be a promising solution for the structural glass industry.

Another solution to the above problem could be finding a new binder that can tolerate high temperatures.

06.4 EXPERIMENT 4

The failure of experiment forced in finding an alternative binder system which can tolerate higher temperatures. ExOne, the company behind manufacturing binder jetting 3D printers, was contacted asking for samples regarding the new binder system that was recently listed on their website. These binder systems were still in prototype stage and are not available commercially.
3 new binder systems were gained access to and were tested for higher temperatures.

Objective: Understanding the behaviour of 3 new binder system at high temperatures.

Specimen: Moulds made of 3 different binders and sand.

1. Anorganic (German for inorganic)
- Binder type: Waterglas binder
- Sand type: Silica sand
- Curing Process: The binder is cured in the job box with a built-in microwave inside the printer.

2. HHS – High heat strength
- Binder type: Phenolic binder
- Sand type: Synthetic sand (used for high temperature foundry application
- Curing Process: The phenolic binder is cured in the job box with the activator using microwave technology built inside the printer.

3. CHP- Cold hardening phenolic
- Binder type: Phenolic binder
- Sand type: Silica sand
- Curing Process: The binder and the activator cures inside the job box (print box) and then after desanding (removal of loose sand), the printed geometry is cured in a conventional Owen at 160 degree for 1 hour to attain full strength.

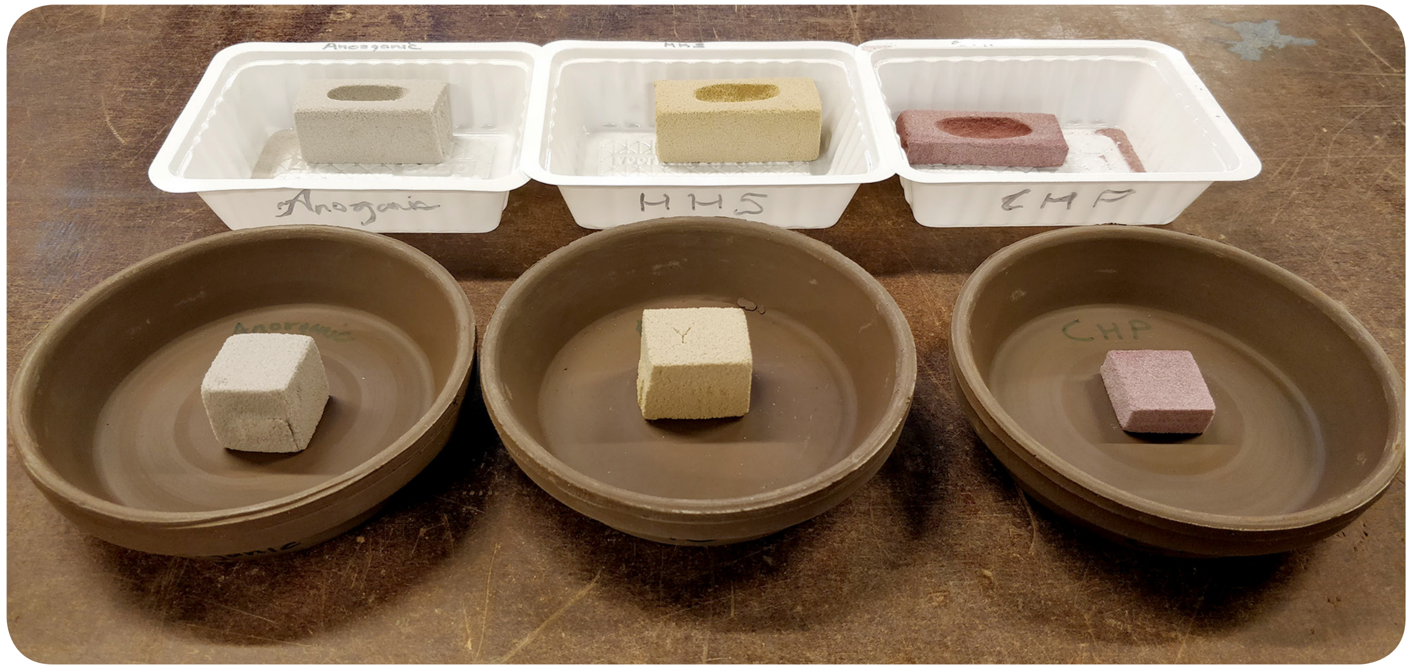


Fig. 06.4 a: This figure illustrates the 3 types of binder system in same order of description above.

Kiln type: A different kiln was used for testing of the moulds because of unavailability of previous kiln.

Helmut Rohde
Model no: ELS 200 S
Max operating Temperature: 1320 degree Celsius

Fig. 06.4 b: Helmut Rohde kiln used for the experiment

Procedure:
The specimens were placed on a terracotta dish and were kept inside the furnace. The furnace was put to a temperature of 500 degree Celsius initially (annealing point of glass) with an inclination rate of 1 degree per minute. The specimens were then tested at different temperature till 900 degree Celsius (Melting point of glass). After every 100 degree of raise, the specimens were checked and were touched with a tong to check the integrity and strength of the mould.

Result:
Except for HHS (High heat strength), all other mould seemed to be intact at all the temperatures ranging from 500 to 900 degree Celsius as being depicted in the fig. 06.4 c

Observation:
Following can be observed from the experiment for each binder:

1. Anorganik binder system was able to sustain the heat even at 900 degree Celsius and there was no change in the appearance of the mould. The mould was strong and didn't disintegrate during or after the experiment even on scratching.

Fig. 06.4 c: Specimens behavior on exposure to heat at 500 degree celcius

2. HHS binder system was expected to be the best performing due to its specific use in high temperature foundries but to the astonishment, the binder failed in the first attempt at 500 degrees. The binder vaporised and heap of synthetic sand was left behind.
3. The last binder system, CHP, was also able to sustain the heat, even at higher temperature of 900 degree. The colour of the binder evaporated. On touching the mould with a tong, nothing happened but one was able to create impressions on the geometry when scratched as seen in the fig. 06.4 d

Fig. 06.4 d: CHP binder system after exposure to heat at 900 degree

Conclusion:
The Anorganik and CHP binder system can easily tolerate exposure to high temperature and don't disintegrate. Though the colour of CHP binder vanishes but the strength of the mould still holds up.

06.5 EXPERIMENT 5

We still don't know how would the glass behave inside the furnace when kept with these binder systems. So, this experiment involves interaction of the binder system with broken pieces of glass for kiln casting.

Objective: Kiln casting of glass in sand moulds made of anorganik and CHP binder.

Specimen: Manually carved impressions in 3D printed sand moulds having anorganik and CHP as binder.

- Sand type- silica sand
- Binder- Anorganik and CHP binder
- Casting method: Kiln casting
- Kiln type: Carbolite HTF 1700

Fig. 06.5 a: Kiln casting of glass piece in manually carved impression in sand mould

Procedure:
Broken pieces of glass were placed inside the cavity carved in the moulds and the moulds were placed on a terracotta tray which was further placed inside the furnace.
The furnace was programmed to run with the same instructions as discussed in Expt 3.

1. A rise of 1 degree per minute till 780 degree Celsius. (melting point of the soda lime glass)
2. A dwell of 90 minutes at 780 degree Celsius (dwell in this context means maintaining the same temperature) to allow complete melting of glass and escape of air bubbles.
3. Followed by quenching at -2.7 degree per minute till 430 degree Celsius.
4. A dwell of 60 minutes at 430 degrees to allow the glass piece to anneal.
5. The kiln is allowed to turn off and allow automatic cooling.

Fig. 06.5 b: Experiment setup inside the kiln

Result:
The experiment resulted in glass being casted properly inside the mould. Fig 06.5 c & Fig 06.5 d shows the casted result.

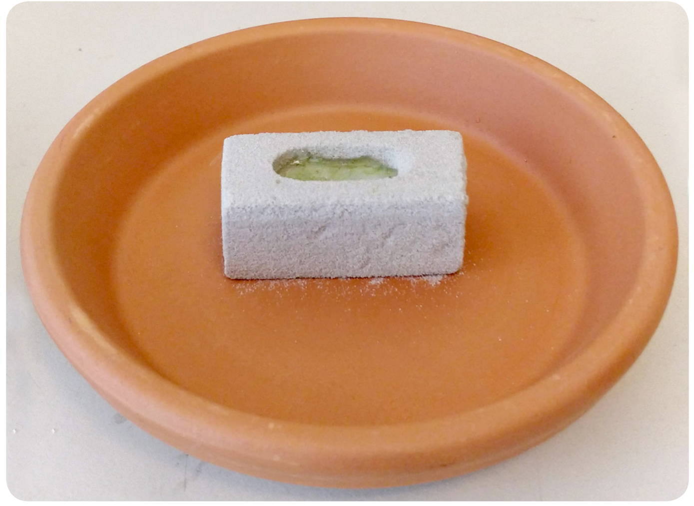


Fig. 06.5 c: Casted glass piece inside Anorganik binder system

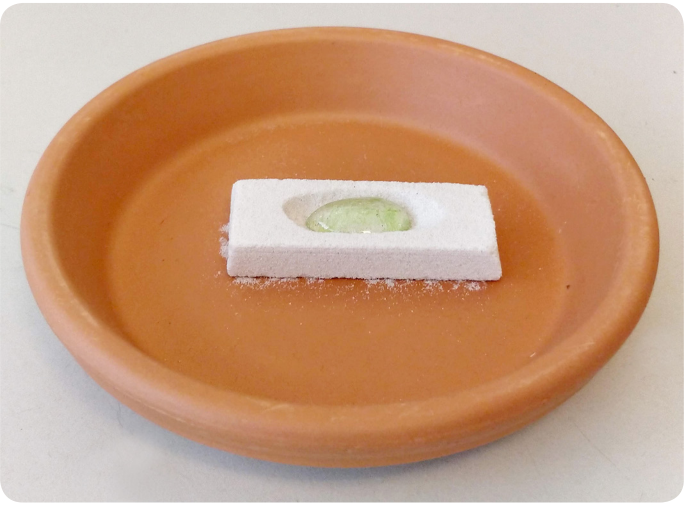


Fig. 06.5 d: Casted glass piece inside CHP binder system

No foul smell or disintegration of surface occurred from outside during the experiment but there was a sprinkle of sand on the base of both the specimen as seen in fig. 06.5 e & fig 06.5 f.

Fig. 06.5 e: Binder disintegration at the bottom of the Anorganik mould

Fig. 06.5 f: Binder disintegration at the bottom of the CHP mould

The glass piece was gripped to the mould, so it was not possible to remove it without disintegrating the mould. So, the glass along with the mould were dipped inside warm water for 15 minutes to allow the binder to dissolve and disintegrate the mould resulting in the final glass piece as seen in the fig 06.5 g & fig 06.5 h

Fig. 06.5 g: Easy disintegration of CHP binder inside water

Fig. 06.5 h: No reaction of water to the strength of Anorganik binder system

Observation:
It was observed form the experiment that CHP binder can easily be dissolved in water disintegrating the mould as shown in fig while Anorganik binder is not water soluble and a chisel and a hammer was used to break the mould. The fig 06.5 i shows the complexity involved in removal of casted glass piece from the mould without harming the casted piece.

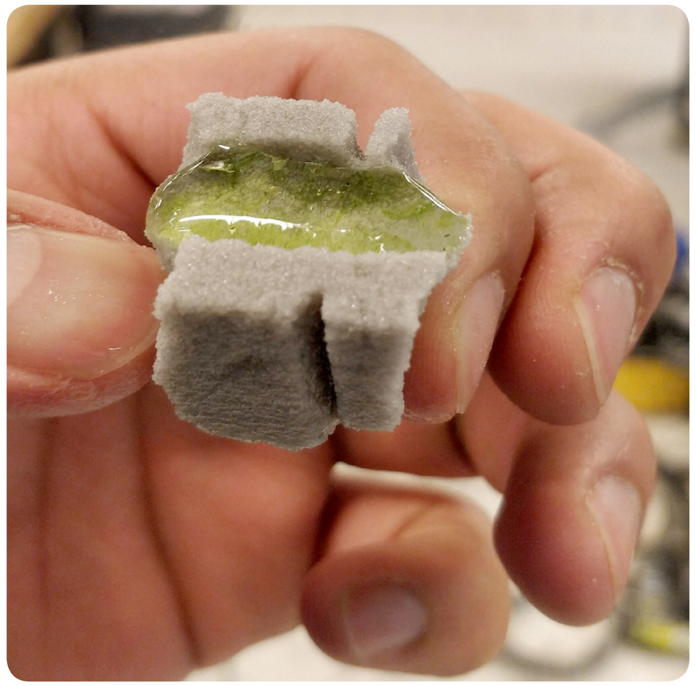


Fig. 06.5 i: Casted glass piece in anorganik binder system

The front surface of the glass piece was smooth. The green colour of the glass piece corresponds to the old green coloured soda lime glass being recycled.

Fig. 06.5 j: Casted glass piece in CHP binder system

After breaking apart of the mould, the glass pieces bear a rough surface on the side in contact with the mould and required post processing.

Fig. 06.5 k: Surface finish in regions of surface contact

Conclusion:
It can be concluded from the above experiment that the combination of molten glass with the moulds made from anorganik as well as CHP binder system works great and has a potential in casting large structural elements. The surface finish offered by the mould is very rough due to grainy surface of the mould and require coatings for finished surface.

06.6 EXPERIMENT 6

We still don't know how would the glass behave inside the furnace when kept with these binder systems. So, this experiment involves interaction of the binder system with broken pieces of glass for kiln casting.

Objective: This experiment concentrates on exploring different coatings on top of the mould to provide smooth surface to the casted objects.

Specimen: The experiment requires an initial impression on the workability of coatings. So, only one binder system was selected for the current experiment. Also, 2 types of impressions were carved in the mould. One was a simple oval and the other one had a bit complex geometry to understand the workability of the process with complex shapes.

- Sand type- silica sand
- Binder- CHP binder
- Casting method: Kiln casting
- Kiln type: Carbolite HTF 1700

Fig. 06.6 a: Boron Nitride Aerosol spray

Following coatings were used on the moulds-

- Boron Nitride – Boron Nitride is a high temperature release agent traditionally used in glass industry. The spraying of the material can create a uniform surface of the mould giving it a smooth finish. Also, the glass piece can be easily removed due to its release agent properties.

- Crystal cast (Gypsum)- Crystal cast is a powder based material which is most commonly being used for creating disposable moulds for glass objects. A coating of the material would result in same finish, as being achieved using disposable moulds.

Procedure:
First of all, impressions were carved inside the mould manually as shown in fig. 06.6 b. Then the mould was cleaned with high air pressure.

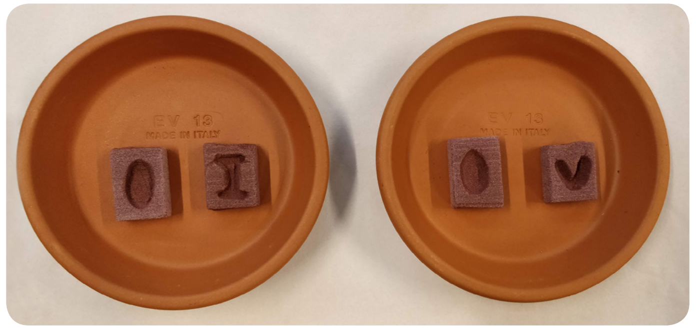


Fig. 06.6 b: Manually carved impressions in CHP binded sand mould

A liquid form of crystal cast was prepared and the mould was dipped in the solution to create a thin coating of top of the mould.
For boron nitride, since it's a spray, a distance of 20 to 30 cm was maintained from the mould and then sprayed for uniform thickness.
3 layers of each coating was applied on the moulds in an interval of half an hour. The moulds were left to dry for a complete day.

Broken pieces of glass were then placed inside the mould and these specimens were then placed inside the furnace. The furnace followed

Fig. 06.6 c: Layers of coating applied for surface finish

the same program of heating and annealing cycle as in Experiment 3 and 5.

Result:

The experiment was successful in casting the glass pieces. The casted glass was easily removed from the moulds by dipping the moulds in warm water.

Fig. 06.6 d: Casted glass piece in boron nitride coated moulds

Fig. 06.6 e : Casted glass piece in crystal cast coated moulds

Observation:

Starting with the surface quality of the coatings, it was observed that after drying of the coats, boron nitride developed cracks on the surface while crystal cast coating was completely smooth.

Fig. 06.6 f: Boron nitride coated moulds before experiment

Fig. 06.6 g: Crystal cast coated moulds before experiment

But the crystal cast moulds were very fragile after the experiment. It is considered that on dipping the mould in a liquidy crystal cast solution, the binder gets dissolved in solution and hence the mould becomes weak.

In terms of the finish quality, glass casted in boron nitride coating was smooth in surface finish but had a dusky optical quality. While the crystal cast ones had a rough feel on touching the side in contact with the mould but had a clear vision.

Fig. 06.6 h: Clear optical quality of glass in crystal cast coated mould

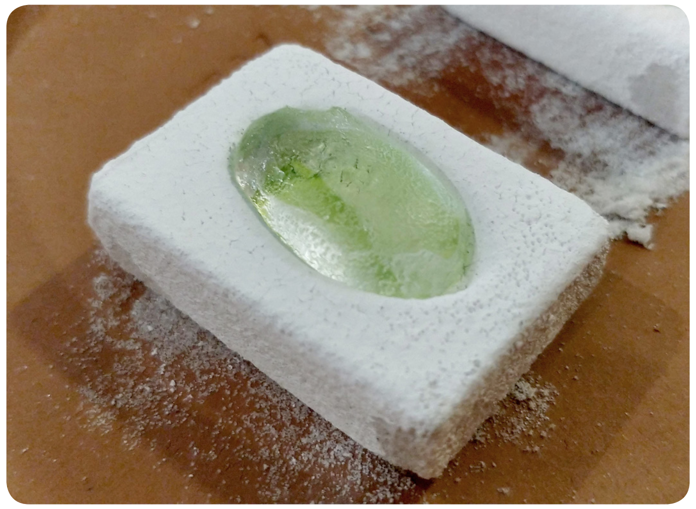


Fig. 06.6 i: Dusky optical quality of glass in boron nitride coated mould

Conclusion:

Crystal cast provides a clear vision but the surface quality needs post processing while the boron nitride provides a smooth finish but the optical quality is dusky.

06.7 EXPERIMENT 7

Objective: This experiment explores more coatings that can be used for providing surface finish to the casted glass

Specimen: CHP binder system mould was used for understanding the relation of the coating and glass finish

- Sand type- silica sand
- Binder- CHP binder
- Casting method: Kiln casting
- Kiln type: Carbolite HTF 1700

Following coatings were used on the moulds-

- Mold mix 6- Zircar is a US based manufacturing firm creating products for glass artist. A sample of mold mix 6 was attained from the company which offers high surface finish specifically created for glass. The product is typically used for creating moulds and is available in form of paste.
- • Boron Nitride and Crystal cast: As observed in the previous experiment, boron nitride develops minute cracks on the surface of the mould. So, a layer of crystal cast was applied first and then boron nitride was sprayed on top of the dried layer to remove the surface cracks.

Fig. 06.7 a : Mold mix 6 coating

Procedure:

Same method was used as depicted in last experiment. Impressions were carved inside the mould manually. Then the mould was cleaned with high air pressure.

For the first specimen, the paste of mold mix 6 was applied on the surface using a paint brush. Two layers of the same were applied after an interval of 1 hour.

The other specimen was first coated with crystal cast, 2 layers applied after an interval of 1 hour, and then sprayed over with boron nitride after a day of drying. 2 layers of boron nitride were sprayed in a span of 30 minutes and was then left for drying for a day.

Fig. 06.7 b: Specimens coated with mold mix 6

Fig. 06.7 c: Specimens coated with crystal cast and then boron nitride

Broken pieces of glass were then placed inside the mould and these specimens were then placed inside the furnace. The furnace followed the same program of heating and annealing cycle as in Experiment 3 and 5.

Result:

The experiment was successful in casting the glass pieces. The casted glass was easily removed from the moulds by dipping the moulds in warm water.

Fig. 06.7 d: Result of glass casted in mold mix 6 coated moulds

Fig. 06.7 e: Result of glass casted in dual layered coating of crystal cast and boron nitride

Observation:

The surface finish of the mould having mold mix 6 coating before the experiment appeared to be smooth and the glass casted in it also had a clear vision, but, the main concern was removal of the coating from the glass surface as can be seen in the fig. After dipping the specimen in water, the mould got segregated but the coating was stuck to the base of the glass piece casted. Also, on removal of the coating, a rough surface finish was discovered.

Fig. 06.7 f: Mold mix 6 coating being stuck to the glass piece

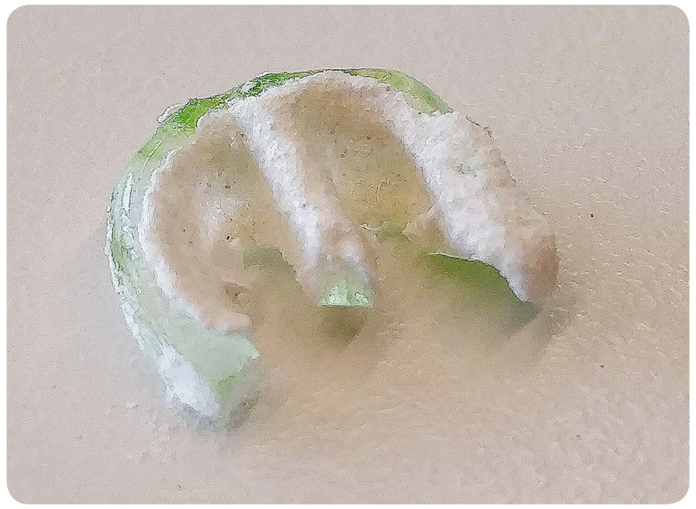


Fig. 06.7 g: Mold mix 6 coating being stuck to the glass piece

The second specimen having 2 layers of crystal cast and 2 layers of boron nitride sprayed over it had less cracks as compared to the last experiment. It was observed that the surface quality remains the same as observed in boron nitride experiment. The dusky optical quality is probably a result of mixture of boron nitride with the molten glass at high temperature.

Fig. 06.7 h: Casted glass pieces with crystal cast and boron nitride coating

Fig. 06.7 i: Dusky optical quality of glass casted

Conclusion:

Both the coatings have a major affect on the quality of glass being casted. So, the idea of using either mold mix 6 or boron nitride, both, are not suitable for this manufacturing technique.

06.8 CONCLUSION

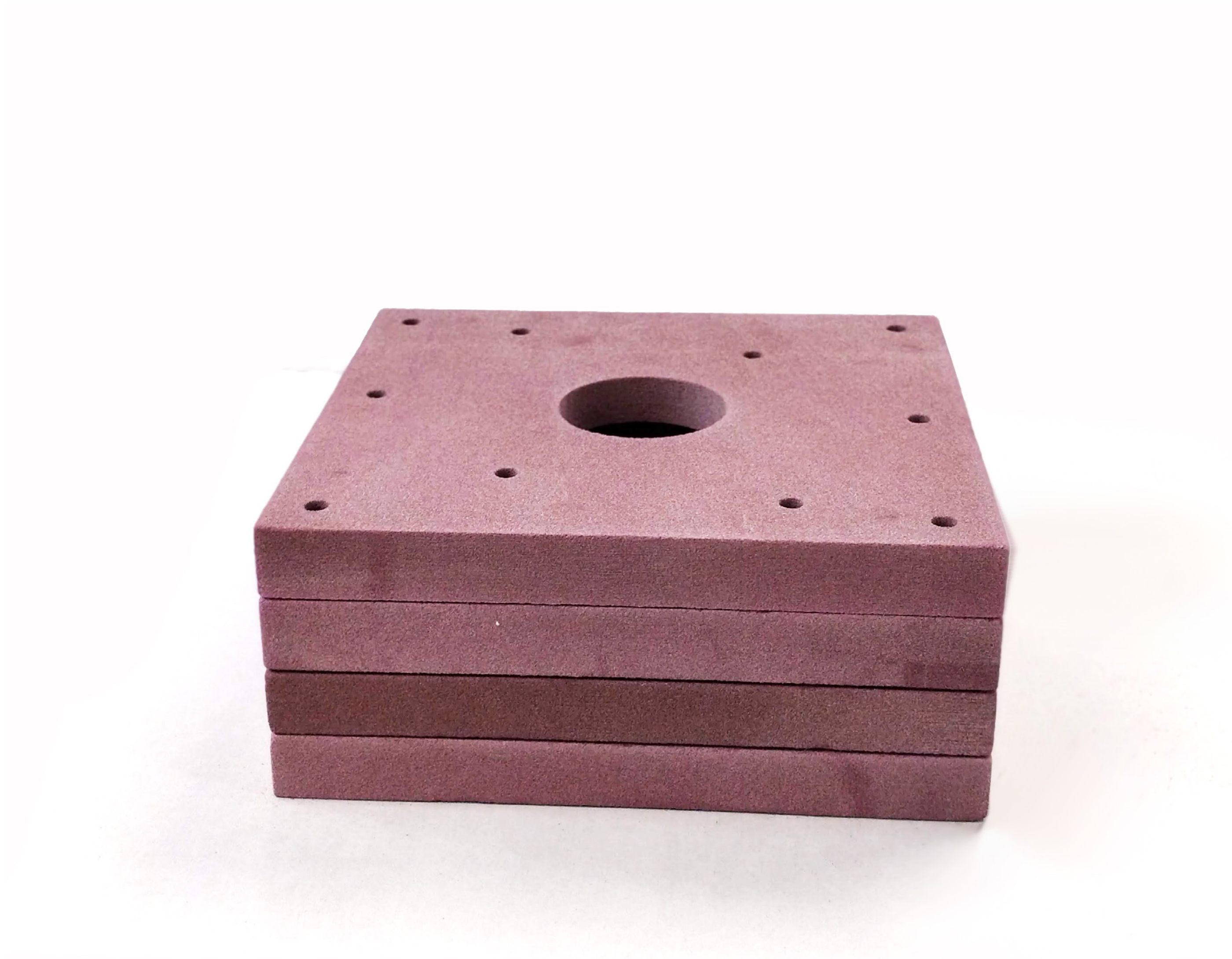
Glass has been casted in sand moulds in art industry for several years now but the fact that the process and the finish of the sand mould achieved by compacting sand is very different to the one that is 3D printed. The years of experience cannot draw inspiration from the traditional way. The new production technique using 3D printing has many possibilities in creating complex geometries in the most time efficient manner taken into account the laborious labor as well as the annealing time.

The series of above experiments conducted proved the workability of the whole idea of fabricating cast glass structures using 3D printed sand moulds. The commercially available binder system (furan binder) for producing 3D printed sand moulds was a success for the hot pouring process but was not a suitable match for kiln casting technique. 2 new binder system discovered during the search, proved to be successful in tolerating the high heat exposure for prolonged period of time inside the kiln becoming the perfect candidate for creating glass moulds- the CHP binder system and Anorganik binder system.

Both the binder system yields the same result but can be thought to have different usability. The CHP binder system is observed to lose its strength after exposure to heat and is water dissolvable. So, this system can be used for only one-time casting. Also, the sand can be reused after the whole process, creating a sustainable circular loop of manufacturing.

