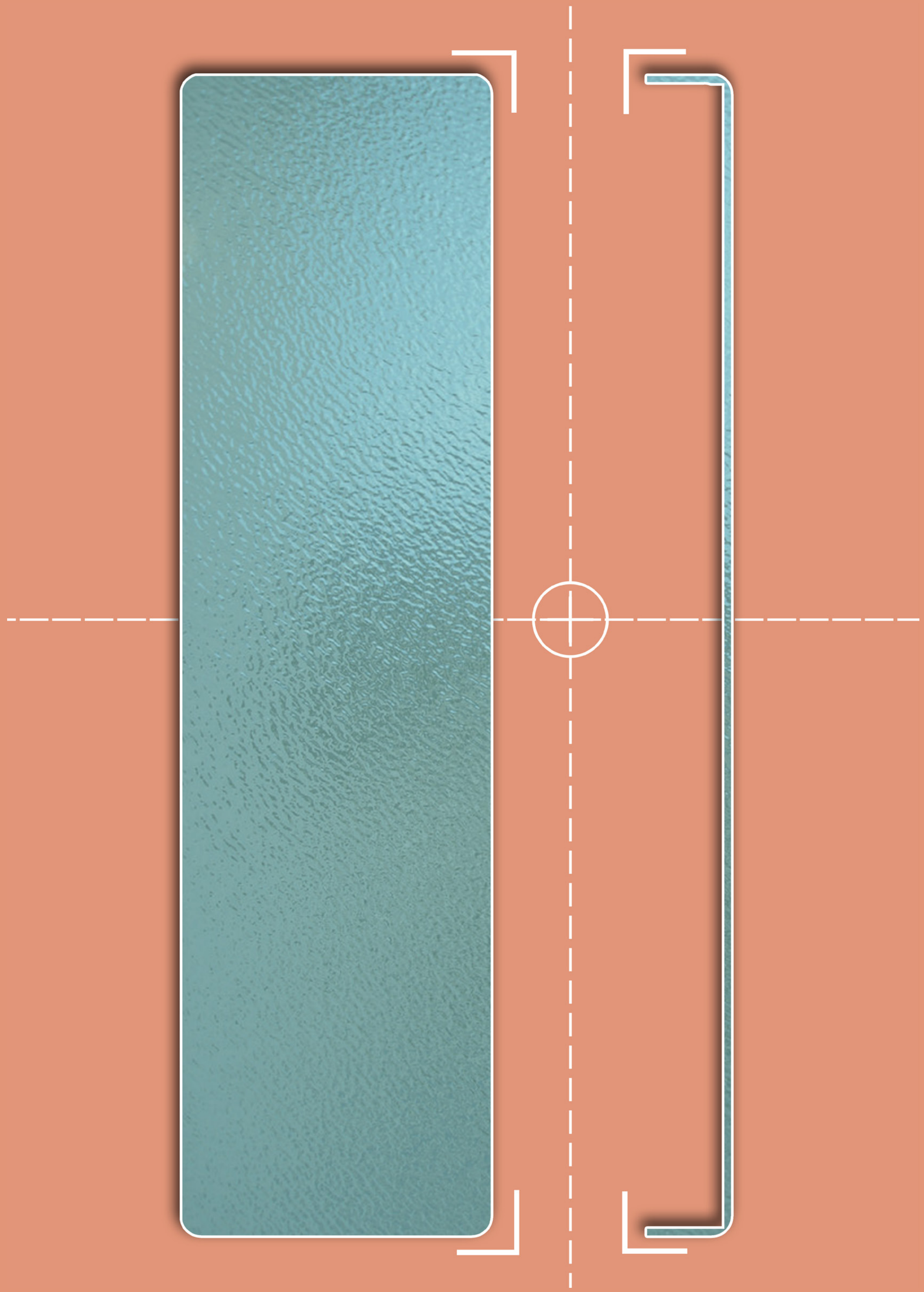

HYBRID GLASS BLOCK

Load bearing and thermally sound glass block

TU DELFT MSC ARCHITECTURE, URBANISM & BUILDING SCIENCES
[BUILDING TECHNOLOGY TRACK]

STUDIO SUSTAINABLE DESIGN GRADUATION STUDIO

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Thank you all for believing in me!
Twinkle

Abstract

Keywords: hybrid glass block, cast glass, interlocking, embedded connections, thermal performance

The wide application of glass in buildings is due to its innate transparency and durability. This quality has led to the development of hollow glass blocks during the industrial revolution. These blocks are durable, fire-resistant, exhibit heat resistance, and sound deadening properties. In recent years, new explorations have begun to uncover the structural potential of glass. It is no longer just a cladding material but is also being used for load-bearing applications due to its high compressive strength. One of the most significant drawbacks of cast glass bricks' current systems is the unsatisfactory thermal performance due to the absence of a cavity and the thick cross-section, which acts as one thick single glazed unit. On the other hand, hollow glass blocks are non-load-bearing due to their thin cross-section of the inner wall which results in buckling under a load and thus, the system is susceptible to failure.

A promising solution to these problems is to develop a block that can exhibit structural strength and thermal insulating properties. To do this, design guidelines were developed by carefully studying both the systems followed by different design options which were analysed for their thermal performance. It was observed that the incorporation of cavity, inert gas and coatings greatly influences the thermal property. Also, the presence of continuous glass cross-section is important for structural integrity which generates thermal bridges that negatively impacts the thermal performance of the system. This analysis resulted in two different design options; the fusion block and the lattice block.

To fabricate these blocks, careful consideration was taken in the design of the moulds and the chosen glass type. For the two designs, two separate connection systems are employed; one an embedded connection and the other an interlocking pattern. Both connections generate a dry assembly system which is reversible, easy to assemble and easy to maintain. To understand the feasibility of the proposed design solutions, a case study of Ports 1961 store in Shanghai was considered. The blocks were applied on the façade of the building and this was then analysed based on the developed design criterions. The proposed blocks have better thermal performance values, optical and aesthetical qualities. The installation process is much simpler and reversible. The fabrication process is however complex but that is due to the absence of standardized manufacturing system for cast glass bricks.

The present research does not conclude in a single suitable design option but rather two concepts. The exploration of different concepts for thermal performance, it's fabrication and installation results in a general understanding of the parameters that affect the development of this technology. To realize the proposed system, structural verification, fire safety and acoustics still need to be carefully considered and additionally this need to be validated experimentally to derive statistical data for its safe application. Nonetheless the performance values indicate a great potential in the technology.

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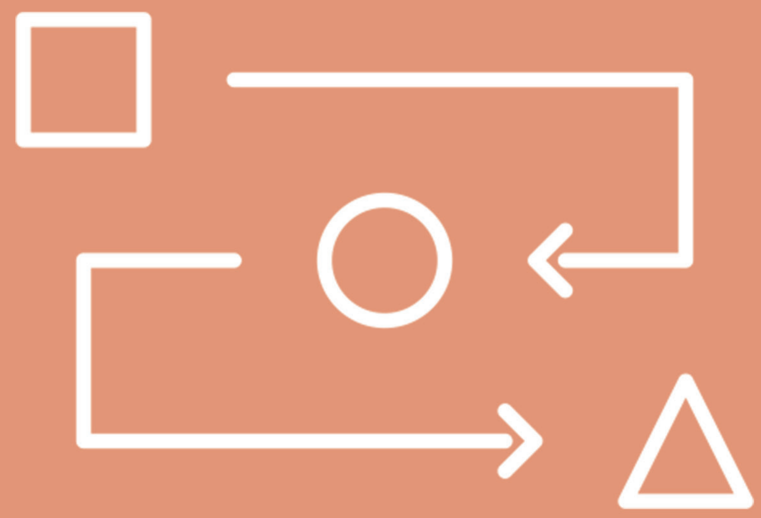


01 Research Framework

01.1 Problem Statement

Glass's use as a building material dates to ancient times, one of the first appearances in Roman bath-houses, where it was used in windows to trap the heat inside. Since then, it has been extensively used in various forms in the built environment. The reason behind its wide application is its innate transparency, which allows for unhindered light in a space and visual connectivity between the inside and outside. This quality led to the development of hollow glass blocks during the industrial revolution. These blocks are durable, fire-resistant, exhibit heat resistance, and sound deadening properties. Since then, technologies in glass have constantly been developing to adapt to the changing trends. In recent years, new explorations have begun to uncover the structural potential of glass. It is no longer just a cladding material but is also being used for load-bearing applications due to its high compressive strength. One such fine example is cast glass bricks in Crystal House, Amsterdam. The volumetric cast glass components minimize the risk of failure due to buckling (and thus due to the introduction of peak tensile stresses). Thus, they are highly stable as they take full advantage of the high compressive strength of glass.

One of the most significant drawbacks of cast glass bricks' current systems is the unsatisfactory thermal performance due to the absence of a cavity and the thick cross-section, which acts as one thick single glazed unit. On the other hand, Hollow glass blocks are non-load-bearing due to their thin cross-section which results in internal buckling under a compressive load and thus, the system is susceptible to failure. Therefore, this research aims to develop a Hybrid block that can exhibit structural strength and meet modern energy criteria. The objective is to bridge the gap between solid glass brick's stability and the hollow block's efficiency.

01.2 Research Question

The main objective of the research is to contribute towards the innovation of Glass Structures by developing a new hybrid block that bears advantages of both hollow and solid glass blocks, namely a satisfactory insulating and load-bearing performance and can meet the challenges of the modern time. Thus, the main research question formulated is:

"In what ways can we develop a Hybrid glass block that exhibits a combination of structural and thermal properties and can be efficiently manufactured?"

The sub-research questions formulated are:
1. What are the main engineering criteria and challenges involved in the development of a Hybrid block?

2. Which are the main factors influencing the thermal performance of the system? What methods can be employed to increase the efficiency and what are the advantages and limitations of these methods?

3. Which are the main factors affecting the manufacturing process of these blocks? What methods can be employed and what are the advantages and limitations of these methods?

4. What are the main factors affecting the build-ability of Hybrid blocks in a structure?

01.3 Design Assignment

The research will lead to designing, experimenting and validating different hybrid blocks and engineering its fabrication and assembly in accordance with the design criteria.

01.4 Methodology

The process of development of the novel hybrid glass block is divided into four phases:
- -Phase 1: literature research and data review,
- -Phase 2: design and analysis
- -Phase 3: manufacturing and constructibility
- -Phase 4: conclusions and reflections.

Phase 1
The first phase primarily focuses on studying various books, research papers, journals, and websites relevant to the chosen topic and developing a thorough understanding of the problem in question. This phase serves as the base for the next steps in the research framework. Therefore, an in-depth study will be conducted on hollow and solid glass blocks, their distinguished properties, manufacturing and installation processes. A case study of Ports 1961, Shanghai building was selected and analyzed to provide a realistic scenario in defining structural, thermal properties, and assembly criteria. These helped in defining preliminary design guidelines. Upon referring to building codes from the region of selected case-study and Eurocodes, the guidelines were refined into final design criteria. Based on the said criteria, concepts for improving structural and thermal performances were also explored and evaluated to suggest the most probable ideas to be taken forward in the next phases.

Phase 2
In the second phase of design and analysis, design solutions for the hybrid block were investigated in detail. The first design ideas were evaluated on the criteria mentioned in the design guidelines. The design was then developed from the chosen ones by exploring methods to make the block resistant to heat. This was verified using the software TRISCO. Various alternatives of different sizes, cavity widths, and insulative material were developed and analyzed for their thermal transmittance values. These options were then evaluated on their ease of manufacture, optical properties, and recyclability to shortlist the best ones. A risk analysis was carried out to inform the design of the structural process. The analysis identified scenarios that can impact the performance of the system and the measures for those were considered in the design process. The chosen options at the end of thermal analysis were then optimized to carry the loads based on the materials' parameters and constraints. Various connection options were studied and evaluated to design the final connection system for the block. This phase was a continuous back and forth process, which ended in two designs that meet the set rules. Further, the manufacturing and installation process was investigated for the new block, and the designs were evaluated based on the parameters set for this procedure.

Phase 3
The third phase largely focuses on feasibility study of the developed prototypes by it's application in the case study building Ports 1961, Shanghai. Initially, this phase was set out for verifying the final designs through prototyping but due to the current unprecedented circumstances with no access to the faculty labs, it was not possible to develop, experiment, and test prototypes. Therefore, the manufacturing and assembly of the blocks were investigated in theory. A set of guidelines were developed for the preparation and procedures required for the manufacturing and assembly of these units on site.

Phase 4
The fourth phase finally focuses on summarizing details about the hybrid block; its properties, engineering, and installation. The research is concluded with the evaluation of the method, and recommendations are provided to develop the technology further.

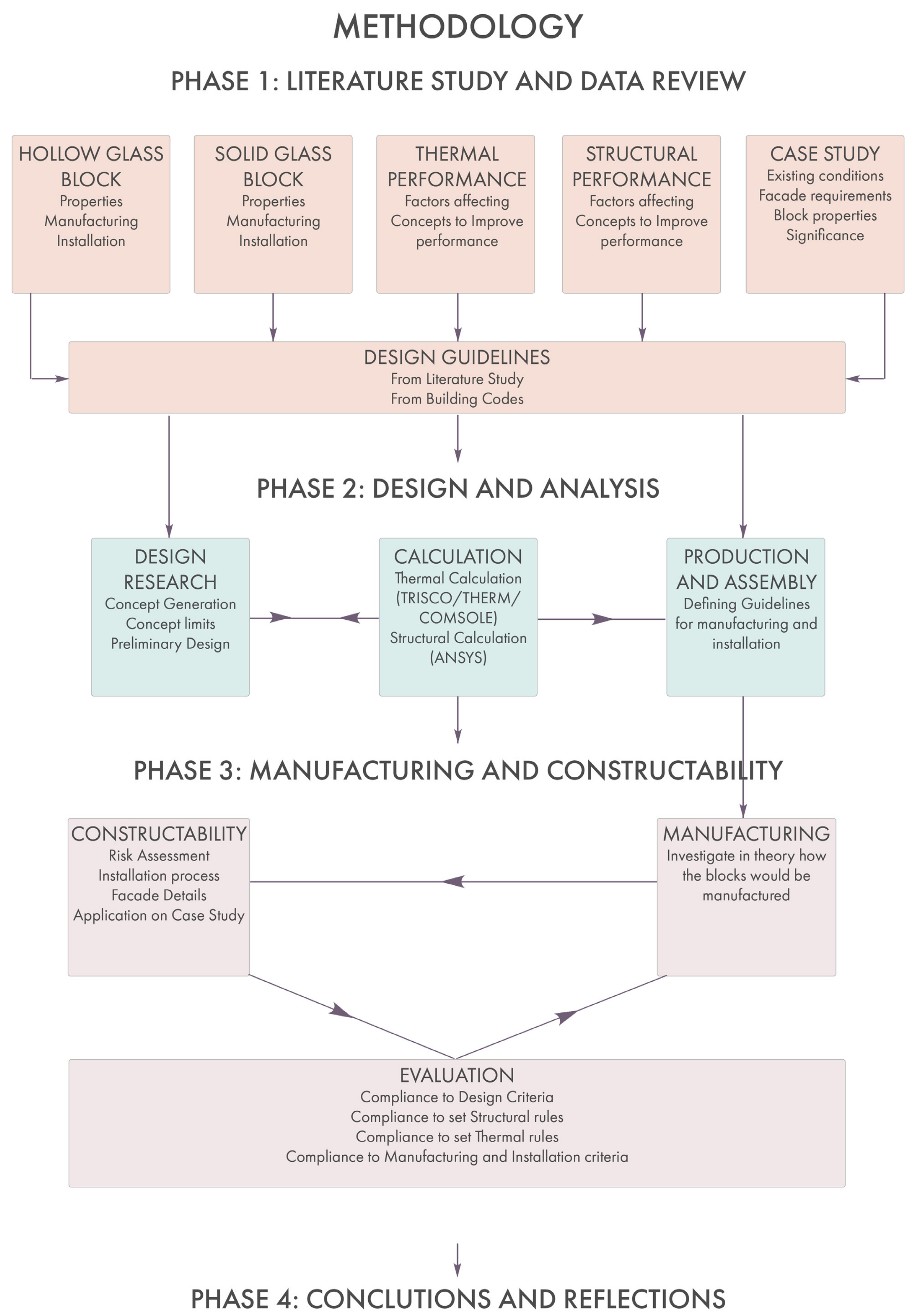


FIGURE 1: Figure showing methodology used in this research (drawn by author)

01.5 Relevance

Relevance between Graduation topic and Master Studio

The sustainable design graduation studio aims for innovative design technologies in the built environment. The material glass is widely used in the building industry for its unique optical properties in various forms, for example, glazing units, glass blocks, etc. The present glass block systems used in building facades have limited potential as they offer either structural stability or optimal thermal performance. With the increasing demand for energy-efficient constructions, it is important to explore the possibilities of making glass blocks energy compliant. Therefore, this research focuses on developing a novel glass block system that responds well mechanically and adheres to the new energy criteria. This system in an examination is new, and not many experiments have been done in this area. This makes studying and experimenting with this technique challenging but gives a great amount of freedom in exploring new ideas. A thorough understanding of the system in a realistic environment is possible in combination with a case study. The topic is related to the ongoing research at TU Delft on sustainable structures. The focus is on Structural and Climate design, two sub-directions of the Building Technology track. The hybrid glass assembly under consideration is self-bearing; therefore, it will significantly affect the structural system of the applied building. The thermal performance of the entire system will also serve as valuable inputs to evolve this technology further.

Scientific and Social Relevance

In recent years, the world is slowly transitioning towards creating robust environments due to rapid climate change, scarcity of natural resources, and depletion of fossil fuels. The infrastructure needs to be adaptive more than ever, have less carbon footprint, and be compliant with the energy regulations. While we have developed many building systems (smart façade's, EWF for ventilation, etc.) that can help, it is also important to investigate the unit level (the size of a brick) for overall impact. Glass and energy efficiency has been an oxymoron for a long. A lot of research has been conducted to make glass buildings use less energy, and we have achieved it by applying coatings, making them non-recyclable. Thus, this thesis aims at developing a block of glass that adheres to the energy regulations by changing the design and alternating the way we perceive glass.

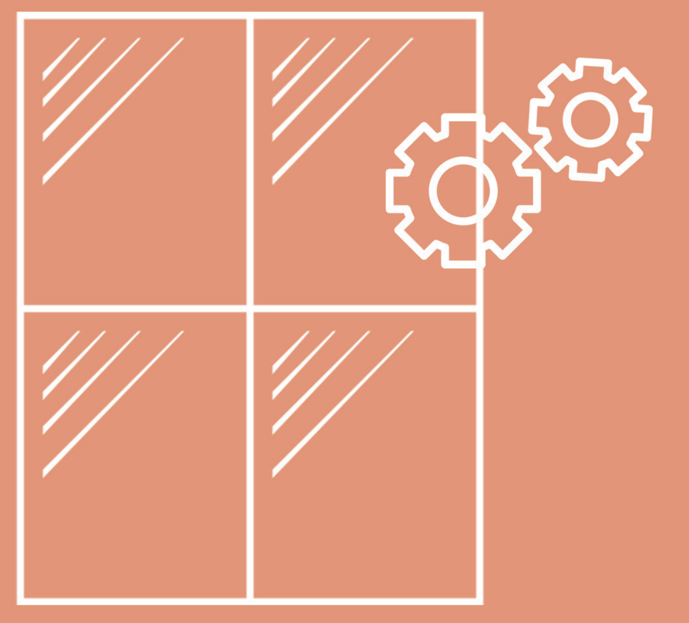
The current research can function as a basis on how 3-dimensional structural glass components can be made more energy-efficient. This study provides fundamental insight into various methods explored in developing the novel technique, which can further lead to more energy-compliant glass structures. Hence, this research provides a scientific relevance as it illustrates possibilities of glass in structural configuration and is also socially relevant as it will improve the portrayal of glass structures in being energy giants.

01.6 Planning and Organization

The time planning for the research has been tactically spread between the five presentations.

The first phase lies between P1 and P2 focuses on literature study and data collection. A case study will also be selected for a more realistic approach and this will end into the development of final design criteria. The second phase lies between P2 and P3 is the design and analysis phase. This will be directed towards developing the block and testing it computationally on software for thermal verification. The third phase between P3 and P4 will focus on fabrication and assembly of the design in real world conditions. The fourth and final phase between P4 and P5 is marked for refinement of the research and final report will be produced at the end.

FIGURE 2: Figure showing planning and organization (drawn by author)



02 Glass Technology

02.1 Introduction

Glass is widely used in the building industry due to its innate property of transparency which integrates the exterior and the interior together while maintaining a physical barrier between them. It is an expression of openness and lightness in architecture and responds to the elementary human need for sunlight and close attachment to nature. Pure glass can also be recycled without losing its quality. (Barou,2019).

Until now it has been used extensively as a façade element but recent advances have allowed its application as a structural member too due to its high compressive strength and resistance to corrosion. (Nijsse 2003) However, one of glass's biggest challenges is that it is brittle. This is due to the organization of its molecules which doesn't change when glass changes its state from liquid to solid due to the fast and controlled cooling process. The molecular structure remains motionless (like solid) and contains gaps (like liquid) which give rise to its amorphous structure. Therefore, plastic deformation of glass at room temperature is not possible. However, when glass is heated up to its softening point, the bonds can be easily broken and be fixed and it can be formed plastically. (Giezen, C. 2008)

The softening point of quartz is around 1700 °C which is quite high and can incur in additional manufacturing costs. Therefore, to lower the melting point and viscosity of glass, modifiers and intermediates are added which results in different glass types based on the composition. (Giezen, C. 2008)

02.2 Material Composition and Properties

Soda-lime glass

Soda-lime glass is the most commonly used glass in window application. The presence of soda lowers the melting temperature of silica and lime helps in stabilizing the silica. Soda-lime glass is chemically stable, inexpensive and easily workable. It is also a softer glass and is very easy to fabricate in different shapes. Due to its softness, it is not scratch resistant. It has wide range of applications. (Mills, n.d.).

Borosilicate glass

Borosilicate glass is the material of choice in wide range of application due to its durability and heat resistance. It has a lower thermal coefficient value which makes it less susceptible to material stresses than regular glass. This contributes to its exceptional performance at high temperatures. (Oikonomopoulou, 2019) Borosilicate glass is often used to make laboratory equipment since it has good chemical resistance and retains its shape well throughout changes in temperature. (Mills, n.d.).

Lead glass

Lead glass is also called the soft glass as it is easier to cut into various designs. It Is used for electrical and nuclear applications due to its lower working temperature and ability to absorb X-rays. (Mills, n.d.). But it has limited resistance to thermal shock and high temperature and is susceptible to scratching due to its softness and therefore is unsuitable for architectural applications.

Aluminosilicate glass

Aluminosilicate glass is made up of 20 to 40% aluminium oxide. They are of two types: alkaline earth aluminosilicate, which has a very high softening point and is used in halogen lamps, high temperature thermometer etc and alkali aluminosilicate which are very hard and scratch resistant due to the presence of high alkali content and are used for touch displays, smart phone screens and laminated safety glass. (Mills, n.d.). It has more resistance to heat, can tolerate temperatures up to 800 C and has better chemical resistance. Due to its heat resistance, it becomes difficult to melt and fabricate and therefore has an impact in the increased manufacturing costs. (Oikonomopoulou, 2019)

High Silica glass

High silica glass is made by removing all the non-silicate elements by melting the glass mixture. It has very low thermal expansion, good chemical durability, optical and mechanical

properties. This glass in turn has a deformation temperature of 1700 C due to the absence of fluxing agents which becomes a limiting factor for production and application on larger scale. It is used for making UV-transmissive lamp tubes, precision optics, refractory tubes and fibre reinforcer in composites. (Mills, n.d.)

Fused quartz glass

Fused quartz glass is made from naturally occurring crystalline silica, found in sand or rock crystal. This crystal is melted and purified by electrical means that results into a glass with high transparency and resistance to weather and shock. As the fusing occurs at approximately 1650 C, it is very difficult to fabricate this glass and the process becomes expensive. Although this quality becomes useful in aerospace applications especially in the windows of manned spacecraft where high temperatures cannot be avoided. (Mills, n.d.)

02.3 Production Method

Structural glass has captured interest of many architects, designers and engineers with novel ideas being developed worldwide. Innovative ways of glass's application as column, beam, in load bearing walls and as a bridge have been carried out with numerous geometric possibilities. (Oiknomopolou, 2019) suggests that glass can be made flat, extruded or as a solid element depending on the type of manufacturing process. The most prevalent method of production is float glass which is commonly used in windows and facades of buildings. However, glass can also be manufactured through extrusion, 3D printing and casting. These processes are described below along with the size limitations of each of them. The choice of process depends on the application and desired geometry.

Float Glass

Float glass method was developed in 1959 by Sir Alastair Pilkington and still remains the most common process for manufacturing window glass. In this process, the raw materials are melted in a furnace at 1500 C, from there a continuous ribbon of glass floats along a bath of tin at 1000 C. As glass has lower density than tin, it floats and forms perfectly smooth surfaces of desirable thickness. (Giezen, C. 2008) The glass is moved out of the tin bath and cooled down to 600 C where it solidifies. Then it is put into the annealing lehr where it is slowly and controllably cooled down to 100 C. Finally, the glass is cut to the required size. In the process, the thickness of the glass can be adjusted with the help of the top rollers. The standard thicknesses of float glass are between 2 and 25mm. The standard size is 6m X 3.21m but larger plates can be obtained as well on special demand. (Oiknomopolou, 2019)

Glass Type	Softening Point (°C)	Annealing Point (˚C)	Strain Point (˚C)	Density (kg/m^3)	Coefficient of Thermal Expansion (0 -300 ˚C) 10^4/˚C	Young's Modulus (GPa)
Soda-lime	730	548	505	2460	8.5	69
Borosilicate	780	525	480	2230	3.4	63
Lead	626	435	395	2850	9.1	62
Aluminosilicate	915	715	670	2530	4.2	87
High silica glass	1667	1140	1070	2200	0.55	69
Fused quartz glass	1500	910	820	2180	0.8	67

TABLE 1: Table showing different properties of different glass mixtures based on (Shand, Armistead 1958). Mean Melting Point at 10 Pa.s as stated by (Martlew 2005). (Oikonomopoulou, 2019)*

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

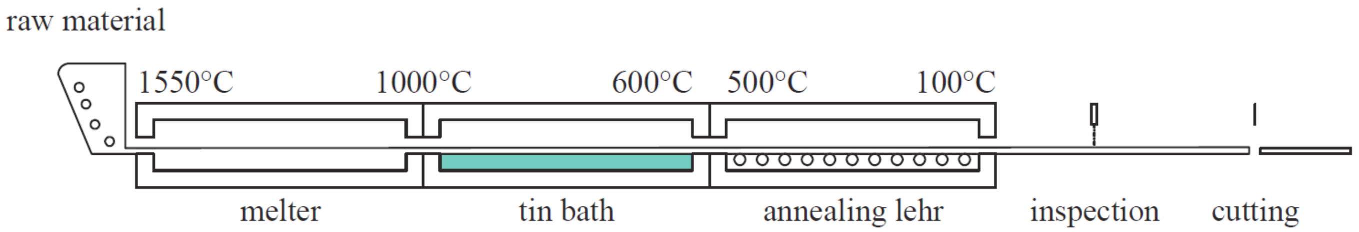


FIGURE 3: Figure showing manufacturing process of float glass process (Oikonomopoulou, 2019)

FIGURE 4: Figure showing use of float glass (Carlen Glass, 2021

Extruded Glass

Glass can be extruded to make tubes, rods and other glass elements of variety of shapes and cross-sections. This process can be used for glass compositions with a steep viscosity curve, increased tendency to crystallize and/or a considerable high softening point. (Roeder, 1971). The most common method is the Danner process, in which molten glass flows through a feeder channel and arrive through a nozzle on a rotating mandrel. The slight inclination of the mandrel allows glass layer to continuously flow downwards to the drawing machine. Air is blown through the axial passage in the mandrel and helps in creating profiles of different diameters and wall thickness by varying the air flow, drawing velocity and temperature in the furnace. (US patent, 1991)

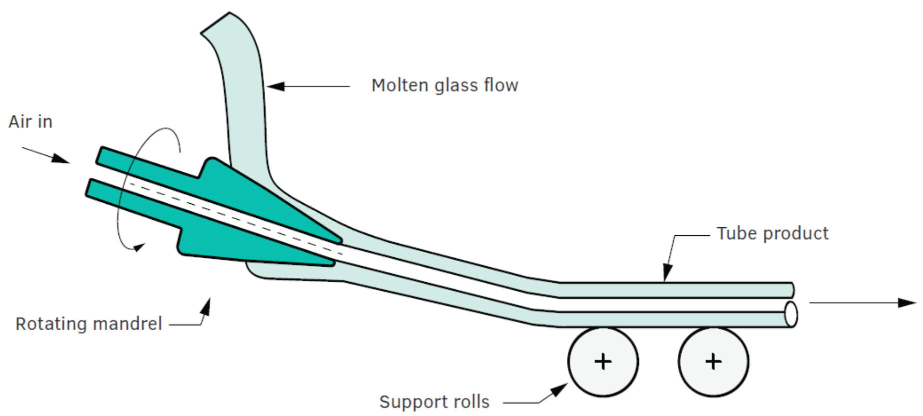


FIGURE 5: Figure showing Danner Process (Oikonomopoulou, 2019)

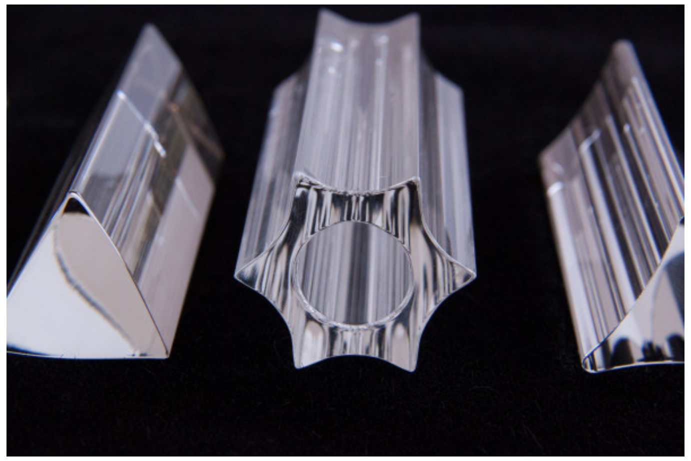
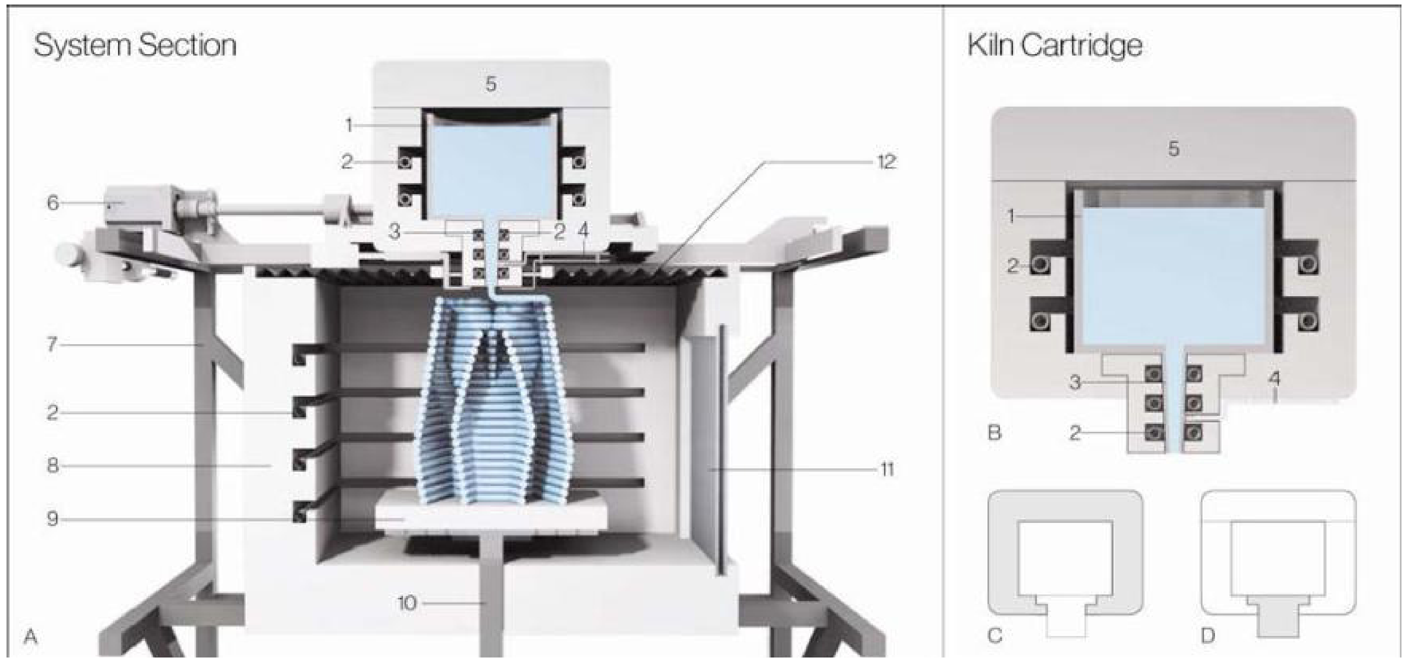


FIGURE 6: Figure showing extruded glass profiles (Conturax - MaterialDistrict, 2021)

3D Printed Glass

The use of 3D printed glass in the building industry is an ongoing research. Recent developments made in this field by Mediated Matter Group at MIT can 3D print glass in variety of shapes, profiles, colours and subsequently different optical properties and degree of opacity. The printer works on the concept of dual chambers with the upper chamber heated to approximately 1040 C (1900F) which acts as a kiln cartridge holding sufficient molten glass to build a single component. The lower chamber is kept at 480 C (896 F) just below the glass annealing temperature (515 C) to resist the printed objects from thermal shocks. This bottom chamber is called the print annealer. The entire geometry on completion is moved to a proper annealing lehr. This process was conducted with small objects of height 20cm. It has now been developed to large scale additive manufacturing technology (G3DP2) for building components. 3D printing of glass objects requires highly controlled annealing chamber to reduce the breakage of glass due to stresses and therefore this still remains a big challenge in this method. (MIT Media Lab, 2018)



Printer cross-section showing (A) the printer during fabrication; (B) the kiln cartridge; (C) the crucible kiln; and (D) the nozzle kiln. The numbered parts are: (1) the crucible; (2) heating elements; (3) the nozzle; (4) the thermocouple; (5) feed access lid; (6) stepper motors; (7) printer frame; (8) print annealer; (9) ceramic print plate; (10) z-drive train; (11) ceramic viewing window; and (12) insulating skirt. (Wanda, 2015)

FIGURE 7: Figure showing 3D printer cross-section developed by Mediated Matter Group at MIT Media Lab (Wanda, 2015)

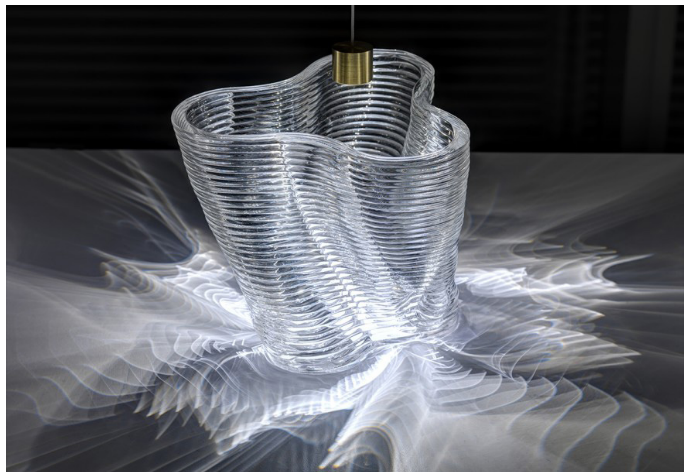


FIGURE 8: Figure showing 3D printed glass (Wanda,2015)

Cast Glass

Cast glass technique requires molten glass to be poured into mould of desired shape to form a glass object that is then cooled controllably to room temperature into an annealing chamber or kiln. Glass casting can be done in two ways: primary casting where glass is moulded as a hot liquid from its raw materials and secondary casting where glass pieces are remolten to be shaped to the desired object. Glass casting produces 3 dimensional objects of high transparency quality. While 3D printing presents opportunities of mass customization and design freedom of the final object, the layered nature of the additive manufacturing process compromises the optical quality of the final product. (Oikonomopoulou, 2019)

FIGURE 9: Figure showing casting process. (Sterling Studios, 2021)

FIGURE 10: Figure showing cast glass block (Sterling Studios, 2021)

FIGURE 11: Figure showing cast glass facade of Optical House, Japan (Archdaily, 2020)

Glass Process	Optical Characteristics	Main type of glass applied	Standard Size (mm)	Thickness (mm)
Float glass	Smooth, Transparent	Soda - lime	3120 x 6000	2-25
Extruded	Smooth, Transparent	Borosilicate, Silica	1500 to 10,000 in length	Hollow: 460 Ø, Solid: 300 Ø
3-D Printed	Layered, Transparent	Soda - lime	upto 30 kgs	Currently approx 30mm
Cast Glass	Smooth, Transparent	Soda - lime, Borosilicate, Lead	upto 20,000 kgs	na

TABLE 2: Table showing different production process and their current size limitations (Oikonomopoulou, 2019)

02.4 Glass Connections

Connections play a crucial role as they are responsible for transferring the loads between the glass members. These should have appropriate strength and stiffness to support the assembly and should be durable. Traditionally glass connections have been developed in metals with intermediate materials like plastic, resins, neoprene, injection mortars, aluminum or fibrous gaskets to avoid the direct contact between glass and harder materials. Promising developments in chemical or glued connections have also been made which has opened up possibilities of an entirely transparent structure. (Haldimann et. al , 2008)

Depending on the force-transfer mechanism, the connections in glass can be classified as mechanical fixings, adhesive connections or embedded connection (combination of mechanical and glued). The commonly used connections in the building industry are clamps, bolts, adhesives and embedded connections.

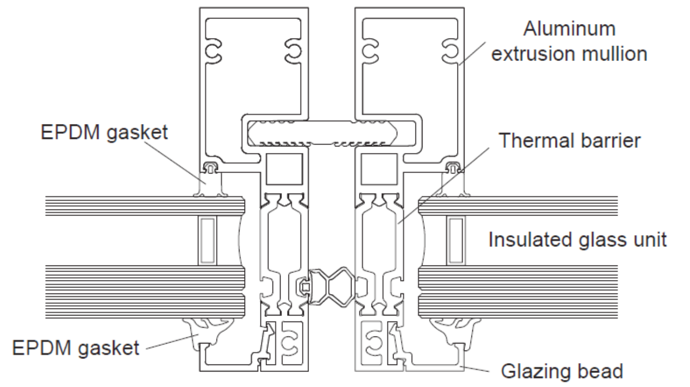


FIGURE 12: Figure showing linear support clamp (Haldimann et. al , 2008)

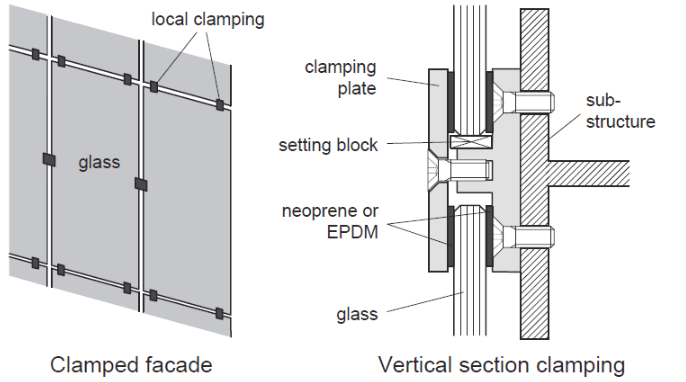


FIGURE 13: Figure showing clamp connection (Haldimann et. al , 2008)

Clamped Connection

In framed constructions, the glazing is linearly supported along two or four edges. (Fig 14) The self-weight of glass is transferred to the frame through the intermediate layer of either plastic setting blocks or neoprene to the bottom frame. Lateral loads from wind pressure and suction is resisted by clamping the glass between the frame system on one side and glazing bead or a capping/pressure cap on the other side. (Haldimann et. al , 2008)

FIGURE 14: Figure linear support connection (Q-railing, n.d)

Clamped fittings were developed to minimize the visual impact of linear supports. The edges of glass panels are fixed to the sub-structure at discrete locations with clamps. (Fig 15) These transfer the loads perpendicular to the glass panes and the setting block at the bottom glass edge allows for the dead load. The clamp simply holds the glass in position and is separated by an intermediary layer of a soft material. (Haldimann et. al , 2008)

FIGURE 15: Figure showing clamp connection. (Q-railing, n.d)

Bolted Connection

In bolted connections, the lateral (direct force) and in-plane forces (transverse-shear) are transmitted directly to the bolt. These bolts are made from stainless steel and are supported on aluminum bushings, POM or injected mortars. (Fig 16) These also separate the glass and bolt contact thereby reducing the bearing stress concentrations in the glass. (Overend, 2012)

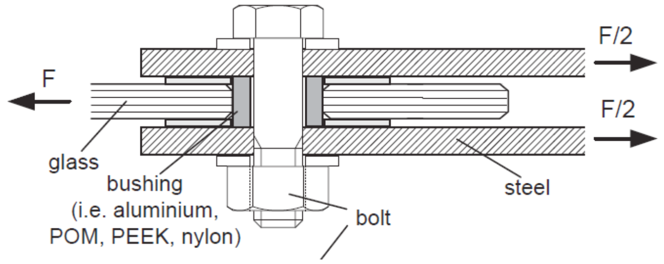


FIGURE 16: Figure showing bolt connection. (Haldimann et. al , 2008)

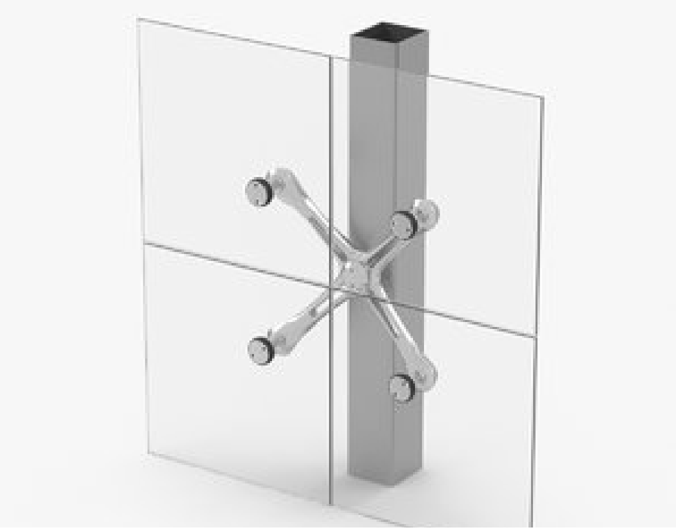


FIGURE 17: Figure showing bolt connection in spider fitting (Turbosquid, n.d.)

Adhesive Connection

The adhesives transfer the principal loads from glass to glass or glass to metal and are made from thermosets ((e.g. UV-cured acrylics, two-component acrylics and two-component epoxies). These are stronger and stiffer than structural silicone. The adhesive connection requires little or no preparation as compared to bolted connections where holes need to be drilled in the glass. However, since these adhesives layers are very thin, very little tolerances can be accommodated in the structure and therefore the components need to be very accurate. (Overend, 2012)

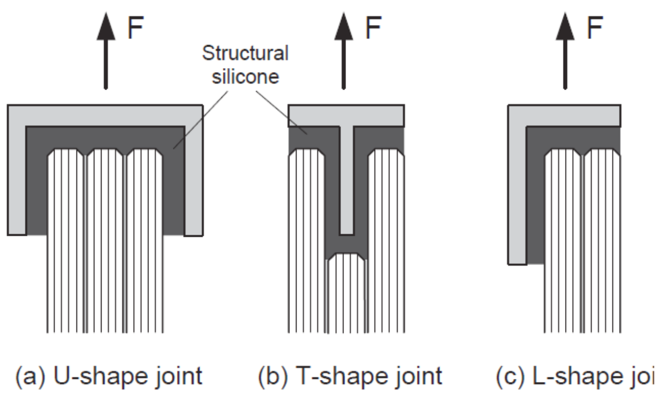


FIGURE 18: Figure showing bolt adhesive joint. (Haldimann et. al , 2008)

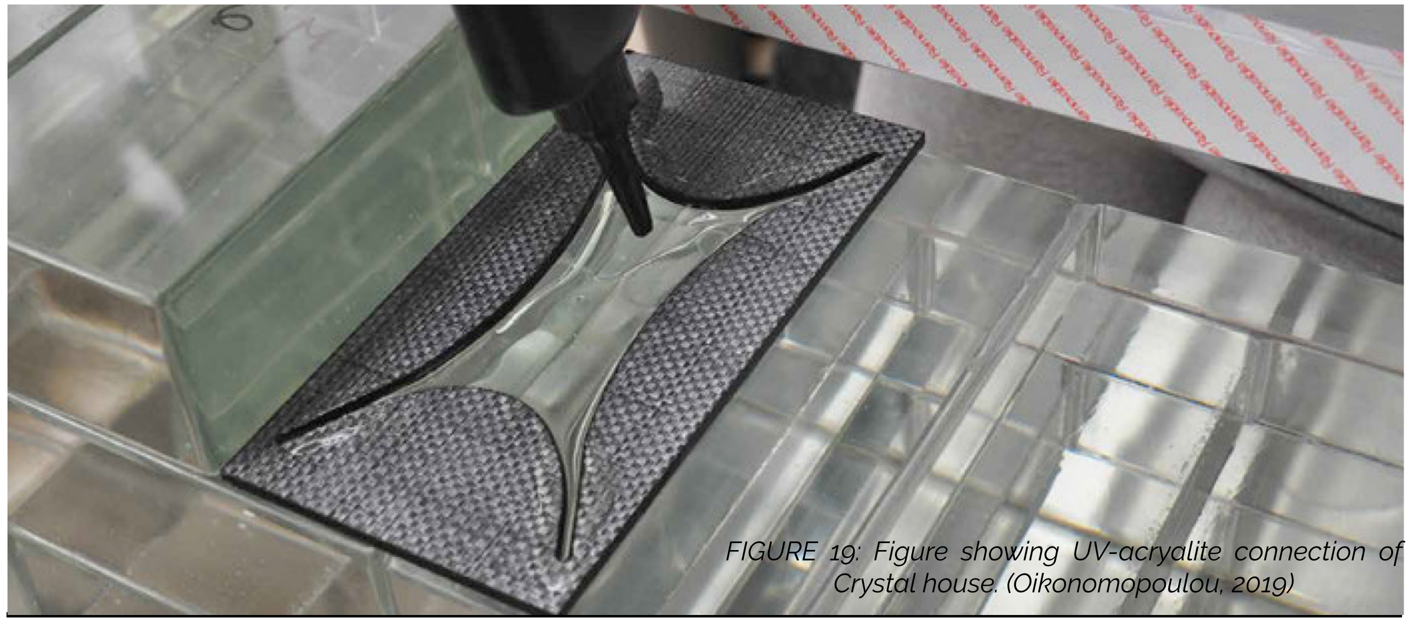


FIGURE 19: Figure showing UV-acryalite connection of Crystal house. (Oikonomopoulou, 2019)

Embedded Connection

Embedded connections are fairly new and involves a combination of bolting and bonding. When both are used simultaneously, the effective stiffness of adhesive tends to be greater than that of the bolts. The bolts only come into effect when the adhesive has deformed significantly which is often at failure. In embedded connections, the bolting and bonding are used in series where the glass is bonded to a steel plate which in turn is bolted to the steel substructure. (Overend, 2012)

FIGURE 21: Figure showing Embedded steel connection. (Torres, J., Guitart, N. & Teixidor, C, 2017)

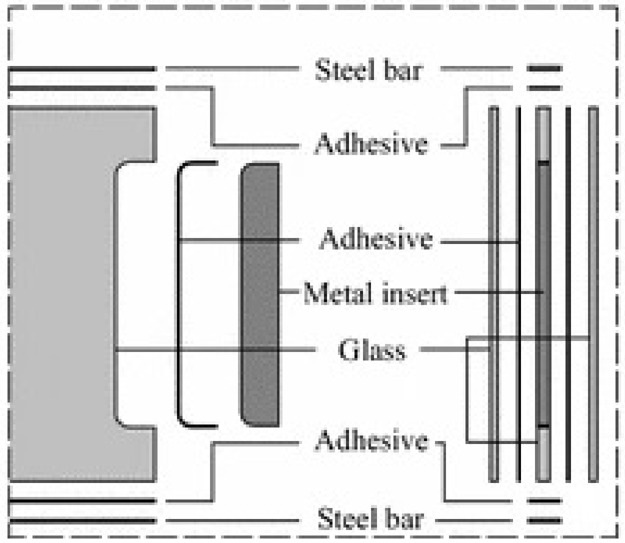


FIGURE 20: Figure showing Embedded connection. (Torres, J., Guitart, N. & Teixidor, C, 2017)

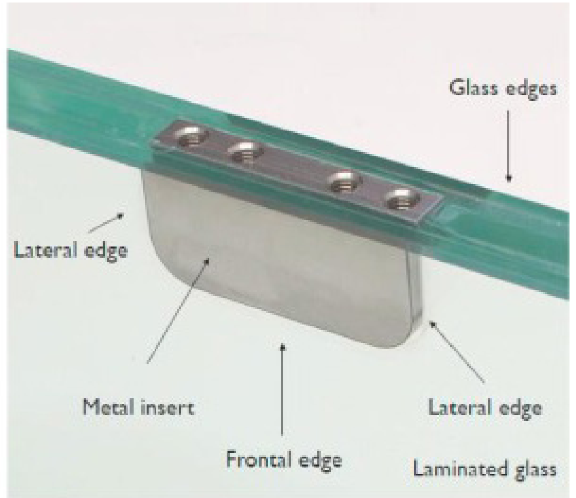


FIGURE 22: Figure showing detail of connection. (Torres, J., Guitart, N. & Teixidor, C, 2017)

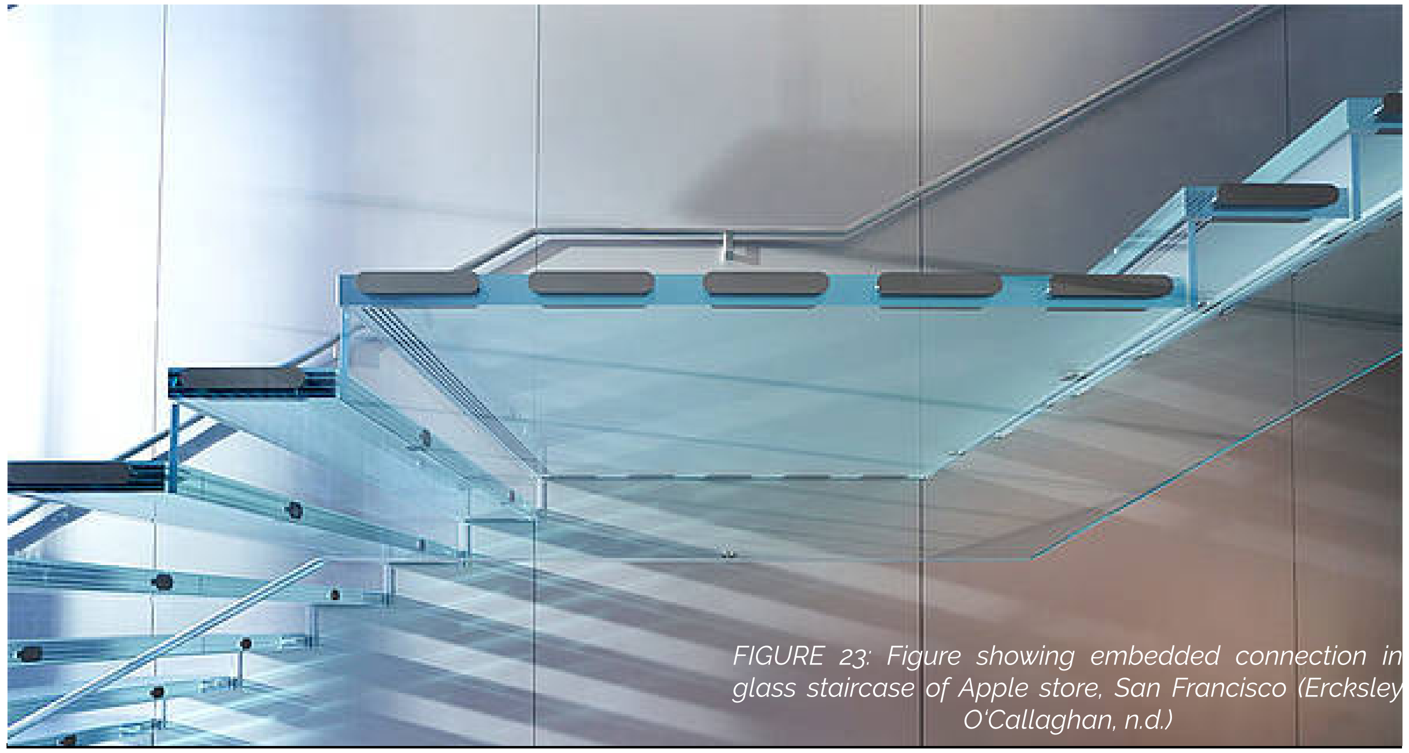


FIGURE 23: Figure showing embedded connection in glass staircase of Apple store, San Francisco (Ercksley O'Callaghan, n.d.)

Connection Type	Performance under load	Unobstructed View	Reversibility	Notes
Clamped	+++	++	++++	Susceptible to panes slipping out of fixing.
Bolted	+++	++	++++	Peak stresses due to drilling and point supports
Adhesive	++++	++++	++	Uniform Distribution of Loads
Embedded	++++	+++	+++	Uniform Distribution of Loads

TABLE 3: Table showing overview of different glass connections (drawn by author)

02.5 Overview and Discussions

The various types of glass presented in this chapter suggests that soda-lime, and borosilicate are the most commonly used glass types for making glass elements. Lead glass comes close but its limited resistance to thermal shock and softness makes it unsuitable for architectural application. Aluminosilicate, High silica glass and Fused quartz glass have very high operating temperatures which makes them unsuitable for fabrication and large-scale application. Between soda-lime and borosilicate glass, soda-lime has limited resistance high temperatures and rapid temperature fluctuations whereas borosilicate glass is resistant to thermal shocks and due to the lower thermal expansion coefficient requires less time for the annealing process. Therefore, borosilicate glass is the chosen one for this research.

The current prevalent manufacturing technologies for glass discussed in this chapter are summarized in table- . Float glass technology is the most widespread method of producing glass for architectural applications. However, only thin cross-sections of glass can be produced. 3D printing and casting are the only two methods of producing 3D shapes of considerable volume and size. With the challenges of annealing process and optical quality of 3D printing, casting remains the only method to produce glass elements of substantial cross-section and complex geometry with high optical qualities.

The use of glass in façade systems aims at minimal visual interference. Often, the use of connections and frames used to support glass negatively impacts the desirable optical properties and hinders transparency. The challenge with developing a novel technology such as hybrid glass block is that there is no one right answer. The connection systems can vary depending on the desirable optical quality, load conditions and also the design of the block. In this research, importance is given to the overall performance under load, unobstructed view and reversibility of a connection system and the different connections are evaluated based on these criteria. Adhesive based connections perform well under load, generates unobstructed views but are not reversible. The bolted and clamped connections can develop peak stresses, reduces the transparency but are reversible. Embedded connections perform fairly well in all three categories. However, at this point a connection system is not chosen rather all these connections or a combination of two types will again be developed for the final design options.