The second system, Anorganik binder system, is a high strength system which retain its qualities even after prolonged exposure to heat. This system is not water soluble and is a bit hard to remove if used in a natural state. So, this system can be predicted to be used for casting heavy geometries. Also, due to its strength, it can be predicted to survive 3 to 4 cycles of casting.

Though these binder systems have a rough surface finish, so, various coatings were experimented. It can be concluded from various iterations that crystal cast performed the best in relation to others. Though it still requires a bit of post processing, the optical quality remains comparable to the current way of making disposable moulds.



07

PROTOTYPING OF GEOMETRY

The fabrication technique of using 3D printed sand moulds required actual prototyping at a bigger scale to prove the workability of the system. Three different sections from the designed column were selected for fabrication at different scale.

Various parameters like air vent, interlocking of moulds, clamping of moulds together were explored.

This chapter illustrates the whole process of testing the mould using PLA printing to casting of glass in the sand moulds

07.1
MOULD DESIGNING

GEOMETRY 1

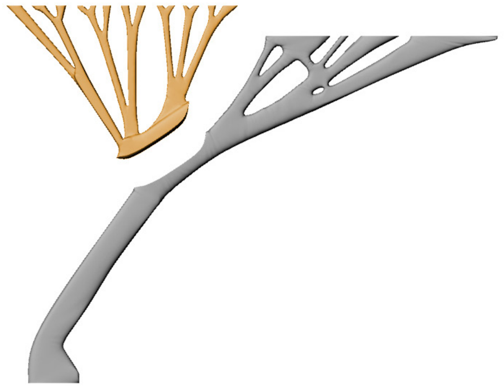


Fig. 07.1 a: Selection of highlighted geometry for fabrication

The first geometry for prototyping was one of the splitted pieces. The restriction for prototyping the geometry was constrained to a certain dimension on basis of the Owen size in the glass lab. Scale of 1:20 satisfied the dimensions for fabrication. A mould of the geometry was prepared with following into account.

- An opening for pouring of molten glass inside the mould
- Holes for clamping the moulds together.
- Vent pipes to avoid trapping of air bubbles inside the mould
- Minimum thickness of 3 to 4mm in any section of the mould
- An added thickness of 15 mm around periphery of the geometry.

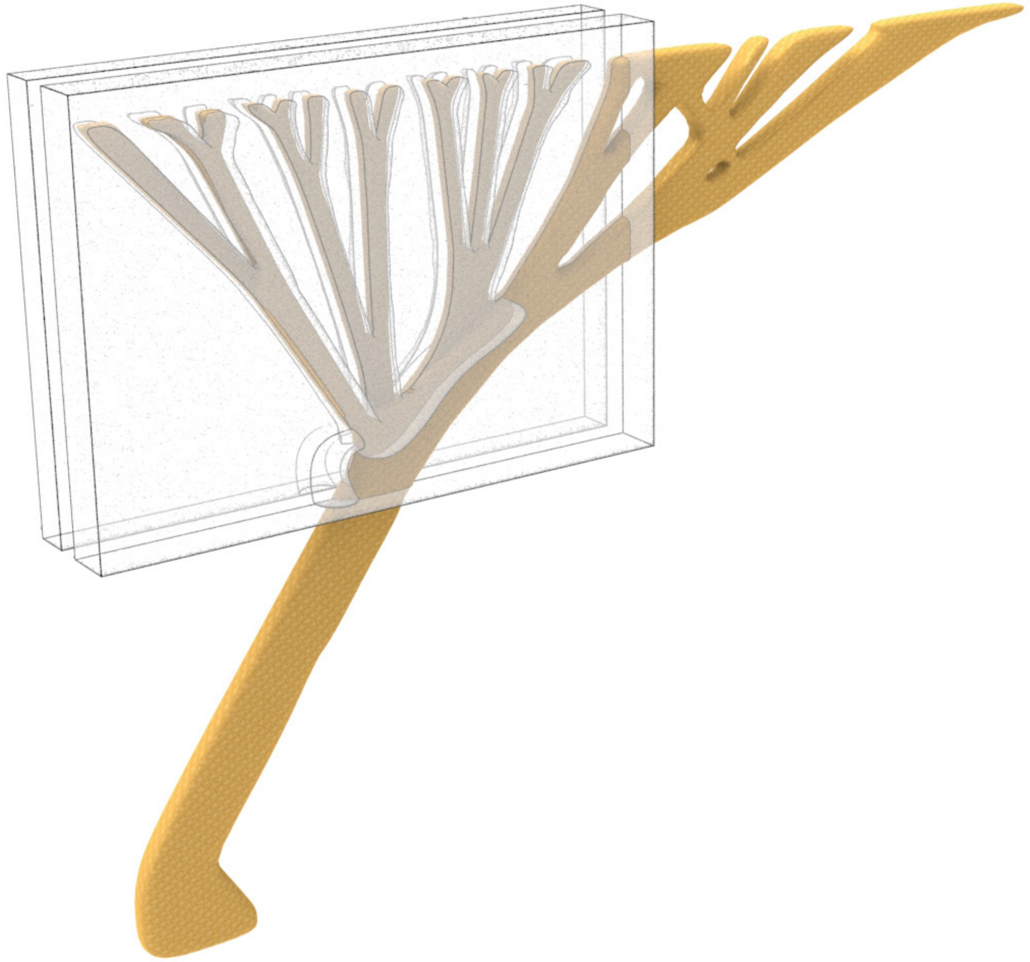


Fig. 07.1 b: Mould design with respect to geometry.

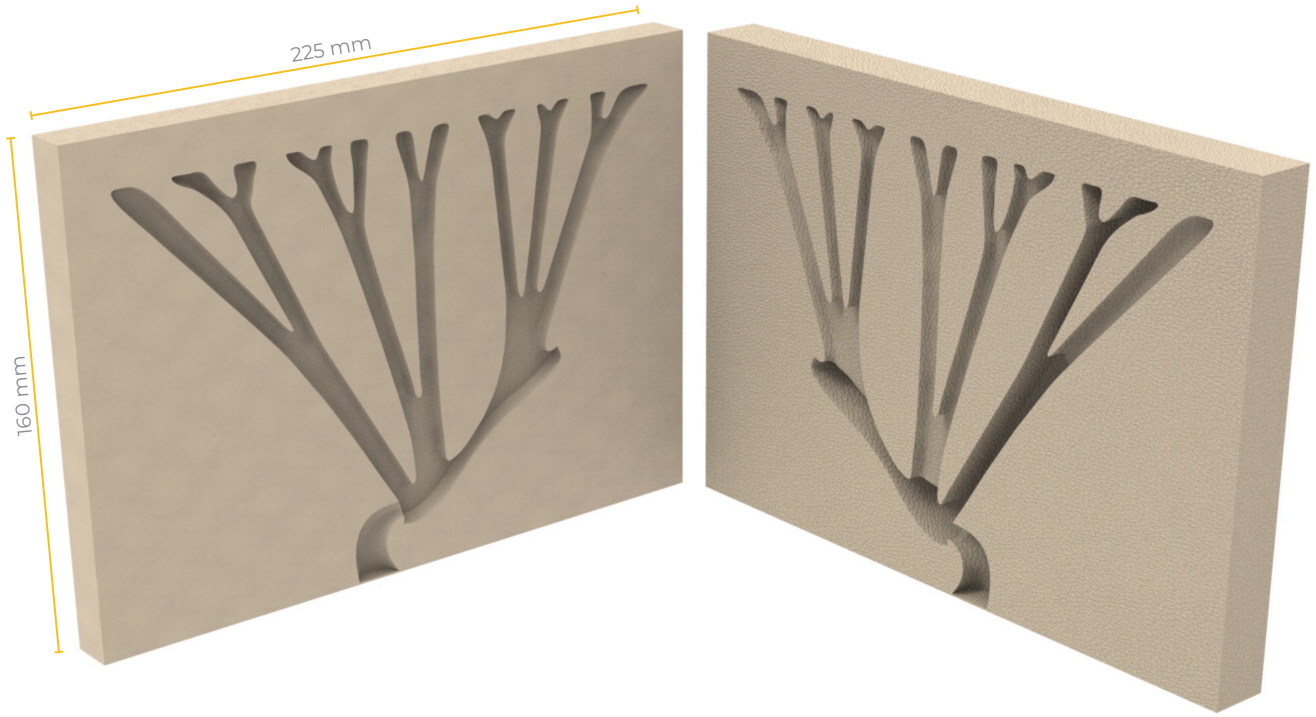


Fig. 07.1 c: Mould of Geometry 1 at 1:20 scale

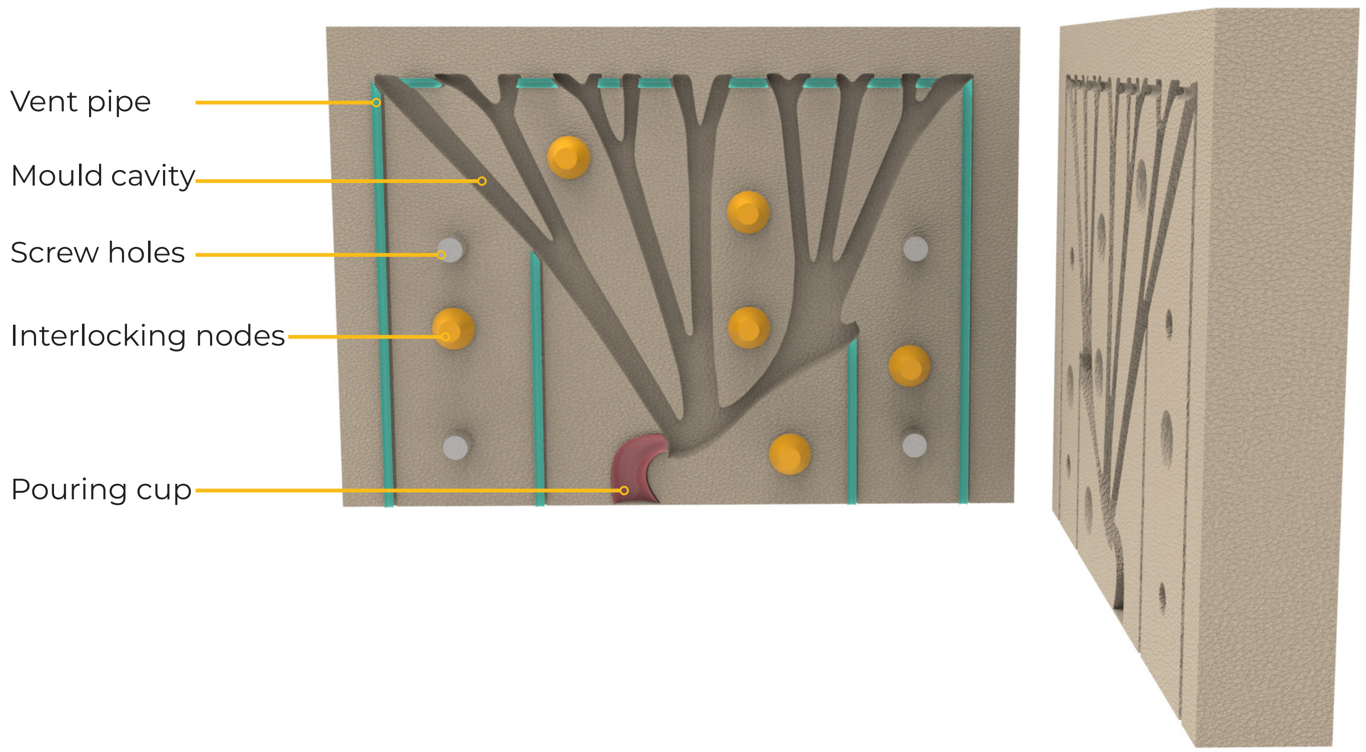


Fig. 07.1 d: Final mould design for prototyping

The second & third geometry are small sections of the first prototype having a more reasonable scale closer to the actual size to cheack the workability of moulds at real scale.

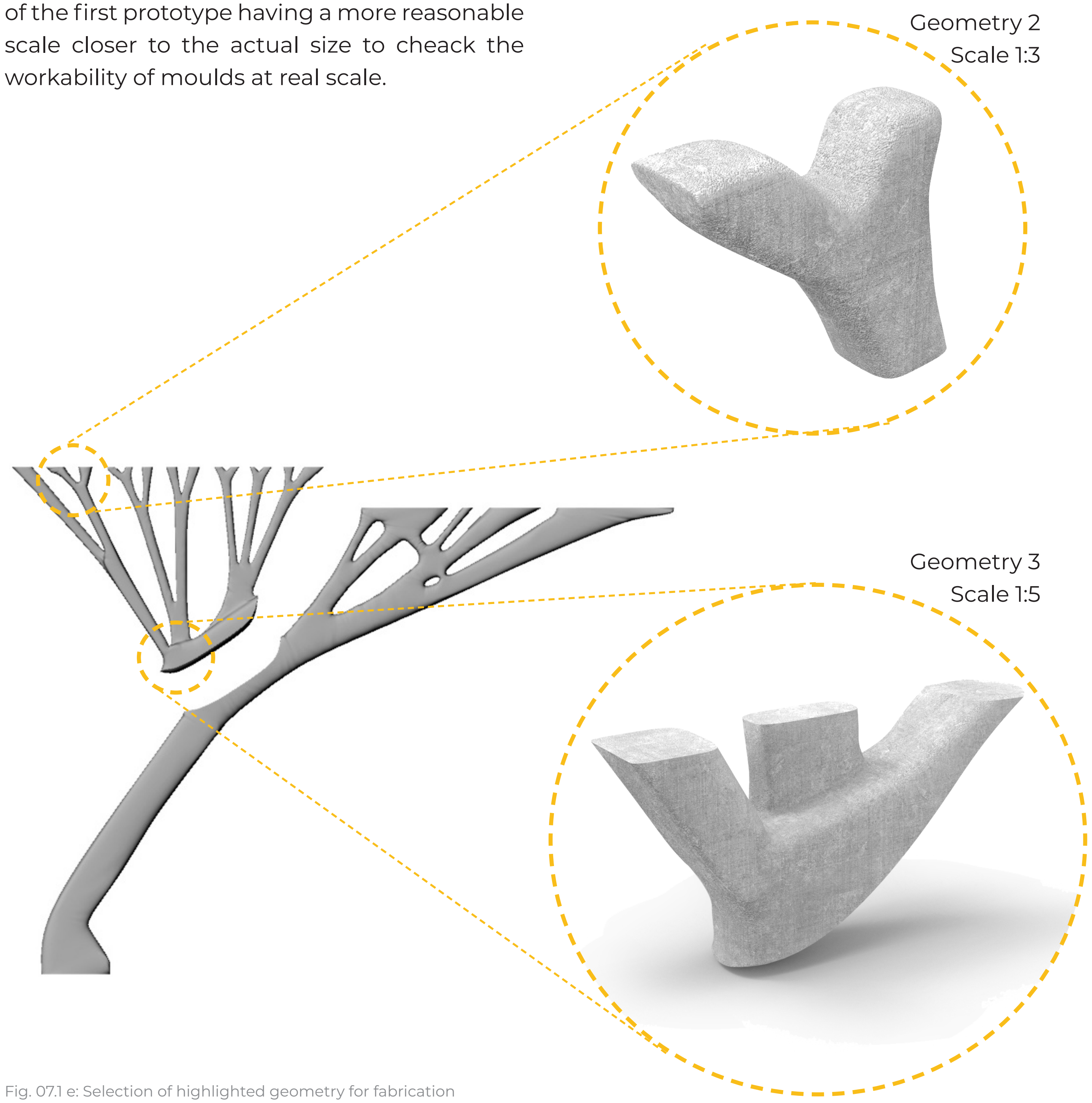


Fig. 07.1 e: Selection of highlighted geometry for fabrication

Similar process was used to design the moulds for geometry 2 and 3. The mould for these geometries were prepared by slicing the geometry horizontally rather than vertically (geometry 1).
The scale for prototyping was decided on basis of the size of owen in the glass lab.

GEOMETRY 2

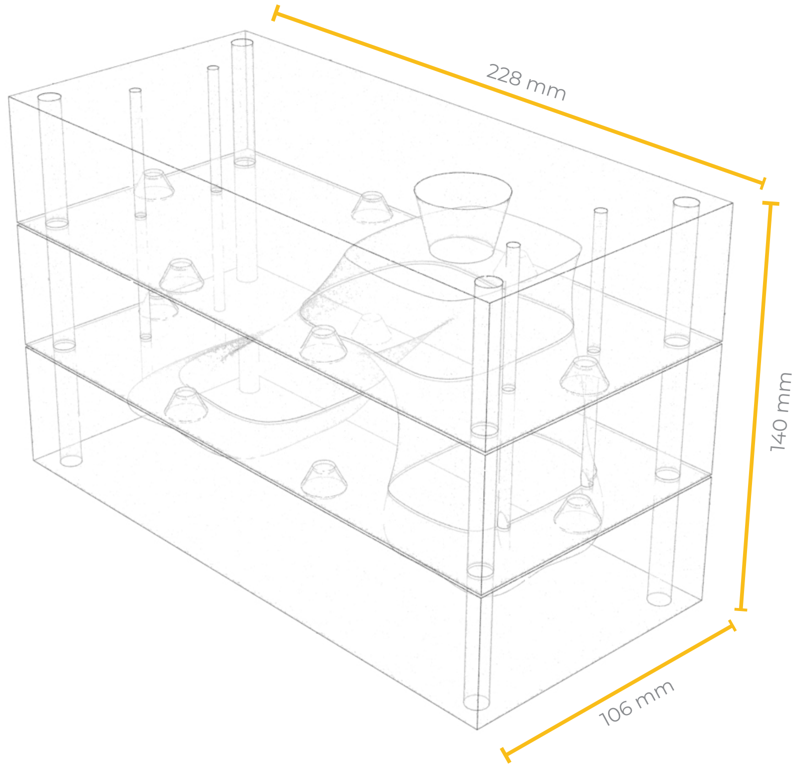


Fig. 07.1 f: Mould of Geometry 2 at scale 1:3

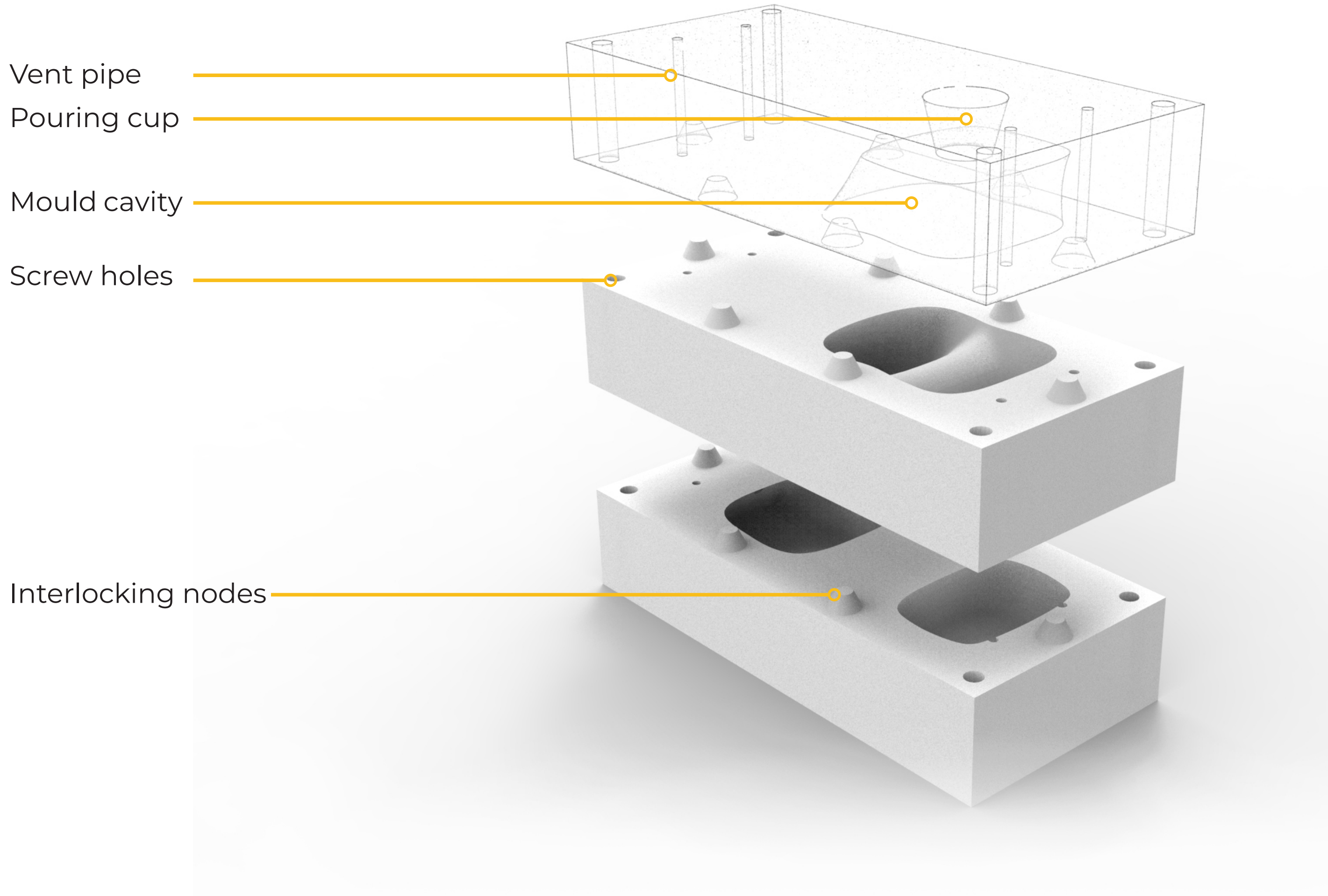


Fig. 07.1 g: Final mould design for prototyping

GEOMETRY 3

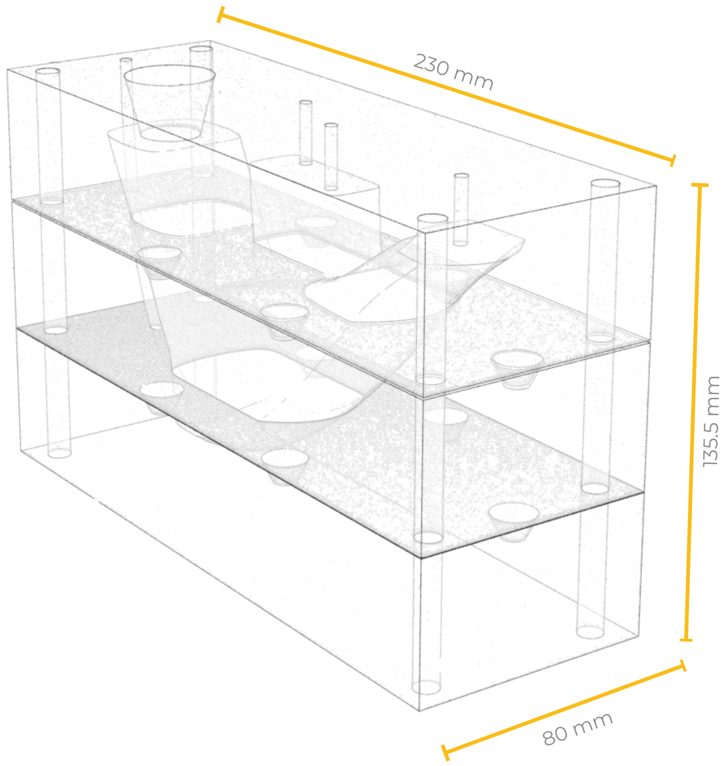


Fig. 07.1 h: Mould of Geometry 3 at scale 1:5

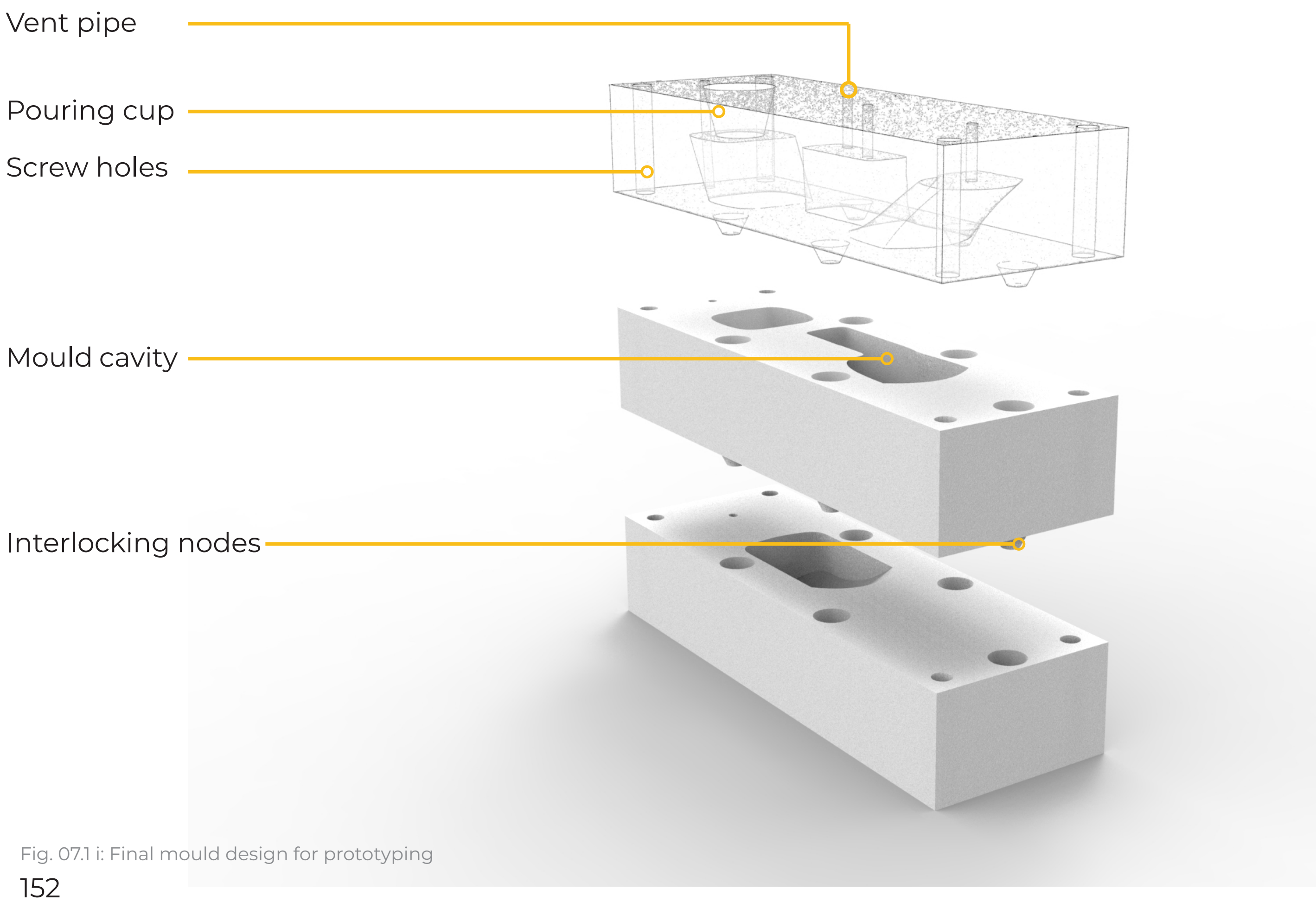


Fig. 07.1 i: Final mould design for prototyping

07.2
MOULD PREPARATION FOR CASTING

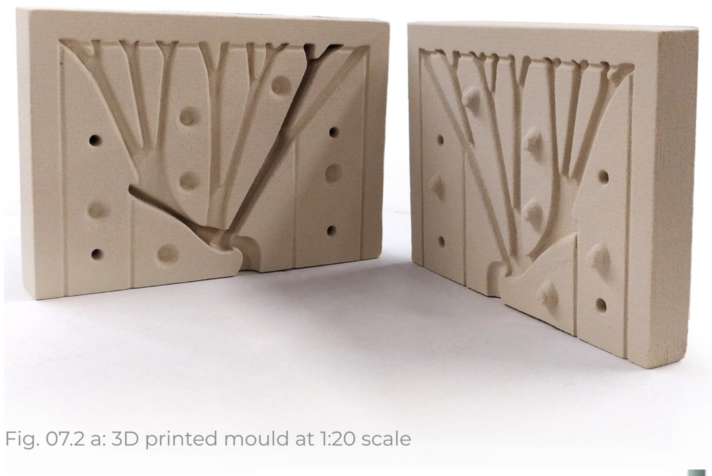


Fig. 07.2 a: 3D printed mould at 1:20 scale

GEOMETRY 1

The designed moulds were then 3D printed by ExOne company in Germany and shipped to Netherlands. The printed mould were then coated with a thin liquidy layer of crystal cast as shown in fig. 07.2 a, 07.2 b & 07.2 c
The binder system selected for this geometry was Anorganik system with synthetic sand that can tolerate higher temperatures according to the company ExOne.