Glass Type	Softening Point (°C)	Annealing Point (°C)	Density (kg/m^3)	Notes
Soda-lime	730	548	2460	Soda-lime glass is chemically stable, inexpensive and easily workable
Borosilicate	780	525	2230	It has lower thermal coefficient value and exceptional performance at high temperatures.
Lead	626	435	2850	It has lower working temperature and ability to absorb X-rays but has limited resistance to thermal shock and high temperature and is susceptible to scratching due to its softness
Aluminosilicate	915	715	2530	It has a very high softening point and is scratch resistant due to the presence of high alkali content. It is heat and chemical resistance. Due to its heat resistance, it becomes difficult to melt and fabricate
High silica glass	1667	1140	2200	It has very low thermal expansion, good chemical durability, optical and mechanical properties. However, it has a deformation temperature of 1700 C due to the absence of fluxing agents which becomes a limiting factor for production.
Fused quartz glass	1500	910	2180	It has high transparency and resistance to weather and shock. As the fusing occurs at approximately 1650 C, it is very difficult to fabricate this glass.

TABLE 4: Table showing analysis of different glass types (Oikonomopoulou, 2019)

Glass Process	Optical Characteristics	Main type of glass applied	Standard Size (mm)	Notes
Float glass	Smooth, Transparent	Soda - lime	3120 x 6000	Limited only to thin glass cross-sections (2-25mm)
Extruded	Smooth, Transparent	Borosilicate, Silica	1500 to 10,000 in length	Results in virtually 2-dimensional glass objects of high slenderness ratio.
3-D Printed	Layered, Transparent	Soda - lime	upto 30 kgs	The layered nature of a 3D-printed object compromises the overall transparency
Cast Glass	Smooth, Transparent	Soda - lime, Borosilicate, Lead	upto 20,000 kgs	Provides greatest freedom in the volume and size of the resulting glass object with good optical quality.

TABLE 5: Table showing analysis of different production process (Oikonomopoulou, 2019)

03 Glass Block Technology

03.1 History of Glass Blocks

Since ancient times, the material Glass has been in the built environment and was used often for decorative arts and tools. Glass's use as a building material is credited to the Romans as they were the first to use it as windows in bath-houses. Structures in Pompeii and England dating back to the early Imperial Period still possess remnants of glass pieces in window frames. However, it was not until the Renaissance that Glass was commonly used. During this time, the material truly flourished and was commonly used for windows. It became more accessible and widely used in the majestic and detailed stained-glass windows of medieval cathedrals across Europe. (Fagan, 2015)

At the time, glass was made by blowing its molten form into a bubble using a blowpipe and molding it into the desired shape. This process was known as Glassblowing. (Fagan, 2015) suggests that improvements were made in plate glass production around the twentieth century, which impacted the use of glass in architectural design. Glass could now be produced in large pieces and installed in façade, which impacted the storefronts in particular as they could now better sell goods. In 1937, Pilkington Brothers and Ford Motor Company partnered to develop a fully mechanized system for manufacturing plate glass. The process dictated molten glass to be pressed between two rollers to form a thin sheet. Once glass cooled, the surface could be ground and polished from both sides simultaneously. This created a smooth, unmarked surface that was free of distortion.

With the development of a mechanized system for glass production, it was more widely available. The reason behind its wide application is its innate transparency, which allows for unhindered light in a space and visual connectivity between the inside and outside. This ability to transmit light brought about a reform in the use of glass during the Industrial revolution. As more and more factories started to spring, the cities became crowded and dirty. Therefore, in the late nineteenth century, vault lights and prismatic tiles were developed to respond to the dingy interiors. This innovation provided more light, air, and overall cleanliness, which resulted in more usable and habitable spaces. (Fagan, 2015)

Vault lights are small, round pieces of solid glass set into a cast iron panel and were often used in sidewalk construction to allow light to reach the cellar. These are often seen in urban areas in commercial and industrial buildings. With the cellar being more daylit, building owners had more rent able and usable spaces. Thaddeus Hyatt patented this system of Vault lights in 1845. However, with improvements in concrete construction during the late nineteenth century, vault lights were being set into the reinforced concrete, which was more

FIGURE 24: Figure showing Vault tiles in sidewalk (Wikipedia)

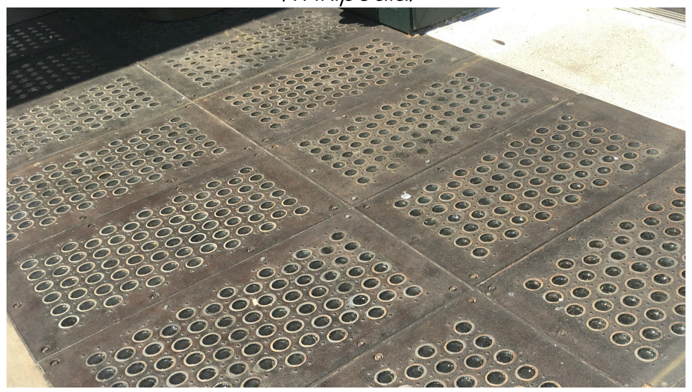


FIGURE 25: Figure showing Vault tiles (Paul. R, 2017)

durable than the cast-iron system.

Another popular method of daylighting was Prismatic glass tiles. This was manufactured as solid square tiles and had prismatic ridges on its inside face to direct and diffuse light deep into a room. These were commonly used in urban storefronts, comprising long panels above doors and awnings. The Luxfer Prism company was the first to produce these tiles, and they manufactured them in different colors and patterns (including the flower pattern designed by Frank Lloyd Wright). This provided an architectural interest to the facades that was appreciated by everyone alike. The prismatic daylight also helped in gaining higher rentals and therefore was mostly used in commercial buildings. The correlation between light, advertisement, and commerce was a keystone in the development and use of glass block during the 1900s. (Fagan, 2015)

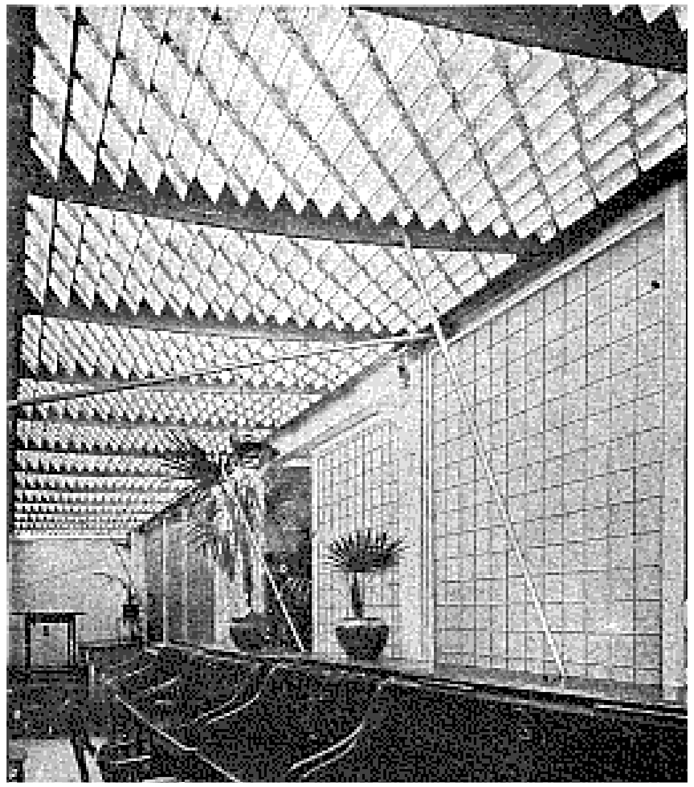


FIGURE 26: Figure showing prism tiles in restaurant (Wikipedia)

FIGURE 27: Figure showing prism tiles Paul. R, 2017)

Following these precedents, French engineer Gustave Falconnier in 1886, first introduced the concept of hollow glass block and patented a hexagonal or lozenge-shaped unit exhibited in 1893 World's Columbian Exposition in Chicago. These blocks enjoyed success but discontinued due to problems with stability and internal condensation. (Neumann et. al., 2000) After many years of research and development by various companies, Owens-Illinois in 1935 introduced Insulux, which were the first widely used hollow blocks. These blocks could be used as masonry units in non-load-bearing walls and served as a response to society's daylight needs. The early 20th century saw a boom in the glass block industry as this new material was being used extensively by architects for its unique properties of light transmittance, durability, thermal barrier, and sound deadening. Glass blocks at the time

FIGURE 28: Figure showing Falconnier glass block (Glassian, n.d.)

FIGURE 29 Figure showing installed Falconnier blocks (Glassian, n.d.)

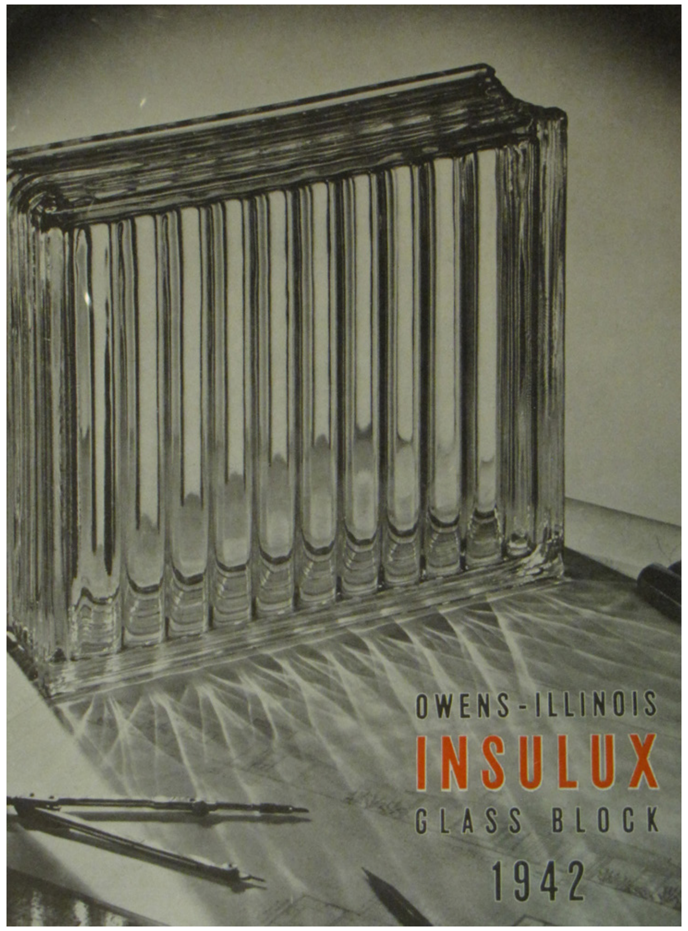


FIGURE 30: Figure showing Owens INSULUX block (Fagan, 2015)

were a novelty. They signified an idealistic vision for future practices. (Neumann et. al., 2000)

The Impressionist artists of the nineteenth century, such as Monet, recognized the transient effects of lights and their impact on buildings and landscapes. Soon, architects began to capitalize on glass's visual effect and its relationship with light. The Glass Pavilion at the Cologne Deutscher Werkbund Exhibition, designed by Taut in 1914, was a remarkable example of glass structure and its architectural possibilities. In 1915, the Panama Pacific Exhibition held in San Francisco portrayed a building covered in 100,000 Novagems and incorporated floodlights to illuminate the structure. The Tower of Jewels consisted of a triumphal arch with a tower on top and stands as a characteristic example in the architectural history of lighting design. It was the first building to use glass for emitting light from within. Undoubtedly, Maison de Verre, Paris is one of the most influential glass buildings of the early twentieth century. The blocks were solid glass

FIGURE 31: Figure showing interior staircase of Glass Pavilion (Fagan, 2015)

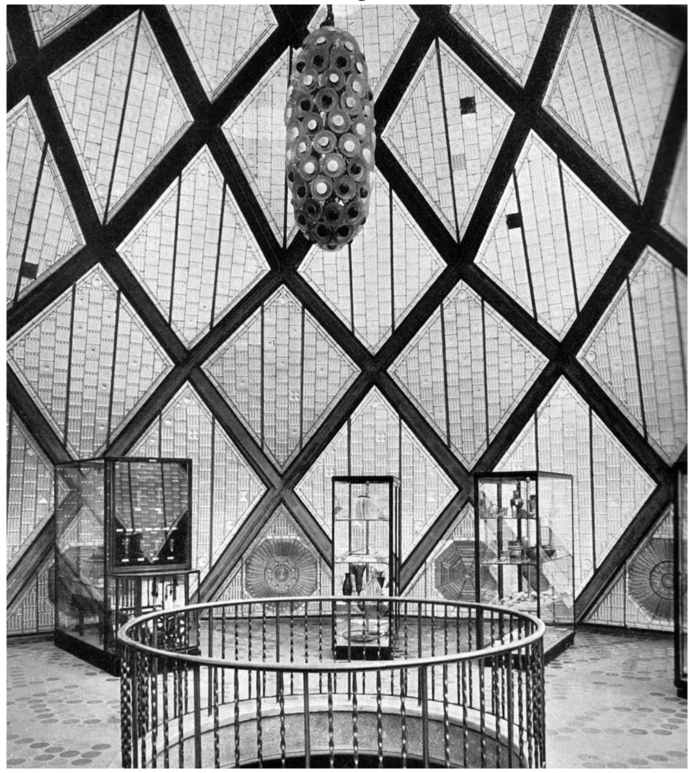


FIGURE 32: Figure showing inside the dome of Glass Pavilion (Fagan, 2015)

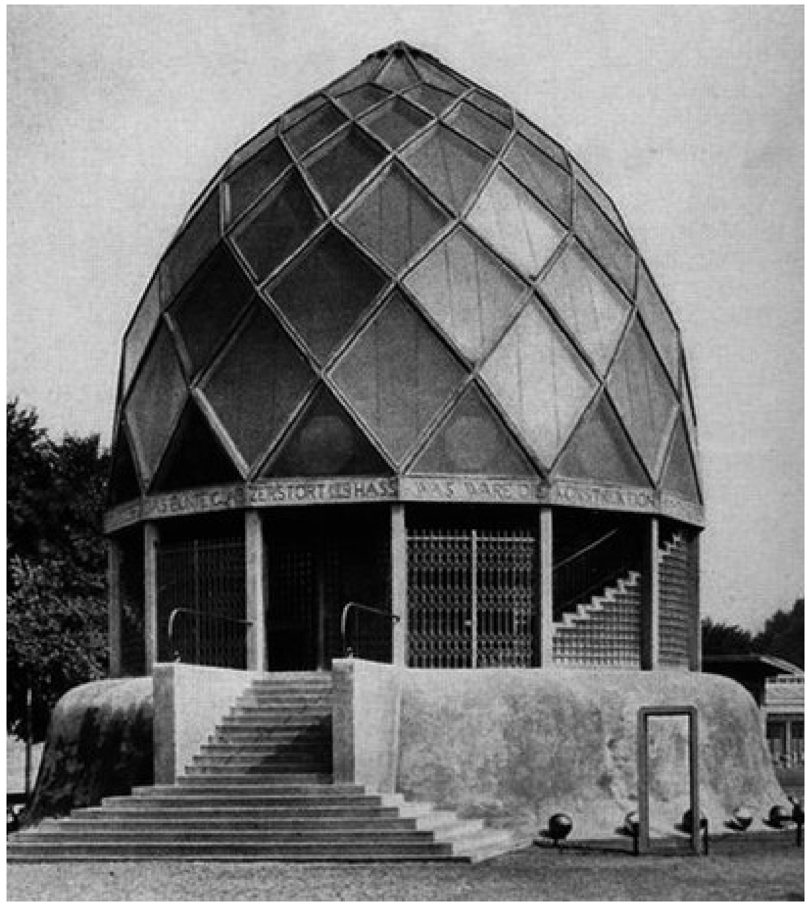


FIGURE 33 Figure showing Glass Pavilion by Bruno Taut (Fagan, 2015)

FIGURE 34: Figure showing Tower of Jewels (Fagan, 2015)

FIGURE 35: Figure showing facade of Maison de Verre (Fagan, 2015)

and were incorporated for the most part of the façade. This put forth the idea that glass blocks could replace the traditional masonry wall and were extensively used hereafter. (Fagan, 2015)

In recent years, new explorations have begun to uncover the structural potential of glass. It is no longer just a cladding material but is also being used for load-bearing applications due to its high compressive strength. Cast glass can be molded in optimum shapes to reduce the risks of buckling in a structure, thereby being highly stable; for example, the solid glass bricks of Crystal House have significant compressive strength due to their thick cross-section and monolithic nature. This renders them suitable for numerous design possibilities and has excellent potential to be used in the building industry. Some examples for the same are Atocha Memorial in Spain, Optical House in Japan, and Crystal House in Amsterdam. (Oikonomopoulou, 2019)

The Atocha memorial (2007) in Madrid consists of approximately 15,600 solid glass bricks. The shape of the brick is specially designed to allow for a change in the curvature of the elliptical plan. In Crystal house (2016), the bricks are cast in optimum shape for load-bearing applications. The other examples are Crown Fountain (2011) in Chicago and Optical House (2012) in Japan; both have a minimal steel substructure that transfers the load from the blocks to the base. These examples have an adhesive as the bonding material between blocks, which gives the required rigidity to the composition. (Oikonomopoulou, 2019)

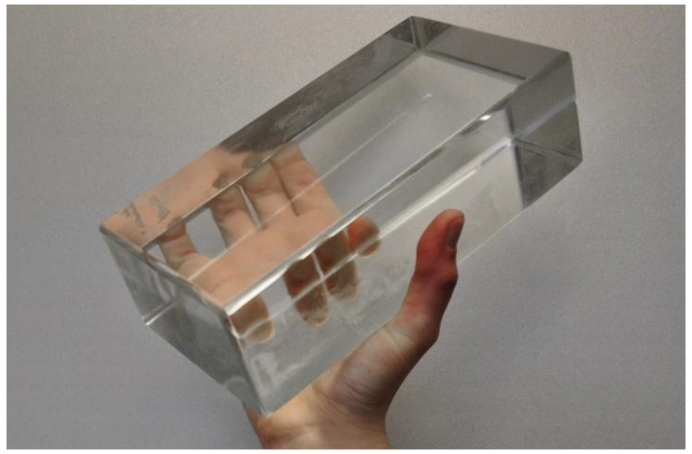


FIGURE 36: Figure showing solid glass block (Oikonomopoulou, 2019)

FIGURE 37: Figure showing glass block of Atocha Memorial (FAM Arquitectura y Urbanismo, 2017)

FIGURE 38: Figure showing glass block of Optical house (Hiroshi Nakamura & NAP, 2020)

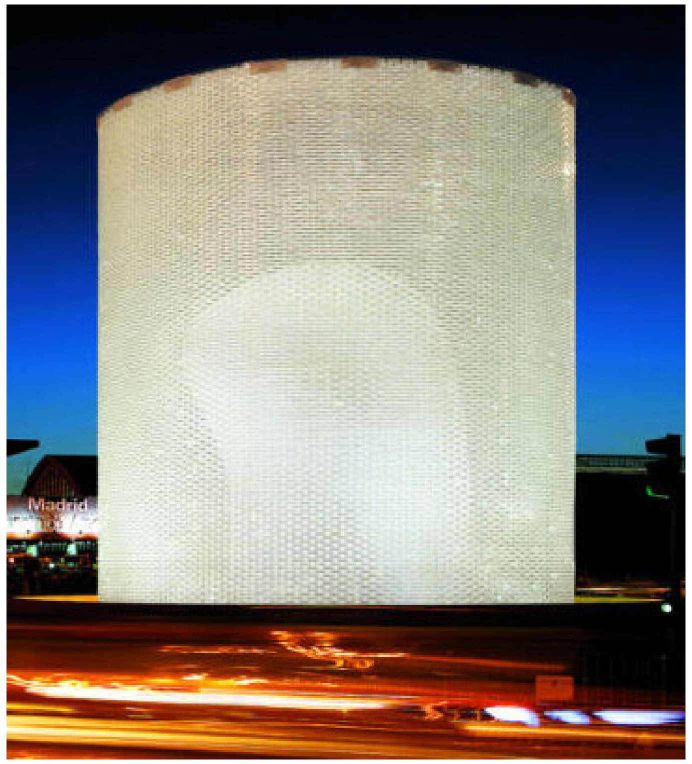


FIGURE 39: Figure showing Atocha Memorial (FAM Arquitectura y Urbanismo, 2017)

FIGURE 40: Figure showing Crystal House (Archdaily, 2016)

FIGURE 41: Figure showing Optical House (Archdaily, 2020)

FIGURE 42: Figure showing masonry detail of Atocha memorial (FAM Arquitectura y Urbanismo, 2017)

FIGURE 43: Figure showing masonry detail of Optical House (Archdaily, 2020)

FIGURE 44: Figure showing masonry detail of Crystal House (Archdaily, 2016)

03.2 Hollow Glass Blocks

Introduction

Hollow glass blocks are made by sealing together two halves of U-shape sections creating a cavity in-between. It has a fascinating response to natural as well as artificial light. The product offers a great range of light and privacy conditions depending on the block's pattern and transparency. Hollow glass block is also energy efficient, provides sound control, security, and fire resistance due to the presence of the cavity. However, the multiple layers result in severe optical distortion of the objects. The most common usage is in police stations, subway terminals, schools, etc.

Characteristics:

a. Thermal and acoustic insulation
b. Non-load bearing
c. Transparent with optical distortion
d. Manufactured by casting and then sealing
e. Substructure required for assembly

Manufacturing Process

The hollow glass blocks are manufactured by mixing sand, soda ash, and limestone in tanks, where they melt at 1300 degrees Celsius. A precise amount of molten glass is taken out with a computerized system and poured into the mold. The glob of glass is evenly spread in the said mold with the help of a plunger. This creates one half of the block. If a surface finishing pattern is required, the mold/plunger will have a curved or waffled pattern. These half blocks are then cooled rapidly from 1000˚C to 600˚C by passing ambient air as at this temperature, it is less prone to deform and can be easily handled.

In the next step, the components are passed through several burners to keep a uniform temperature, and the edges are again heated to attain a melting form. This step is crucial as it is necessary not to have any drastic change in temperature but maintain a uniform range. The two blocks are then pressed together, forming an airtight seal. This complete block is then put into an annealing lehr, where it gradually cools down and attain the required strength.

Once the block is out, it is measured to check if it complies with the standards. Digital alignment gauge are used to make sure both halves are flushed. These are then coated with special edge coatings (e.g., vinyl coating) to increase the bonding capacity between blocks and mortar. (Pittsburgh Corning Corporation, 2007)

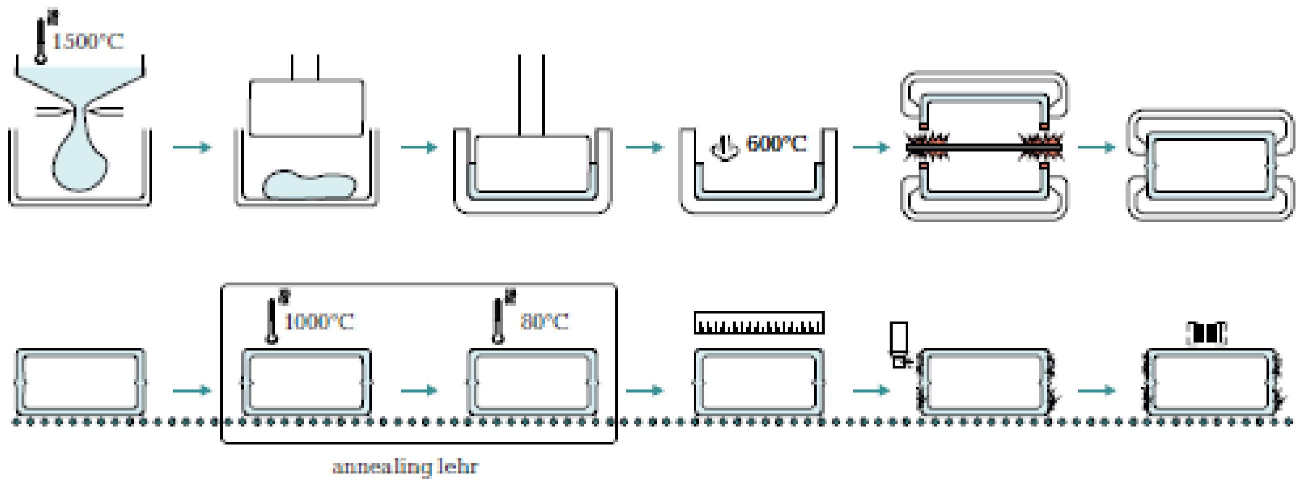


FIGURE 45: Figure showing manufacturing process of Hollow Glass Block (Velden, 2020)

Installation Process

As stated earlier, hollow glass blocks are non-load-bearing therefore, the installation requires them to be supported on a substructure. Thus, there are two main components when installing hollow glass blocks are; block structure and bearing structure. Care should be taken that both these components are independent of expansion and contractions and must never be in direct contact with each other. Since glass is brittle it's important to avoid any load or external restraint conditions that would concentrate stresses on glass block. (Seves, n.d.) The installation process consists of three phases:

<u>Preliminary phase:</u> In this phase, it is required to make sure the wall is perfectly horizontal and vertical to avoid eccentric loads on the assembly. Horizontal strips are placed at the bottom where the wall will begin. Vertical guides are then arranged at a distance of 100-120 cm apart to provide support while laying the blocks. (Fig 46) A slip joint is placed between the horizontal strips and the vertical edge of the wall and also at the joints to prevent expansion/contraction between base of the panel and supporting structure.

<u>Installation phase:</u> The cement mortar is applied on the base strips and position the first layer blocks. (Fig 46) After the first course is placed, the spaces are put to make even joints. After two courses of blocks, the reinforcement bars are placed in between the mortar. This is done to make sure the rod doesn't touch the glass directly. The reinforcement bars should be placed horizontally and vertically and should not be more than 50cm apart. (Fig 46) Next, remove the excess mortar from joints using a piece of wood and wipe the glass blocks with a wet sponge. If the wall reaches the ceiling, then place a slip joint between the block and the top part as was done in the start.

<u>Finishing phase:</u> Finish the joints once the mortar hardens. (Fig 46) Remove the spacers and fill in the joints well with soft brushes and plastering towels. For exterior installations, finish by applying a water-proof paint over the joints. (Seves, n.d.)

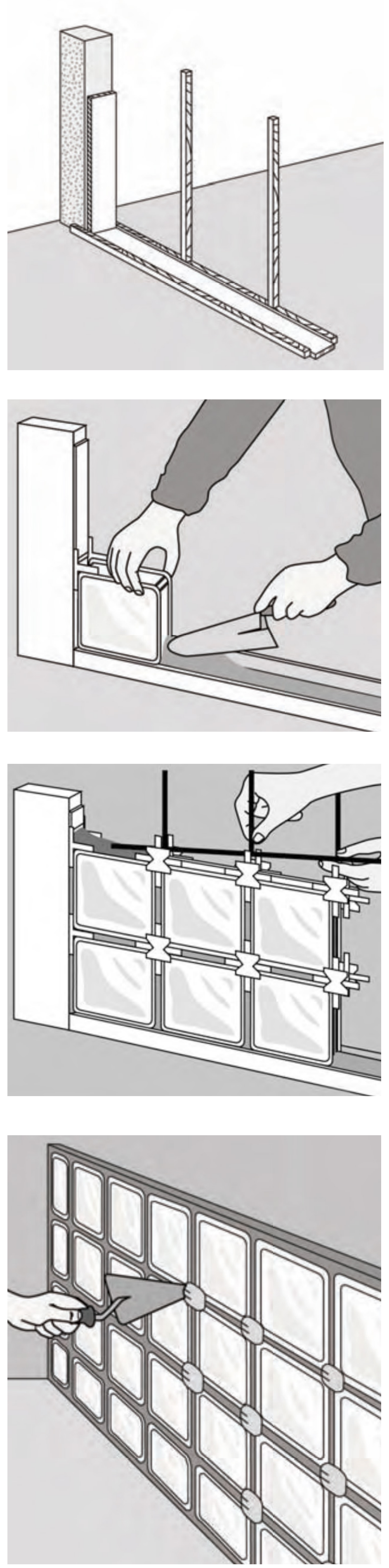


FIGURE 46: Figure showing installation of Hollow Glass Block (Seves, n.d)

Properties

Hollow glass blocks come in variety of patterns, sizes and colours. They are widely used for their distinguished properties that are explained in detail below:

<u>Light Transmission:</u>

The glass blocks are clear and admits full tones of light. The blocks with patterns pressed into their interior faces distort the image for visual privacy. The units made with glass fiber insets reduce glare and brightness.