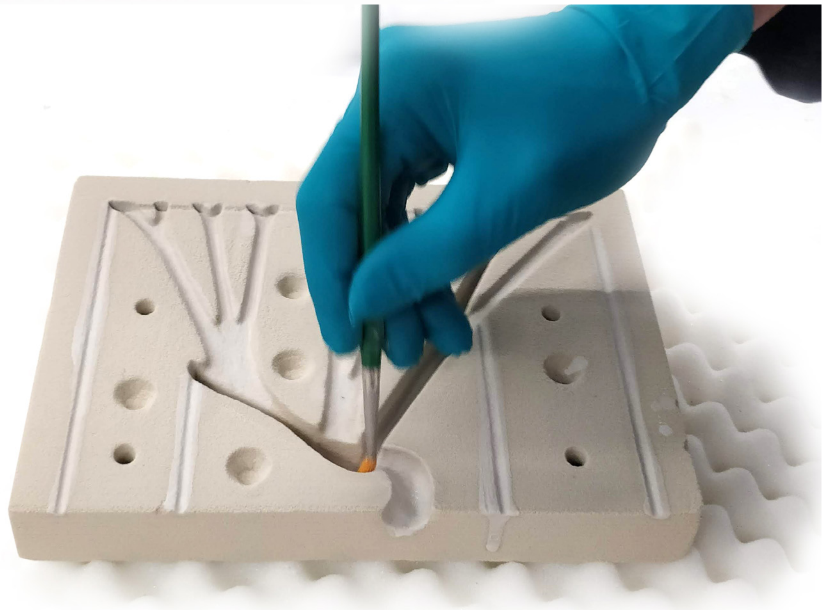


Fig. 07.2 b: Applying a coating of crystal cast for smooth finish of glass using a paint brush

Fig. 07.2 c: 2 layers of dried crystal cast coating on the mould

Fig. 07.2 d: 2 layers of dried crystal cast coating on the mould

The mould was then screwed together using stainless steel M8 bolts & nuts with few preventive measures like sealing the seam between the moulds and putting blanket around the screws.

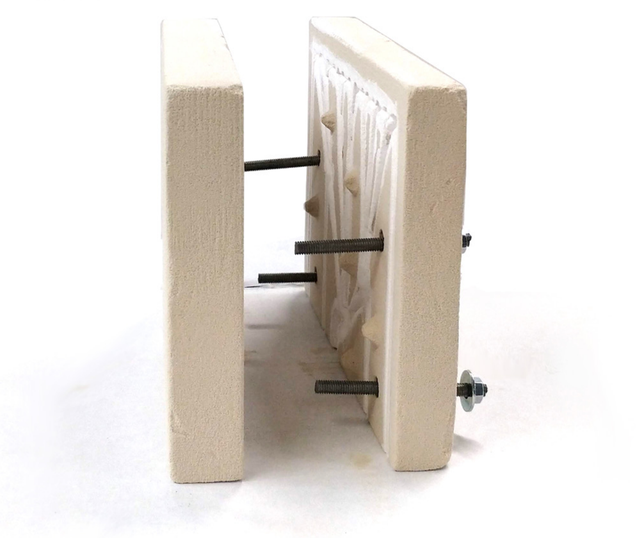


Fig. 07.2 e: clamping on moulds together using M8 bolt & nut

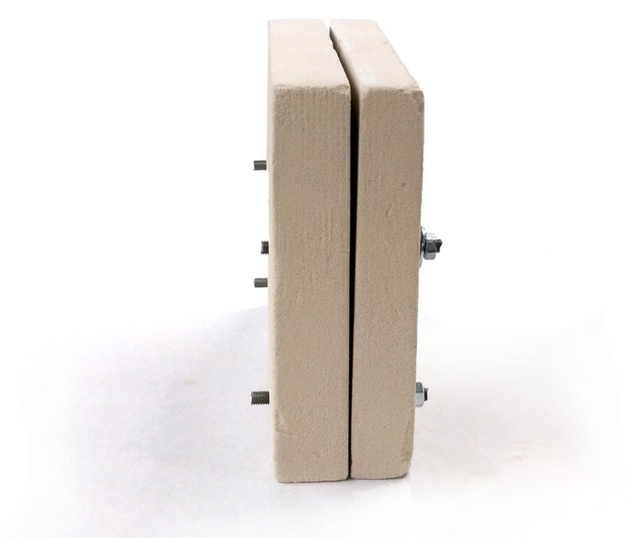


Fig. 07.2 f: clamping of mould together using M8 bolt & nut

Fig. 07.2 g: sealing the seam between the mould pieces to avoid leakage of glass

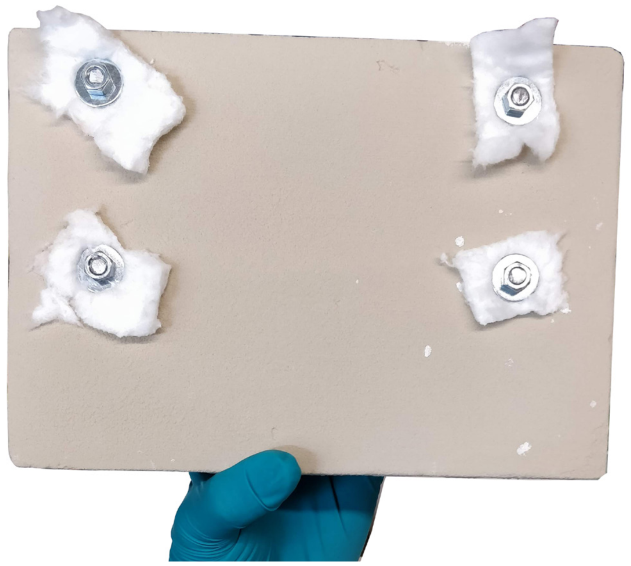


Fig. 07.2 h: putting blanket around screws to avoid sticking of glass around screws during breakage of mould or overflow of glass.

The mould was then put in a crystal cast mould for protection purposes. A layer of coarse sand was put around the sand mould inside the crystal cast mould to compact the sand mould.

Fig. 07.2 i: setting up a bed of coarse sand before placing sand mould inside crystal cast mould.

Fig. 07.2 j: placing sand mould inside the crystal cast mould and filling the remaining cavity with coase sand.

Fig. 07.2 k : Placing an earthen pot on top of mould to allow glass to melt in the pot and flow inside the sand mould.

Finally, the mould is placed inside the kiln and fired according to the below program (fig 07.2 m)

Fig. 07.2 l: Specimen being put inside the kiln- Helmut Rohde (model no. ELS 200 S)

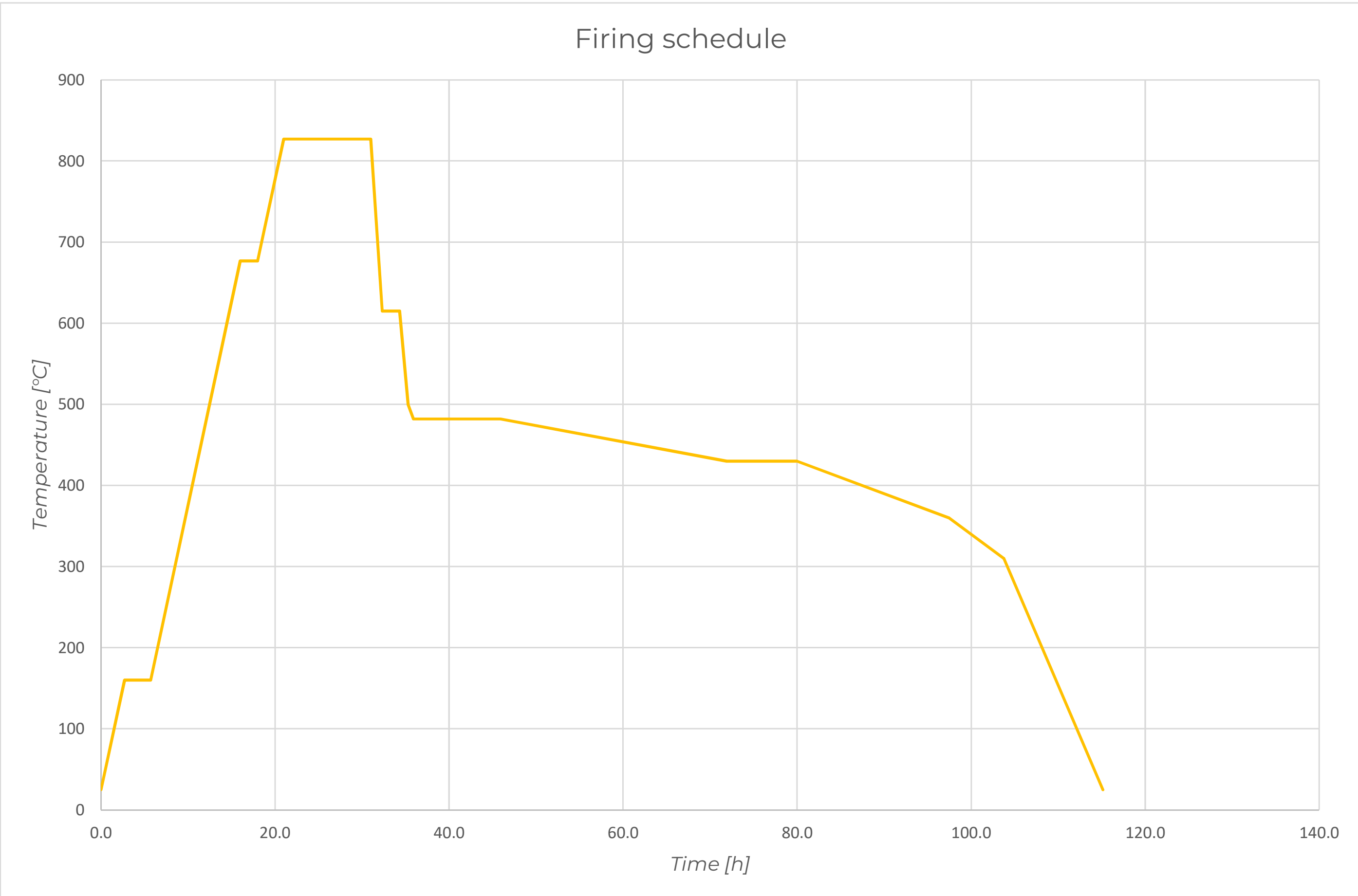


Fig. 07.2 m: Firing schedule of the kiln temperature v/s time

GEOMETRY 2

Mould pieces for geometry 2 were printed with CHP binder system. Similar process was followed for preparation of mould but the mould was not compacted with sand as seen in fig 07.2 q. Also, the earthen pot was directly resting on top of mould.

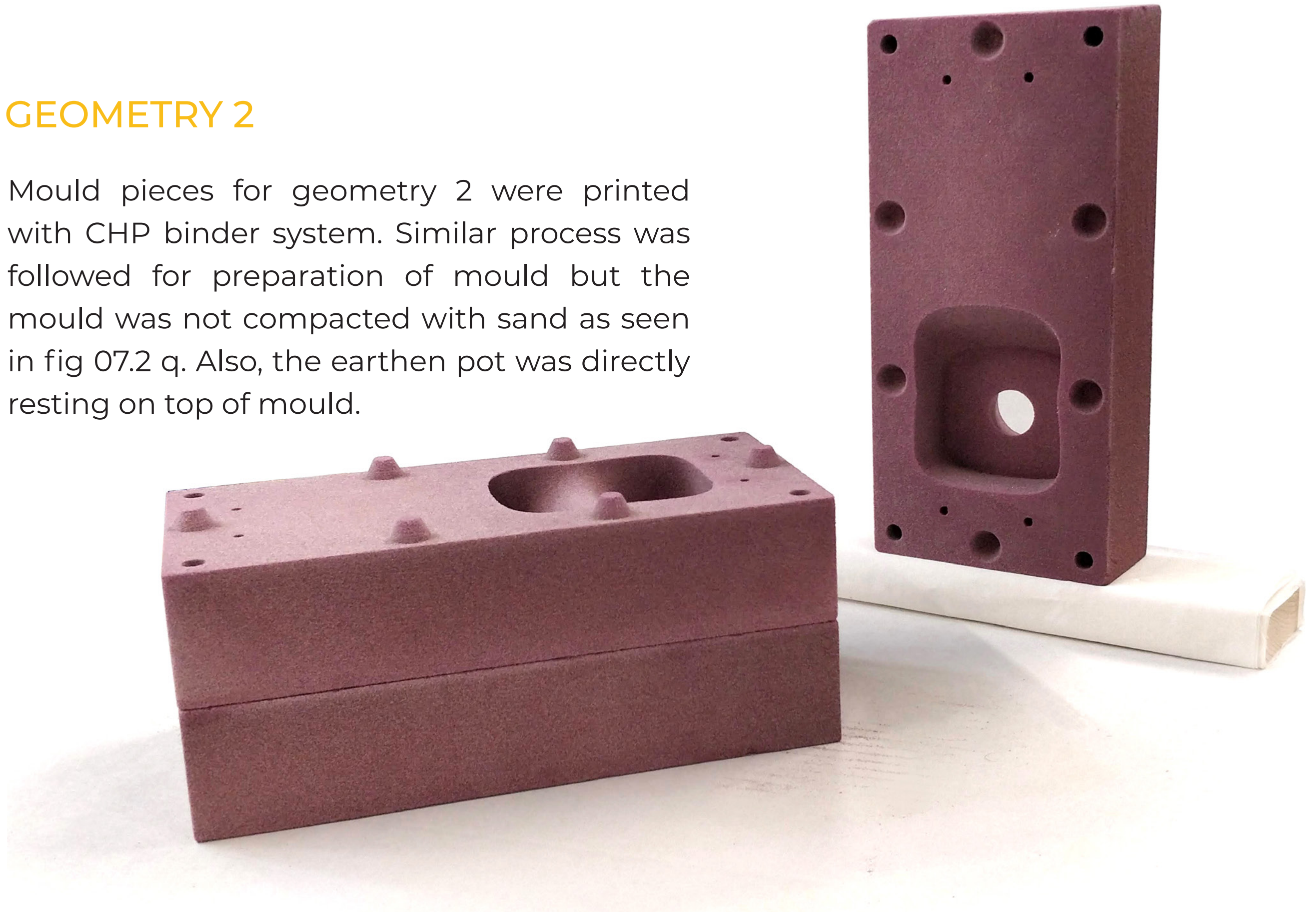


Fig. 07.2 n: 3D printed mould at 1:3 scale for prototyping

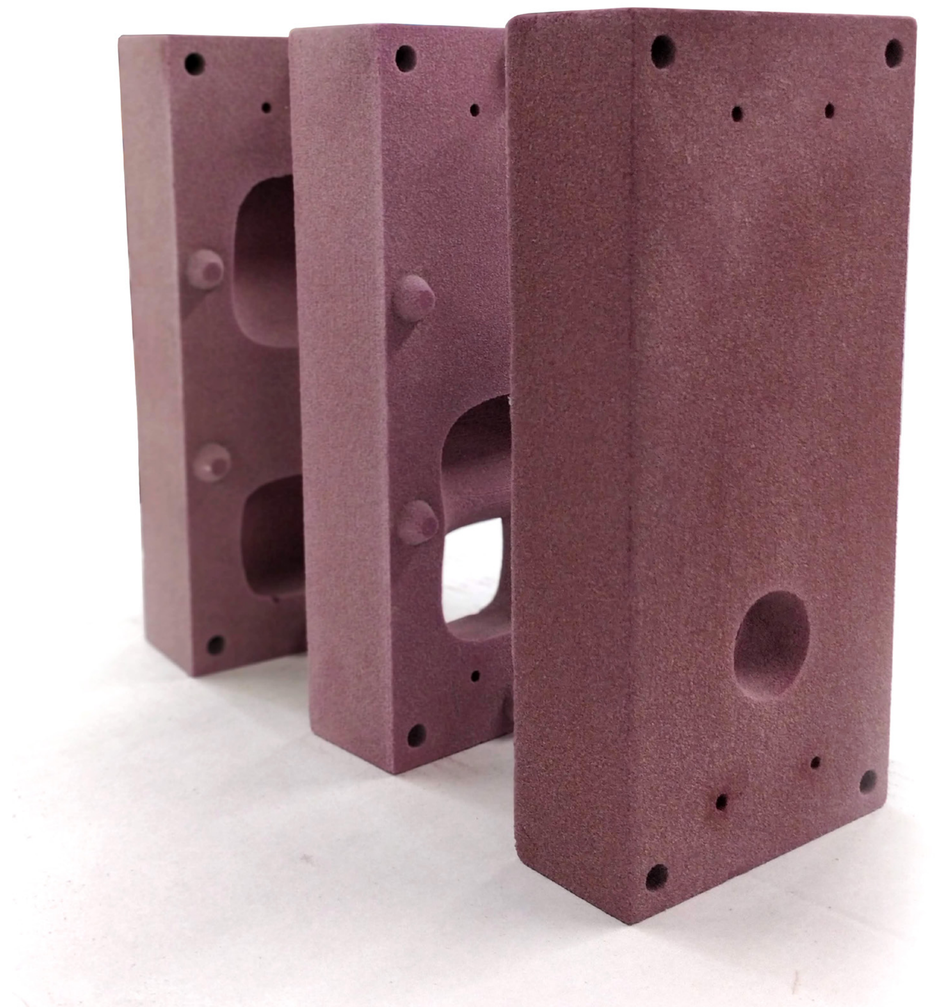


Fig. 07.2 o: 3D printed mould at 1:3 scale for prototyping

Fig. 07.2 p: Final setup of mould inside the furnace

Fig. 07.2 q: Final setup of mould inside the furnace

GEOMETRY 3

Mould piece for Geometry 3 were printed with same binder system as for geometry 2- CHP binder system. The mould pieces were coated with 2 thin layers of crystal cast and same process was repeated for preparing the moulds for kiln. Course sand was used to compact the 3d printed mould against the walls of crystal cast mould. The earthen pot containing the broken pieces of glass was resting directly on top of the sand mould. Fig 07.2 v depicts the exact setup of experiment.

Fig. 07.2 r: 3D printed mould at 1:3 scale for prototyping

Fig. 07.2 s: 3D printed mould at 1:3 scale for prototyping

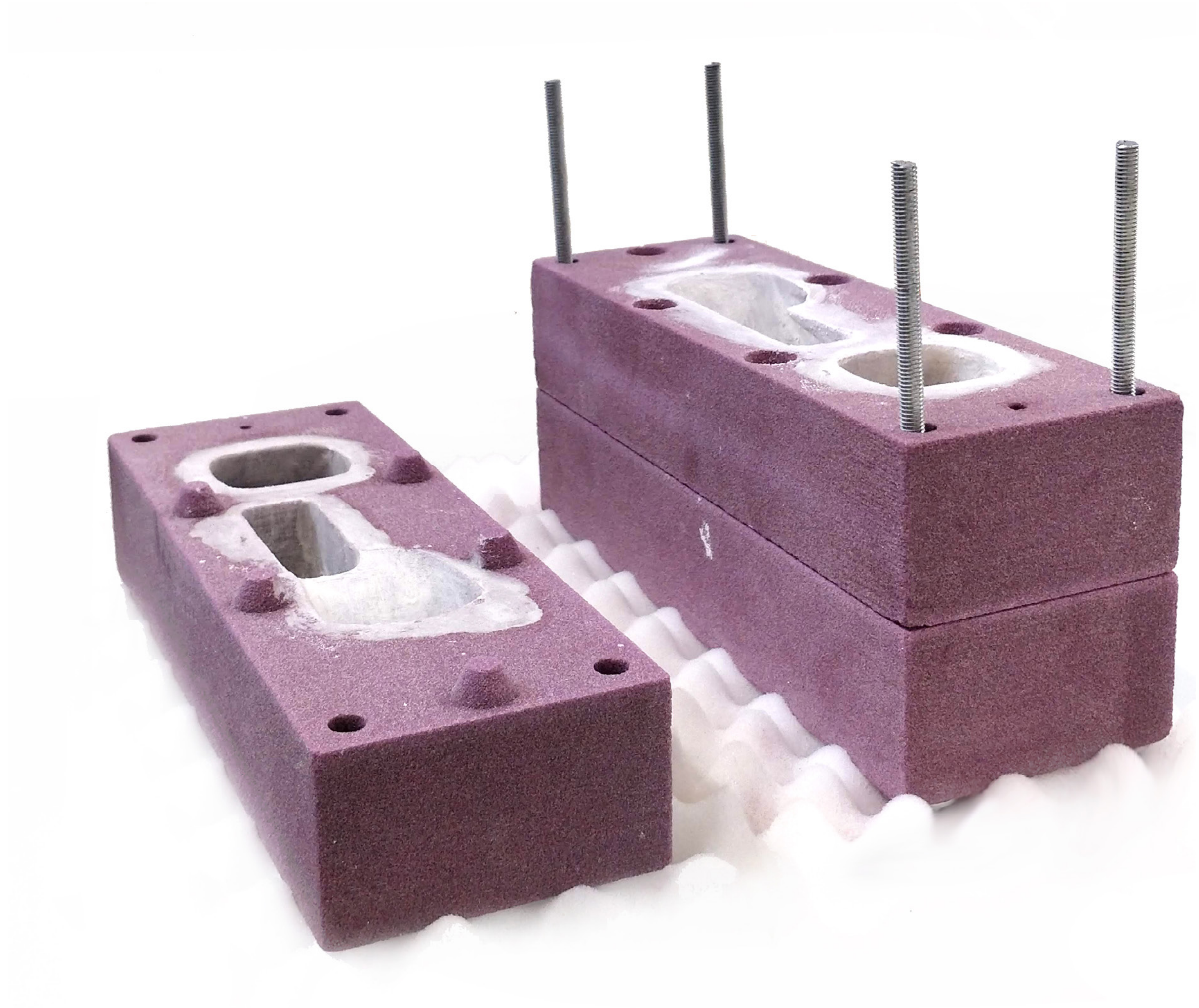


Fig. 07.2 t: Crystal cast coated mould prepared for casting inside the kiln

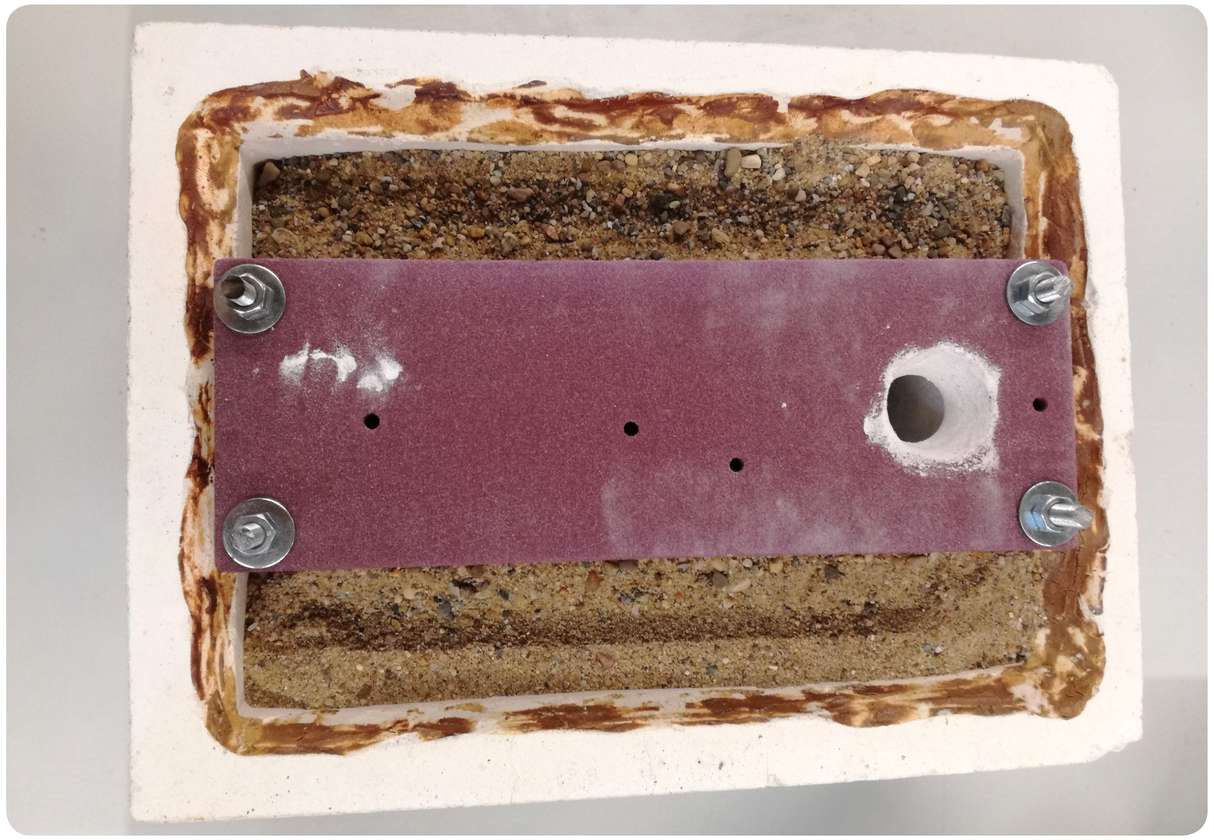


Fig. 07.2 u: Crystal cast coated mould prepared for casting inside the kiln

Fig. 07.2 v: Crystal cast coated mould prepared for casting inside the kiln

07.3
PROTOTYPE RESULTS

GEOMETRY 1

It can been observed that the mould is intact with a bit overflow of glass as shown in the fig 07.3 a. After removal of the sand mould from the setup, the mould was observed to contain the same strength as before the experiment.
Upon demoulding, it was observed that the nuts and bolts have fused together at high temperature and was impossible to open. Another possible method was disintegrating the binder, but anorganik binder system cannot be disintegrated using water and no other disintegration method has been explored, so the mould was finally broken into pieces gently with the help of trowel.
The glass can be seen to be casted fig 07.3 c but due to small opening of the pouring cap in relation to the size of opening of the earthen pot, most of the molten glass got poured outside the mould leading to failure of casting full geometry.

So, it can be concluded that Anorganik binder system is a suitable match for the fabrication technique and redesigning the mould opening could result in a final prototype.

Fig. 07.3 a: Specimen after experiment completion

Fig. 07.3 b: Sand mould upon removal from the setup could still susteain its own weight along with the casted glass piece

Fig. 07.3 c: On breaking the mould, half casted pieces of glass can be observed. Also, nuts & bolts are burnt and are fused together.

GEOMETRY 2

The prototype failed to cast, as the sand mould was observed to become weak. Since there was no material compacting the mould, the mould collapsed into pieces due to heavy weight of the earthen pot and glass leading to no final geometry. Fig below showcase the specimen straight out of the kiln.
Hence the experiment was a fail and no geometry was casted.

It can be concluded that the binder system is not strong enough at high temperature to sustain the weight of glass.

Fig. 07.3 d: Failure of the sand mould during the casting process

Fig. 07.3 e: Failure of the mould due to weight of the earthen pot and glass

Fig. 07.3 f: Specimen after experiment completion

GEOMETRY 3

This was the first geometry to be put inside the furnace. It was observed that during casting the bottom most mould broke leading to leakage of glass creating a weird geometry at the bottom as seen in fig 07.3 g. It can be inferred that the mould was week at high temperature when kept for more than a day inside in the kiln. The compacting of sand was apparently holding the printed mould in place.
It can be concluded that the CHP binder system is not strong enough at high temperature to sustain the weight of glass.

Fig. 07.3 g: Casted geometry after removal from sand mould

Fig. 07.3 h: Final finished geometry

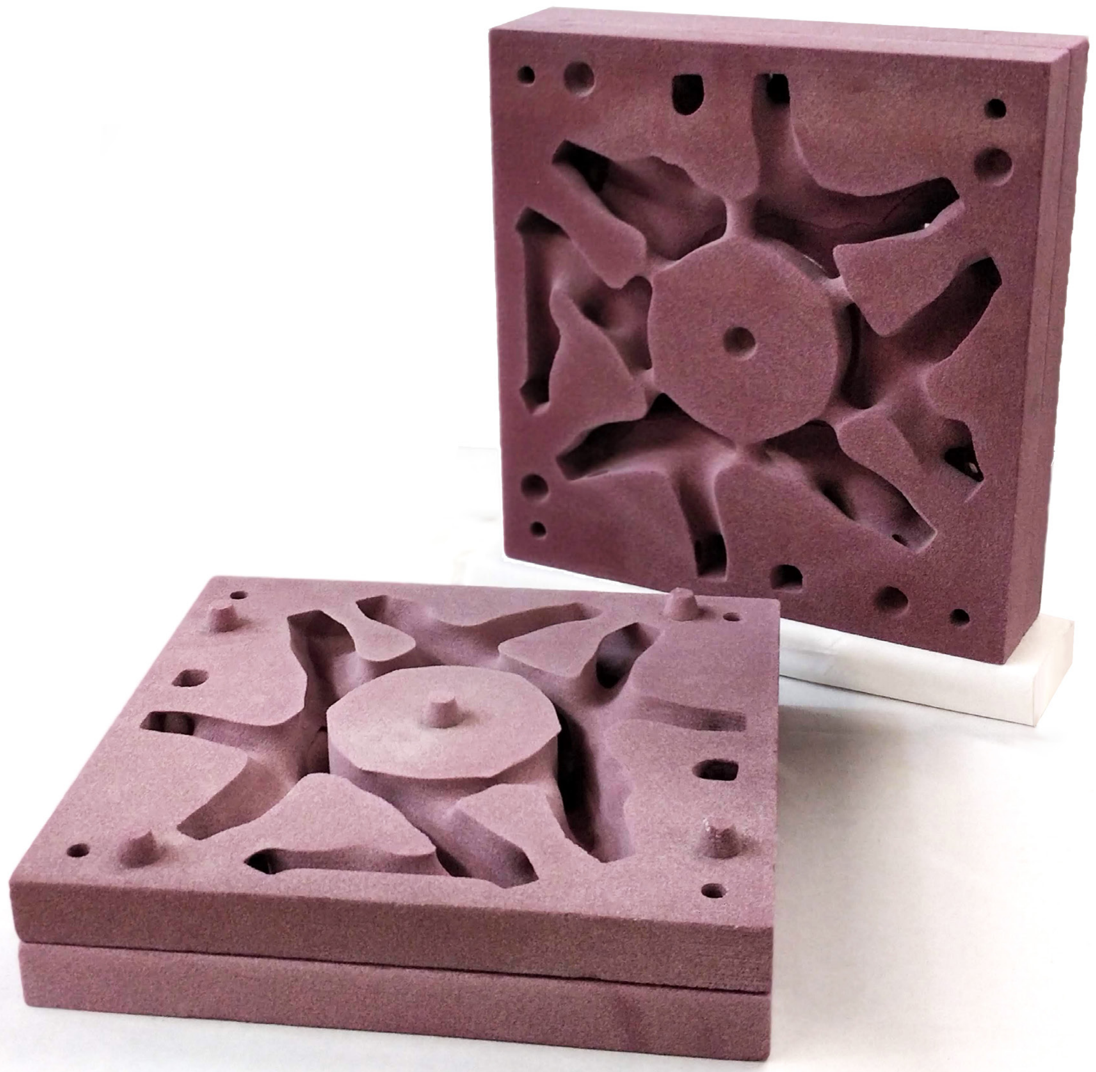
07.4
CONCLUSION

All the experimentations discussed above concluded that 3d printed sand moulds can be used to cast glass. The use of anorganik binder system for printing sand moulds have resulted in promising results. Due to design problems, a proper geometry wasn't casted at the end, but learnings from current experiments can be drawn and further experimentations can be conducted to confirm the results.

It can also be concluded, the use of stainless steel nuts and bolts are not suitable for process as they fuse together making it impossible to unlock the moulds after the experiment. Another alternative to clamping of moulds together needs to be addressed for future experimentation.

While casting complicated geometries where moulds need to be disintegrated, since the Anorganik binder system is not water dissolvable, a solution for dissolving the binder requires further research to avoid any damages to the casted glass piece.

Fig. 07.3 i: Anorganik binder system with artificial sand as mould showcasing the small casted glass pieces inside the mould



08

PRODUCTION TO ASSEMBLY

An important aspect of building technology track is the concept of DfMA- Design for Manufacturing & Assembly. This chapter discusses step by step process of producing the optimized column from the fabrication of the moulds to the casting and then transportation to the final erection at the site.

Step 1:
The production process starts with designing the mould of the geometry, using the parameters discussed in the chapter 05. The maximum size of the printable geometry in a ExOne binder jetting sand printer is 2200 X 1200 X 600 mm.

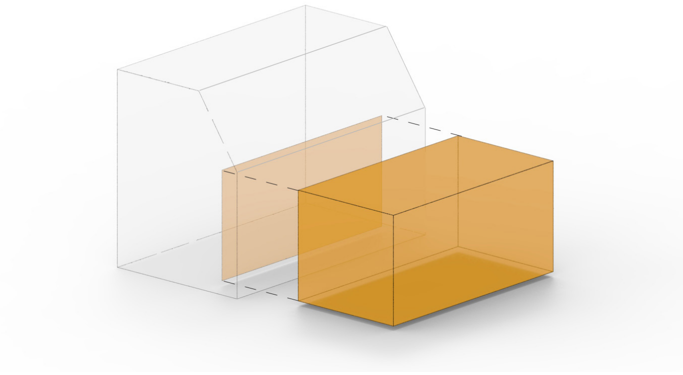


Fig. 08.1 a: Binderjet 3D printer

Step 2:
The geometries that are being produced have dimension more than the size of job box (print bed). So, the whole geometry is divided into printable pieces.

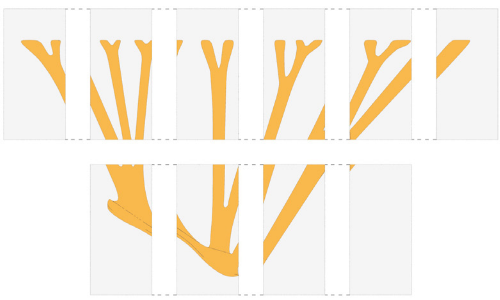


Fig. 08.1 b: Division of geometry on basis of printer bed size

Step 3:
Moulds of these pieces are designed and then printed.

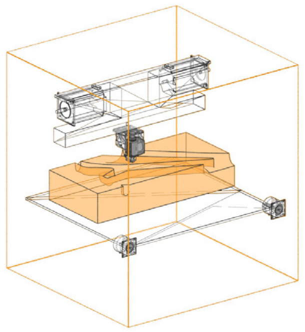


Fig. 08.1 c: Printing of sand mould

Step 4:
After the printing, the moulds are assembled together using inter-lockable nodes.

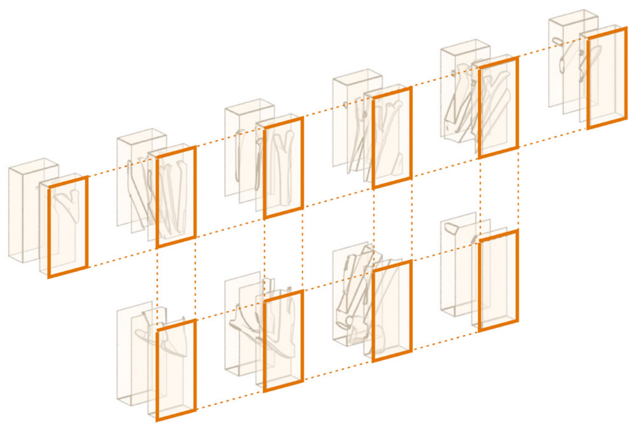


Fig. 08.1 d: Assembly of moulds together

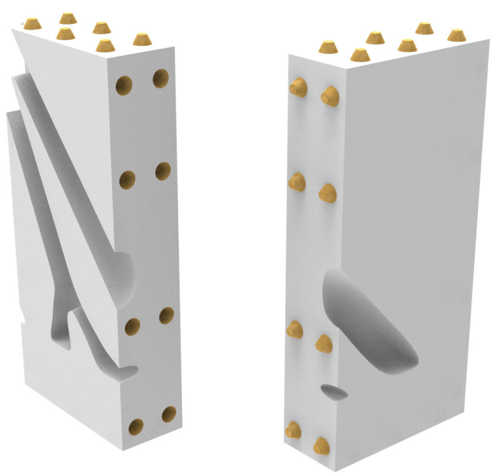


Fig. 08.1 e: Interlocking mechanism of the moulds

Step 5:
The assembled geometry is then held together using C shape steel brackets and are bolted together. The geometry is then held on a metal stand to allow even heating of the geometry to be casted inside the furnace.

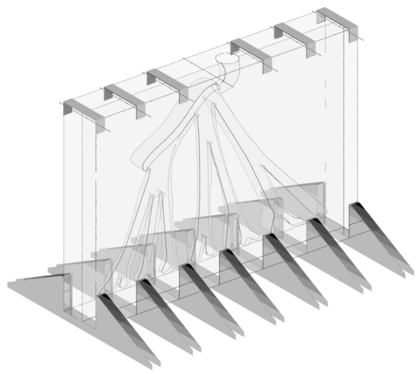


Fig. 08.1 f: Clamping moulds together using steel clamps

Step 6:
The mould is preheated and molten glass is then poured inside the mould

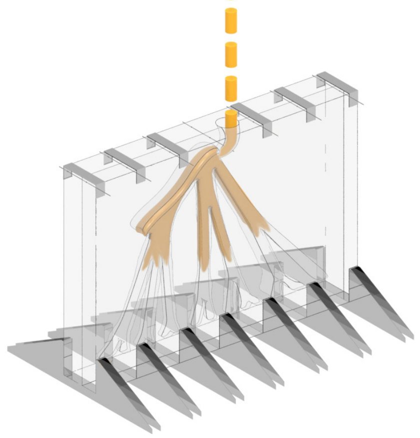


Fig. 08.1 g: Pouring of moulten glass in preheated mould

Step 7:
The mould along with the stand is kept inside the furnace for annealing.

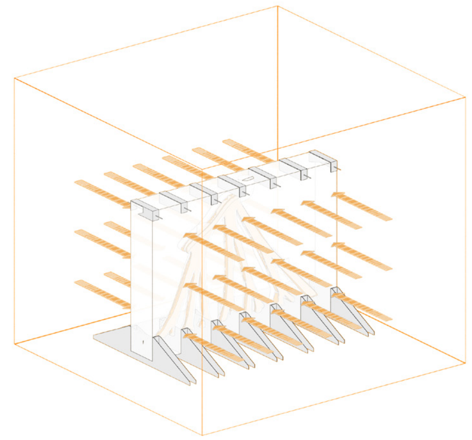


Fig. 08.1 h: Annealing of Glass piece inside the furnace

Step 8:
The mould along with the stand is kept inside the furnace for annealing.

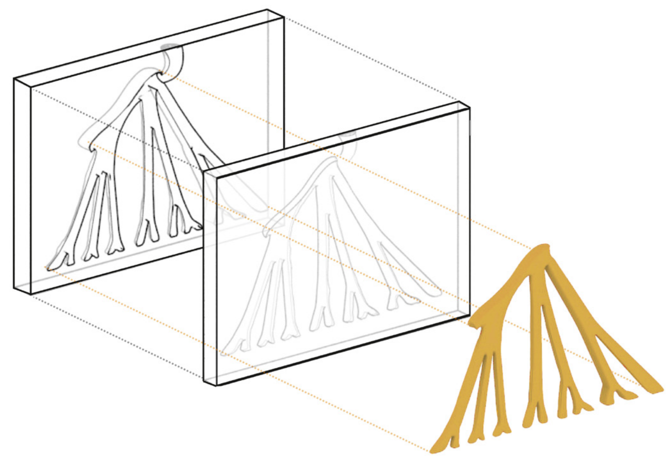


Fig. 08.1 i: Demoulding the casted glass geometry

08.2 TRANSPORTATION

The original geometry is 6 m high and 8 m long. It is not at all feasible to transport the column to the site in one single piece. The dimension of a lorry permitted on German roads is 12m X 2.55m X 4m.

As can been seen in illustration Fig 08.2 a & 08.2 b, the column doesn't seem to fit inside the lorry.

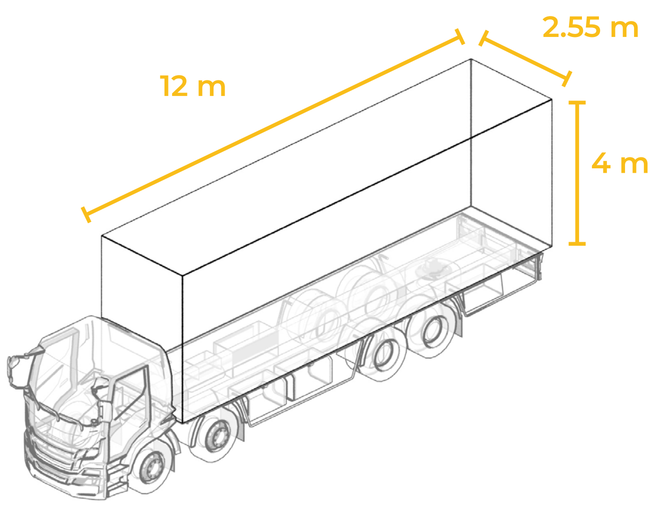


Fig. 08.2 a: Maximum permissible dimension of a truck on German roads

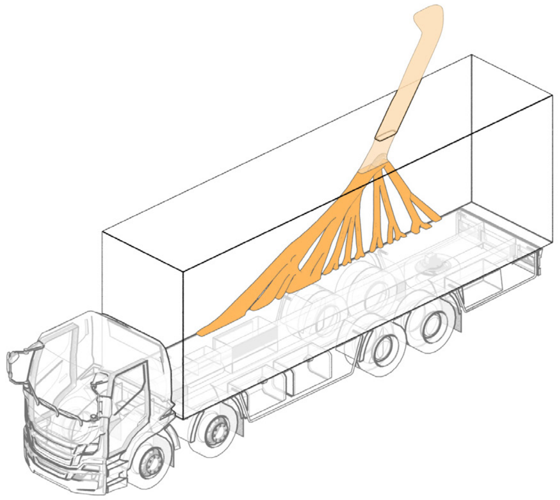


Fig. 08.2 b:

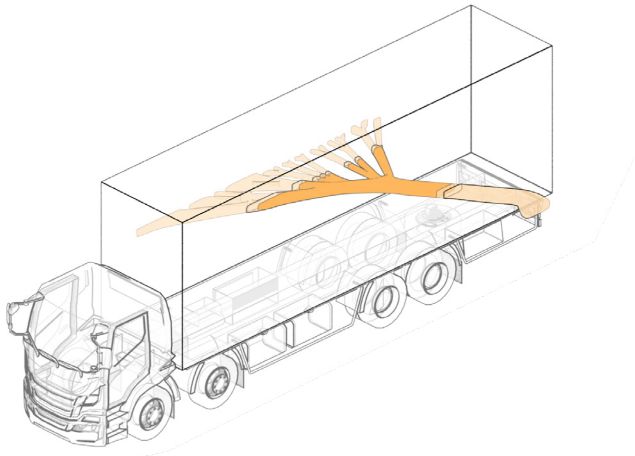


Fig. 08.2 c:

So, the whole column was broken into 3 pieces for the easy transportation. The lorry can carry easily carry all 3 pieces of the column together in a single run.

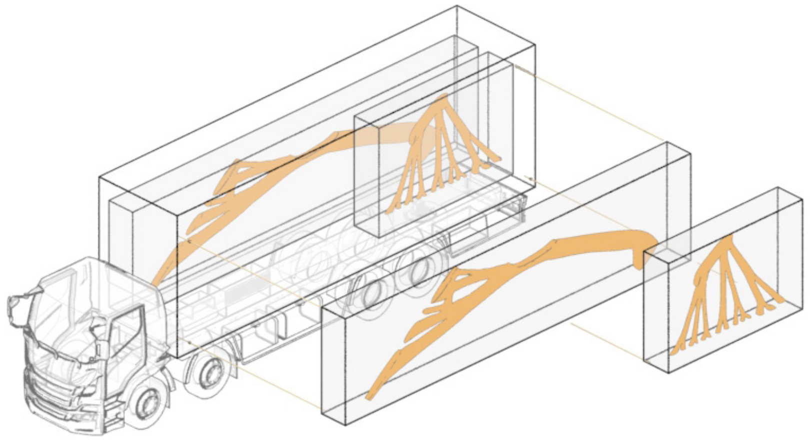


Fig. 08.2 d:

08.3
INSTALLATION

After the glass pieces are transported to the site, they are assembled together using a UV curing adhesive, a rigid adhesive having high stiffness and transparent in nature.

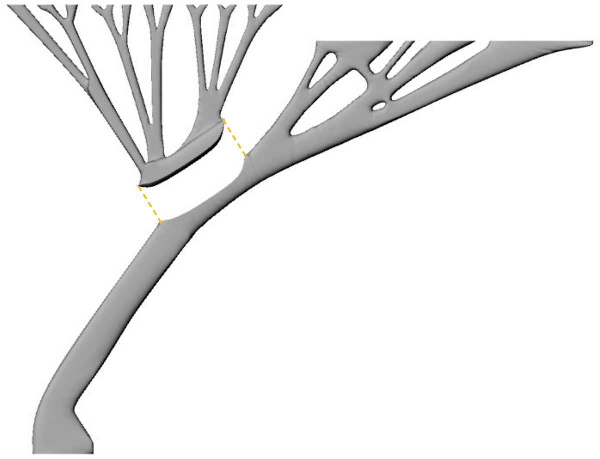
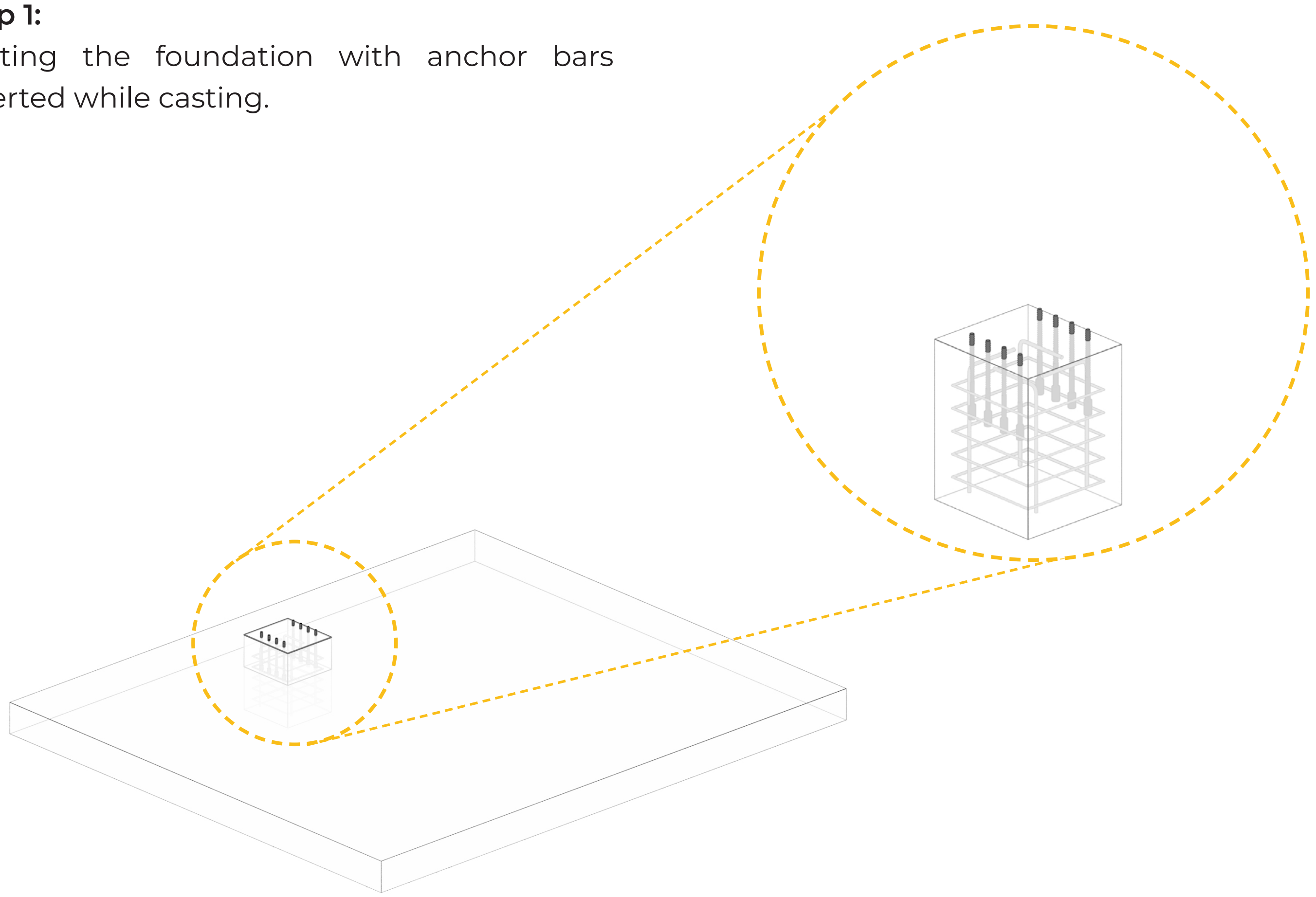


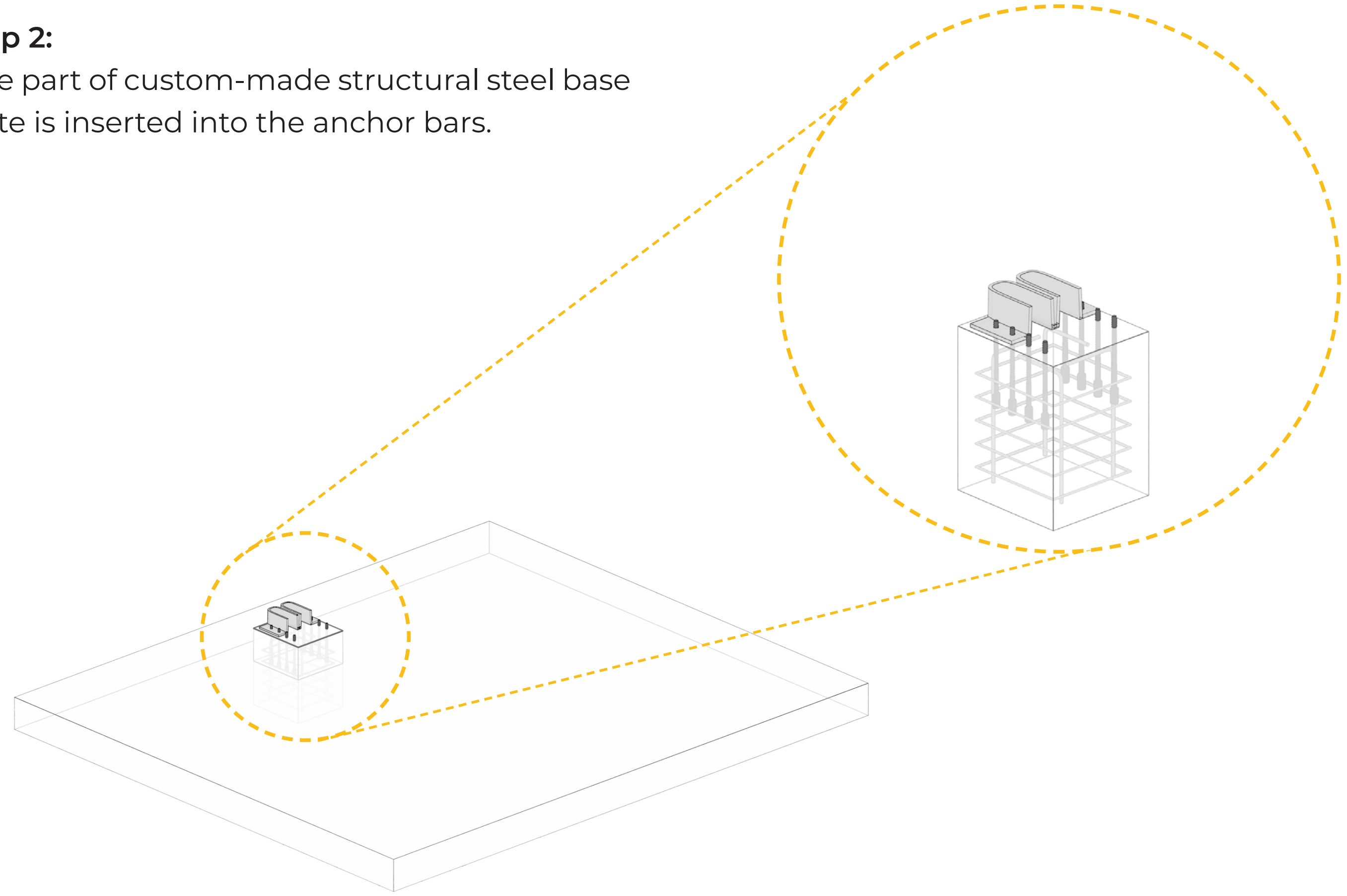
Fig. 08.3 a:

This assembled column is then installed in position. A step by step method has been explained briefly for installation.