<u>Less Heat Gain:</u>

Because of the presence of cavity, they have good thermal resistance. The standard clear units have a U-value of 2.55 W/m²K. (Pittsburgh Corning) The solar reflective units are coated with heat bonded oxide and can reduce the solar heat gain by 80%. The blocks with glass fiber insets can reduce solar gain further by 5%.

<u>Sound, Fire and Condensation:</u>

A 10cm thick wall reduces sound transmission by 40dB and has an STC rating of 43 - 50. The air cavities increase the fire resistance of the blocks. The standard blocks have a fire rating of 45-minute UL or Euro class A1. There is no problem of surface condensation.

The table depicts summarizes the properties, manufacturing and installation process for hollow glass blocks.

Hollow Glass Blocks	Seves (HTI WAVE)	Pittsburgh Corning (Thickset 90 VUE)
Properties		
Compressive	6 MPa	2.75 – 4 MPa
Light Transmission	70%	76%
U-Value	1.8 W/m²K	2.55 W/m²K
Sound	43 STC	50 STC
SHGC	0.68	0.32
Sizes	19cm X 19cm X 16cm	20cm X 20cm X 10cm
Manufacturing		
Process	Casting, Fusing and Annealing	
Glass Type	Soda-lime glass	
Mould Used	Pressed Steel Mould	
Annealing time	Unknown	
Weight of block	2.7 kgs	3 kgs
Constructability		
System	Metal substructure with mortar	
Load Distribution	Not-load bearing. Forces are carried by a metal	
Connection system	Blocks are connected through mortar/adhesives	
Assembly type	Adhesively bonded (mortar accomodates size deviations)	
Transparency	Compromised transparency	
Reversibility	Non-reversible	

TABLE 6: Table showing properties, manufacturing and installation process for hollow glass block.

03.3 Solid Glass Blocks

Introduction

Solid glass blocks are manufactured by pouring liquid glass into a mold. These offer similar transparency levels compared to hollow blocks but have significantly less optical distortion as it is one single thick unit, limiting the re-direction of light only at two external surfaces. Its monolithic nature has inferior thermal properties, and it acts as a thick single pane glass. However, solid glass blocks have remarkable compressive strength, typically over 200 MPa, which allows them to be used as load-bearing units.

Characteristics:
a. Load bearing
b. Inferior thermal and acoustic performance
c. Transparent with much less optical distortion
d. Manufactured by casting into desired shape
e. Substructure is not required if designed optimally for assembly.

Manufacturing Process

Glass casting is a challenging process; it is important to carry out this step meticulously. Any mistake in the process can lead to inhomogeneous stress distribution or even failure due to cracking. The glass is heated to around 1000 degrees Celsius, where it is viscous enough to be deformed into any shape. This is then poured into the mold and fired in the furnace. After this, a rapid cooling down process is required to avoid the temperatures in the crystallization region to achieve an amorphous structure with high optical value. Once the glass temperature reaches its softening point, it is hard enough to retain its shape and not deform under its own weight.

The next step is the annealing process. The time for the same depends on the size of the component. The different annealing times of the glass blocks used are given in table _. A careful annealing process eliminates any possibility of differential strain build up between casting and demolding and prevents the generation of internal residual stresses during further cooling. Once the prototype is taken out of the mold, it undergoes post-processing. In this, the excess overflow is sawn off, defects and imperfections are sanded out, and the surface is treated to achieve a smooth, shiny, and transparent end product. (Oikonomopoulou et. al., 2014)

Installation Process

There are three types of structural systems employed in installing the solid glass bricks:
- With a metal substructure
- Adhesively bonded bricks
- Interlocking units

<u>With a metal substructure</u>

The metal substructure is provided to carry the tensile forces to achieve the desired stiffness and buckling resistance. This, in turn, allows the glass units to perform purely under compression. The characteristic example of this method is The Optical House in Japan. It consists of an 8.6m x 8.6m façade of 6000 glass blocks. These blocks have punctured holes on the top and bottom faces, which holds pre-tensioned rods of 75mm, creating a vertical mesh suspended from a steel beam encased in reinforced concrete. The mesh withstands lateral forces and allows the façade

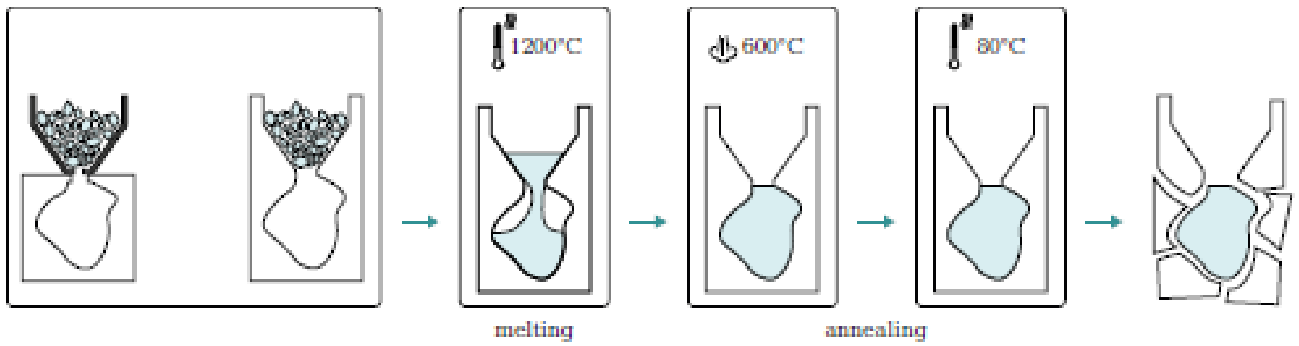


FIGURE 47 Figure showing manufacturing process of Solid Glass Block (Velden, 2020)

to have a high slenderness ratio. The rods are connected to stainless steel flat bars (40mm x 4mm) at 10-centimeter intervals and pass from within the glass blocks (50mm thick) to render them invisible. This results in a mortarless transparent façade. (Oikonomopoulou, 2019)

FIGURE 48: Figure showing installation of facade of solid blocks with metal support in Optical house (Archdaily, 2020)

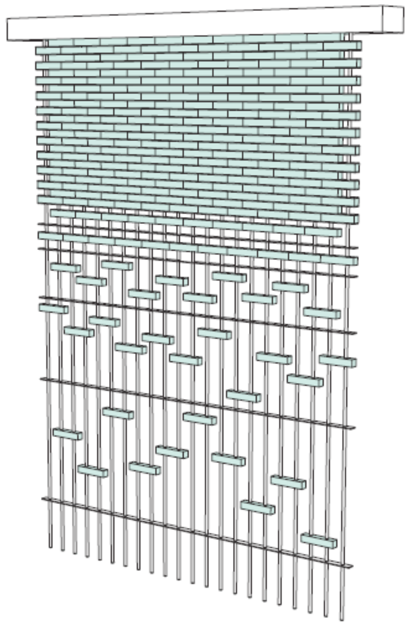


FIGURE 49: Figure showing illustration of installation of Optical House facade (Oikonomopoulou, 2019)

Adhesively bonded bricks

In this system, a completely transparent structure is achievable and results in homogeneous load distribution. The adhesives' mechanical properties play a crucial role in the system; the interaction between the blocks and adhesives defines the performance of the structural system. They should behave as a single rigid unit under loading. Therefore, adhesives such as acrylate and epoxies are necessary to ensure the desired bond

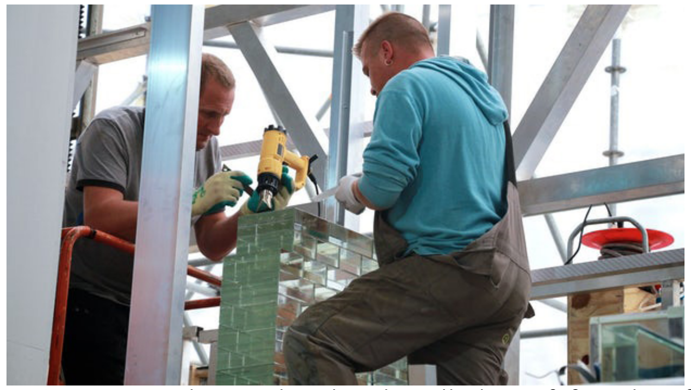


FIGURE 59: Figure showing installation of facade of solid blocks with adhesives in Crystal house (Archdaily, 2016)

strength. One of the prominent examples is the Crystal House in Amsterdam. The structural experiments and mock-up development indicated an optimum bonding strength between 0.2-0.3mm and tolerances ranging from 0.25mm to 0.5mm. Tolerances above 0.25mm resulted in an uneven spread of the adhesive, which in turn affects the structural performance. The chosen adhesive was Delo Photobond 4468, a colorless, UV-curing, one component acrylate. This remarkable high level of accuracy and transparency influenced the glass recipe and mold type. Thus, soda-lime glass and open high precision mold were chosen to prevent an unnecessary increase in production costs as post-processing of the block's bonding surfaces is unavoidable due to high accuracy requirements. The annealing time ranged between 8-38 h, depending upon the size of the block. (Oikonomopoulou, 2019)

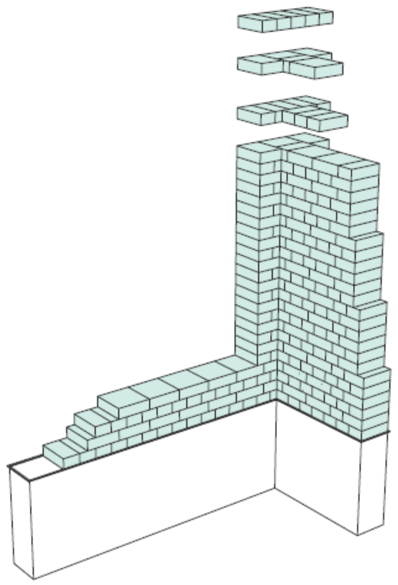


FIGURE 51: Figure showing illustration of installation of Crystal House facade (Oikonomopoulou, 2019)

Interlocking units

The interlocking system's principle is that overall stability is achieved through compression provided by the self-weight of the construction and the interlocking geometry that restrains lateral movements. In such a mortar free system, the factors holding the components in place are weight and friction. This is still a new concept, and research has been going on to develop it further. One of the most distinguishing examples is the osteomorphic interlocking brick concept developed by (Oikonomopoulou, 2019). The shape is engineered with non-planar concavo-convex surfaces. The block's convex parts fit perfectly with the concave parts and vice versa, impeding the movements in both planar directions. This system consists of a dry, colorless interlayer such as Polyurethane rubber (PU) or Polyvinyl Chloride (PVC) as an in-between medium between glass units to prevent stress concentrations due to contact and compensates for dimensional tolerances. This renders them demountable and enables the circular use of glass components. (Oikonomopoulou, 2019)

FIGURE 52: Figure showing osteomorphic interlocking glass blocks (Oikonomopoulou, 2019)

FIGURE 53: Figure showing interlocking glass blocks (Oikonomopoulou, 2019)

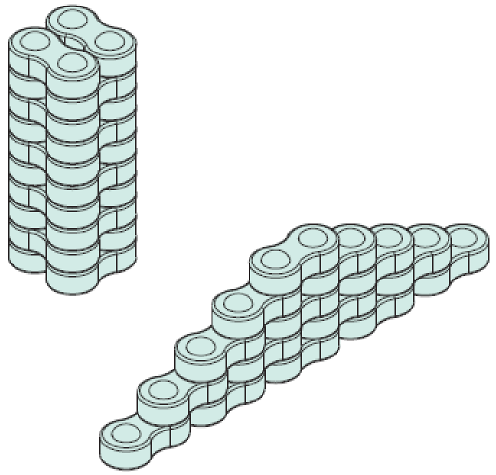


FIGURE 54: Figure showing illustration of installation of interlocking cast glass block (Oikonomopoulou, 2019)

The installation process consists of three phases:

<u>Preliminary phase:</u> This phase is similar to the installation of hollow glass blocks. The walls are checked to make sure it perfectly aligns to avoid eccentric loading on the assembly. Vertical and horizontal guides are laid to support the assembly during the installation phase.

<u>Installation phase:</u> Since the development of solid load-bearing glass blocks are fairly new. There is no standardized process to assemble these. Therefore, the types mentioned above dictate the assembly sequence and choice of adhesive or dry interlayer. A disadvantage of using rigid adhesive in solid glass block construction is that the blocks require high dimensional accuracy which is in contrast with mortar types used in hollow glass brick systems, as they can accommodate size deviations within the bricks. In general, the assembly is similar to masonry construction; the first block is positioned over a soft rubber material that separates glass's direct contact with the hard base. Consequently, blocks are stacked one by one to form the complete façade.

<u>Finishing phase:</u> As the masonry reached its end, the joints are finished. The blocks and joints are cleaned to avoid any extra spills of the adhesives or leftover material that may cause problems.

Properties

Solid glass blocks are a recent development and are only available in few designs. They are now being widely used for their distinguished properties that are explained in detail below:

Light Transmission:
These blocks are completely transparent and have significantly less distortion because of the homogeneity of the material.

Compressive Strength:
Because of their monolithic nature, their compressive strength is in the range of 300 to 400 MPa. (Pittsburgh Corning Corporation, 2007) Therefore, they are used as masonry units in façade of the buildings.

Sound, Fire and Condensation:
Because of the thickness the STC rating of the block is between 43 – 53 and they perform well against fire and condensation.

The table depicts summarizes the properties, manufacturing and installation process for solid glass blocks.

Solid Glass Blocks		Seves (VISTABRICK)	Pittsburgh Corning (VISTABRICK)
Properties			
Compressive Strength		83 MPa	421 MPa
Light Transmission		160%	190%
U-Value		4.1 W/m²K	4.9 W/m²K
Sound		44 STC	54 STC
SHGC		1.52	0.75 – 0.79
Sizes		19.7cm X 19.7cm X 8cm	19.4cm X 19.4cm X 7.6cm
Manufacturing			
	Crystal House	Atocha Memorial	Optical House
Process	Casting and Annealing		
Glass Type	Soda-lime glass	Borosilicate glass	
Mould Used	Open Steel Mould	Pressed Steel Mould	
Annealing time	8-38h (size dependent)	20h	unknown
Weight of block	3.6 - 7.2 kgs	8.4 kgs	unknown
Constructability			
System	Metal Substructure	Adhesive bonded bricks	Interlocking units
Load Distribution	Tensile forces are carried by a metal substructure	Homogeneous load transfer via rigid adhesive	Stiffness is obtained by the interlocking geometry
Connection system	Interlayer	UV-cured adhesive.	Interlayer
Assembly type	Dry-assembly/ adhesively bonded (Interlayer accommodates size deviations)	Adhesive bond. Adhesive's thickness requires high precision in unit size	Dry-assembly (Interlayer accommodates size deviations)
Transparency	Compromised transparency	High transparency	High transparency
Reversibility	Reversible	Non-reversible	Reversible

TABLE 7: Table showing properties, manufacturing and installation process for solid glass block.

03.4 Investigation to improve Thermal Performance

Numerous researches have been done to increase the thermal performance of glass blocks and windows to comply with the new energy codes. Therefore, this section aims to develop upon the existing study and apply this in the hybrid block context.

Change in Cavities

Still air has a good thermal conductivity value as low as 0.025 W/(mK) at room temperature and standard pressure, but its resistance reduces by the flow of air within the cavity.

The research done by (Binarti et al., 2014) on increasing thermal performance with the change in air cavity suggested increasing the number of cavities within the same thickness increases the thermal performance. In this research, the combination of the layer number, the cavity type, number, width, and position of cavities are taken into account.

Model l20_l4x2_r3_20 with 3 cavities of 20mm each has a U-value of 2.3 W/m²K, whereas model l21_l4x3_r3_15 with 3 cavities of 15mm each has a U-value of 2.28 W/m²K. Although the increased number of cavities contributes towards a lower visual transmittance value due to multiple internal reflections however, if visual property is not the primary criteria than this concept has great potential. Also, generating multiple air cavities is easier in terms of manufacturing process and recyclability. The table - shows all the models along with their U-values that were simulated in this research.

Additional insulating material

As mentioned earlier, air cavities lead to improved thermal performance, but if these voids are filled with insulating materials, the system's performance is significantly increased. The common filling materials are:

Table 1. Energy Performance of Glass Block Models Based on Analytical and Simulation Approach

Model codes[a]	U (W/m²K)	T_{s0}[b] (°C)	T_{si}[c] (°C)	VT	SHGC	LSG
l10_l2x2_r1_30	2.60	77.5	31.5	0.52	0.65	0.80
l11_l2x3_r1_25	2.54	65.5	30	0.41	0.65	0.63
l12_l2x2_r1_40	3.24	78	30	0.52	0.74	0.70
l13_l2x3_r1_35	3.17	67	29	0.40	0.73	0.55
l14_l4x2_r3_10	2.55	75	28	0.40	0.71	0.56
l14_l3x2_r2_20	2.56	77.5	28	0.40	0.72	0.56
l15_l3x3_r2_15	2.50	67	28	0.28	0.70	0.40
l15_l2x3_r1_45	3.06	67	28	0.40	0.71	0.56
l18_l3x2_r2_30	2.60	77	27	0.31	0.57	0.54
l19_l3x3_r2_25	2.54	67	27	0.27	0.59	0.54
l20_l4x2_r3_20	2.30	78	27	0.31	0.67	0.46
l21_l4x3_r3_15	2.28	65	27	0.19	0.66	0.29

[a] Models are coded using lA_lBxC_rD_E formula, which means that A is the total layer number, B is the glass layer number per group, C is the group number, D is the cavity number, and E is the thickness of each cavity in mm.
[b] T_{s0} = outdoor surface temperature
[c] T_{si} = indoor surface temperature

FIGURE 55: Figure showing analysis of glass block with different cavity and thicknesses (Binarti et al., 2014)

<u>Inert Gases</u>

Inert gases are already filled in Insulated glass units for increasing the thermal performance of the system. The company Seves also has developed a high performing glass block with cavities filled with inert gases. The block achieves a U-value of 1.8 W/m²K. This is done by adding a low coated glass in the middle that divides one large cavity into two parts. Each of these parts are then filled with argon gas. This block however has a thin cross-section and therefore cannot be used for load-bearing applications but this idea has much potential to be developed.

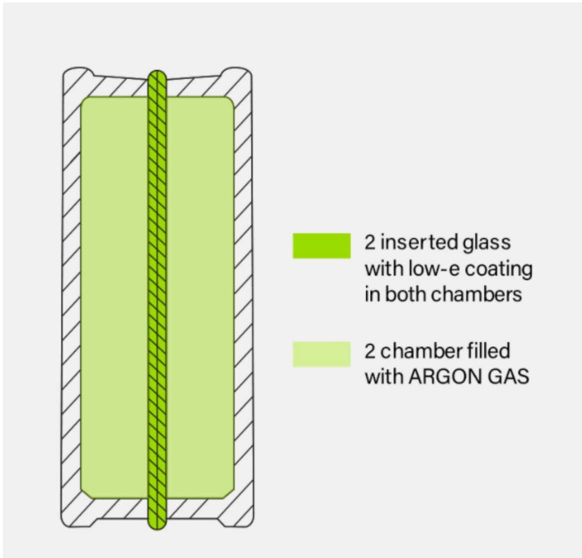


FIGURE 56: Figure showing SEVES glass block with inert gas as infill material for cavity (Seves, n.d)

<u>Aerogel</u>

Research done by (Beccali et al., 2010) on reducing the U-value of the glass-blocks suggests that aerogel is very effective. It completely avoids the convective heat transfer and inhibits the radiative heat exchange due to its high absorptivity.

The calculated U-value for the first family of configurations (A2) reached 1.66 W/m²K. In these configurations, aerogel is added in the entire cavity of the hollow glass blocks.

However, the production and handling of aerogel are challenging as it is a very fragile material and is therefore expensive.

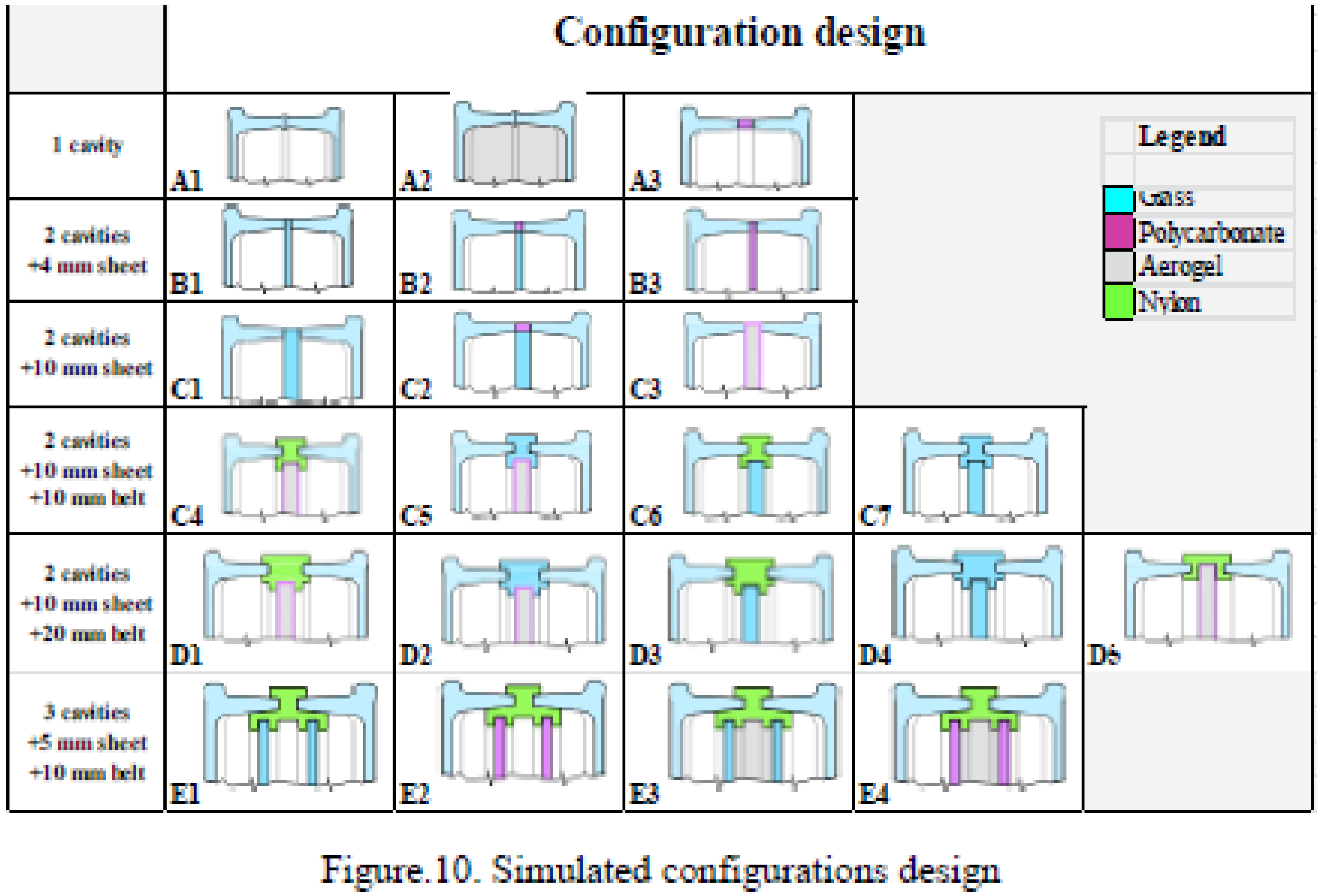


FIGURE 57: Figure showing analysis of configurations with aerogel (Beccali et al., 2010)

Glassblock configuration

configuration		material: cavity	material: sheet	material: belt	thermal belt	thickness [cm]	U- value [W/m²K]	Convective Cell
1 cavity	A1	air	no	no	no	8	2.88	Yes
	A2	aerogel	no	no	no	8	1.66	No
	A3	air	no	PC	yes	9	2.68	Yes
2 cavities +4 mm sheet	B1	air	glass	no	no	8.4	2.34	Yes
	B2	air	glass	PC	yes	8.4	2.28	Yes
	B3	air	APC	no	yes	8.4	2.19	Yes
2 cavities +10 mm sheet	C1	air	glass	no	no	9	2.28	Yes
	C2	air	glass	APC	yes	9	2.19	Yes
	C3	air	PCA	no	yes	9	1.37	Yes
2 cavities +10 mm sheet +10 mm belt	C4	air	PCA	FRN	yes	9	1.59	No
	C5	air	PCA	glass	no	9	1.89	No
	C6	air	glass	FRN	yes	9	1.91	No
	C7	air	glass	glass	no	9	2.06	No
2 cavities +10 mm sheet +20 mm belt	D1	air	PCA	FRN	yes	10	1.46	No
	D2	air	PCA	glass	no	10	1.86	No
	D3	air	glass	FRN	yes	10	2.13	No
	D4	air	glass	glass	no	10	2.32	No
	D5	air	PCA	FRN+PCA	yes	10	1.06	No
3 cavities +5 mm sheet +10 mm belt	E1	air	glass	FRN	yes	9	1.53	No
	E2	air	APC	FRN	yes	9	1.64	No
	E3	air	glass	FRN	yes	9	1.70	No
	E4	air	APC	FRN	yes	9	1.51	No

Legend

$U<1.3 W/m^2K$ high efficiency

$1.3<U<1.7 W/m^2K$ efficiency

$1.7<U<2.0 W/m^2K$ low efficiency

FIGURE 58: Figure showing analysis of configurations with aerogel (Beccali et al., 2010)

<u>PCM</u>

Phase change material is another recent investigation that helps in the improvement of thermal performance. This material changes its state as it absorbs/releases energy to provide heating/ cooling. The challenge with this is maintaining the desired optical properties. Also, the production of such a unit is difficult and time taking process.

Applying coatings

Coatings also help in improving the insulating properties by blocking out the infrared radiations. The coatings have an impact on the emissivity value of the surface which changes the conductivity of air cavities.

There are two types of coatings; hard coatings and soft coatings. Soft coatings provide high visible transmission, low emissivity, and great optical clarity. Edge deletion of the coating is required to ensure a proper sealed insulated unit. The advantage of hard coatings is durability, which allows for ease of handling. The hard coatings do not improve the U-value in general.

The disadvantage of using coatings is the reduced recyclability potential of glass as it becomes tough to separate the two and, therefore, is not very sustainable.

Concepts	Thermal Performance	Ease of manufacturing	Transparency & Optical distortion	Recyclability	Final Score
Altering the cavities	++++	+++	+++	++++	++++
Adding Insulative material – Inert gas	++++	+++	+++	++++	++++
Adding Insulative material – Aerogel	++++	+++	+	+++	++
Adding Insulative material – PCM	+++	++	+++	+++	++
Applying coatings	++++	++++	++++	++	+++

TABLE 8: Table showing scoring chart for concepts to improve thermal performance

The above mentioned ideas are scored based on their impact on thermal performance, ease of manufacturing, optical quality and recyclability.

The three most promising concept are:
1. Altering the cavities: changing the cavity sizes and/or introducing multiple air cavities

2. Adding inert gas: for additional insulating material, putting inert gas is the most simple and effective way of increasing the thermal performance

3. Applying coatings: the application of coatings is very common in the windows. With a very thing layer of coating, there can be tremendous impact on the thermal performance. Even though there are recyclability challenges with this idea. These can be catered to in the design of the block.

Adding aerogel improves the thermal performance tremendously however it is challenging to manufacture and is very expensive. It also impacts the transparency and optical quality of the system as it is opaque.

Reference case study:
Increased thermal performance of structural cast glass brick wall - Mariska van der Velden

The research done by (Velden, 2020) on "Increased Thermal performance of Structural cast glass brick wall" suggested that the three typologies that performed the best were: the single cavity, the double-wall and the shard brick.

The double-wall has the best thermal performance since it is literally twice a wall. The downside of this is the material usage (and thus sustainability). The shard brick scores well to high in every criterion except transparency. The single cavity is one of the simplest designs and scores average in almost every category.

			Aesthetical potential (2)	Producibility (2)	Sustainability (3)	Thermal performance (4)	Transparency (1)	Total
0		Solid						
1		Single cavity	0.68	0.55	0.68	0.0935	0.889	5.76
			0.68	0.55	0.75	0.1360	0.889	6.14
			0.68	0.55	0.77	0.1586	0.889	6.29
2		Double cavity	0.50	0.30	0.74	0.1105	0.778	5.04
			0.50	0.30	0.75	0.1700	0.778	5.31
			0.50	0.30	0.77	0.2040	0.778	5.50
3		Single cavity with spacers	0.38	0.60	0.57	0.3286	0.804	5.79
4		Float glass with spacers	0.38	0.55	0.41	0.3286	0.804	5.21
5		Thin glass	0.55	0.40	0.40	0.0963	0.804	4.29
6		Double-wall	0.63	0.65	0.55	0.4505	0.889	6.90
7		Secondary float glass wall	0.55	0.75	0.27	0.4023	0.889	5.91
8		Chess	0.85	0.15	0.78	0.1274	0.778	5.63
		Chess 4 mm	0.85	0.15	0.81	0.1675	0.722	5.82
9		Shards	1.00	0.30	1.00	0.3700	0.000	7.08

FIGURE 59: Figure showing analysis of all configurations (Velden, 2020)

03.5 Overview & Discussions

This chapter gives an overview of the current technologies in the glass blocks and their properties, fabrication, and installation process. From the presented data, it can be clearly understood that while hollow glass blocks are the most prevalent and widely used in architectural applications. Nonetheless, solid glass blocks' monolithic nature and load-bearing capacity make them a potential element for future constructions. Both of these have similar light transmission, fire, and surface condensation properties and only present stark differences in the compressive strength and heat transmission values. The hollow blocks exhibit profound thermal insulating properties, while solid blocks present remarkable load-bearing strength.

The manufacturing process for the hollow glass block is standardized due to its long presence in the built environment, while the fabrication for solid cast glass blocks is still new and is being developed. Nevertheless, both these processes are relatively similar to molten glass is being poured to form an element. This element is then controllably cooled to room temperature in an annealing kiln. The casting process presents great flexibility in the geometry and volume of the resulting component. Important factors that influence the manufacturing process are the number of blocks required, volume and geometry of block, and type of mold used.

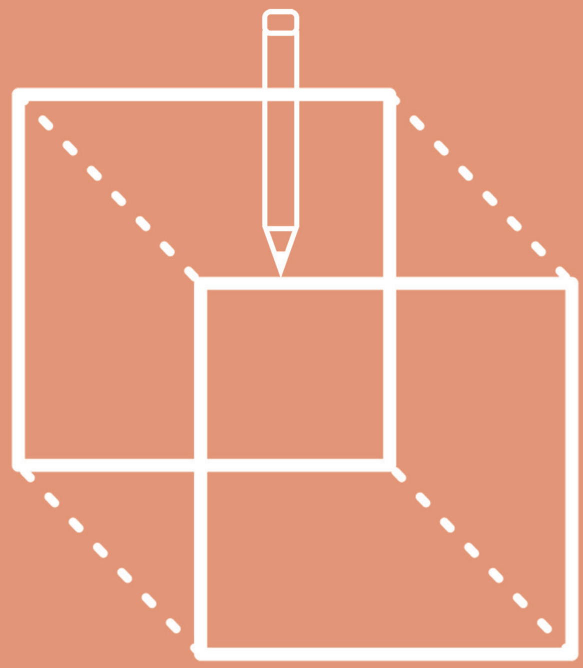
The hollow glass block application is straightforward but not as elegant as the substructure required to support the assembly impedes the transparency of the overall façade. The supporting structure also needs to account for the block's weight which results in more segments in the substructure and increases the small non-transparent elements. The solid glass blocks provide an elegant installation solution that renders a completely transparent façade when using adhesives but this is not a circular solution. However, since solid glass blocks are load bearing, the substructure can be minimized as it does not have to account for the dead load of the glass structure. The block design also plays a crucial role in the overall assembly process and acceptable tolerance values. Therefore, while designing an installation process for the hybrid block, things to keep in mind are the design of the block, boundary conditions, and connection system used for blocks.

Comparative Analysis:

The table compares the properties, manufacturing and installation process for hollow and solid glass blocks.

Glass Block Type	Hollow Block	Solid Block		
	Seves (HTI WAVE) & Pittsburgh Corning (Thickset 90 VUE)	Seves (VISTABRICK) & Pittsburgh Corning (VISTABRICK)		
Properties				
U-Value	1.8 - 2.5 W/m2K	4.1 - 4.9 W/M2k		
Compressive Strength	3 - 6 MPa	82 - 400 MPa		
Light Transmission	70 - 76 %	60 - 90 %		
SHGC	0.32 - 0.68	0.52 - 0.78		
Sound	43 - 50 STC	43 - 50 STC		
Manufacturing				
		Crystal House	Atocha Memorial	Optical House
Process	Casting, Fusing and Annealing	Casting		
Glass Type	Soda-lime	Soda Lime	Borosilicate	
Mould Used	Pressed Steel Mould	Open Steel Mould	Pressed Steel Mould	
Annealing time	unknown	8 - 38 h (size dependant)	20 h	unknown
Weight of block	2.7 - 3 kgs	3.6 - 7.2 kgs	8.4 kgs	unknown
Constructability				
System	Metal substructure with mortar	Metal Substructure	Adhesive bonded bricks	Interlocking units
Load Distribution	Not-load bearing. Forces are carried by a metal substructure	Tensile forces are carried by a metal substructure	Homogeneous load transfer via rigid adhesive	Stiffness is obtained by the interlocking geometry
Connection system	Blocks are connected through mortar/adhesives	Interlayer	UV-cured adhesive.	Interlayer
Assembly type	Adhesively bonded (mortar	Dry-assembly/	Adhesive bond.	Dry-assembly
Transparency	Compromised transparency	Compromised transparency	High transparency	High transparency
Reversibility	Non-reversible	Reversible	Non-reversible	Reversible

TABLE 9: Table showing comparative analysis of Hollow and Solid glass blocks



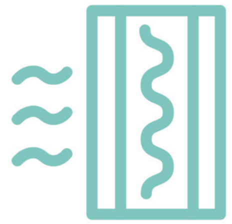
04 Design Guidelines

Design Considerations and Criteria

The research in the field of hybrid glass block is fairly new and therefore establishing design criteria is crucial. These criterions are developed from the inferences of the literature study and building codes (Eurocodes, Bouwbesluit and Shanghai local regulations). These also take into account the considerations for manufacturing and installation.

Compressive Strength

The value for Hollow block is between 2.75 to 6 MPa (Seves n.d) whereas for Solid block is around 400 MPa. (Pittsburgh Corning Corporation, 2007) Therefore, the compressive strength of Hybrid block is aimed at 15-20 MPa. This comes from an understanding that a regular clay brick used for load-bearing construction has a value around 6 to 20 MPa depending upon the type and class of brick (Singhal et al, n.d.) Therefore, the higher value of 400 MPa is also not required and may be redundant. This assumption can be investigated through experiments. However, for this research, various examples will be studied to derive an appropriate size to ensure the load bearing capacity.

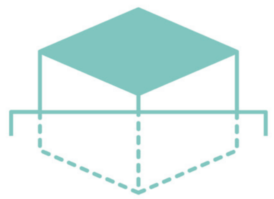


Thermal Insulative properties

The U-value for Hollow block is between 1.5 – 1.8 W/m^{2}K (Seves n.d.) whereas for Solid block is around 4 W/m^{2}K. (Pittsburgh Corning Corporation, 2007). The different building codes suggests the following maximum U-values for glazed part of facades:

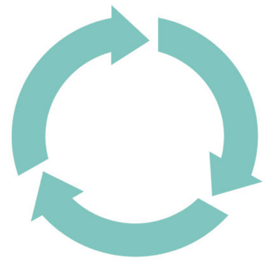
Dutch Building Code <1.65 W/m2K
Eurocode <2.2 W/m2K
Local code <2.5 W/m2K (Chinese National Building Codes)

Therefore, the U-value target of Hybrid block is aimed between 1.5 – 2.2 W/m^{2}K. This comes from the fact that the building codes suggest a maximum U-value of 2.2 W/m^{2}K for glazed façade. Therefore, this range is optimum.



Ease of Manufacturing

Ease of fabrication is important because the amount of material used, energy required to produce, total cost, mold design and annealing time are some factors that can have a great impact on the overall feasibility of the design. However, it is nearly impossible to estimate the true cost and energy required to produce an alternative so an assumption in based on simple logic and complexity of the design. For example, the addition of noble gas is considered an extra step in the manufacturing process as it requires the block to be sealed in a special chamber consisting of that noble gas which can complicate the production process.



Recyclability

Recyclability is a vital factor when designing with glass. Glass, in pure quality can be re-melted to form into different components again and again without losing its quality. However, the presence of coatings renders the block non-recyclable as it is difficult to remove them from the block, so the glass cannot be remelted to form a new shape.

Optical Quality

The quality of transparency is what makes glass a very attractive façade material for architects and designers. Therefore, it is evaluated by calculating the number of refracting surfaces in the design. Every transition from glass to air results in loss of optical quality and image distortion.

Others

Sound Transmission

The value for Hollow block is between 43-50 dB whereas for Solid block is around 43 – 53 dB. For hybrid glass blocks, this needs to be derived through experiments and is beyond the scope of this research.

Durability

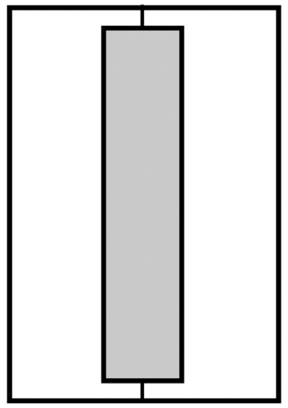
The hybrid glass block system should be fire resistance, water-tight and scratch resistant. Building codes suggests a fire rating of 45-minutes UL or Euro class A1. But the verification for the same is beyond the scope of this research.

04.2 Concepts to improve Thermal Performance

The literature study concluded that various methods can be employed to improve the thermal performance of the system.

Concept 1a: Altering cavity sizes

As observed from the literature study, the cavities make a tremendous impact on the overall performance. Another important parameter is the size of the thermal bridge resulting from the glass edge. Therefore in this concept, different options can be studied with single and double cavities of various widths by changing the cross-section thickness of the glass block .

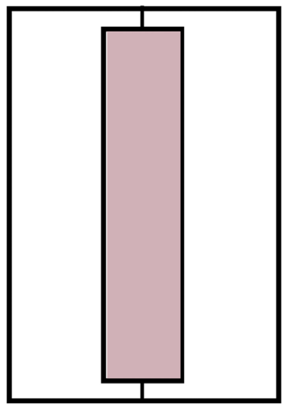


Concept 1a

FIGURE 60: Figure showing section illustration of Concept 1a

Concept 1b: Adding additional insulating material

The addition of extra insulative material in the cavity will further increase the thermal performance of the system. The insulating materials here would be an inert gas as it is the most feasible and cost effect solution.

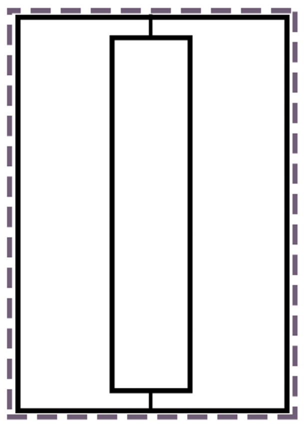


Concept 1b

FIGURE 61: Figure showing section illustration of Concept 1b

Concept 1c: Applying coatings

The coatings also affect the thermal performance, however this option will be analyzed if the above two concepts doesn't work. This is because, coatings make the glass non-recyclable.



Concept 1c

FIGURE 62: Figure showing section illustration of Concept 1c

04.3 Concepts to improve Structural Performance

The literature study concluded that shape plays an important role in stabilizing the block and, in turn, the overall assembly. Therefore, this chapter discusses the ideas that will be explored to improve upon the structural performance.

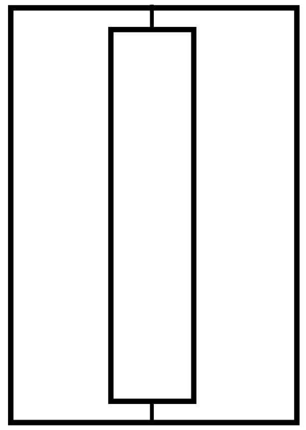


FIGURE 63: Figure showing section illustration of Concept 2a

Concept 2a: Altering the cross-section thickness

As discussed earlier, the main problem with hollow glass blocks not being load-bearing is their thin cross-sectional area. Therefore, it makes sense to alter the block's cross-sectional thickness to provide sufficient area for transferring the load.

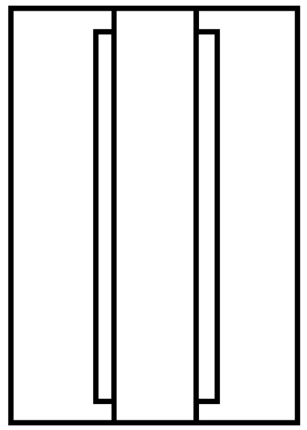


FIGURE 64: Figure showing section illustration of Concept 2b

Concept 2b: Providing coated glass in middle

The idea behind this concept is derived from Seves glass block discussed in Chapter 3, The coated glass can be very thin but will divide the cavity into two parts; thus more area will be available for load transfer with good thermal resistance.

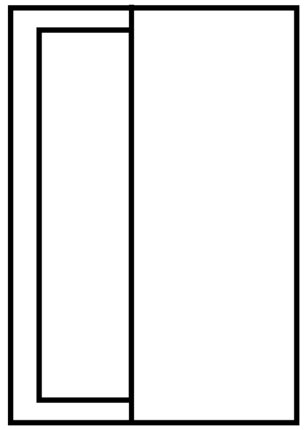


FIGURE 65: Figure showing section illustration of Concept 2c

Concept 2c: Combining hollow and solid glass block

The idea is to combine one half of the hollow block and a solid glass block with a cavity between them so that the solid part carries the load and the cavity helps with the insulative value.

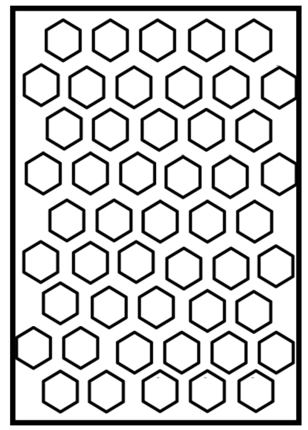


FIGURE 66: Figure showing section illustration of Concept 2d

Concept 2d: Honeycomb structure

It is a well-known fact that honeycomb structures are remarkably stable; therefore, it makes sense to develop a glass block with this technique with smaller but many air pockets that help with the heat resistance.

Concepts	Structural Performance	Ease of manufacturing	Transparency & Optical distortion	Recyclability	Final Score
Concept 2a: Increasing thickness of cross-section	++++	++++	+++	++++	++++
Concept 2b: Merging hollow section with solid block	++++	+++	++++	++++	++++
Concept 2c: Providing coated glass in middle	+++	++++	++	++++	+++
Concept 2d: Honeycomb Structure	++++	++++	+	++++	+++

TABLE 10: Table showing scoring chart for concepts to improve structural performance

04.4 First Ideas

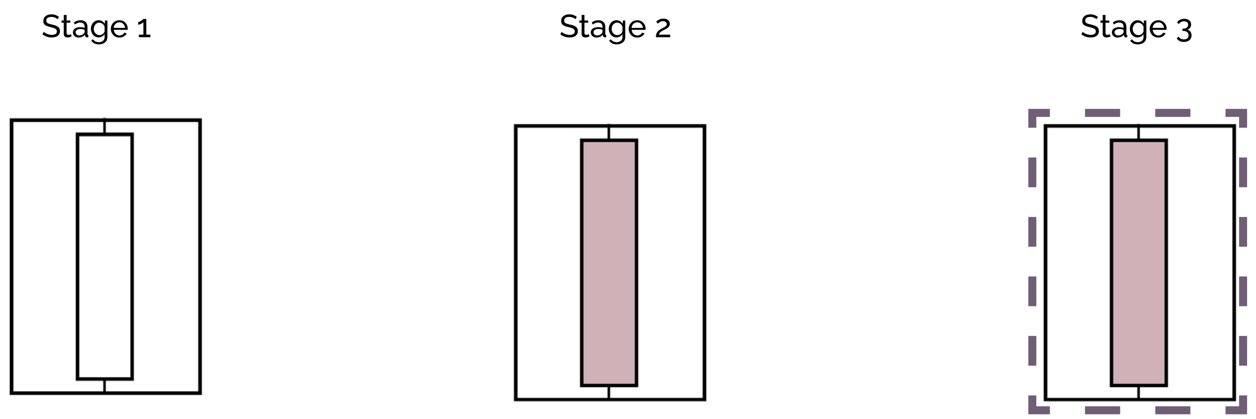
The first ideas are developed by combing the most potential concepts from both and evaluating them based on their thermal performance, structural performance, ease of manufacturing, transparency/ optical distortion and recyclability.

The most suitable concepts for improving thermal performance are derived from a thorough literature study and therefore all the three would be combined with the concepts for improving structural performance and would be further developed. This will be done in stages where the first stage would comprise of changing air cavity widths, in the second stage inert gas can be added and lastly coatings can be applied to further enhance the performance.

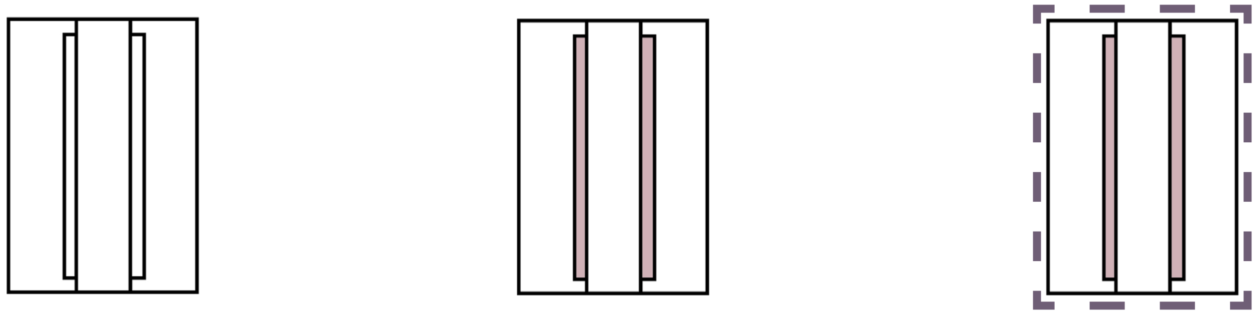
In the table analyzing the structural performance, it can be understood that all the concepts have great potential as most of them score really well in structural performance, ease of manufacturing and recyclability. The deciding factor could be transparency and optical distortion which can be analyzed further during the design phase.

04.5 Overview

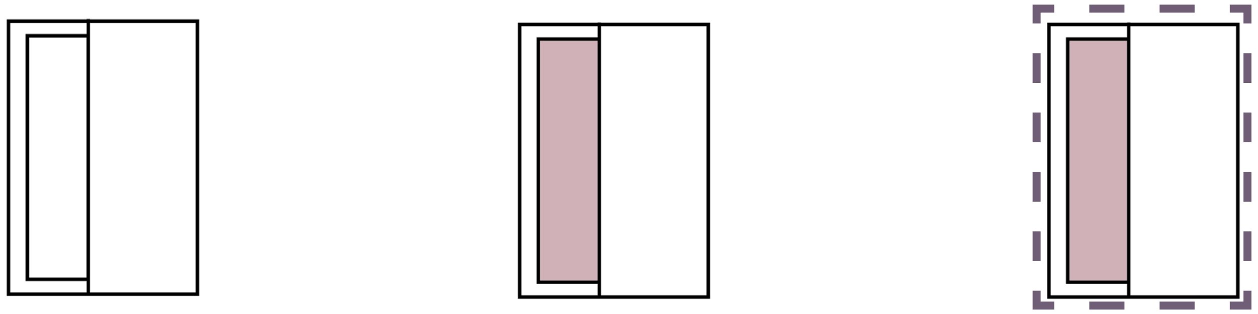
The design criteria mentioned in this chapter will be the basis of evaluation of all the different design concepts developed further. At this stage, a basic assumption is made for all the concepts to pick the most suitable and potential options to be analyzed further. All the different concepts to improve structural performance vary from each other vastly. Thus, combining it with concepts to improve thermal performance generates multiple different iterations to be analyses as can be seen in Fig 67. These first ideas will be detailed out, assessed and validated in later stages and will be verified with the assumptions made in this stage.



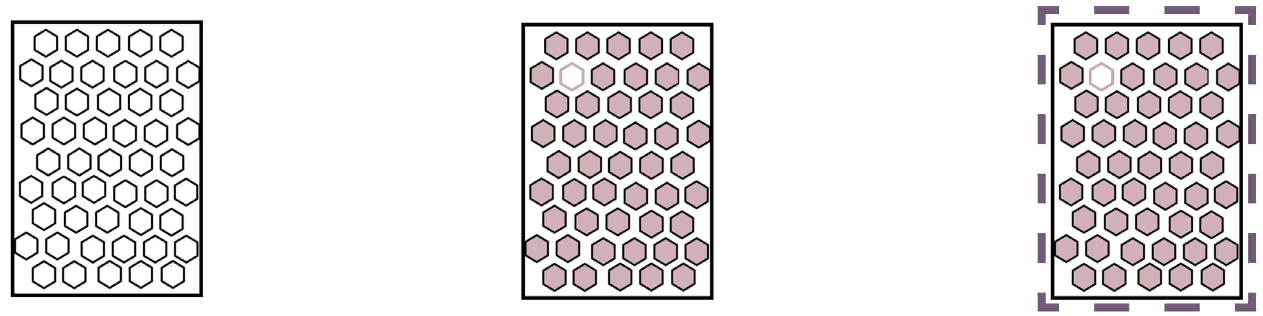
Concept 2a: Increasing the cross-section thickness by changing cavity sizes in stage 1, adding inert gas in stage 2 and applying coatings in stage 3.



Concept 2b: Providing low-e coated glass section in middle and analyzing it for different cavity sizes stage 1, adding inert gas in stage 2 and applying coatings in stage 3.



Concept 2c: Merging different thickness of hollow and solid glass block cross-sections and analyzing it for different cavity sizes stage 1, adding inert gas in stage 2 and applying coatings in stage 3.



Concept 2d: Developing different patterns for the Honeycomb structure by playing around with different cavity sizes and testing them for thermal performance in stage 1, adding inert gas in stage 2 and applying coatings in stage 3.

FIGURE 67: Figure showing most probable combinations - First Ideas

05 Thermal Investigation

This chapter investigates various approaches taken to increase the thermal performance of the glass block system by reducing its thermal transmittance. Various strategies are formulated by changing the design at the unit level by incorporating cavities, adding insulative materials, or using coatings for different blocks. All the concepts are then validated in TRISCO to identify the best possible solution. The chosen solutions are then compared based on other design criteria for the system to fix the final and optimum solution.

05.1 Design Considerations

The various options developed for different concepts were carried out for blocks of thickness 50mm, 100mm, 150mm, and 200mm (Fig 68). Different cavity sizes from 10mm to 50mm were analyzed. One of the problems (as mentioned in the Chapter 3) with the structural stability of hollow glass blocks is their thin cross-section. Therefore, it was made sure that the glass thickness is always kept more than the cavity width to avoid extremely thin cross-sections for all combinations of glass blocks in different concepts. Another consideration was to avoid very thick glass sections due to the prolonged annealing time. (Chapter 3)

05.2 Methodology

Stage 1:
The first stage of analysis is done with simple air cavities without any coatings on glass. For this analysis, the cavities are considered unventilated, which according to Eurocodes NEN-EN-ISO6946, is one in which there is no express provision for airflow through it. The design values of thermal conductivity are given in Table 11.

Stage 2:
In the second stage, the two best options from every block size and concept are picked at the end of stage 1 to be analyzed in this step. The analysis is carried out with changing air cavities with cavities filled with inert gas to improve the thermal resistance values further. Argon gas is selected compared to others because it is the commonly used noble gas for Insulated Glass Units (Saint Gobain, 2016) Filling cavities with noble gas causes a change in heat transfer through conduction and convection. The design values for thermal conductivity of argon in different cavity sizes are given in Table 11.

Stage 3:
In the third stage, to further improve the thermal resistance, coatings are applied on the glass surfaces. These coatings change the emissivity value of the surfaces and impact the heat transfer through radiation and thereby change the total thermal resistance values of the cavity. Here a silver coating is used with an emissivity value of 0.02 as it is the commonly used coating type in window glazing (Ding G. & Clavero C., 2017). These coatings can be applied either on the inside surface of the outer glass or outside the inner glass surface, depending on whether it is applied to stop heat from entering or retaining it inside the room.

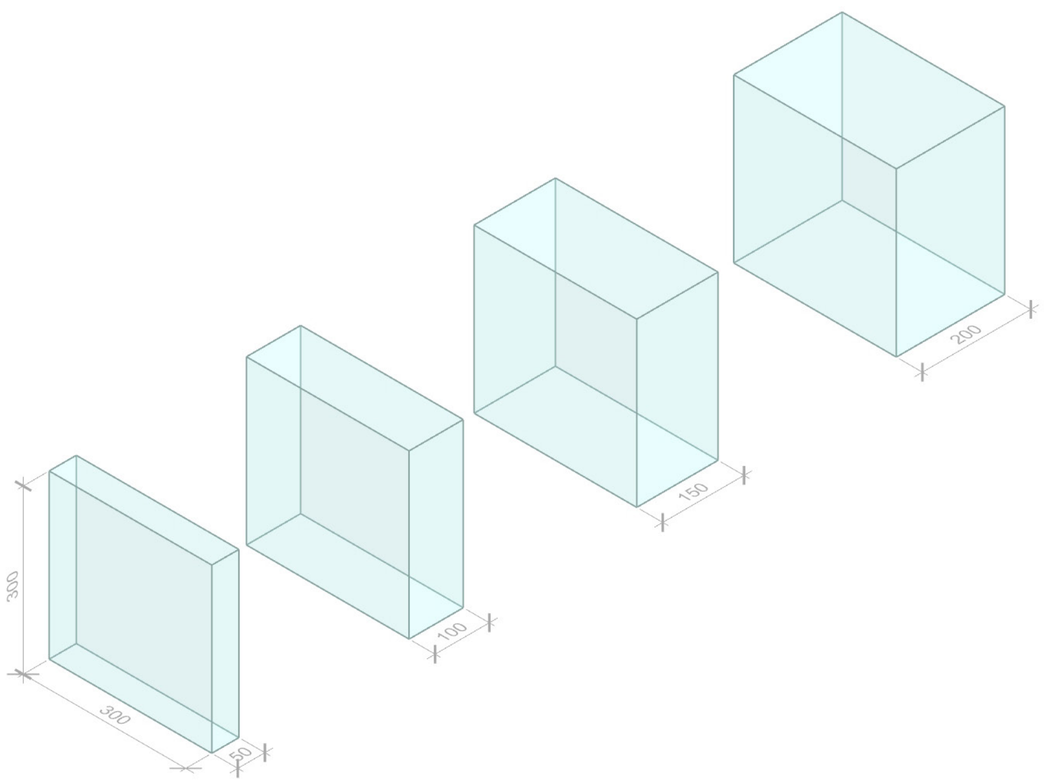


FIGURE 68: Figure showing different block widths

These options are then compared concept-wise, and all options that satisfy the target for thermal transmittance values are selected. They are then compared based on their structural performance, ease of manufacturing, recyclability, transparency, and optical distortion. Out of the shortlisted options, the two best designs are picked and developed in the next stage.

Naming Criteria

The specimens have been named according to the concept, block size, coating, cavity number, width, and filling, as shown in Fig 70.