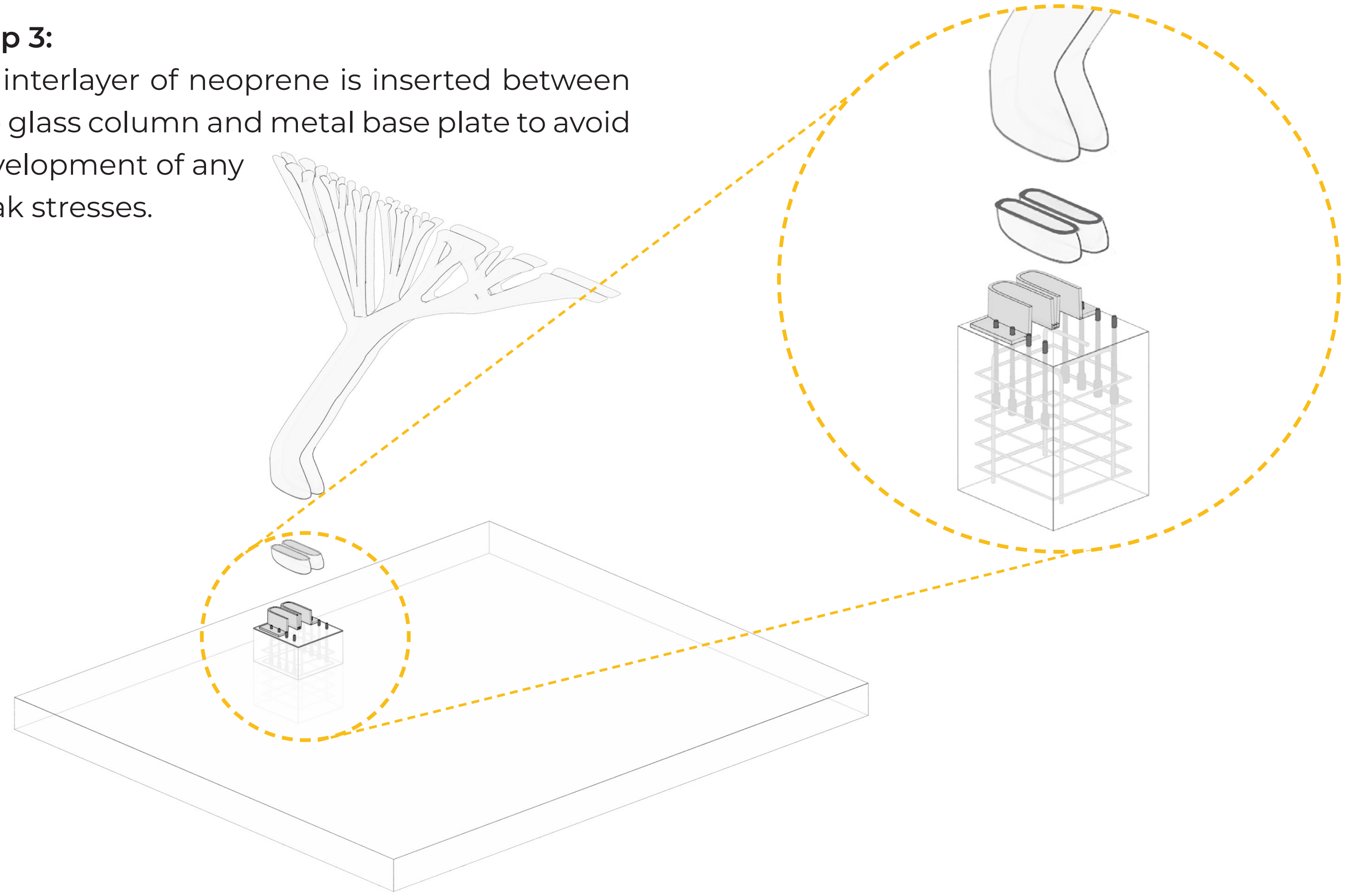
Step 1:
Casting the foundation with anchor bars inserted while casting.



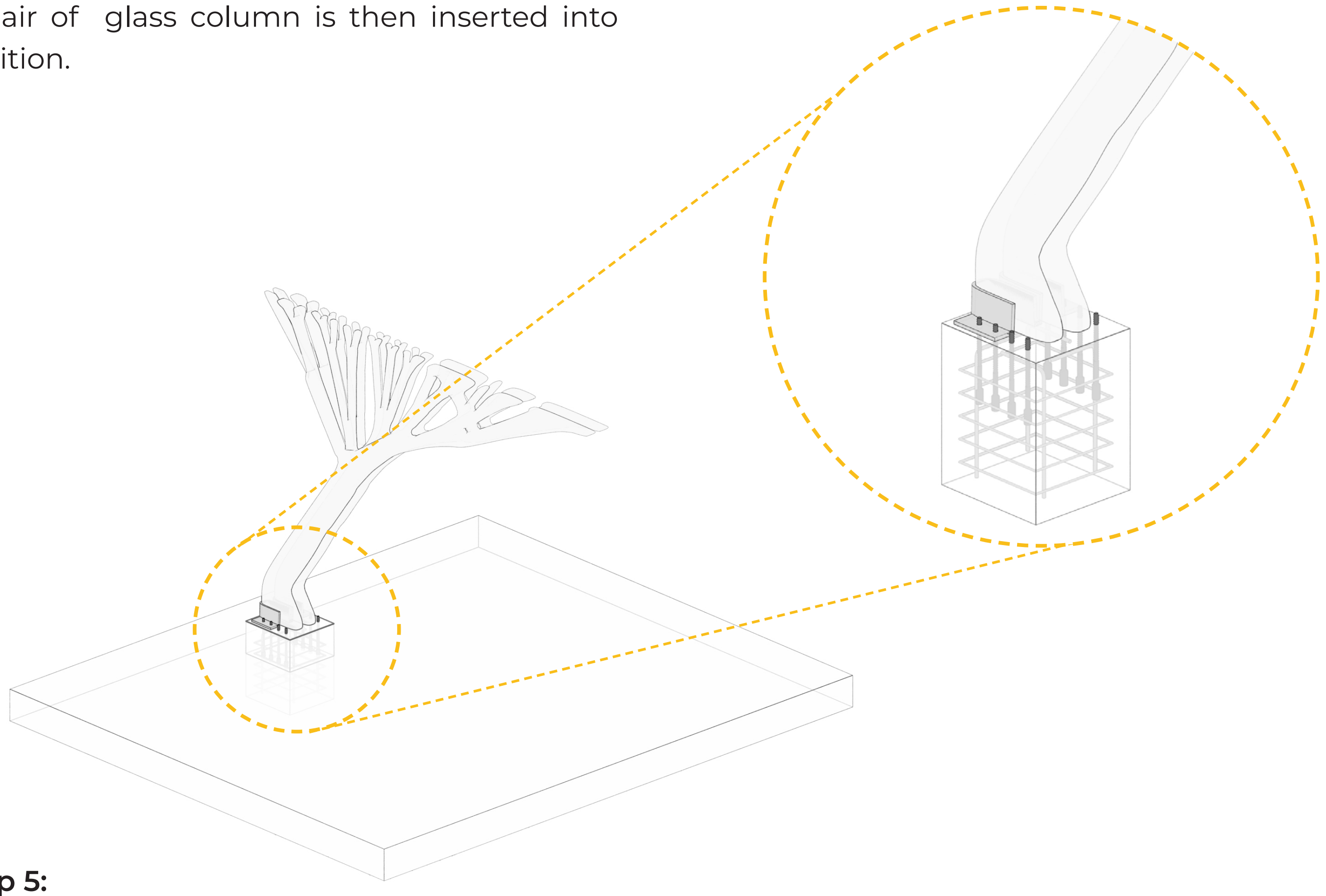
Step 2:
One part of custom-made structural steel base plate is inserted into the anchor bars.



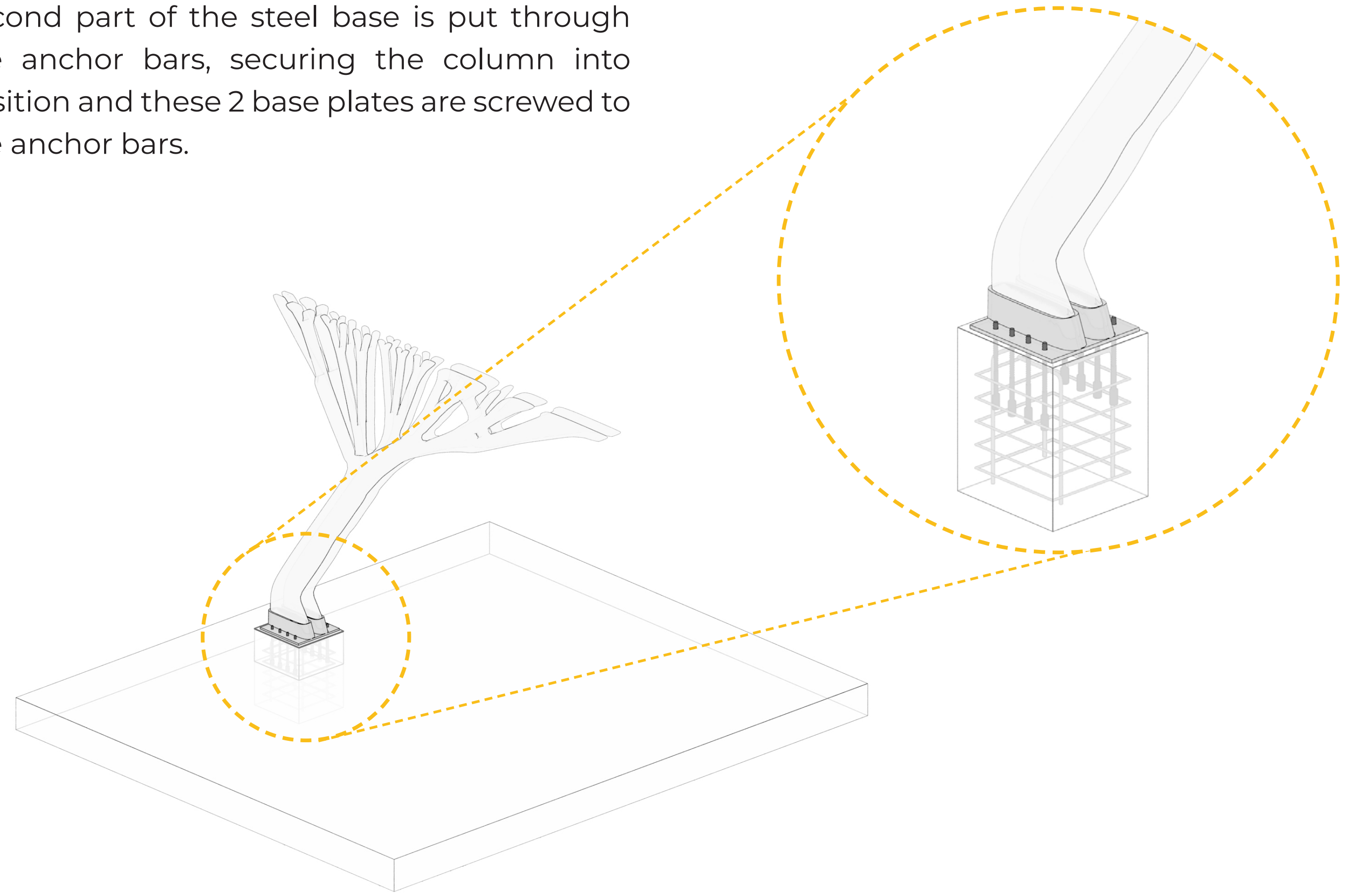
Step 3:
An interlayer of neoprene is inserted between the glass column and metal base plate to avoid development of any peak stresses.



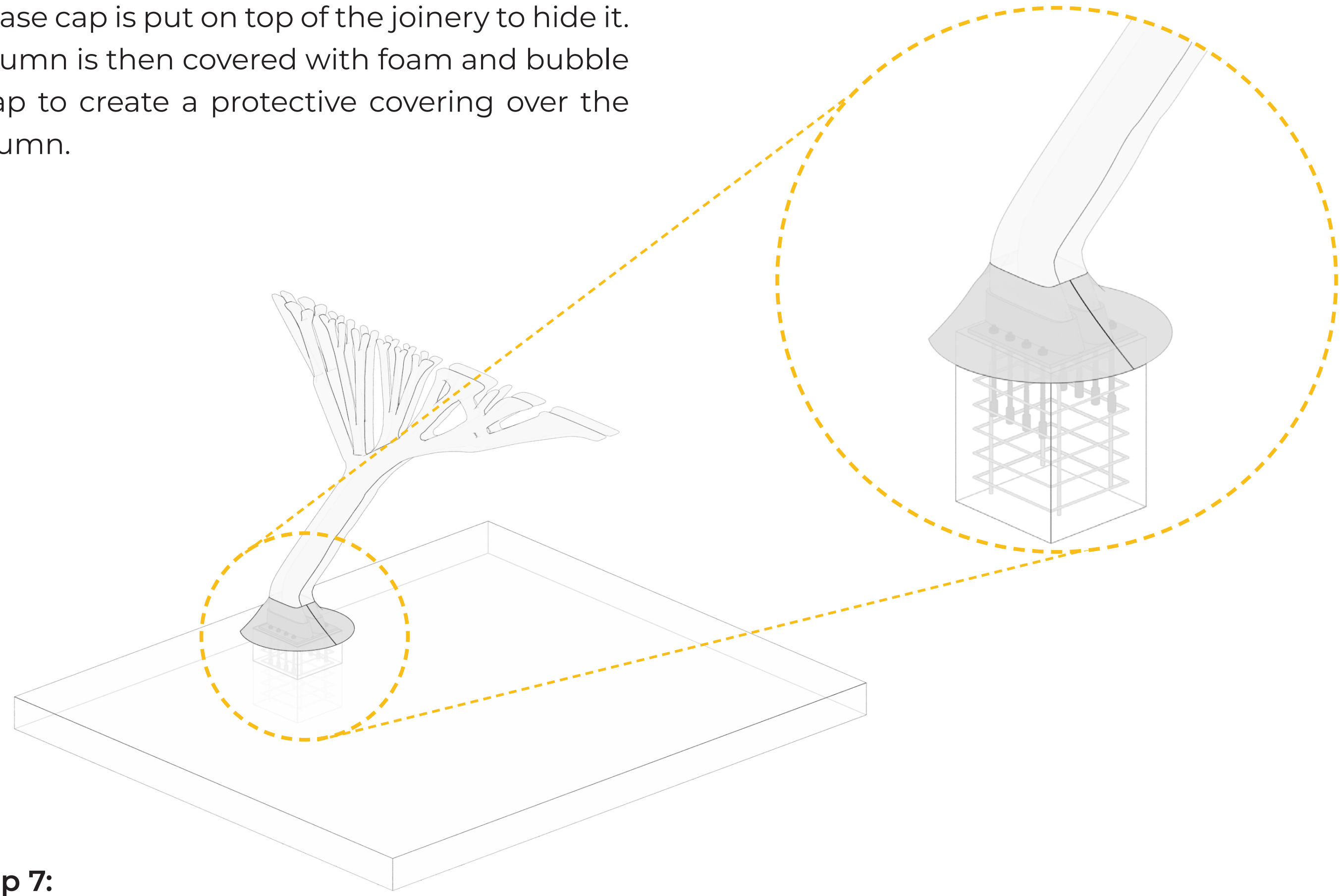
Step 4:
A pair of glass column is then inserted into position.



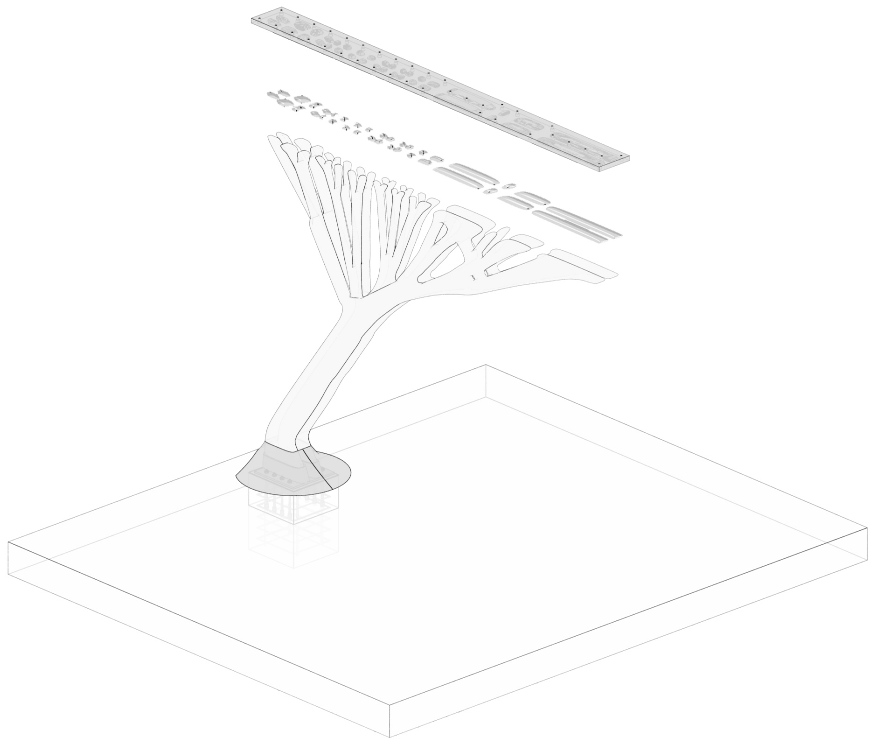
Step 5:
Second part of the steel base is put through the anchor bars, securing the column into position and these 2 base plates are screwed to the anchor bars.



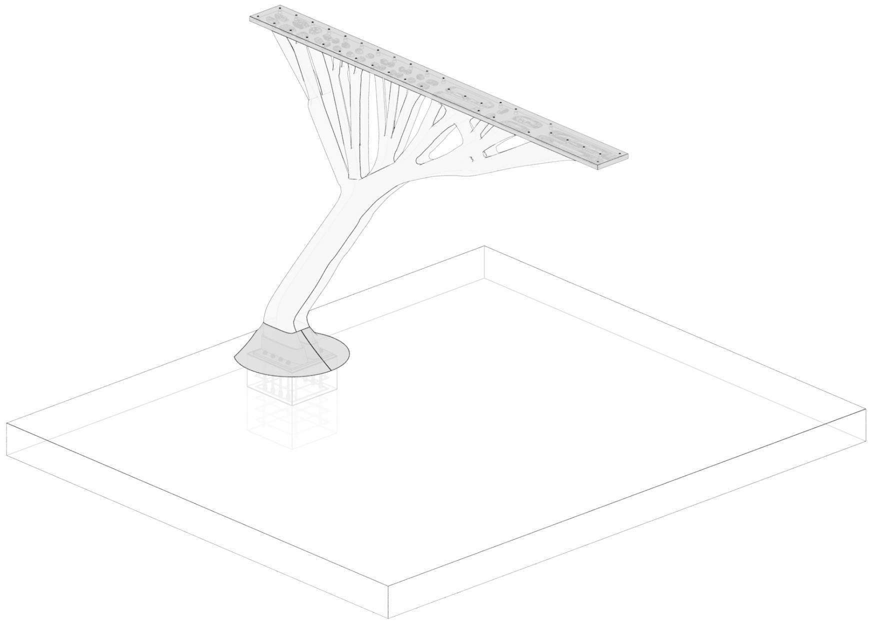
Step 6:
A base cap is put on top of the joinery to hide it. Column is then covered with foam and bubble wrap to create a protective covering over the column.



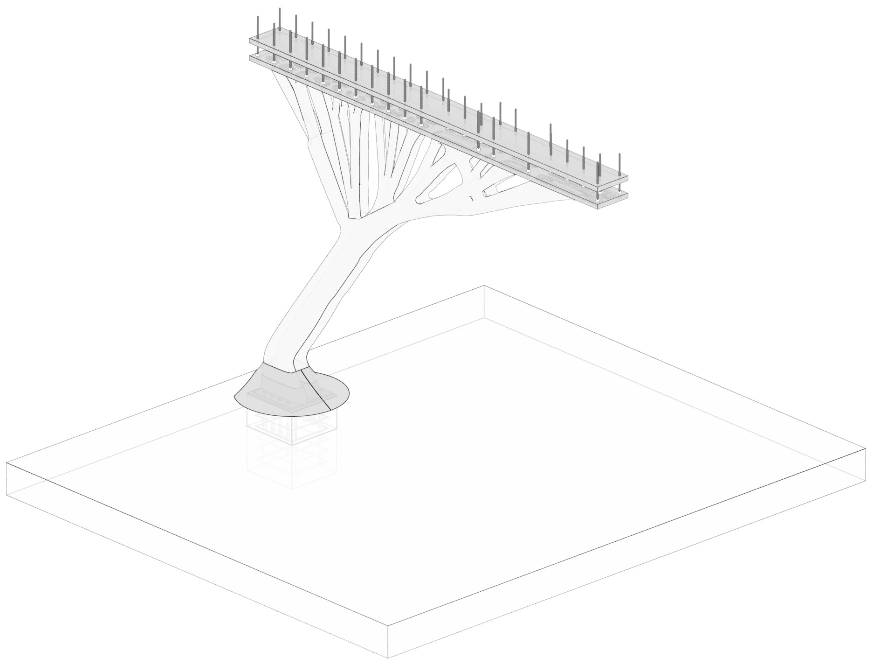
Step 7:
Another layer of neoprene is inserted between the glass column and the steel plate acting as an interlayer.



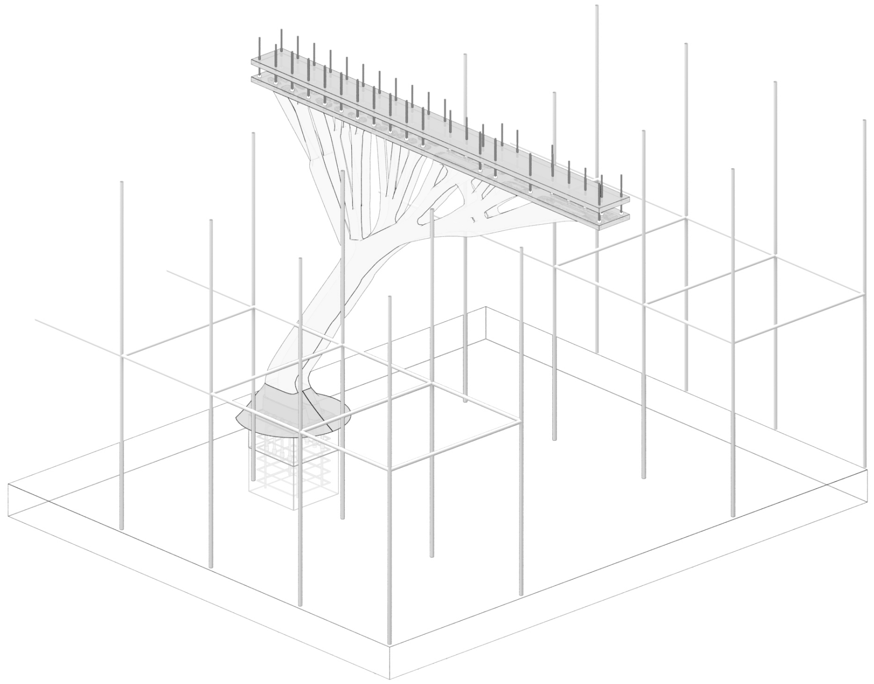
Step 8:
A 100 thk custom made steel plate is put on top of the column using neoprene as interlayer between glass and steel as shown is illustration.



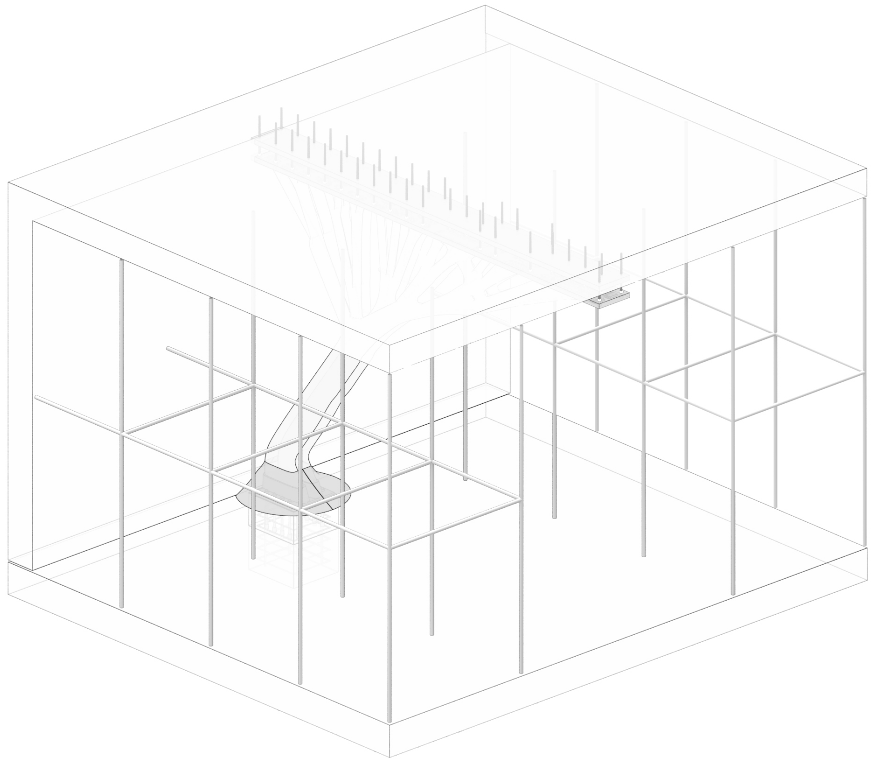
Step 9:
Bolts are inserted into position and a second plate is inserted into position, which would later be used to compress the glass column between foundation and the slab.



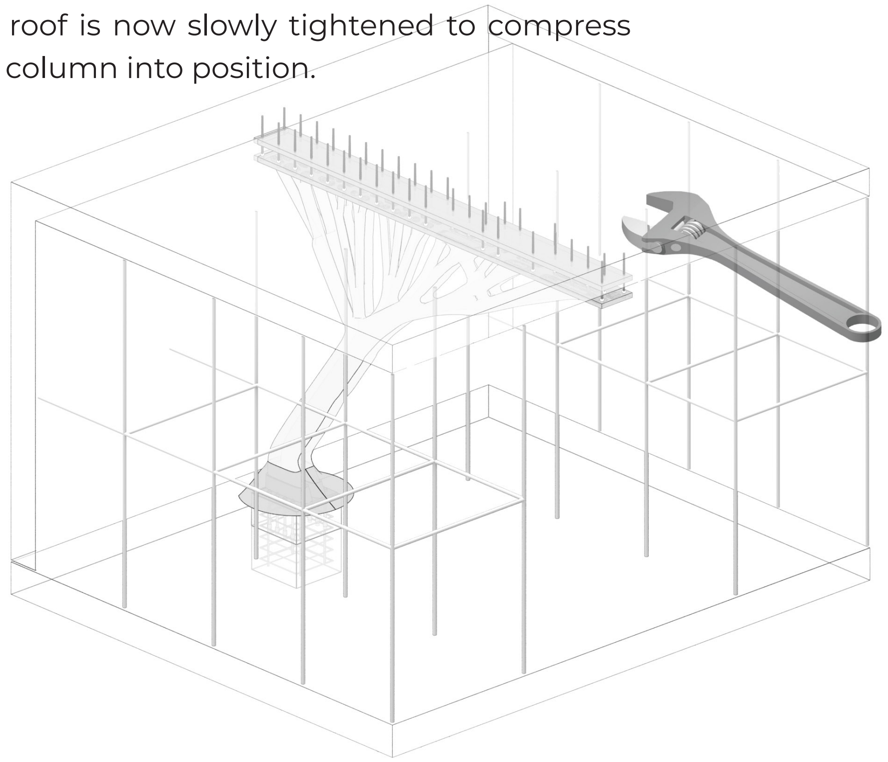
Step 10:
Scaffolding is put around the column, to avoid any physical damage or overloading due to uneven flow of concrete while casting.



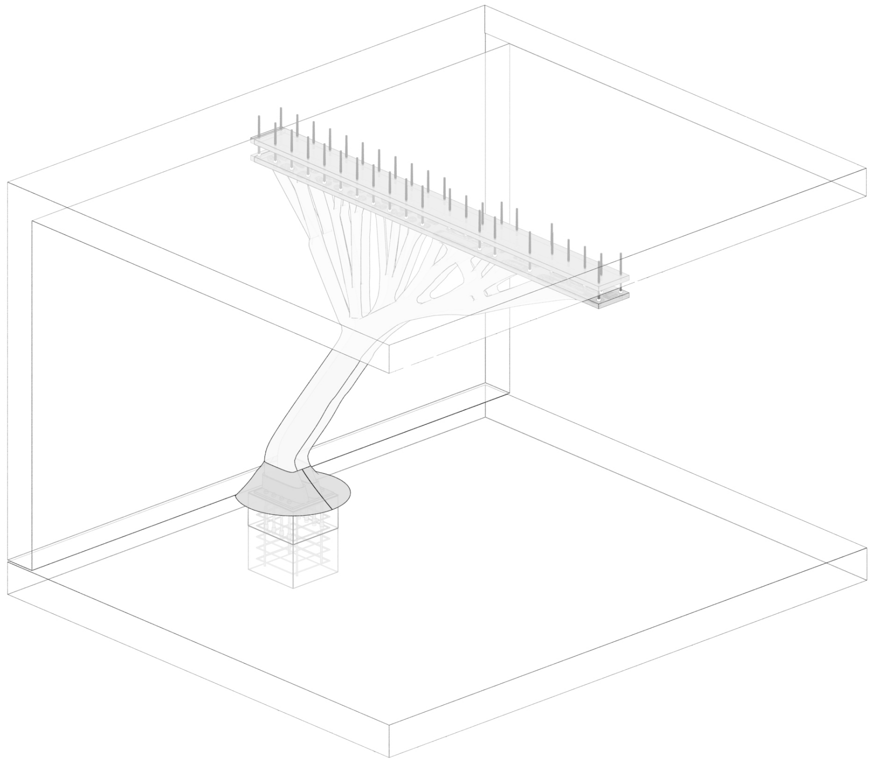
Step 11:
The bolts are then connected to the reinforcements of the slab (to be casted) and shuttering is setup and concrete is poured.



Step 12:
After solidification of slab, shuttering is removed. Steel plate between the column and the roof is now slowly tightened to compress the column into position.



Step 11:
Scaffolding is removed at last and a base clip covering the bottom detail is clipped into position



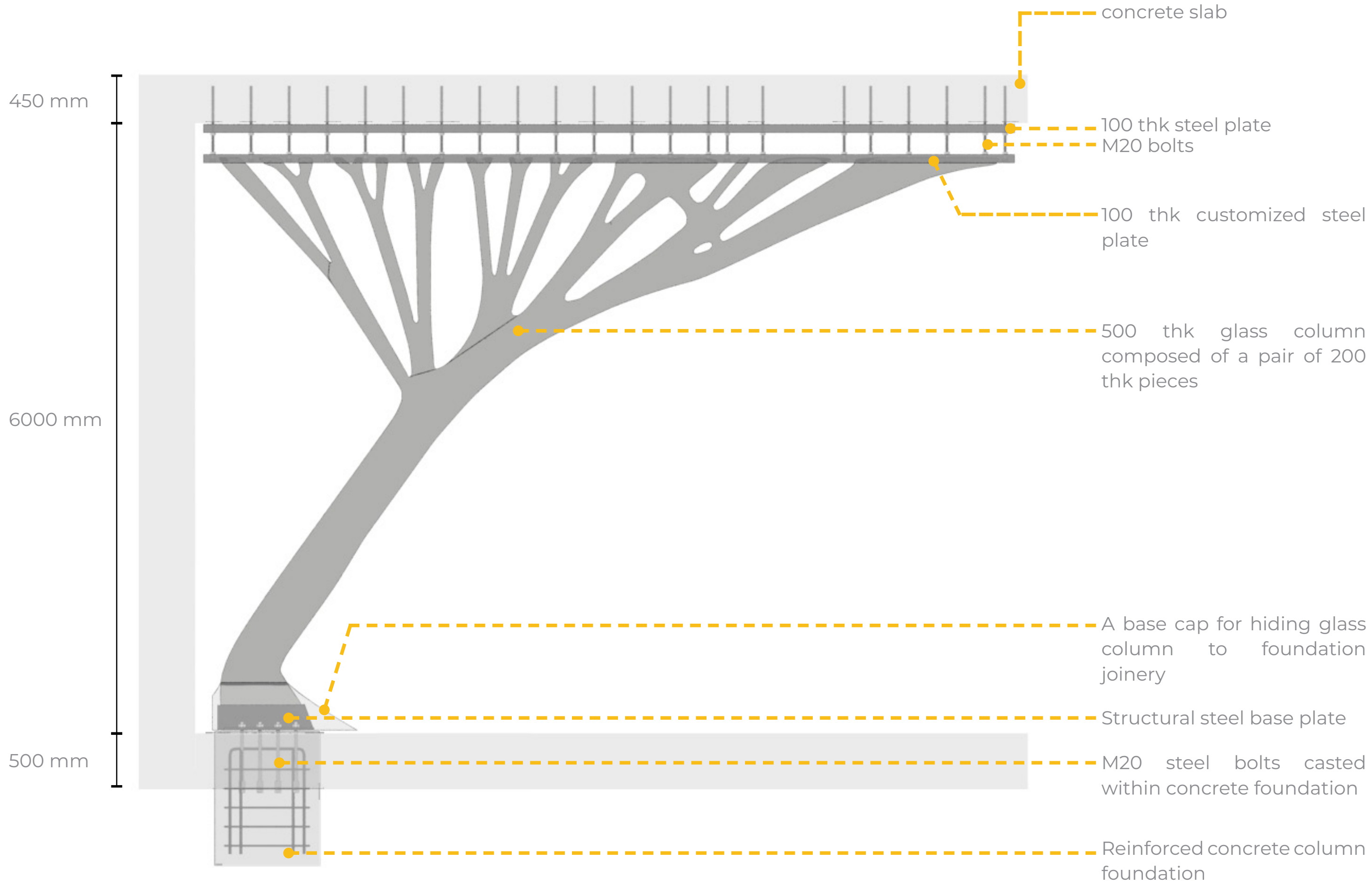
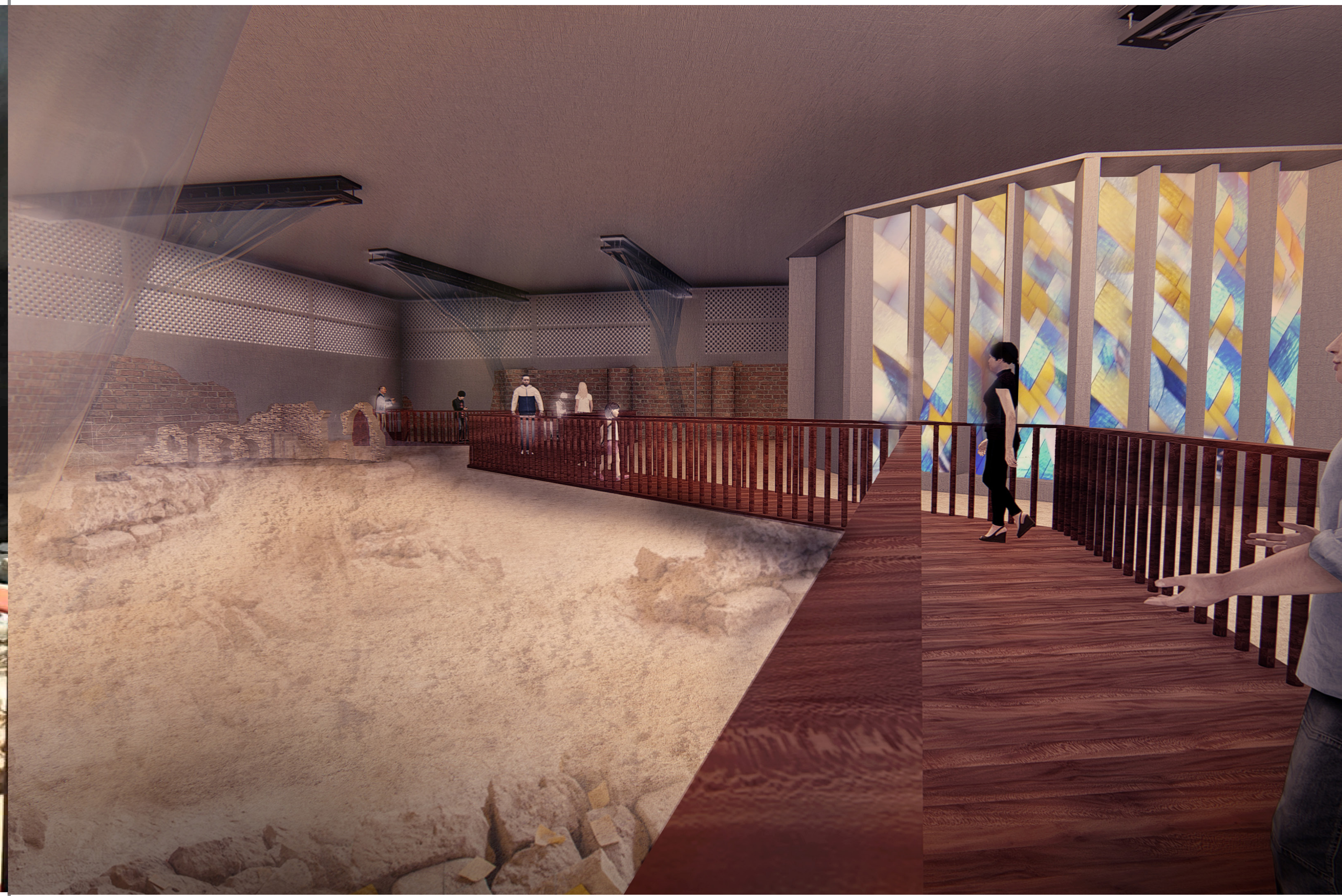
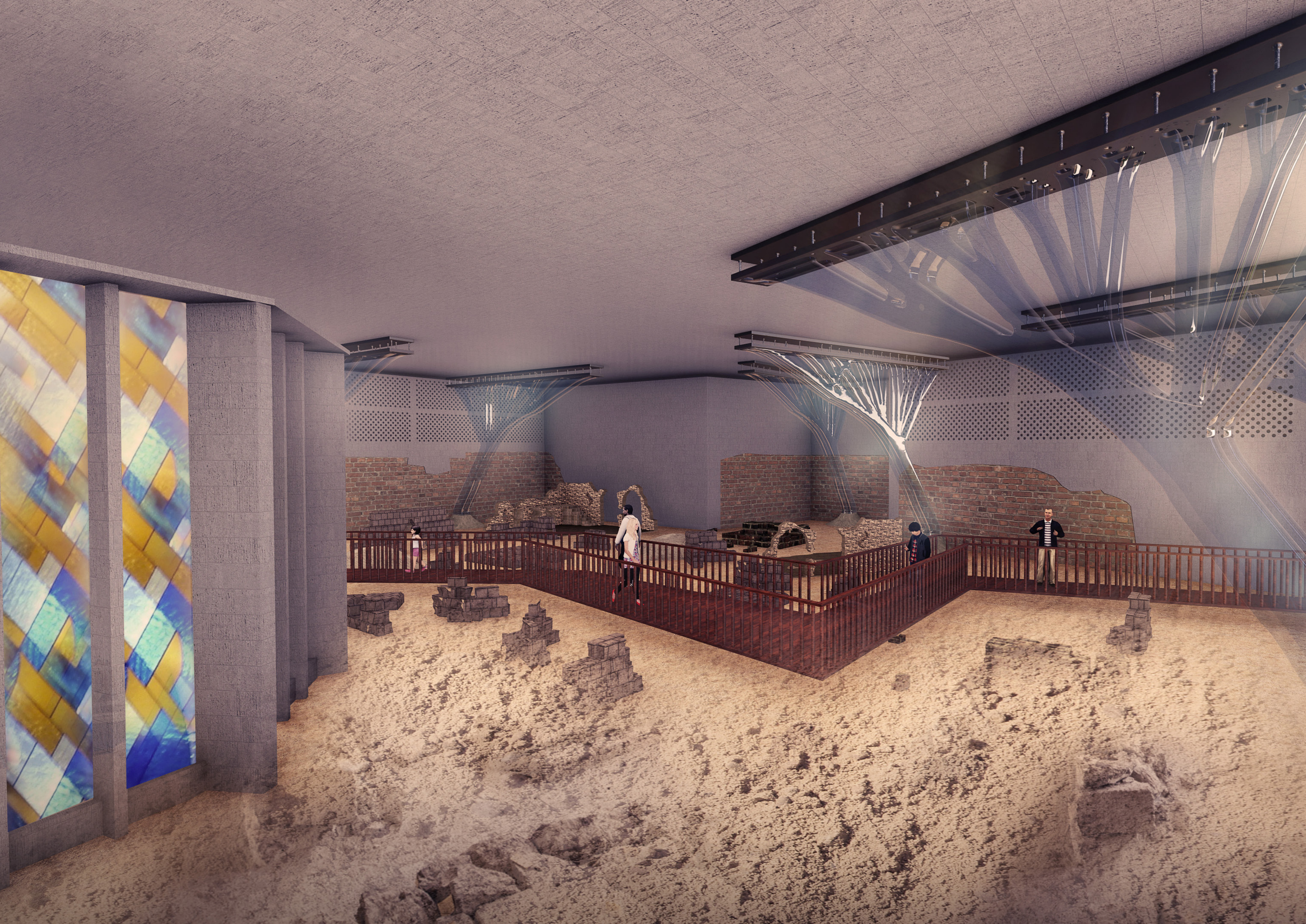


Fig. 08 b: Final assembly of Glass Column

Old View

New View





09

CONCLUSION & DISCUSSIONS

CONCLUSION

This thesis showcases research on how technology can help in casting and fabricating glass structural components through a more feasible, timely and cost-effective approach, using optimization as a means to design and additive manufacturing as a means to fabricate. On basis of the research and analysis presented, the following research question was formulated:

"How to fabricate a Topologically Optimized structural Glass Column using 3D printed sand moulds?"

Potential of topological optimization has always been concentrated on creating a light weight structure but considering glass as a material, optimization plays a crucial role in viability of cast glass structures. Currently, cast glass requires a lot of time in the annealing process to relieve itself of the stresses and this time is dependent on the cross-sectional thickness of the geometry. Optimization allows to create substantially thinner cross section of structural elements which enables to anneal the geometry in significantly less time. This can be evidently seen with the case selected, where topological optimization has reduced the monolithic thick geometry into a thin tree shaped column having significantly smaller cross section. This has not only reduced the weight by 75% but also a year of annealing time which earlier would require almost a month for processing. This process of optimization allows higher flexibility in shaping for the required designed glass structure by eliminating the use of planar float glass sheets which are prone to buckling and have less strength in comparison to a cast glass structure.

It is important to understand that powder bed 3D printing (sand printing) opens a whole new set of opportunities for realizing topologically optimized structures both in macro and micro scale. In case of glass structures, the advantages offered by 3D printed sand moulds over the conventional fabrication technique of investment casting is incomparable. Firstly, moulds for challenging geometries involving fluid design and undercuts can be prepared easily. Secondly, preparation of mould doesn't require extensive labor and are cost effective. Thirdly, the 3D printed sand moulds have an accuracy of +/- 0.4mm whereas the involvement of various steps and materials (wax, epoxy, mdf, crystal cast etc) in the conventional fabrication technique influences the accuracy of the mould and create flaws. In terms of limitation, the sand moulds cannot be used for mass production. For fabricating a standardized geometry, steel moulds or graphite moulds offer much higher precision and durability of mould portraying sand mould as inefficient process.

Glass structures are very new to the construction industry and doesn't have any norms or bylaws for fabrication and in respect to this new fabrication technique, certain design criteria were established. Starting with glass as a material, it is important to have homogeneous mass distribution to avoid uneven stresses during annealing. Secondly, the thickness of the geometry should be reduced to a reasonable dimension. (between 100 to 200 mm on basis of theory available). Thirdly, glass being a brittle material, the geometry should have no sharp corners. And lastly, the size of the geometry should be reasonable enough to fit inside the kiln as well as easily transported to the site. While, the limitation or criteria offered in respect to sand moulds are no sharp corners and a minimum wall thickness of 3 to 4 mm.

Based on established design criteria, few sections of a topologically optimized glass column were prototyped (kiln casted) at different scales- 1:2. 1:5 and 1:20 using the sand printed moulds. The CHP binder system failed to prove the workability of system at a bigger scale while Anorganik binder system gave some promising results. However, one experiment cannot conclude the full workability of the fabrication technique, therefore, more experiments are needed before a strong conclusion can be made.

The research presented provides learnings based on experimenting with few specimens. Firstly, the size of pouring cap should always be bigger than the hole at the bottom of the earthen pot. Secondly, thin geometries like geometry 1 tend to break during the fabrication process. Hence, they should be avoided. Thirdly, clamping of geometry should not be done using stainless steel nut & bolt as they fuse together at higher temperature making it impossible to unscrew them.

The rough surface of the mould requires a coating to facilitate less post production. It was concluded that crystal cast works best amongst the tested specimens but still doesn't provide smooth finish and optical quality. Further work on both coating as well as demoulding of anorganik binder system is required to prove the feasibility of this technique in order to make this fabrication technique more feasible and less labour intensive.

DISCUSSION

Sustainability & Circularity: Glass is assumed to be an unsustainable material due to the requirement of high prolonged working temperature for the fabrication process. However, this research portrays a fabrication process which not only reduces few months of annealing to few days but also creates a circularity in the fabrication process. The cast glass element produced is pure and free from any adhesive or impurities, unlike laminated float glass structures, making it recyclable without any end of life. Just like the glass product, it's mould also bears same property of circularity. The mould disintegrates into a heap of sand after fabrication process, which can be reused in the sand printer to print moulds again creating a circular loop as shown in the fig 09 a.

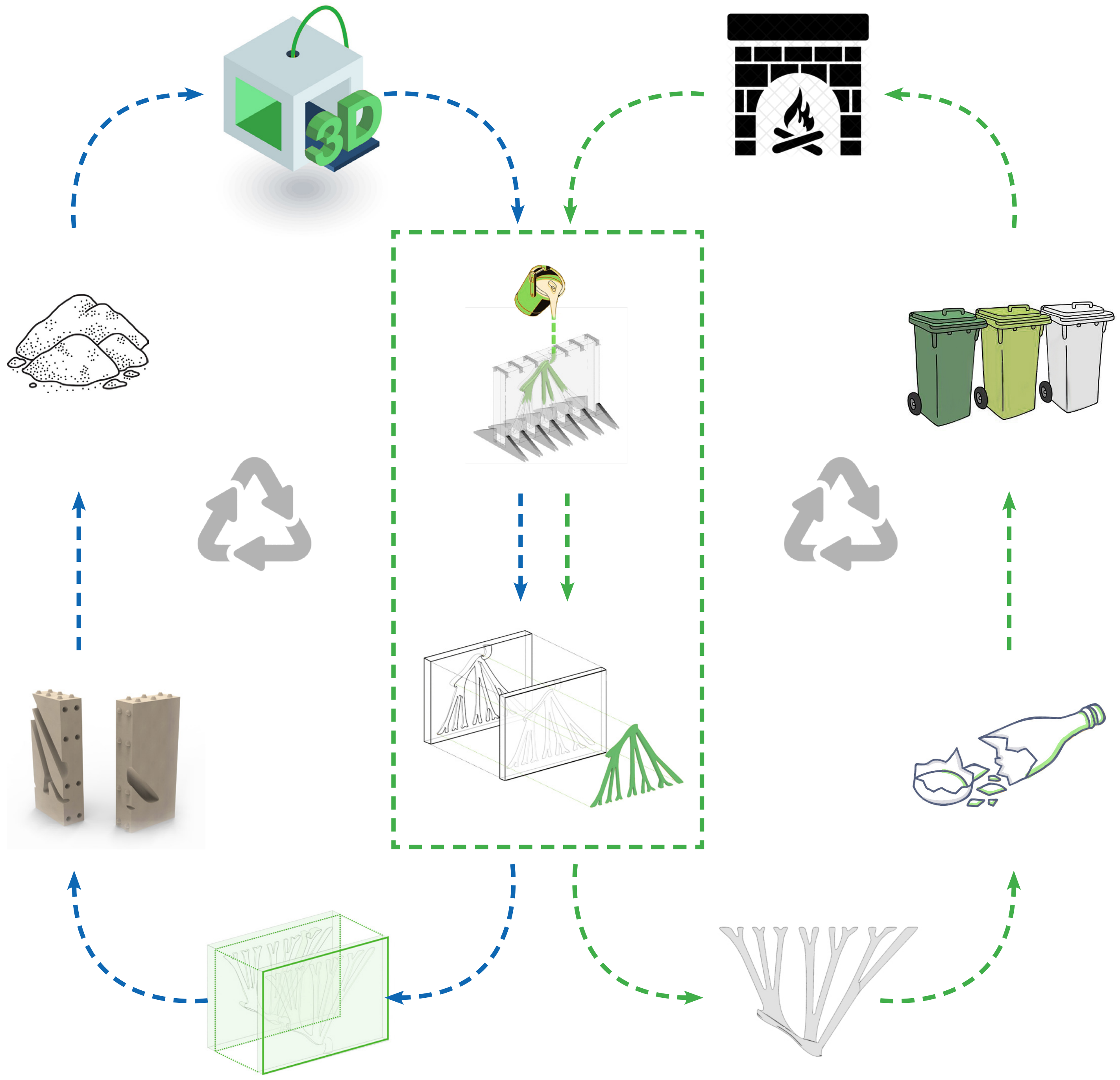


Fig. 09 a: A theoratical Circular and sustainable approach of using sand mould for casting cast glass structures.

Ornamentation and Hybrid Structures:

Ornamentation has always been associated to structural elements since historical times, famous example being the 3 Greek order in columns. With the new fabrication technique, one can fabricate glass structural elements consisting of ornamentation creating a contemporary unique architectural style. Also, hybrid structures can be easily fabricated by introducing tensile components within the moulds before casting glass, creating a unified structural element capable of handling all forces.

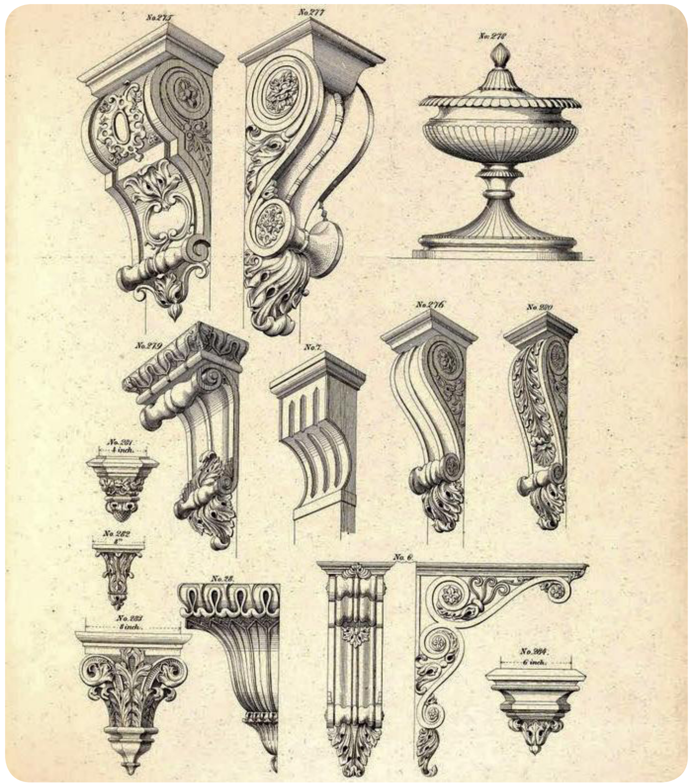
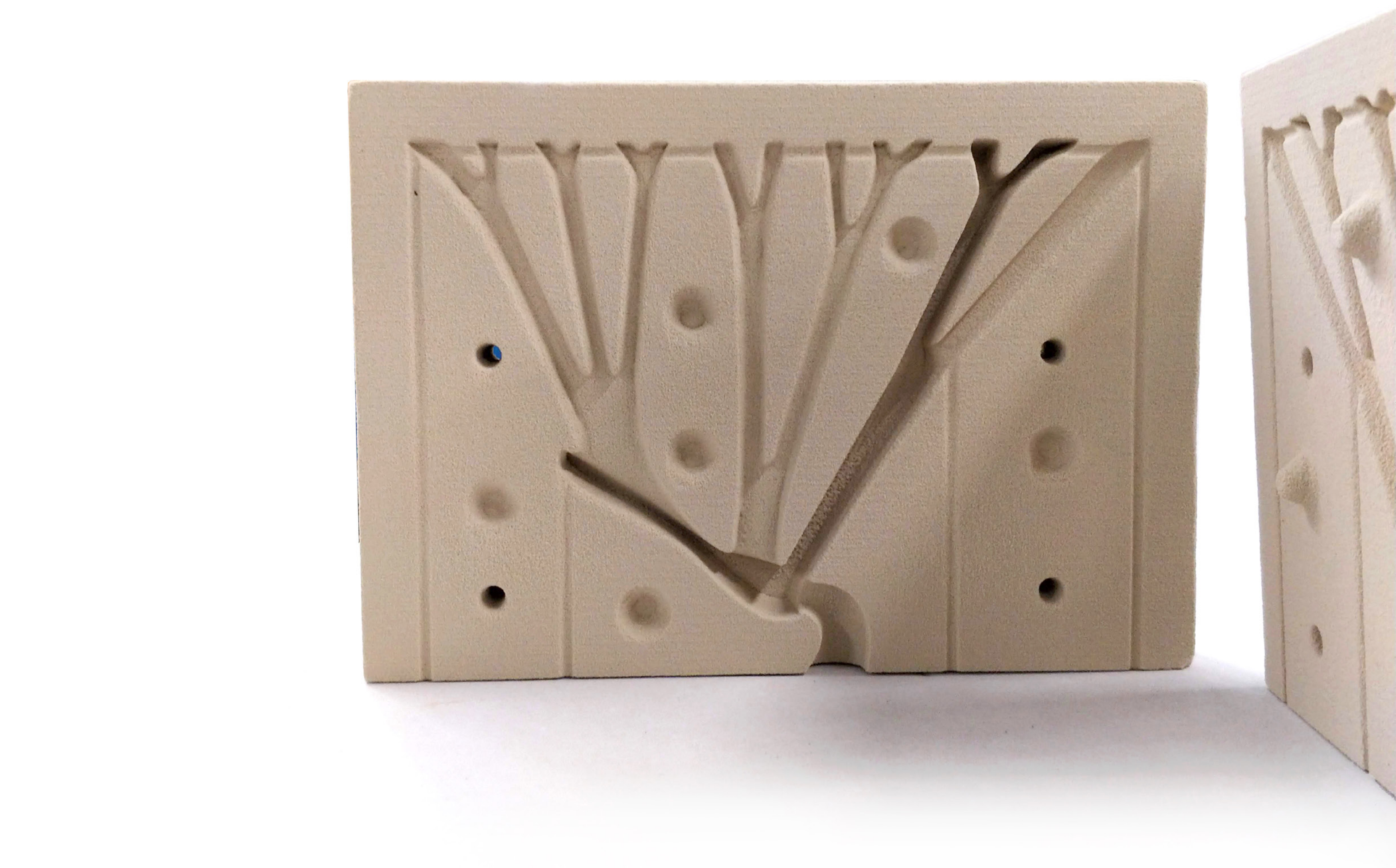


Fig. 09 b: Historical ornamentation can be easily designed and fabricated in cast glass geometry using sand mould technique. (Classically-Inspired Architectural Terms n.d.)