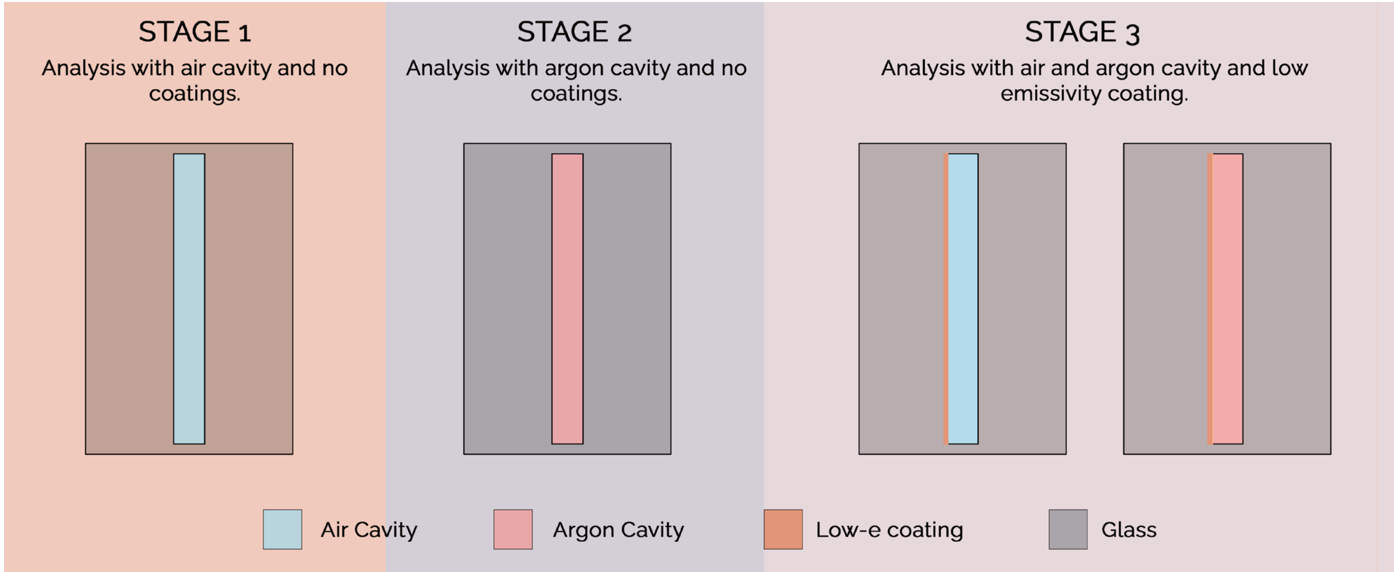


FIGURE 69: Figure showing methodology for thermal analysis

Cavity Width	Cavity Filling	Thermal Conductivity (W/mK)	
		No Coating	With Coating
10 mm	Air	0.066	0.026
	Argon	0.056	0.016
15 mm	Air	0.088	0.028
	Argon	0.0789	0.018
20 mm	Air	0.1184	0.038
	Argon	0.105	0.025
25 mm	Air	0.1485	0.049
	Argon	0.131	0.032
30 mm	Air	0.1785	0.06
	Argon	0.158	0.04

TABLE 11: Table showing different thermal conductivity values for air and argon gas for various cavity widths

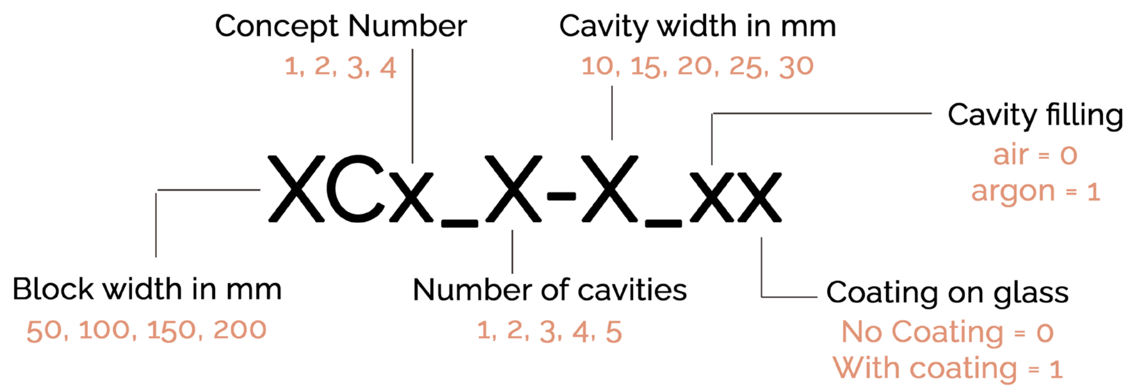


FIGURE 70: Figure showing naming criteria

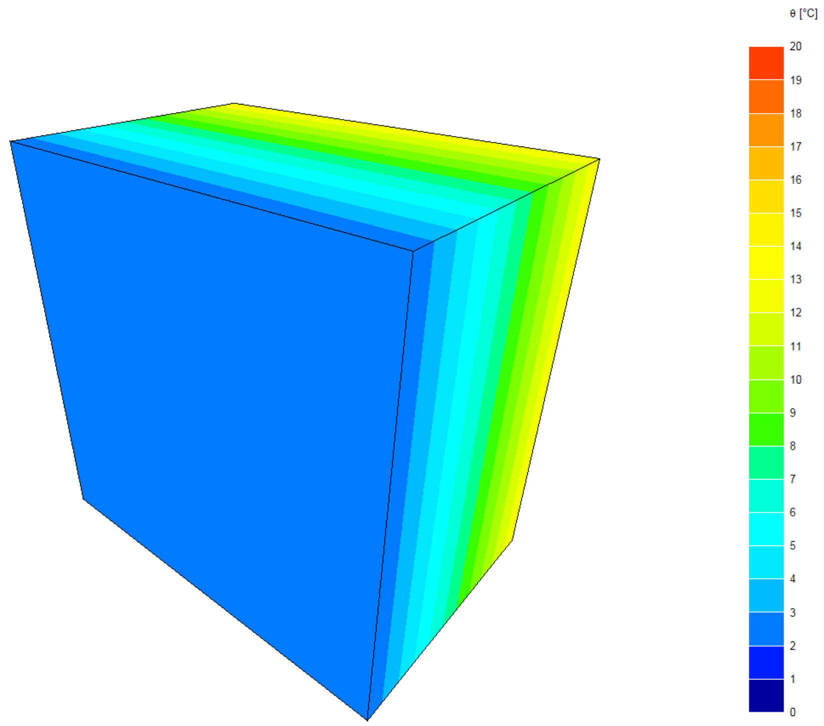
05.3 Validation of Software

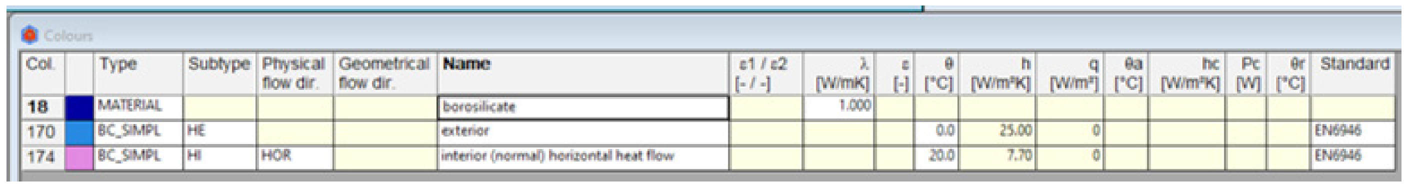
TRISCO is a software used for steady state thermal FDM simulations of two dimensional or three-dimensional orthogonal building components. The steady state thermal analysis means that an equilibrium has been found with the loading conditions and the simulations continues independent of the time. All thermal loads and boundary conditions are constant in time. The parameters and boundary conditions entered in the software are shown below in Table 12.

To validate the software simulations, a simple hand calculation was performed for solid brick of different sizes. This was then measured against the simulated value from TRISCO. The model was accurate up to 99%.

Standard Dutch values for a_i and a_e					
	α conduction	α convection	α radiation	α total	r
inside	0 W/m^{2}K	2.3 W/m2K	5.5 W/m2K	7.7 W/m2K	0.13 W/m2K
outside	0 W/m2K	19.5 W/m2K	5.5 W/m2K	25 W/m2K	0.04 W/m2K
Temperature					
inside	20 °C				
outside	0 °C				
Glass properties					
Glass Type	conductivity	emissivity			
		with coating		without coating	
Borosilicate	1.0 W/mK	0.9		0.02	

TABLE 12: Table showing boundary conditions used for the thermal analysis in TRISCO





Colours

Col.		Type	Subtype	Physical flow dir.	Geometrical flow dir.	Name	ε1 / ε2 [-/-]	λ [W/mK]	ε [-]	θ [°C]	h [W/m²K]	q [W/m²]	θa [°C]	hc [W/m²K]	Pc [W]	θr [°C]	Standard
18		MATERIAL				borosilicate		1.000									
170		BC_SIMPL	HE			exterior				0.0	25.00	0					EN6946
174		BC_SIMPL	HI	HOR		interior (normal) horizontal heat flow				20.0	7.70	0					EN6946

FIGURE 71: Figure showing thermal analysis and boundary conditions for solid glass block


```
TRISCO - Calculation Results

TRISCO data file: 060221_solid_150.trc

Number of nodes = 15376
Heat flow divergence for total object = 6.96707e-07 %
Heat flow divergence for worst node = 0.00086557 %

Ublock = (Q/(ti-te))/A1 = 3.126 W/(m².K)
  Q = 5.627 W
  ti = 20.0000°C
  te = 0.0000°C
  A1 = 0.09 m²
       Xmin=16 Xmax=16 Ymin=0 Ymax=30 Zmin=0 Zmax=30

Col. Type      Name                         tmin     X    Y    Z      tmax     X
Y    Z
                                            [°C]                      [°C]
_
18   MATERIAL  soda_lime                  2.5010    16   16   16   11.8798     1
0    1
170  BC_SIMPL  exterior                   2.5010    16   16   16    2.5010    16
2    4
174  BC_SIMPL  interior_(normal)_horizon 11.8798     1   20   24   11.8798     1
0    1

Col. Type      Name                           ta   Flow in  Flow out
                                            [°C]      [W]       [W]
170  BC_SIMPL  exterior                             0.0000    5.6273
174  BC_SIMPL  interior_(normal)_horizon            5.6273    0.0000
```

Name	Thickness	Thermal conductivity	Surface heat transfer coefficient	Convective resistance	Radiative resistance	Total thermal resistance
	m	W/mK	W/m^{2}K	m^{2}K/W	m^{2}K/W	m^{2}K/W
outdoors			25.000			0.040
glass	0.1500	1.0000				0.150
indoors			7.700			0.130

(teal)	Input Values
(pink)	Calculated Values
(orange)	Result

R_{total} [m^{2}K/W]	0.320
U [W/m^{2}K]	**3.126**

TABLE 13: Table showing hand calculation of U-value for Solid glass block of width 150mm.

05.4 Design Concepts

Concept 1: Altering Cavities

In this concept, different options were made with single and double cavities of various widths by changing the cross-section thickness of the glass block of various sizes. The cavities are located perpendicular to the path of heat transmission.

<u>Observation Stage 1 (Fig 76-77)</u>

It was observed that for the blocks with a single cavity, the cavity width, 25mm and 30mm performs the best in block dimensions of 100mm, 150mm, and 200mm. These cavity widths are not possible in a block of 50mm due to the resulting thin cross-section of the block, and therefore, cavity widths of 15mm perform well. In the single cavity designs, a larger cavity benefits the whole system. However, air cavity sizes more than 30mm are not recommended as they reduce the thermal resistance due to convective heat transfer within the cavity.

In the blocks with a double cavity, widths of 15mm and 20mm perform the best for 100 and 150mm blocks. It is also vital to notice that a block with a thicker overall width performs better with all the different sizes of cavities in all the options with single and double cavities.

<u>Observation Stage 2 (Fig 76-77)</u>

The desired thermal values were not achieved in Stage 1, therefore; the blocks that perform well were chosen and simulated with argon filling in the cavity. In this stage, there is very little difference found in the U-values of block of same size with cavity width difference of 5mm and the desired value is still not achieved. Hence, blocks with a lower cavity width and thicker glass cross-section were chosen for further analysis in stage 3.

<u>Observation Stage 3 (Fig 76-77)</u>

In stage 3, the analysis is further carried out by having a coating on one of the glass parts. It is again carried out by filling air and argon in the cavities. In single cavity design, block widths of 150mm and 200mm generates a U-value within the desired range but thin sections fail to perform well. However, the desired range of U-values are achieved in double cavity options.

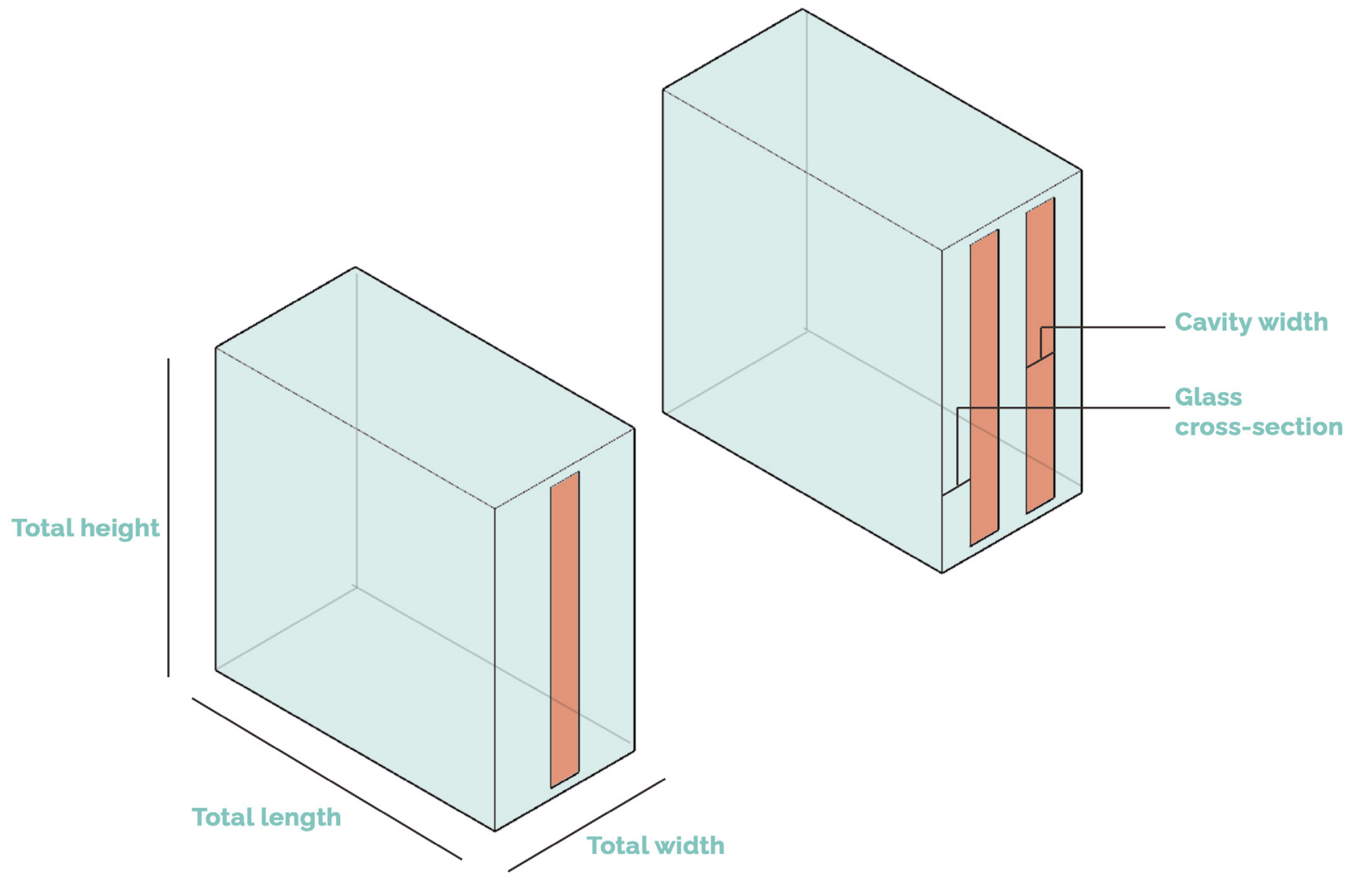


FIGURE 72: Figure showing Concept 1

Concept 2: Providing coated glass in the middle

This concept has blocks that are equipped with a 5mm thin coated glass in between them. This thin glass ensures that the cavity is divided into two parts. Thus, the glass cross-section remains thick, but it performs similarly to a double cavity block. The coating helps in further aiding in the improvement of the thermal resistance of the cavities.

<u>Observation Stage 1 (Fig 78)</u>

It can be observed that cavity performance remains the same as double cavity design options, with 15mm and 20mm cavities performing the best for 100 and 150mm. One interesting observation is that the thicker glass cross-section does not necessarily perform the best all the time in this option. E.g., the block 150mm with a 20mm cavity performs better than the block 200m with a 10mm cavity. This is because, in the case of 200mm with a 10mm cavity, the glass thickness is considerable compared and impedes the effect of the cavity.

<u>Observation Stage 2 (Fig 78)</u>

In stage 2, there is a difference of around 1W/m2K observed in blocks with air and blocks with argon. There is also a significant difference between two blocks of same size with cavity width difference of 5mm. Since this concept already has a coated glass, it is not further analyzed for stage 3. Also, the desired value of U-values is achieved in most blocks.

Concept 3: Merging Hollow block with solid

This concept is designed to have one part take the structural load and increase the system's thermal performance. The thin cross-section aiding in the U-value can be as thin as the float glass as it makes up the non-load bearing part of the system. Therefore, different cross-sections are studied with the thin part ranging from 2.5mm to 45mm. It was derived based on the idea that the solid part of the block is no more than 100mm to avoid very thick sections due to issues of prolonged annealing time. Because of this, reason block of 200mm is not developed for this concept.

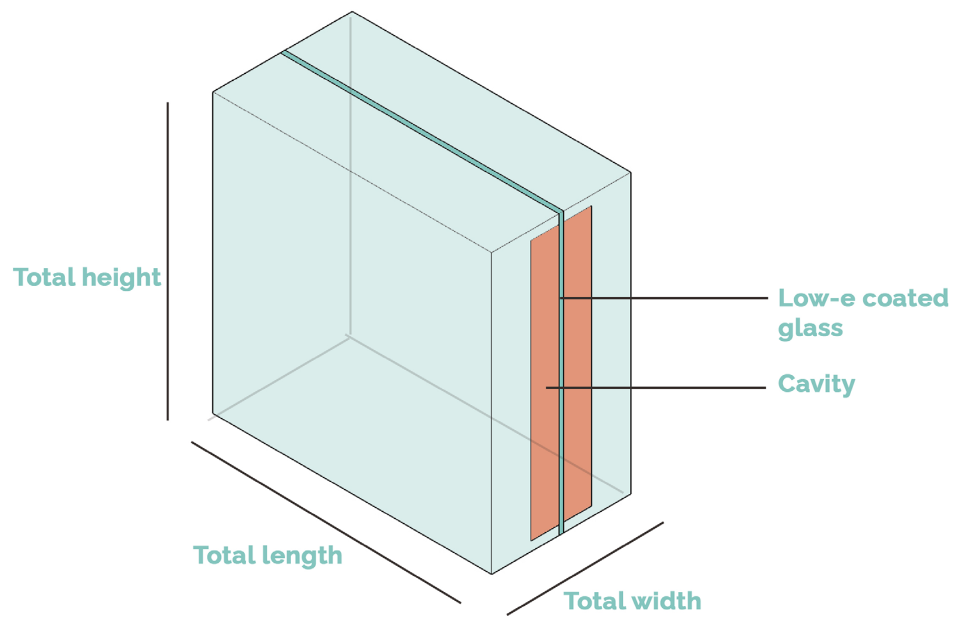


FIGURE 73: Figure showing Concept 2

Observation Stage 1 (Fig 80-82)
In this concept, the blocks with a thin cross-section of the hollow parts perform better due to the lower thickness of the thermal bridge. As the cross-section increases, so does the thermal bridge, which impacts the block's thermal resistance. It is crucial to keep the cross-section of the hollow part the same because of the ease of manufacturing. If there is uneven thickness, it will lead to unequal cooling time, which can cause internal stresses in the component. As for the cavity, the cavity size of 20mm performs well in all the options.

Observation Stage 2 (Fig 80-82)
The results for stage 2 suggest improvement in the U-values of the block of overall width 50mm and 100mm but no significant improvement in 150mm block. The reason for this is the large thermal bridges in this block. Here much like the single cavity design, the U-values are not obtained in the desired range. Therefore, these options are further analyzed in stage 3.

Observation Stage 3 (Fig 80-82)
In this stage, it is simulated with cavities filled with air and argon. Blocks of 50mm and 100mm width achieve the expected results with Block 50mm performing better due to reduced thickness of thermal bridges. However, there is no significant difference in the U-value for block 150mm.

Concept 4: Honeycomb Structure

This concept is developed to have multiple small pockets of cavities. The multiple cavities help increase the thermal resistance and perform well structurally because of even load distribution and redundancy present in case of failure. In this concept, Block 200 is not developed because of the problems with thick cross-sections, as explained before. For this, four different patterns were developed and investigated. The four patterns for different sizes of blocks are shown in Fig 79.

Observation Stage 1 (Fig 79)
Here it can be observed that pattern D performs the best in all the options. This is because there are multiple cavities that aid in the block's thermal resistance. Another important aspect is the absence of thermal bridges along the cavity length, which is present in other options. In other patterns, the division of the cavity leads to the formation of thermal bridges, which negatively impacts the overall performance of the block.

Observation Stage 2 (Fig 79)
In this concept, the U-values achieved in the previous stage are well withing the desired range so this step is carried out to further reduce it down by adding the noble gas. For block 50mm and 100mm, Pattern D is still the only one withing range while for Block 150mm, all the different patterns are in the desired range. Since most blocks achieve the desired thermal performance, they are not analyzed for stage 3.

Summary

After the analysis and observation, it can be concluded that more glass in the edge of the block leads to a larger thermal bridge effect; hence, higher U-value. The thicker layers of glass in the block increases the thermal bridge effect by deflecting more heat towards the edges hence resulting in higher U-value. However, the U-value at the center-of-block improves because of more thermal resistance. The resulting U-value of block depends on the balance between the two.

The thicker air cavity impacts the center-of-block U-value. However, it will slightly reduce the impact of the thermal bridge. Adding argon and a coating slightly improves the U-value further.