Further Development:

- One of the most critical part of this fabrication technique is the surface finish. The experimented coatings still require post processing of casted glass element and this process becomes difficult when a substantially large or a complex geometry is involved. The right coating that creates a perfectly smooth and transparent finish is yet not identified and requires further exploration.
- The mould designing process can be parametrized on basis of design criteria formulated and can be improved with practical experience. So, a parametric tool should be created.
- Using computational fluid dynamics, flow of glass inside the mould can be studied and design criteria can be developed to allow smooth flow of glass inside the mould. This allows glass to be casted without air bubbles as well as avoid spillage of glass outside the mould.



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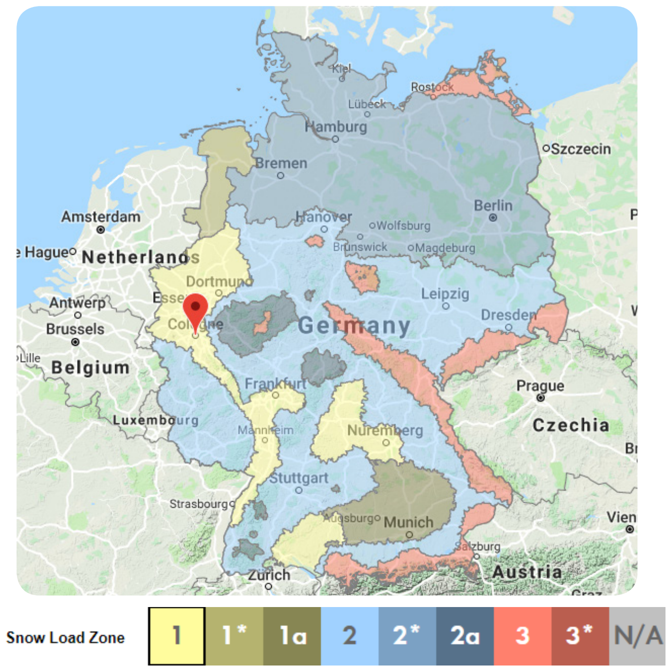
10

APPENDICES

10.1
APPENDIX A- LOAD CALCULATIONS

10.1.1 SNOW LOAD



LOCATION

Street	Unter Käster
Zip Code	50667
City	Köln
Latitude	50.938°
Longitude	6.960°
Altitude	50 m
Snow Load Zone	1

Characteristic value of snow load

$s_k = 0.65\ kN/m^2$

10.1.2 WIND LOAD

LOCATION

Street	Unter Käster
Zip Code	50667
City	Köln
Latitude	50.938°
Longitude	6.960°
Altitude	50 m
Wind Zone	1

Basic velocity pressure

$q_b = 0.32\ kN/m^2$

10.1.3 CALCULATIONS

Area of Slab	881.77	m^2
Length of walls		
perimeter wall	124.87	m
inner wall	97.84	m
Height of First Floor	5	m
Thickness of walls		
perimeter wall	0.25	m
inner wall	0.15	m
Density of Concrete	2400	kg/m^3
Thickness of First Floor	0.2	m
Thickness of Roof	0.15	m
Gravity	9.8	m/s
Snow Load	0.65	KN/m^2
Wind Load	0.32	KN/m^2
Live Load of museum	5	KN/m^2
Live Load of roof	1	KN/m^2
Total Area of outer walls	394.55	m2
Total Area of inner walls	356.1	m2

Roof Slab

Self Weight	3.528	KN/m^2
Snow Load	0.65	KN/m^2
Live Load	1	KN/m^2
Total	**5.178**	**KN/m^2**

First Floor Slab

Self Weight	4.704	KN/m^2
Live Load	5	KN/m^2
Total	**9.704**	**KN/m^2**

Total Load per m2	14.882	KN/m2
Area of Slab	881.77	m2
Total Load of 2 Slabs	**13122.50114**	**KN**

Walls

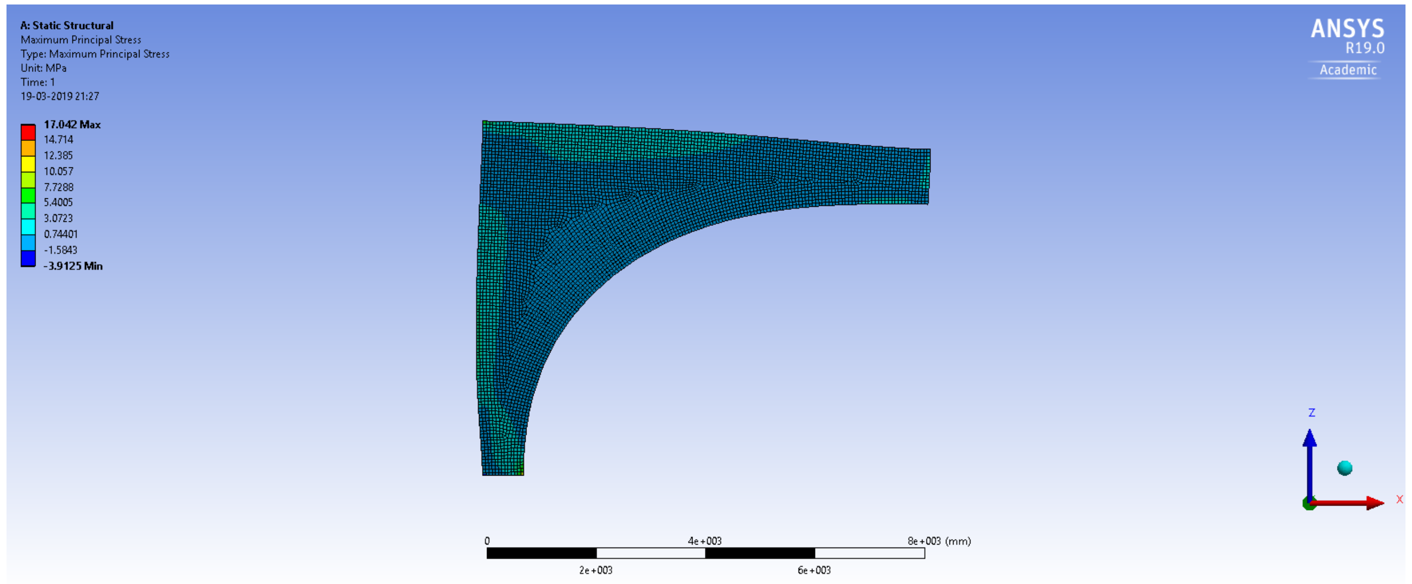
Self Weight	5.88	KN/m^2
Wind Load	0.32	KN/m^2
Total	**6.20**	**KN/m^2**
Total Load of walls	**2093.87**	**KN**

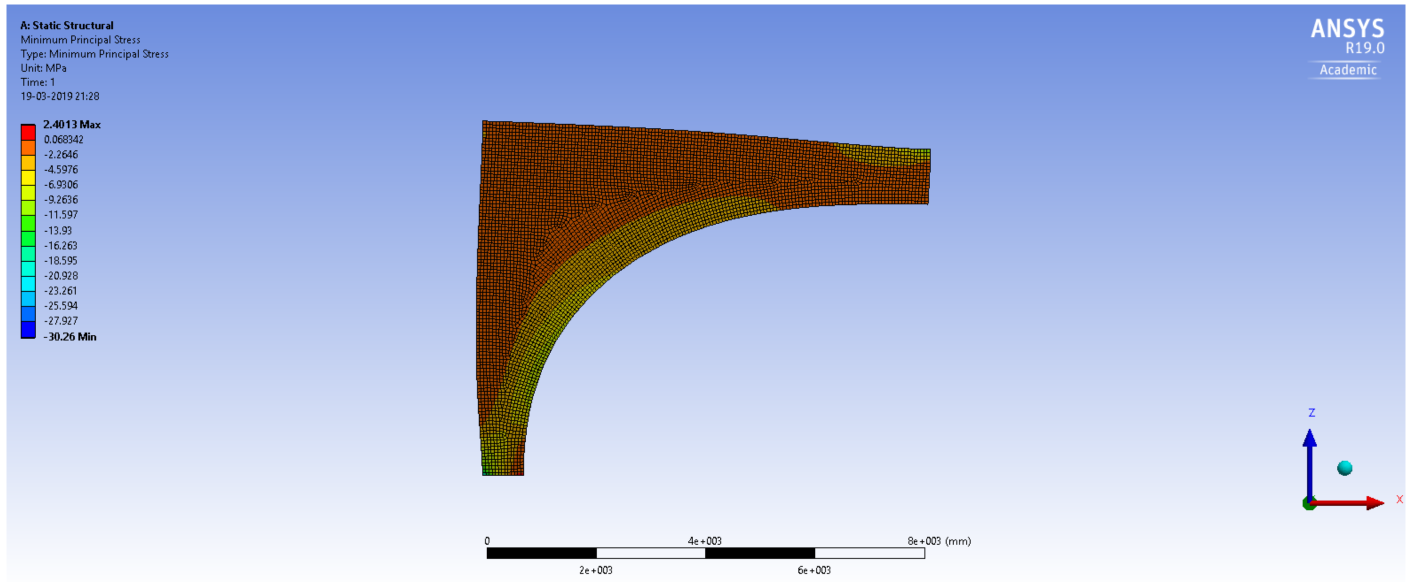
Total Load	**15216.37**	**KN**
No. of Columns	34	
Load on one column	447.55	KN
Safety Factor	1.7	

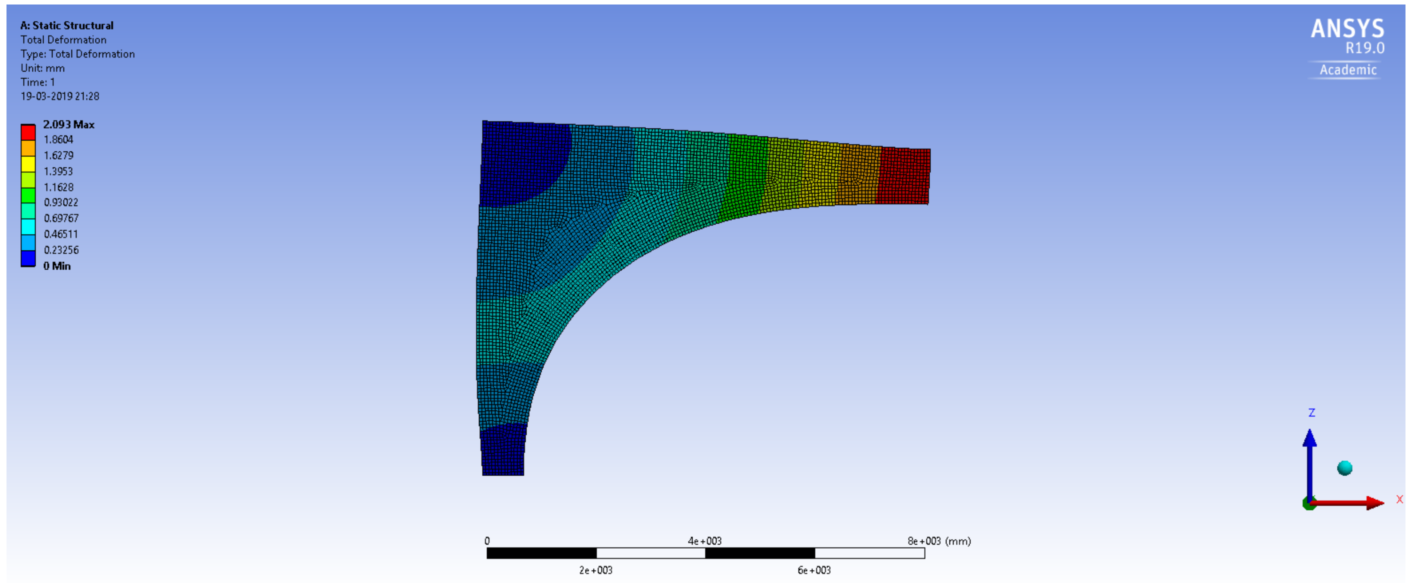
Critical Load on one column is:
760.82 KN

10.2
APPENDIX B- STRESS CALCULATION FOR OPTIMIZATION

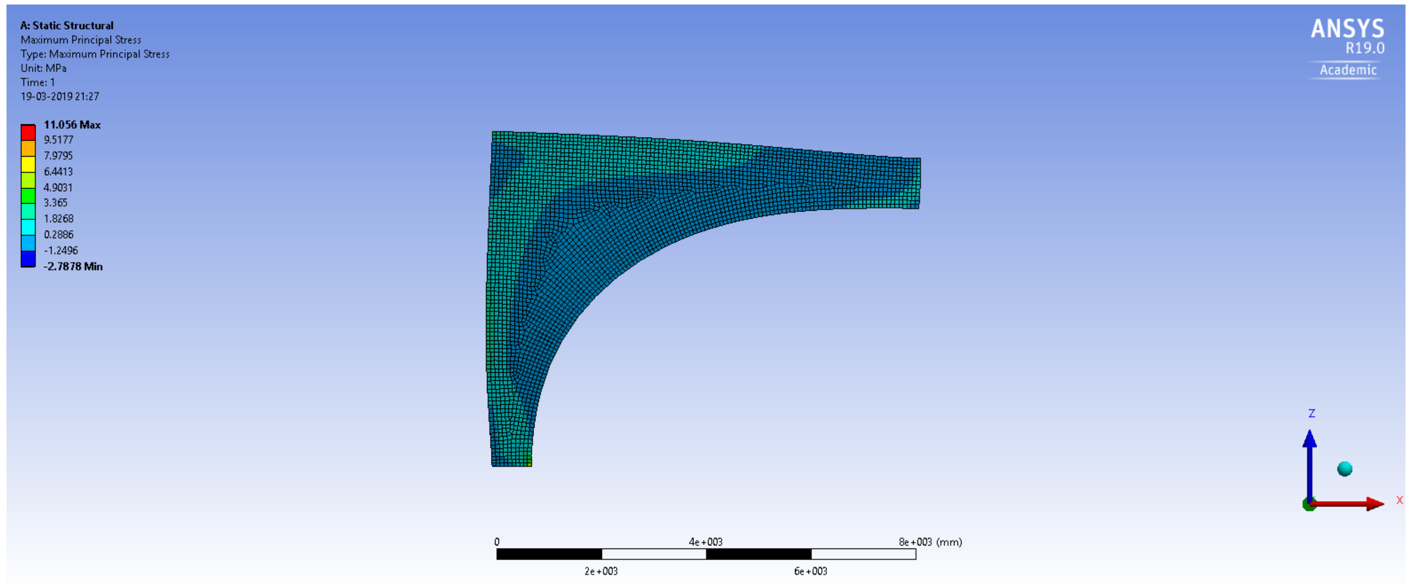
10.2.1 500 THK GEOMETRY

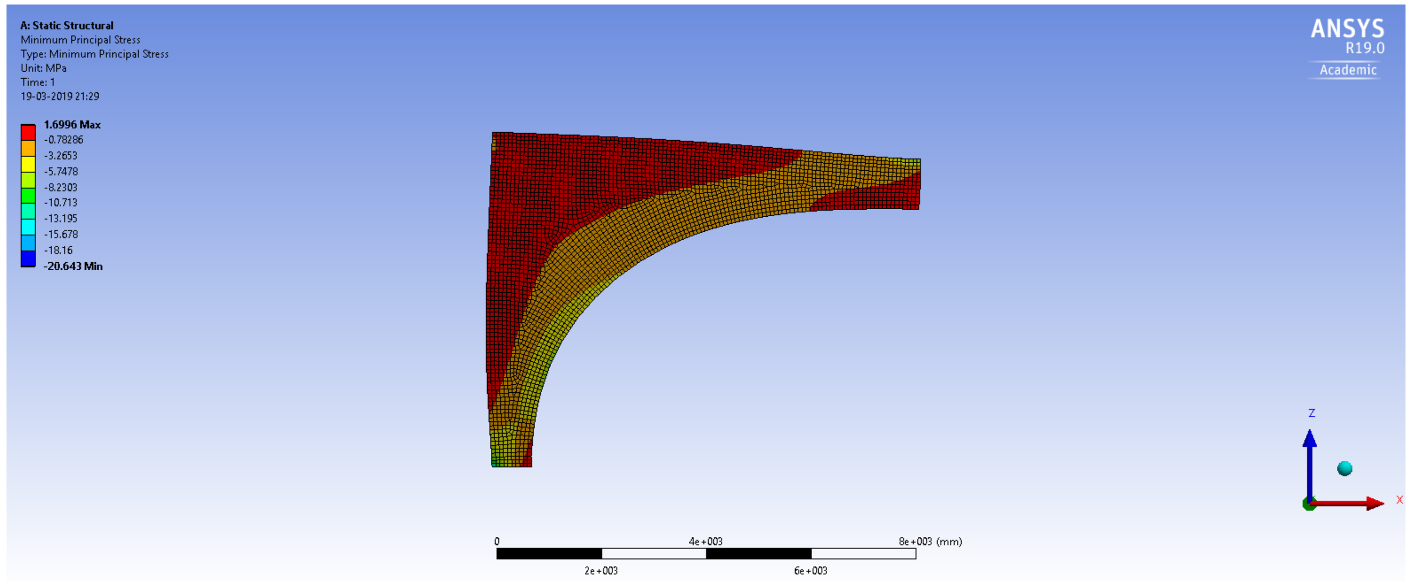


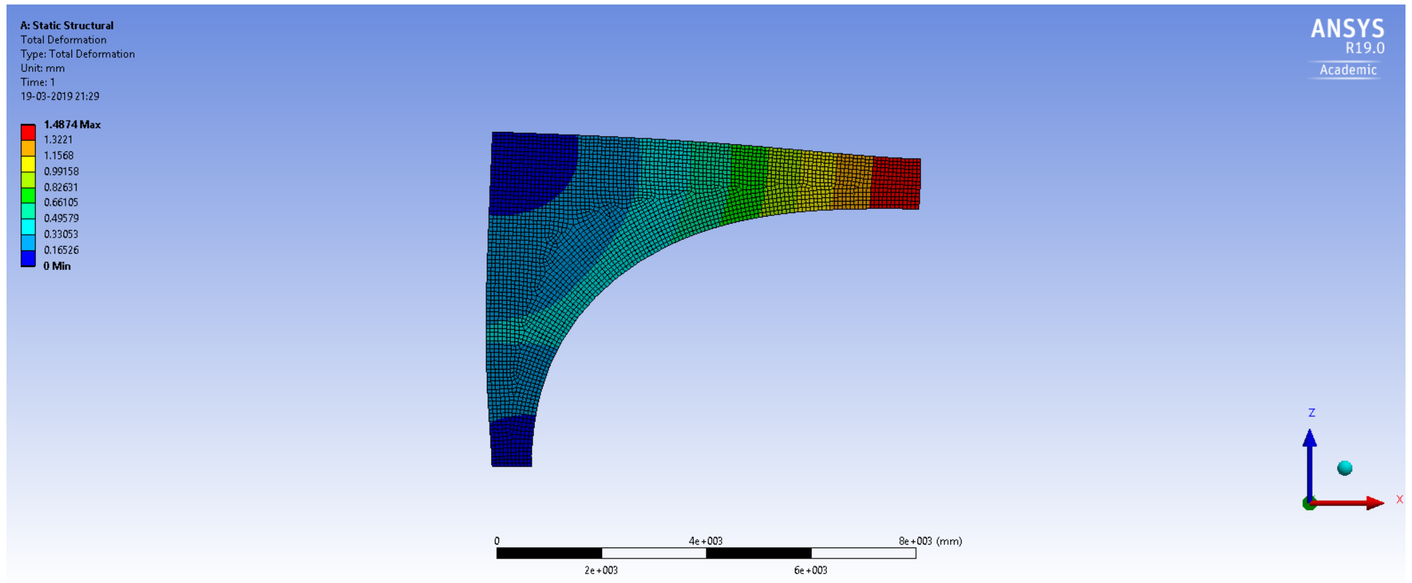




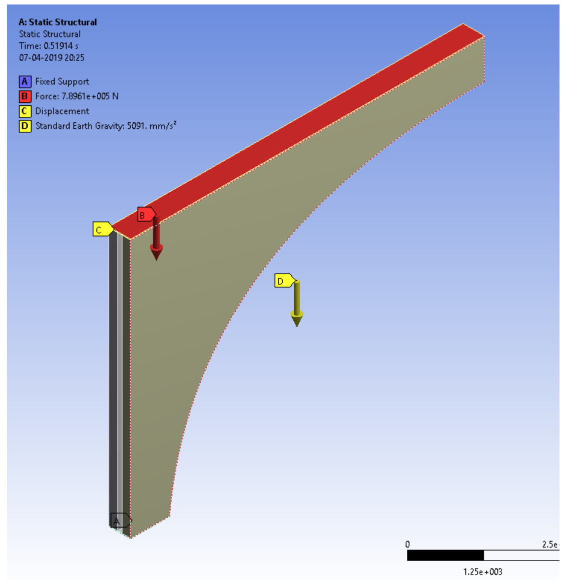
10.2.3 750 THK GEOMETRY

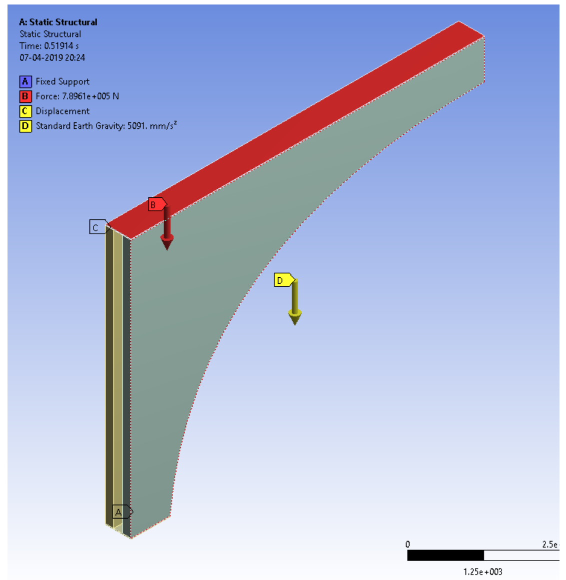


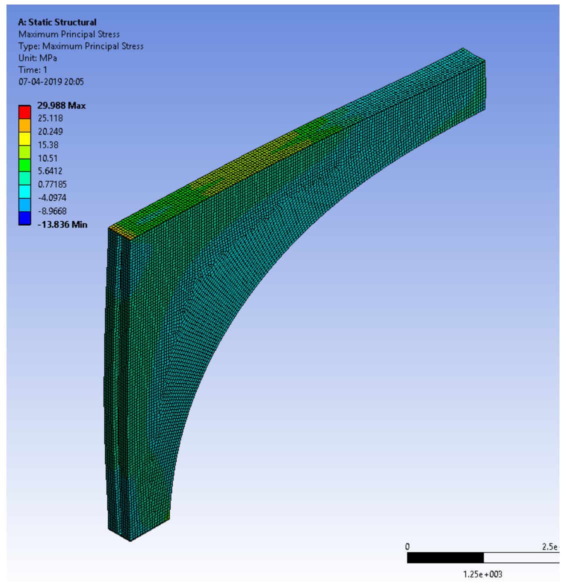


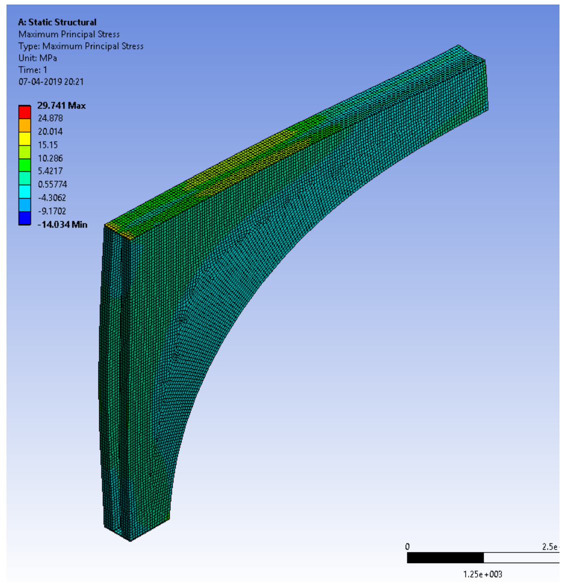


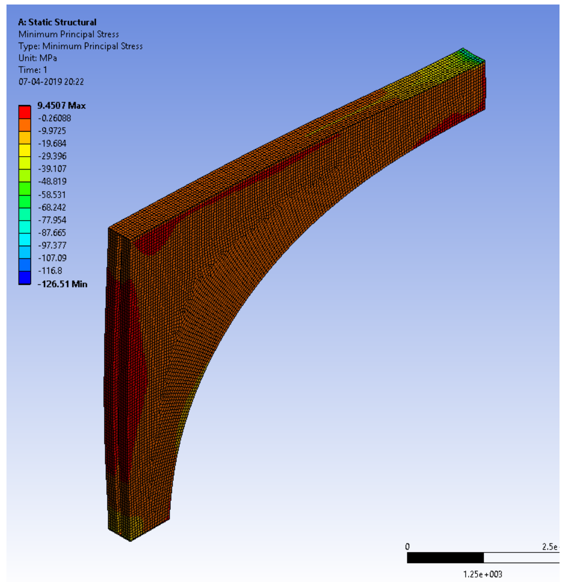
10.2.3 SPLIT GEOMETRY (200-100-200) V/S (200-200-200)

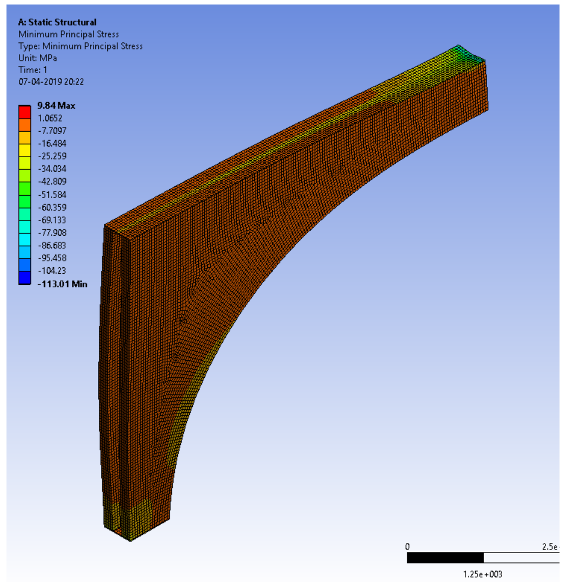


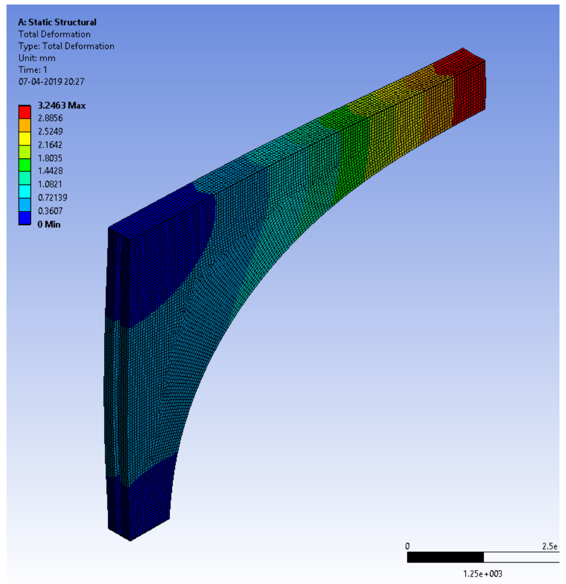


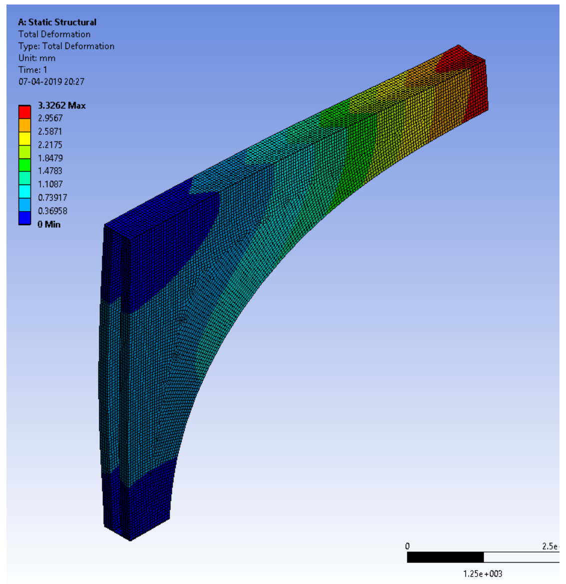


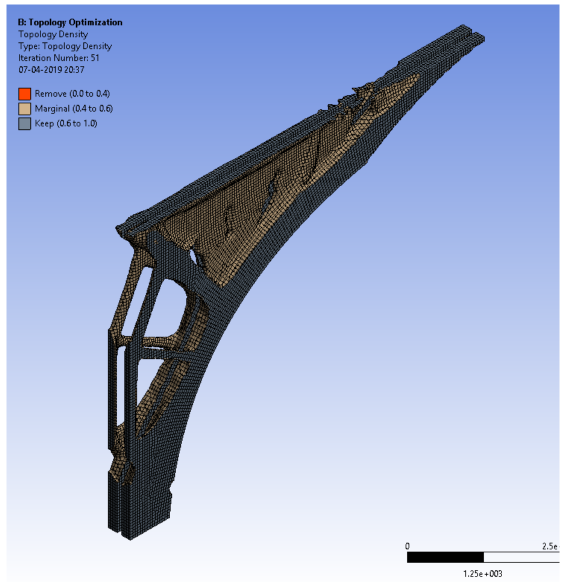


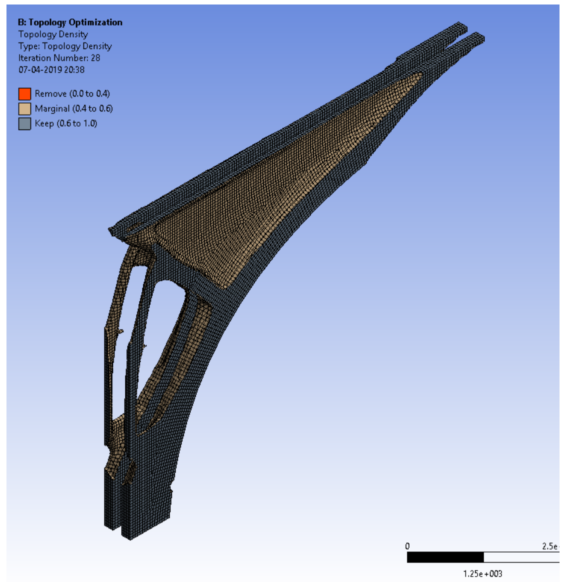




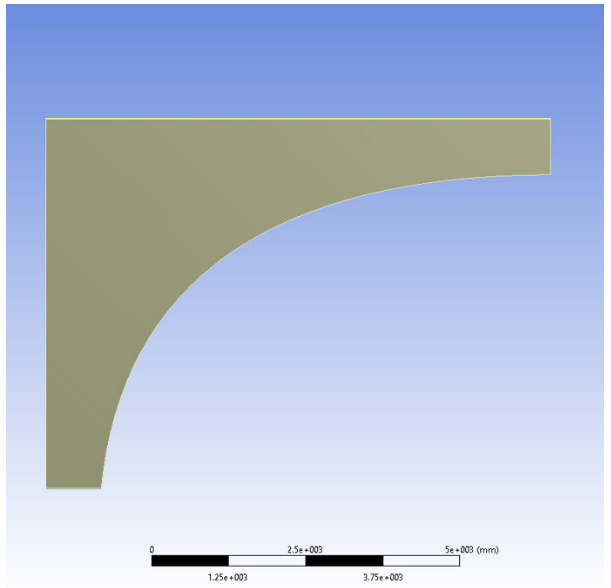


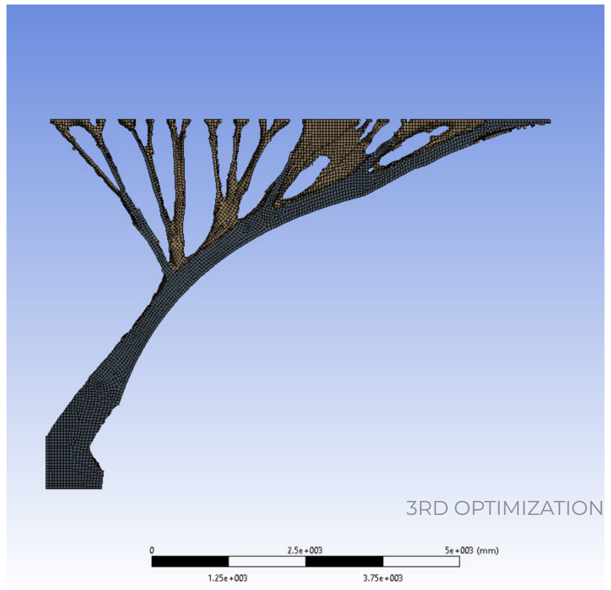


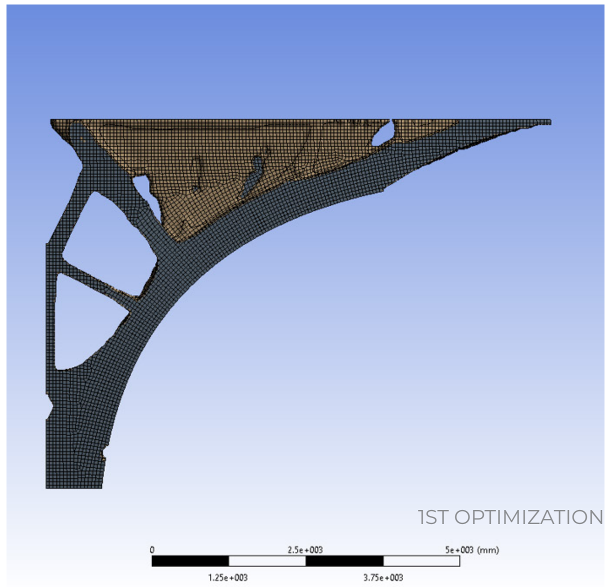


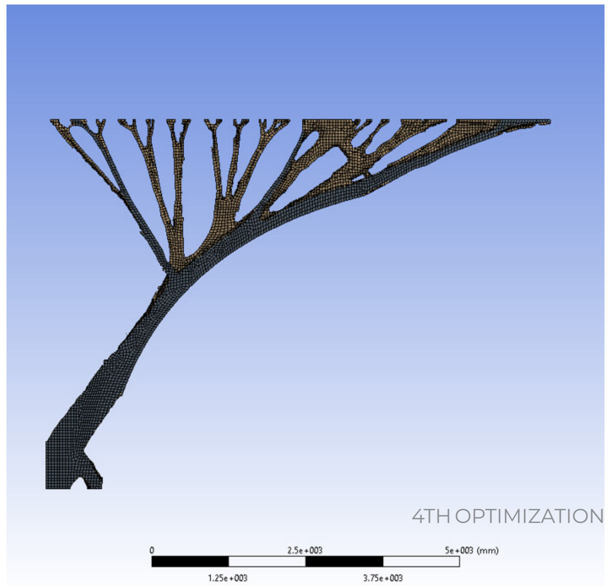


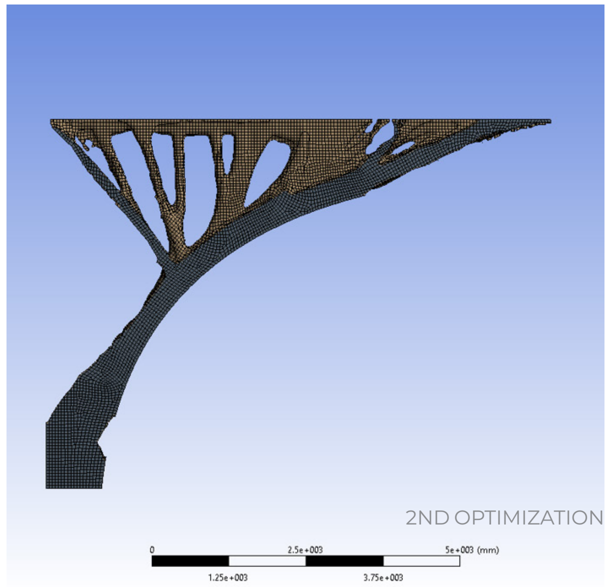
10.2.3 OPTIMIZATION SEQUENCE OF SPLIT GEOMETRY (200-100-200)

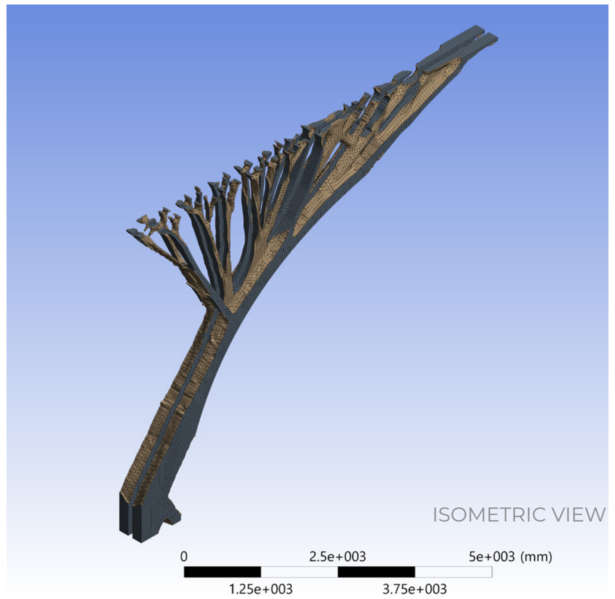






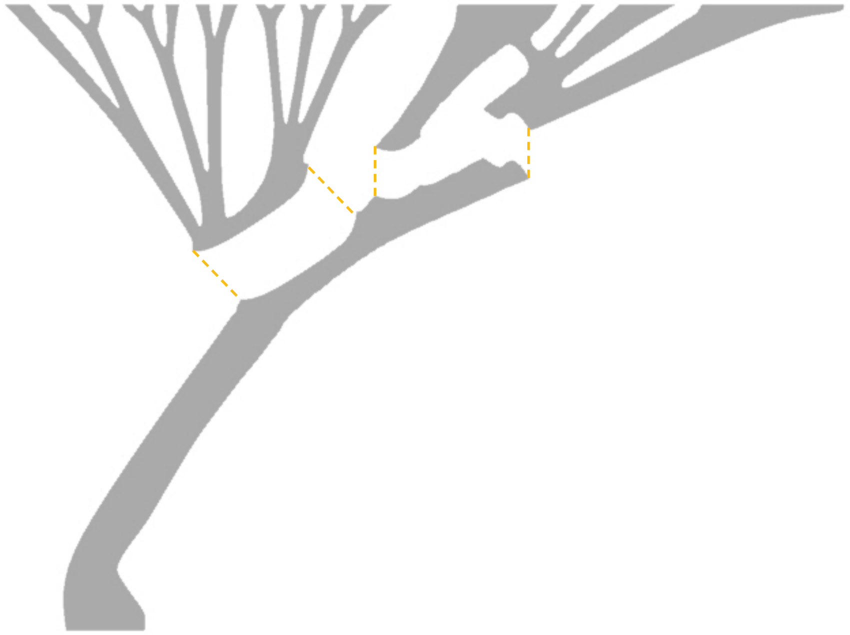




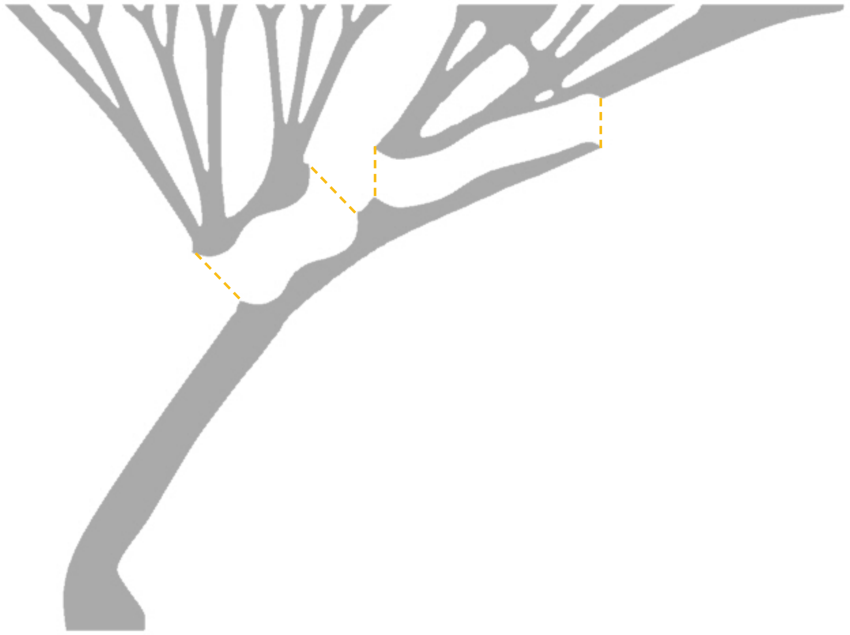


10.3
APPENDIX C- SPLITTING OF GEOMETRY

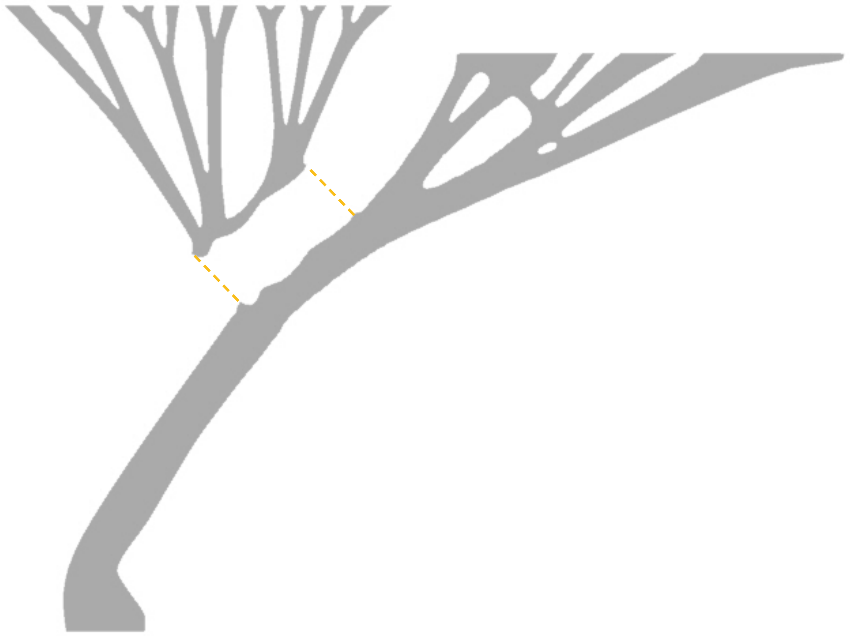
10.3.1 OPTION 1



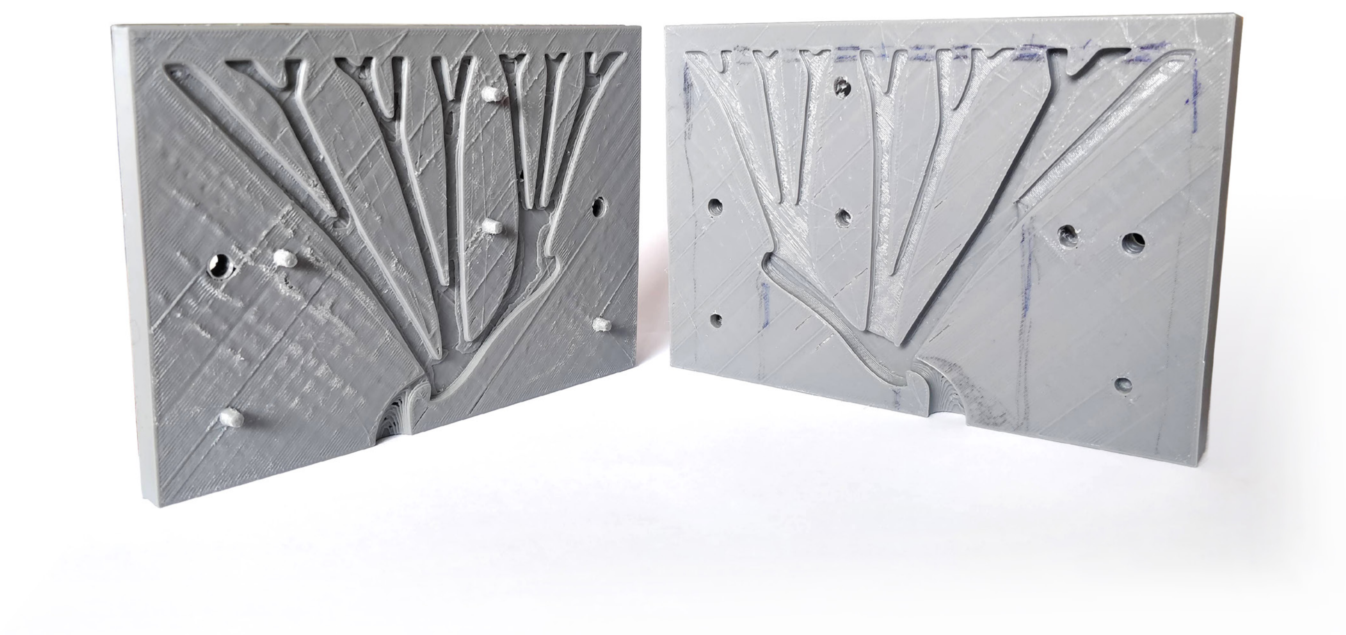
10.3.2 OPTION 2

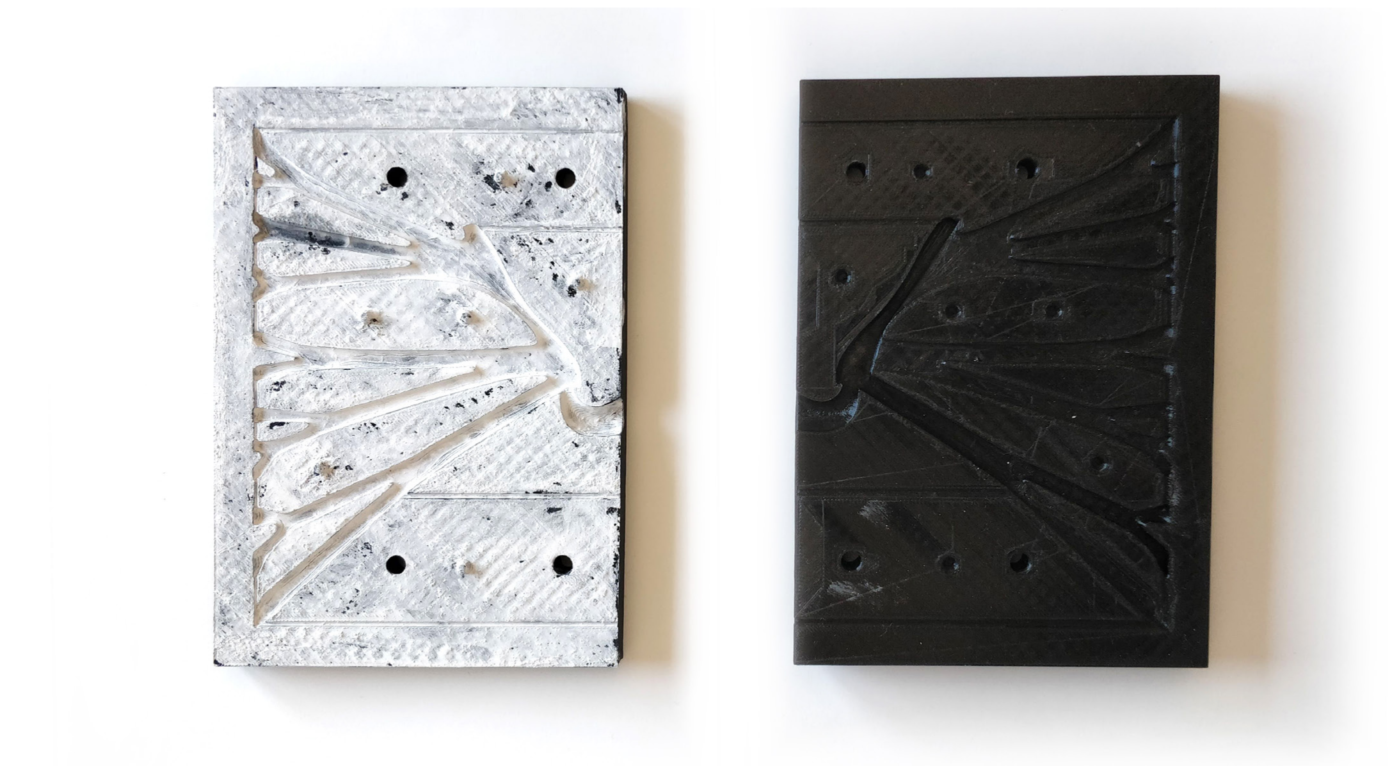


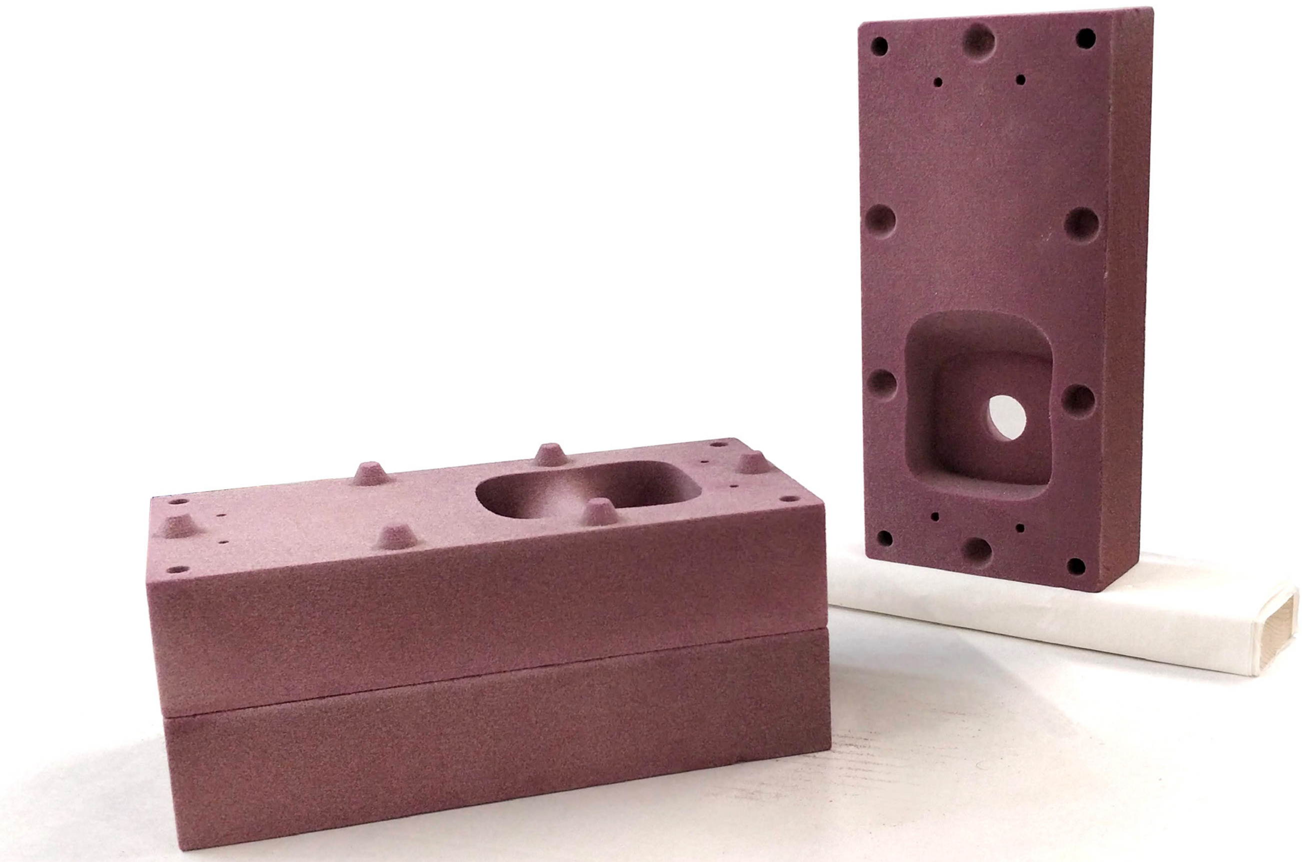
10.3.3 OPTION 3



APPENDIX D- MOULD PROTOTYPING USING PLA







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