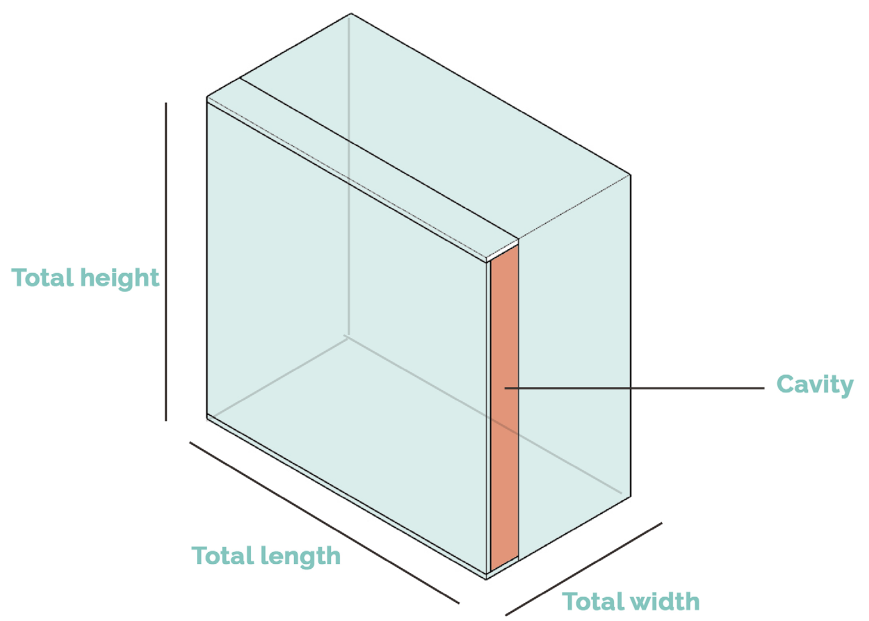


FIGURE 74: Figure showing Concept 3

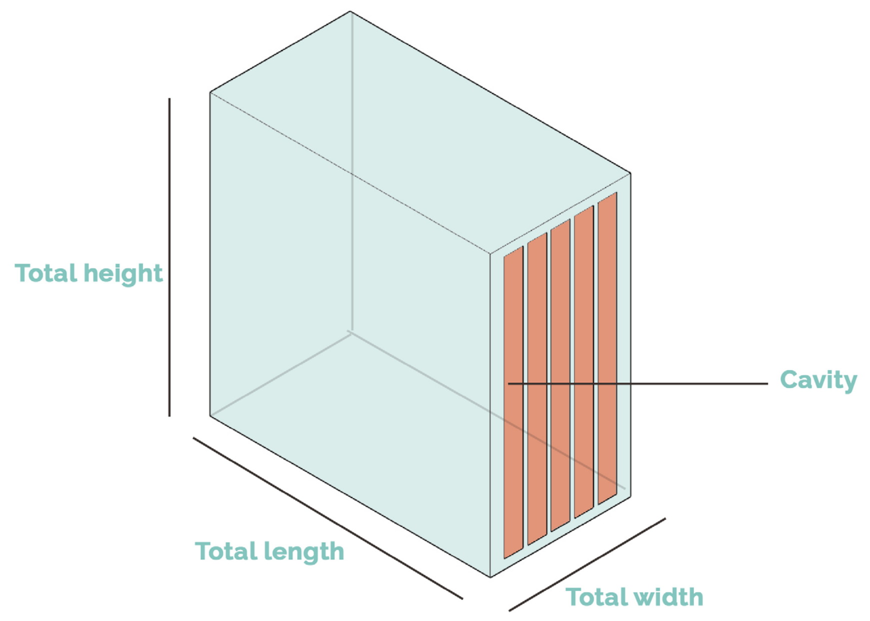


FIGURE 75: Figure showing Concept 4

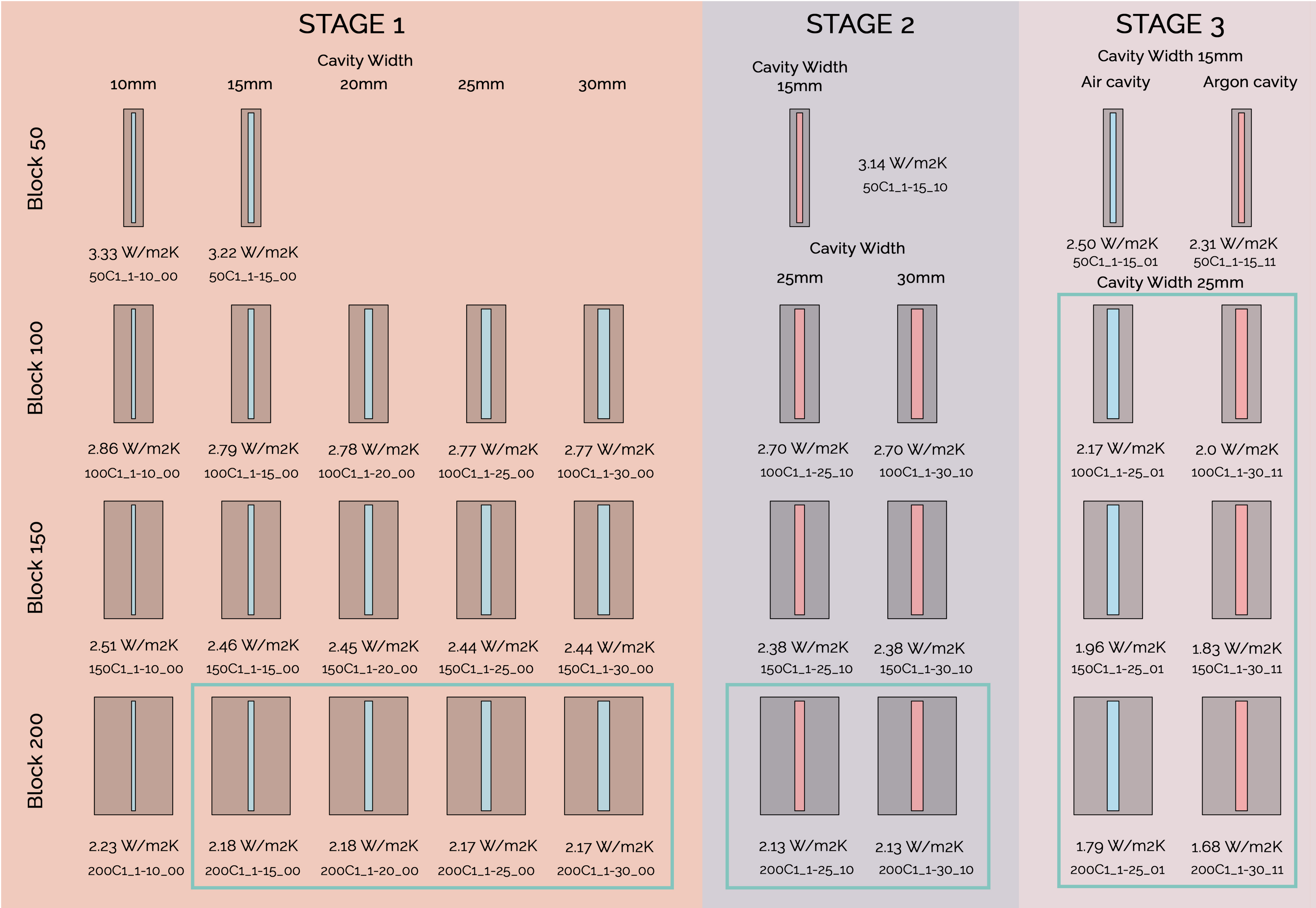


FIGURE 76: Figure showing analysis results form Concept 1: Single Cavity

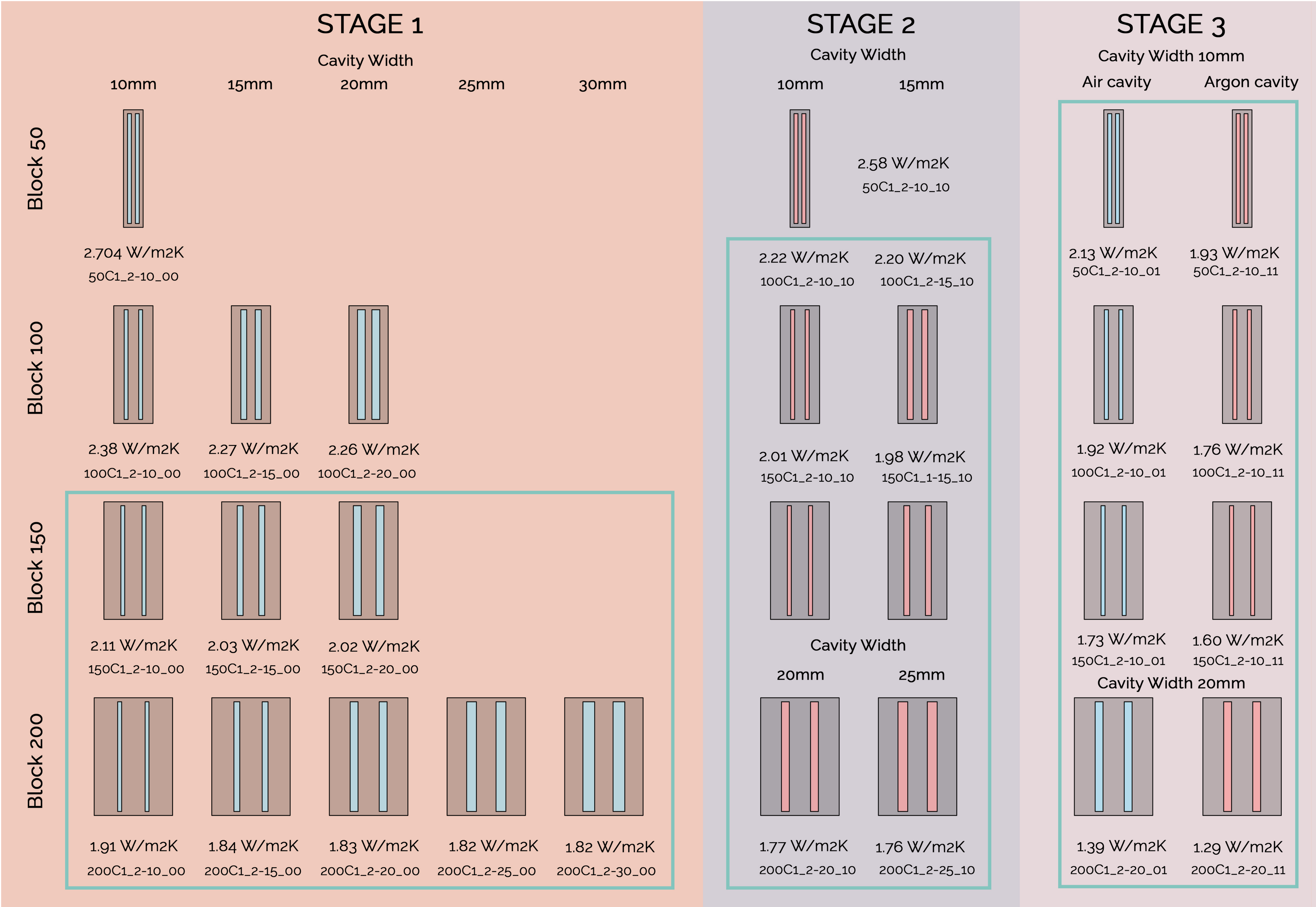


FIGURE 77: Figure showing analysis results form Concept 1: Double Cavity

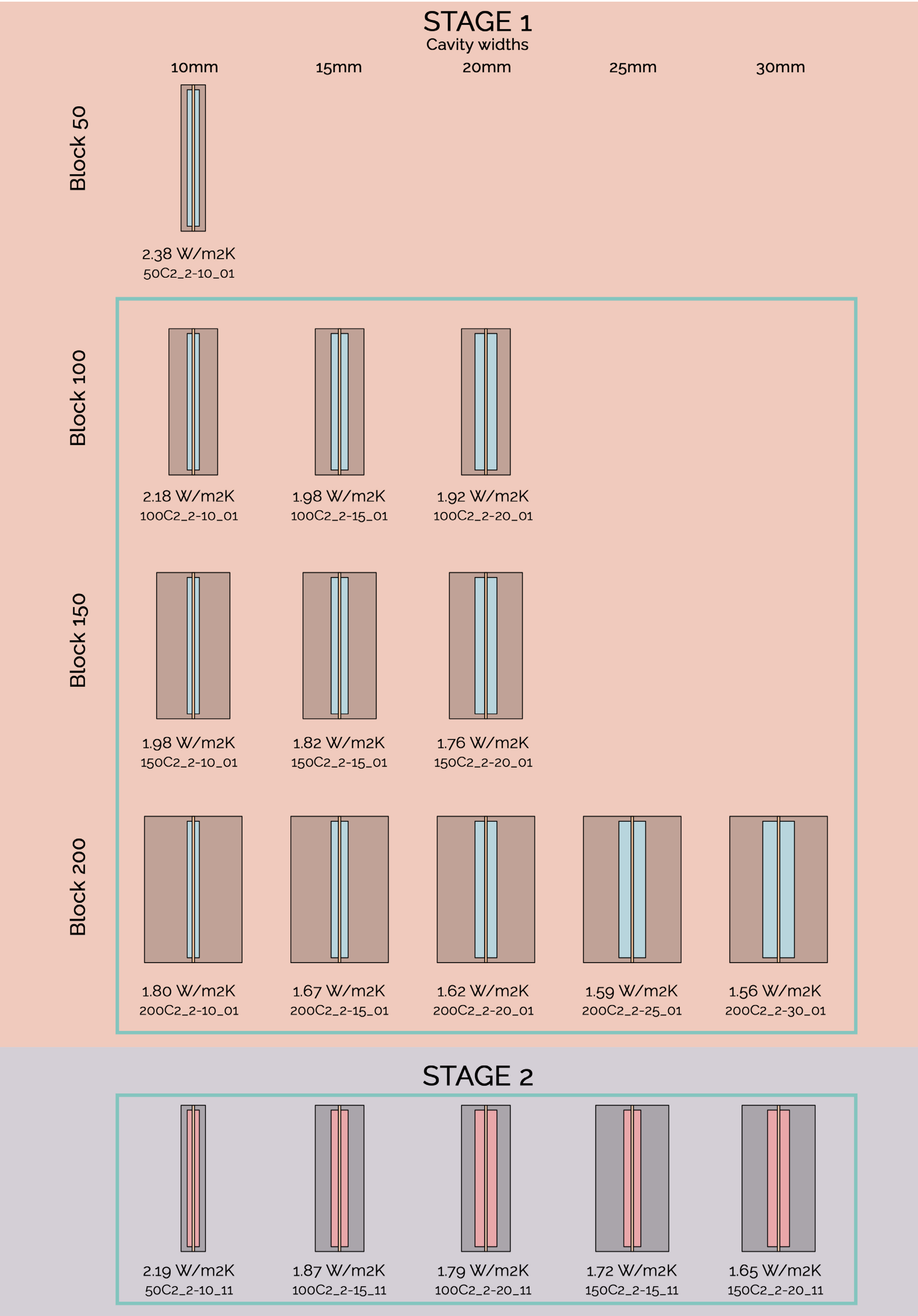


FIGURE 78: Figure showing analysis results form Concept 2

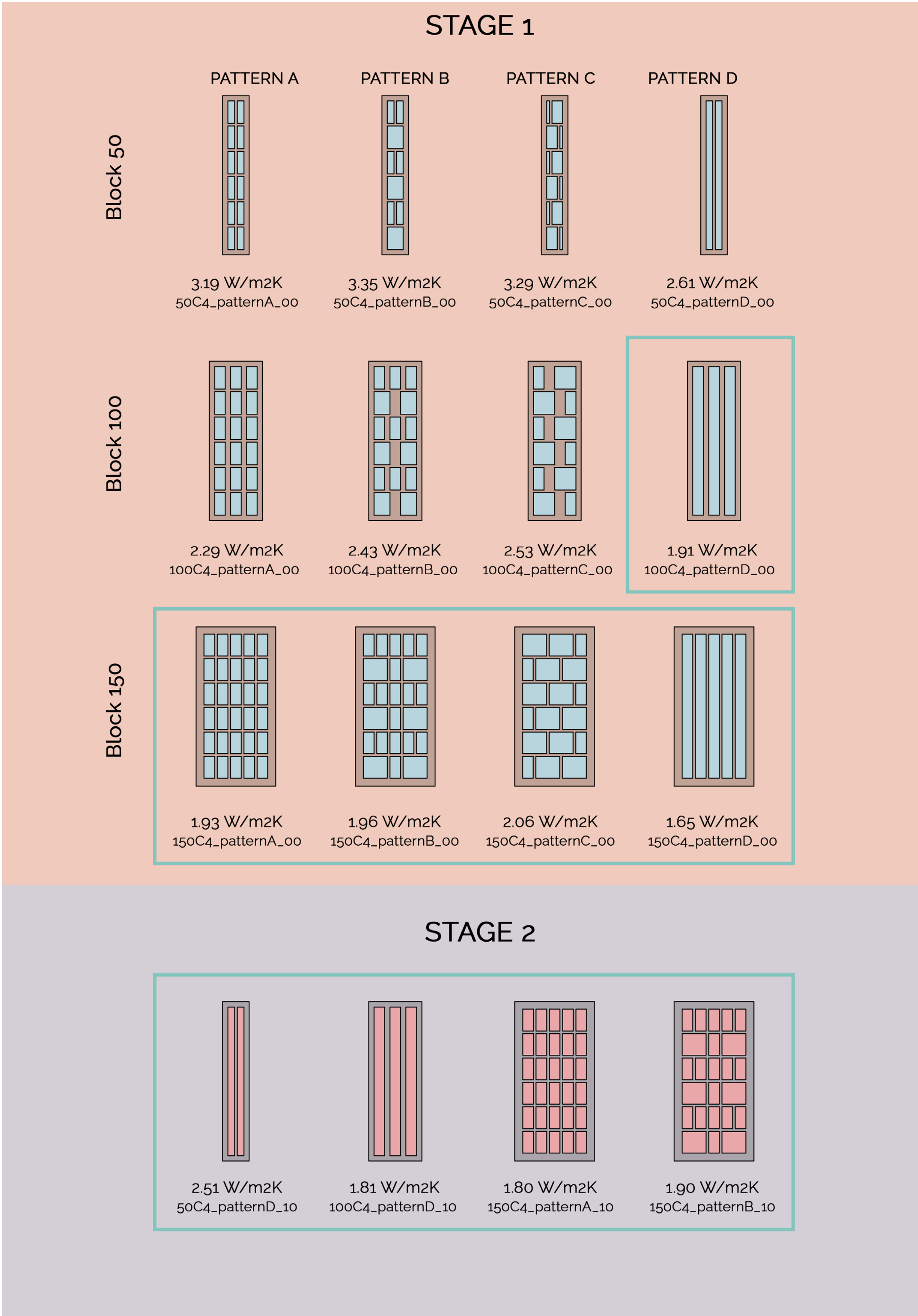


FIGURE 79: Figure showing analysis results form Concept 4

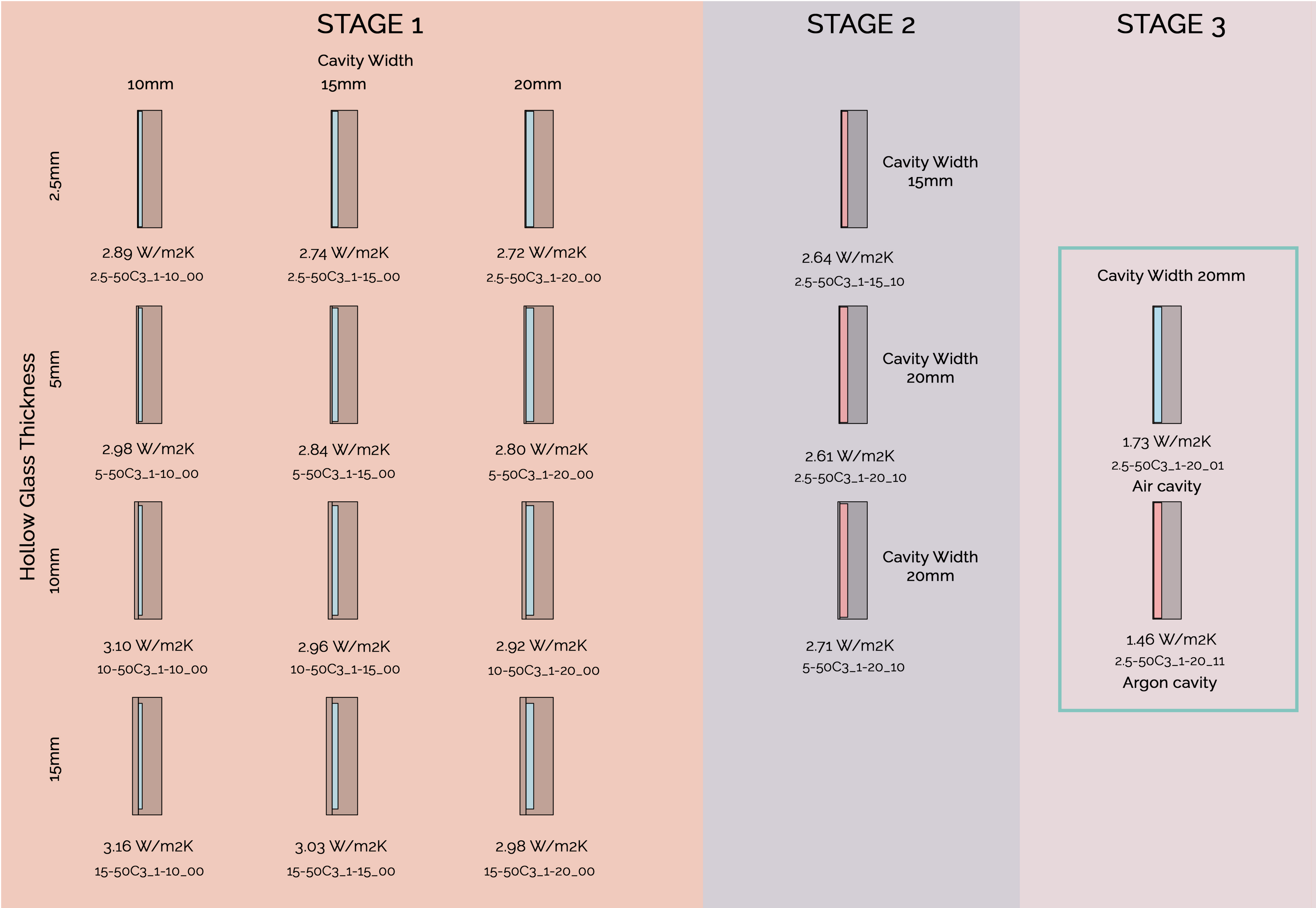


FIGURE 80: Figure showing analysis results form Concept 3: Block of 50mm

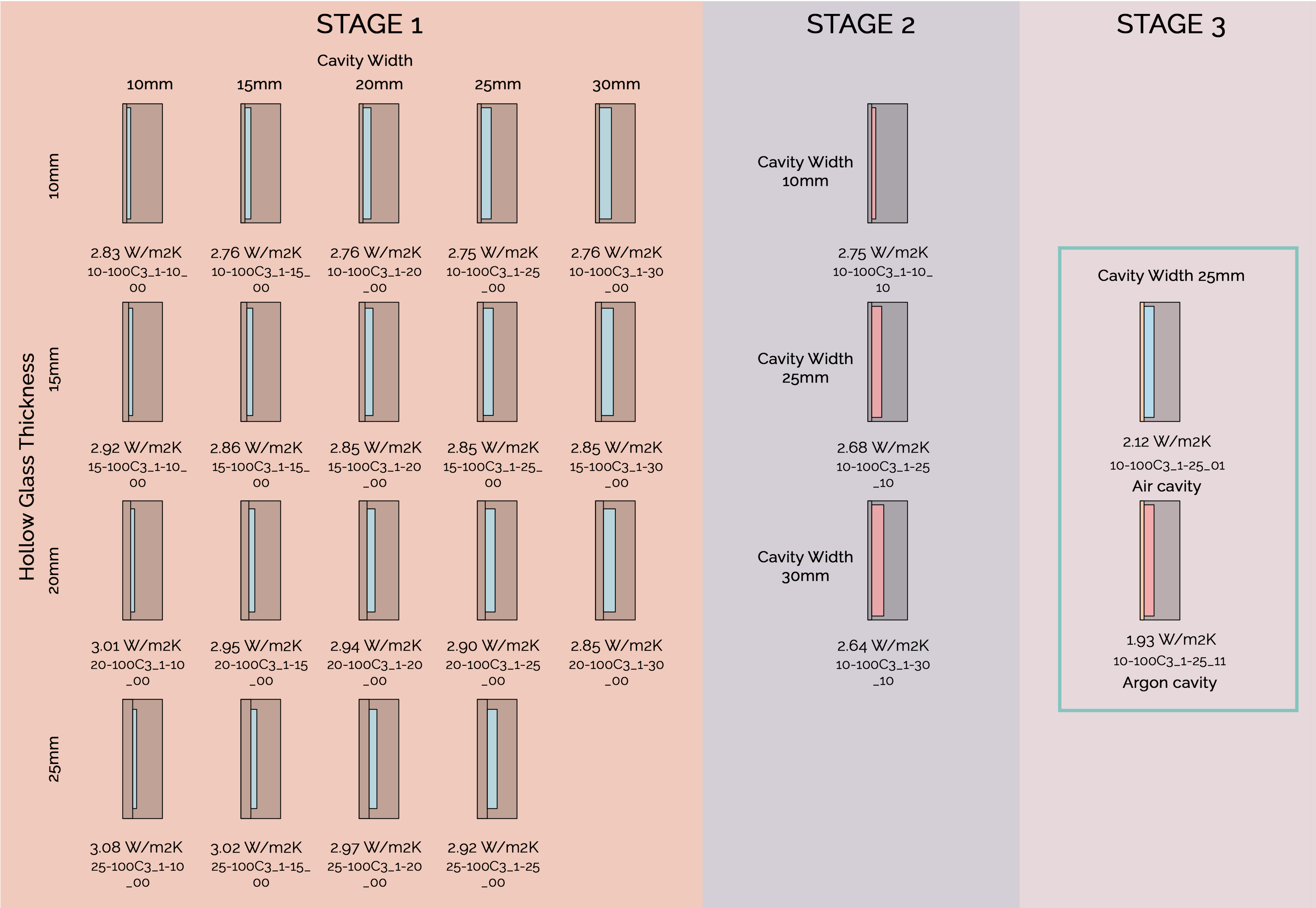


FIGURE 81: Figure showing analysis results form Concept 3: Block of 100mm

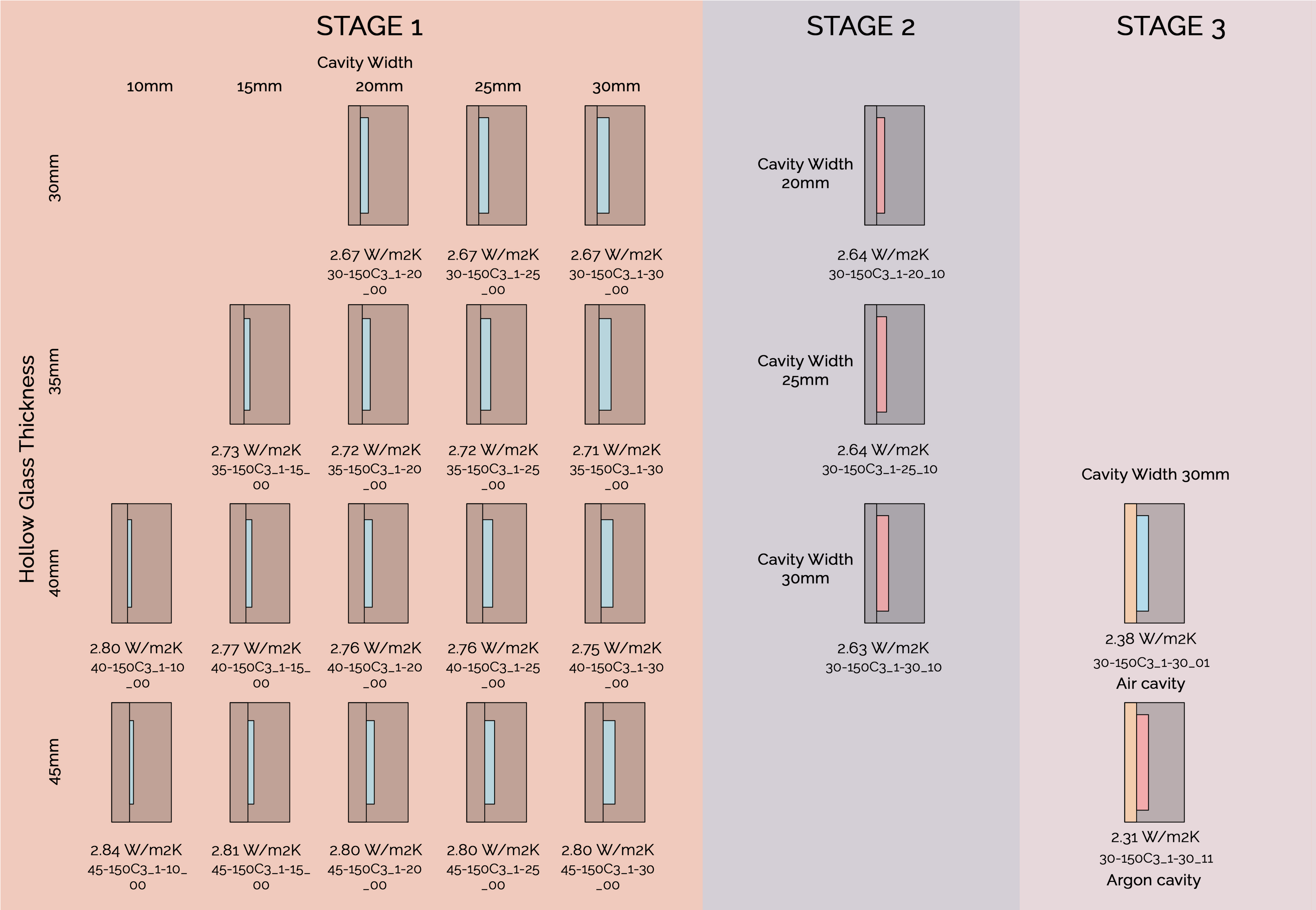


FIGURE 82: Figure showing analysis results form Concept 3: Block of 150mm

05.5 Evaluation of Concepts

All the concepts are then compared for all different block sizes. This comparison was done based on the results from Stage 1. These results give a true picture of the different concepts purely based on their design. It was observed that the performances of the concepts are as follows: C2 > C4 > C3 > C1.

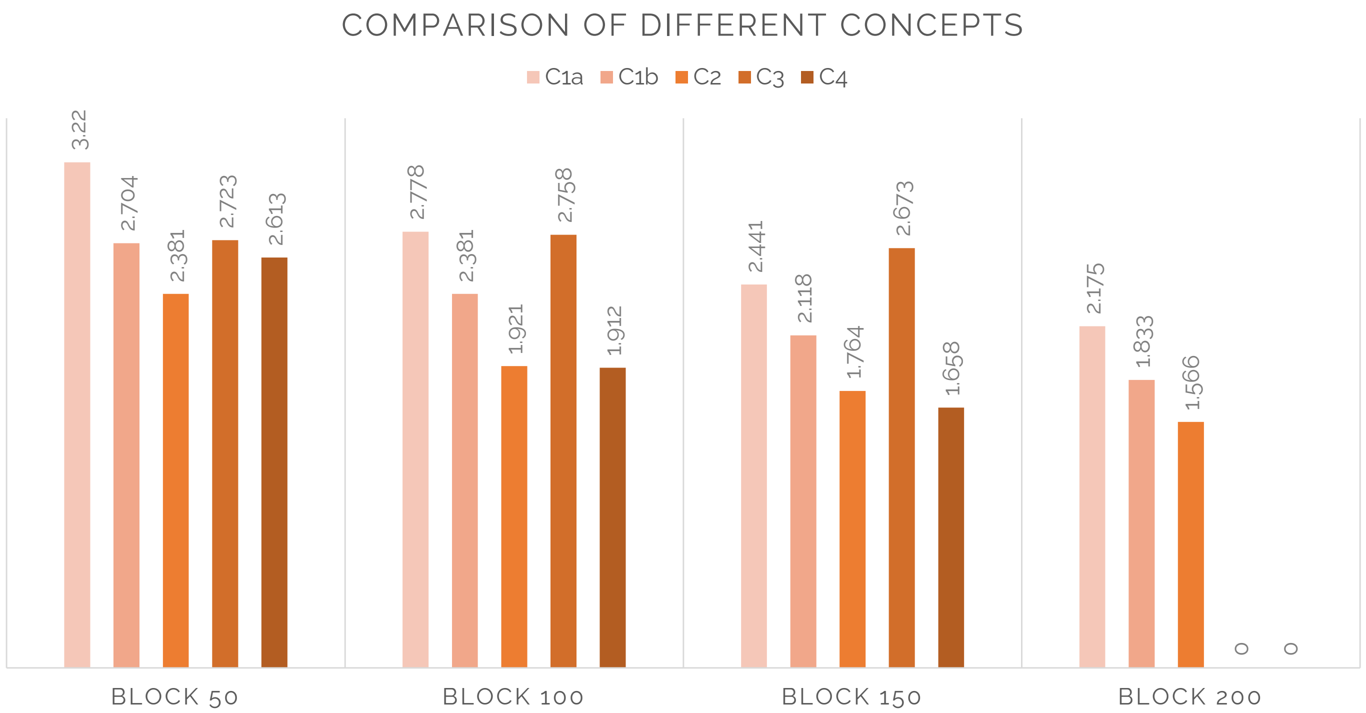
The reason for the excellent performance of concept 2 is that it has a coated glass in the middle. That tremendously improves the overall thermal performance, but having a coated glass also dictates that it will be difficult to recycle the block. Concept 4 proves to be very efficient just with simple air cavities and absence of any coatings. The multiple small cavities have a tremendous impact on the overall thermal performance. Although, having multiple cavities can cause optical distortion and reduce optical quality. As for concept 3 and concept 1, it is difficult to achieve the desired value in thin blocks of 50mm and 100mm. However, with the addition of noble gas and coatings, it becomes possible to achieve good thermal performance values. All the options that fulfill the design criteria are listed in Table 14.

05.6 Defining Criteria

The options in Table 14 are judged based on the primary design criteria mentioned in Chapter 4. The thermal performance is one of the most important criteria and all the blocks are compared based on their U-value. The blocks that comply with the stricter U-value norms of the Dutch regulations (<1.65 w/m2K) are rated equally in these criteria as they are well within the acceptable range of thermal performance.

At this stage, an assumption is made for the other criteria that is derived from lessons learnt in the literature study. For structural performance, it is assumed that a thick cross-section would perform better structurally but the cross-section thickness should not increase 100mm as it would lead to prolonged annealing time.

Another important factor to consider is that glass is brittle therefore redundancy in a structure is crucial in case of failure. Options with argon as an infill in cavities are rated low in terms of ease of manufacture as it increases the complexity of the process. Also, options with coating are rated low in recyclability factor. The



property of transparency is what makes glass a very attractive façade material for architects and designers. Therefore, it is evaluated by calculating the number of refracting surfaces in the design. Every transition from glass to air results in loss of optical quality and image distortion.

05.7 Conclusions

The top four options that score well are 200C1_2-20_00, 200C2_2-20_01, 2.5-50C3_1-20_01 and 150C4_patternD_00. Option 200C1_2-20_00 and 200C2_2-20_01 are disregarded as they are from block size 200mm which is really thick and will use more material than the other two options. For the purpose of easy understanding, 150C4_patternD_00 will be referred to as The Lattice Block and 2.5-50C3_1-20_01 as The Fusion Block. The lattice block performs best in all categories except transparency and optical distortion because of the presence of multiple cavities. However, designs where transparency is not crucial, this option can really work wonders. The fusion block is the simplest and material-efficient option, but it does not satisfy the Dutch U-value requirements. However, by slightly changing the size of cross-section thickness and cavity, it can be made to comply with the Dutch norms as well. It also has coated glass, so recyclability is an issue here as well but this is further dealt with in the next chapters.

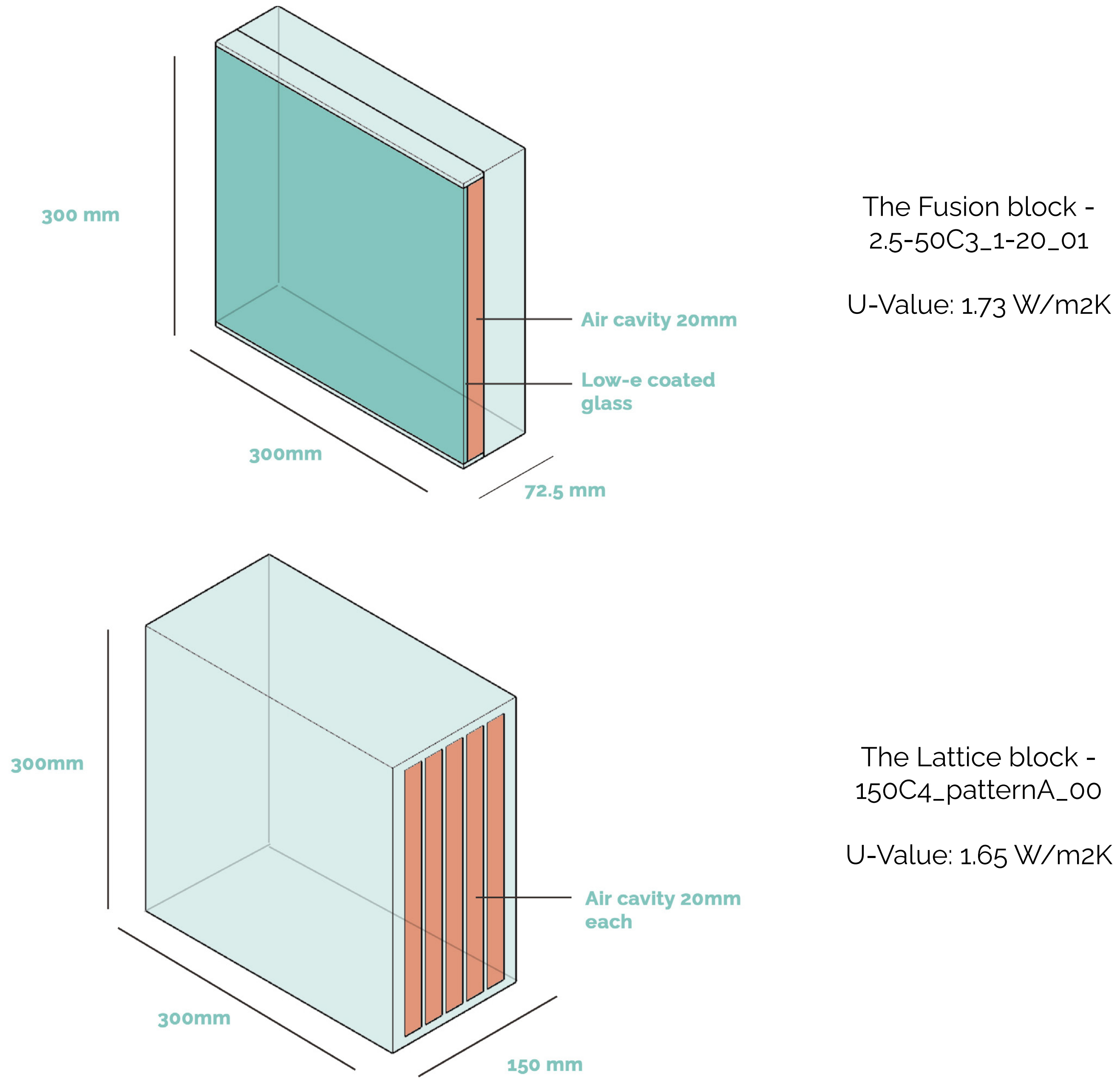


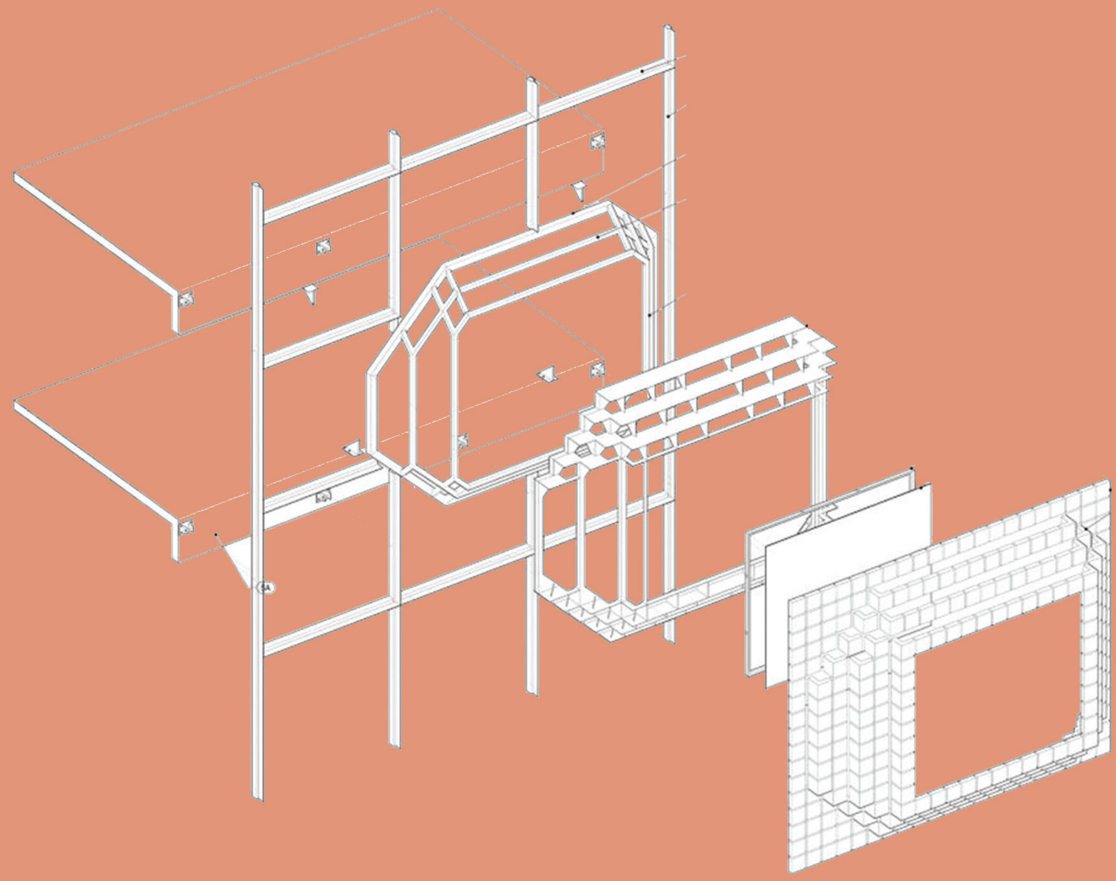
FIGURE 83: Figure showing Final chosen options

Block Size	Block Name	Glass Cross-section (mm)	Number of Cavity	Coating/Cavity filling	Thermal Performance (W/m2K)	Structural Performance	Weight	Ease of manufacturing	Transparency & Optical distortion	Recyclability	Final Score
C1: Altering Cavities											
50	50C1_1-10_01	17.5	1	Yes/Air	2.13	+	++++	+++	++++	+	+++
	50C1_1-10_11	17.5	1	Yes/Argon	1.93	+	++++	+	++++	+	++
100	100C1_1-25_01	35	1	Yes/Air	2.17	+	+++	+++	++++	+	++
	100C1_1-25_11	35	1	Yes/Argon	2	+	+++	+	++++	+	++
	100C1_2-10_10	26.5	2	No/Argon	2.22	+	+++	++	+++	++++	++
	100C1_2-15_10	24	2	No/Argon	2.2	+	+++	++	+++	++++	++
	100C1_2-10_01	26.5	2	Yes/Air	1.92	+	+++	+++	+++	+	++
	100C1_2-10_11	26.5	2	Yes/Argon	1.76	+	+++	+	+++	+	++
150	150C1_1-25_01	62.5	1	Yes/Air	1.96	+++	++	+++	++++	+	+++
	150C1_1-25_11	62.5	1	Yes/Argon	1.83	+++	++	+	++++	+	++
	150C1_2-10_00	43	2	No/Air	2.11	++	+++	++++	+++	++++	+++
	150C1_2-15_00	40	2	No/Air	2.03	++	+++	++++	+++	++++	+++
	150C1_2-20_00	36	2	No/Air	2.02	++	+++	++++	+++	++++	+++
	150C1_2-10_10	43	2	No/Argon	2.01	++	+++	++	+++	++++	+++
	150C1_2-15_10	40	2	No/Argon	1.98	++	+++	++	+++	++++	+++
	150C1_2-10_01	43	2	Yes/Air	1.73	++	+++	+++	+++	+	+++
	150C1_2-10_11	43	2	Yes/Argon	1.6	++	+++	+	+++	+	+++
200	200C1_1-15_00	92.5	1	No/Air	2.18	++++	++	++++	++++	++++	+++
	200C1_1-20_00	90	1	No/Air	2.18	++++	++	++++	++++	++++	+++
	200C1_1-25_00	87.5	1	No/Air	2.17	++++	++	++++	++++	++++	+++
	200C1_1-30_00	85	1	No/Air	2.17	++++	++	++++	++++	++++	+++
	200C1_1-25_10	87.5	1	No/Argon	2.13	++++	++	++	++++	++++	+++
	200C1_1-30_10	85	1	No/Argon	2.13	++++	++	++	++++	++++	+++
	200C1_1-25_01	87.5	1	Yes/Air	1.79	++++	++	+++	++++	+	++
	200C1_1-25_11	87.5	1	Yes/Argon	1.68	++++	++	+	++++	+	++
	200C1_2-10_00	60	2	No/Air	1.91	+++	++	++++	+++	++++	++
	200C1_2-15_00	56.5	2	No/Air	1.84	+++	++	++++	+++	++++	++
	200C1_2-20_00	53	2	No/Air	1.83	+++	+++	++++	+++	++++	++++
	200C1_2-25_00	50	2	No/Air	1.82	+++	+++	++++	+++	++++	++++
	200C1_2-30_00	46.5	2	No/Air	1.82	+++	+++	++++	+++	++++	+++
	200C1_2-20_10	53	2	No/Argon	1.77	+++	+++	++	+++	++++	+++
	200C1_2-25_10	50	2	No/Argon	1.76	+++	+++	++	+++	++++	+++
	200C1_2-20_01	53	2	Yes/Air	1.39	+++	+++	+++	+++	+	+++
	200C1_2-20_11	53	2	Yes/Argon	1.29	+++	+++	+	+++	+	+++

TABLE 14: Table showing scoring chart for all designs that qualify the thermal performance criteria

Block Size	Block Name	Glass Cross-section (mm)	Number of Cavity	Coating/Cavity filling	Thermal Performance (W/m2K)	Structural Performance	Weight	Ease of manufacturing	Transparency & Optical distortion	Recyclability	Final Score
C2: Coated Glass in Middle											
50	50C2_2-10_11	12.5	2	Yes/Argon	2.19	+	++++	+	+++	+	+
100	100C2_2-10_01	37.5	2	Yes/Air	2.18	+	++++	+++	+++	+	++
	100C2_2-15_01	32.5	2	Yes/Air	1.98	+	++++	+++	+++	+	++
	100C2_2-20_01	27.5	2	Yes/Air	1.92	+	++++	+++	+++	+	++
	100C2_2-15_11	32.5	2	Yes/Argon	1.87	+	++++	+	+++	+	+
	100C2_2-20_11	27.5	2	Yes/Argon	1.79	+	++++	+	+++	+	+
150	150C2_2-10_01	62.5	2	Yes/Air	1.98	+++	++	+++	+++	+	+++
	150C2_2-15_01	57.5	2	Yes/Air	1.82	+++	+++	+++	+++	+	+++
	150C2_2-20_01	52.5	2	Yes/Air	1.76	+++	+++	+++	+++	+	+++
	150C2_2-15_11	57.5	2	Yes/Argon	1.72	+++	+++	+	+++	+	++
	150C2_2-20_11	52.5	2	Yes/Argon	1.65	+++	+++	+	+++	+	++
200	200C2_2-10_01	87.5	2	Yes/Air	1.8	++++	++	+++	+++	+	+++
	200C2_2-15_01	82.5	2	Yes/Air	1.67	++++	++	+++	+++	+	+++
	200C2_2-20_01	77.5	2	Yes/Air	1.62	++++	++	+++	+++	+	++++
	200C2_2-25_01	72.5	2	Yes/Air	1.59	++++	++	+++	+++	+	+++
	200C2_2-30_01	67.5	2	Yes/Air	1.56	++++	++	+++	+++	+	+++
C3: Merging Hollow and Solid											
50	2.5-50C3_1-20_01	50	1	Yes/Air	1.73	+++	++++	+++	++++	+	++++
	2.5-50C3_1-20_11	50	1	Yes/Argon	1.46	+++	++++	+	++++	+	+++
100	10-100C3_1-25_01	100	1	Yes/Air	2.12	++++	+++	+++	++++	+	+++
	10-100C3_1-25_11	100	1	Yes/Argon	1.93	++++	+++	+	++++	+	++
C4: Honeycomb-Structure											
50	50C4_patternD_10	50	-x-	No/Argon	2.51	+++	++++	++	++	++++	++
100	100C4_patternD_00	100	-x-	No/Air	1.91	++++	+++	++++	++	++++	++
	100C4_patternD_10	100	-x-	No/Argon	1.81	++++	+++	++	++	++++	+++
150	150C4_patternA_00	150	-x-	No/Air	1.93	++++	+++	++++	++	++++	++
	150C4_patternB_00	150	-x-	No/Air	1.96	++++	+++	++++	++	++++	++
	150C4_patternC_00	150	-x-	No/Air	2.06	++++	+++	++++	++	++++	++
	150C4_patternD_00	150	-x-	No/Air	1.65	++++	+++	++++	++	++++	++++
	150C4_patternA_10	150	-x-	No/Argon	1.8	++++	+++	++	++	++++	+++
	150C4_patternB_10	150	-x-	No/Argon	1.9	++++	+++	++	++	++++	+++

TABLE 14: Table showing scoring chart for all designs that qualify the thermal performance criteria



06 Case Study

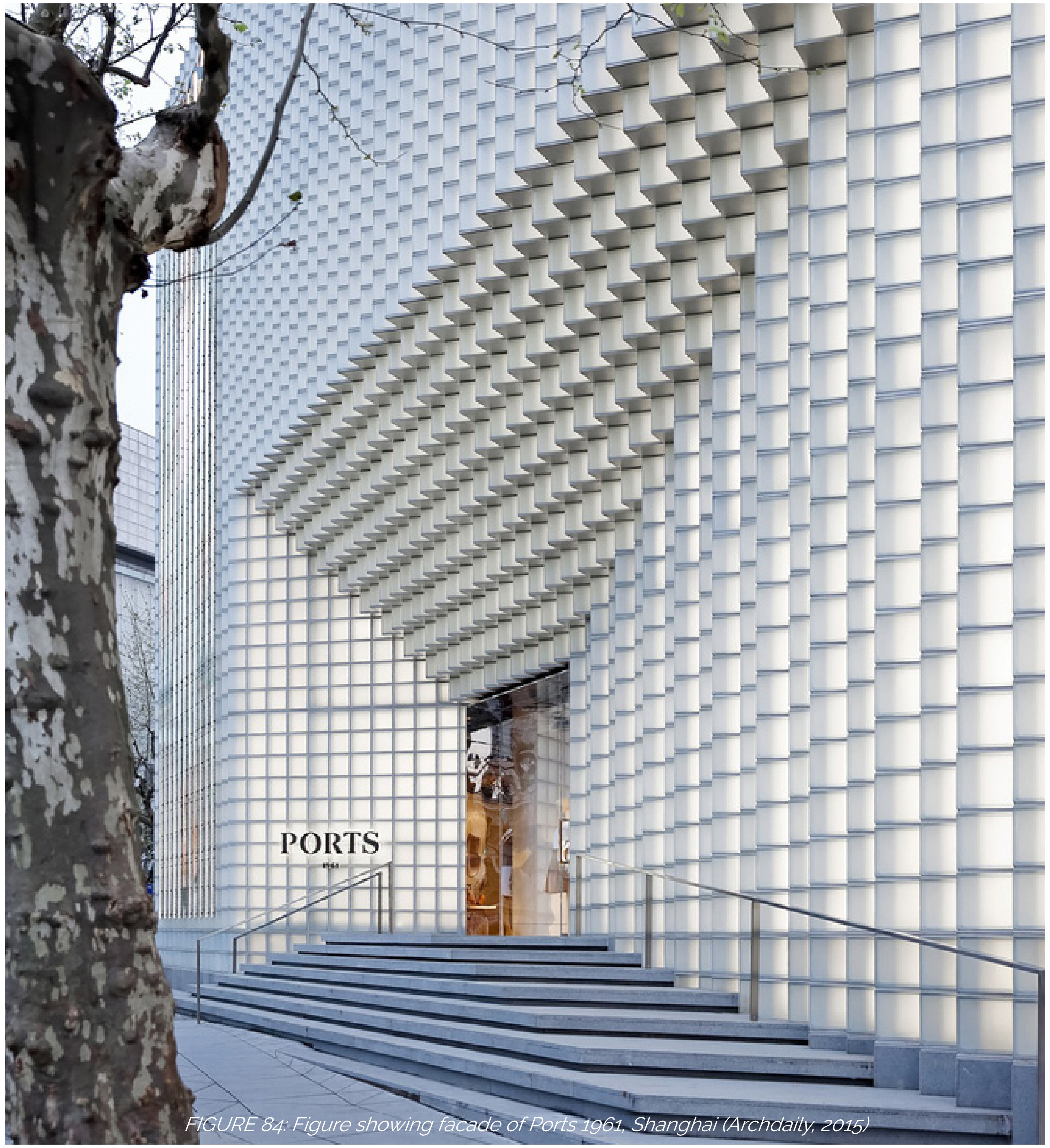
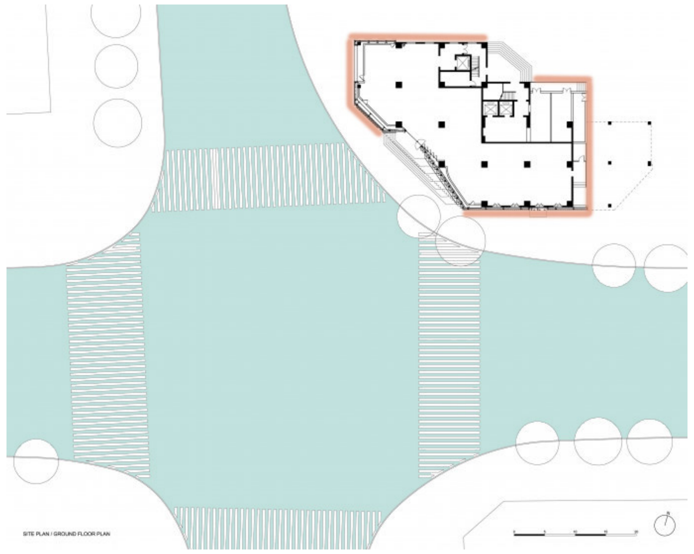


FIGURE 84: Figure showing facade of Ports 1961, Shanghai (Archdaily, 2015)

06.1 Urban Context

The project is located at a major high-end commercial district at the busy intersection of Changde Road and Nanjing West Roads. This unique setting evoked the idea of a landform resembling an iceberg floating in the ocean. The façade exhibits the possibilities of design experimentation; it represents the transformation of form, material, and technology and ties it with its origin and evolution. The structural grandness of the building catches the eye whilst its ambivalent character uniquely varies with its environs. (Architectural SSL, 2016)



Intersection of Changde Road and Nanjing West Roads.

Ports 1961 building

FIGURE 85: Figure showing urban context of Ports 1961, Shanghai

06.2 The Building

Ports 1961 was founded in Toronto as a silk importing business and is now an international phenomenon in high-fashion. (Architectural SSL, 2016) The challenge given to the architects was to design a stand-alone structure that should be a visual magnet both day and night. The façade is carefully designed to synthesize sculptural glass blocks and LED fixtures that generate surface textures and evening glow. Unlike most glass masonry construction, it is not limited to one vertical plane but extends beyond that into a three-dimensional volume. (Castro, 2015)

The combination of satin glass block and shot-blasted steel generates a contrast with the city's disordered character. The glass facade reflects the sunlight during the day while generating an overall glow in the evening. This icy and crisp view is created using LED lights integrated into the joints of the masonry. These 4600K linear LEDs indirectly light the facade to give a sense of depth and a homogeneous lighting effect. The transformative nature of the city and the people of Shanghai are reflected in the varying geometries and perspectives of the facade. It is a classic example of a marriage between innovative design and engineering. (Castro, 2015)

FIGURE 86 Figure showing west facade with corbelled window detail (Archdaily, 2015)

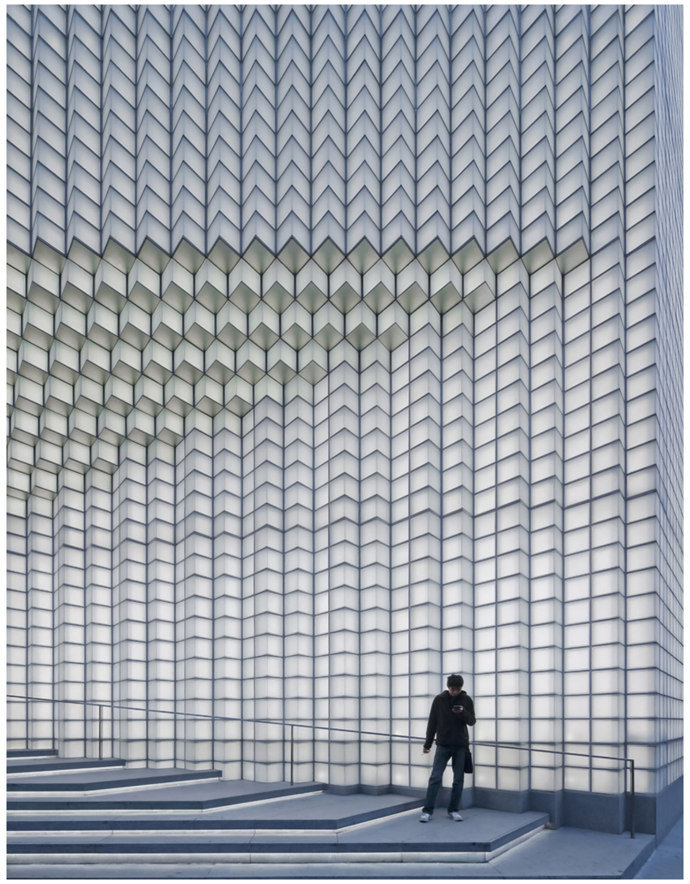


FIGURE 87: Figure showing corbeled entrance (Archdaily, 2015)

06.3 Facade design and Installation

The building consists of three floors each 4.8m high giving it a total height of 14.4m. The facade is composed of two glass blocks with a satin finish; one a standard square block of 300mm x 300mm and the other a custom-mitered block of the same dimension. (Castro, 2015) This custom block is used in the corners to create a corbeled facade (Fig 90). Both the blocks have a U-value of 2.6 W/m²K (reference).

The glass blocks of the straight face of the facade are placed over shot-blasted stainless-steel plates of the same dimension, extending to a steel frame. These metal strips divide the glass blocks into groups of 64. To generate the corbeled part in windows, another steel section shaped in the corbeled form is placed over the existing structure with steel plates that then hold the blocks together. The corbeled part is an aesthetic feature and does not follow the load bearing principles of masonry construction. (Castro, 2015)

06.4 Discussion

This building was chosen as a case study to highlight the changes with a load bearing thermally performing system. The load bearing system eliminates the need for extra steel frame support system. Visually, this extra support system disrupts the translucency of the glass facade system. Also, to join one block to another and to join block to the steel frame, a mortar is used which makes the assembly irreversible. The engineering of a novel load bearing and thermally performing system can provide a solution for the existing problems in the hollow glass block systems.

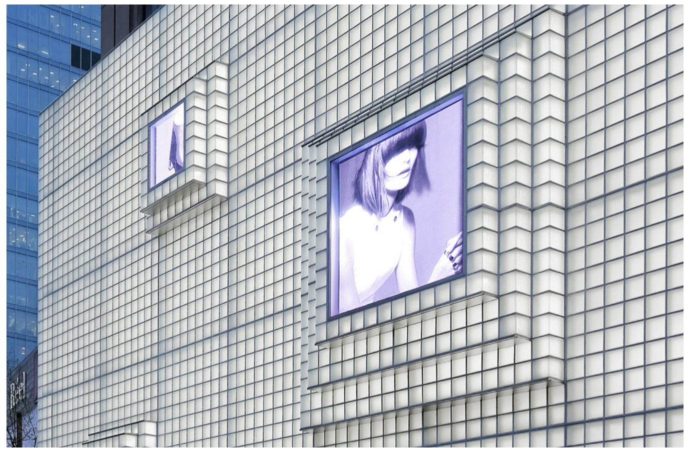


FIGURE 88: Figure showing close-up view of corbeled window (Archdaily, 2015)

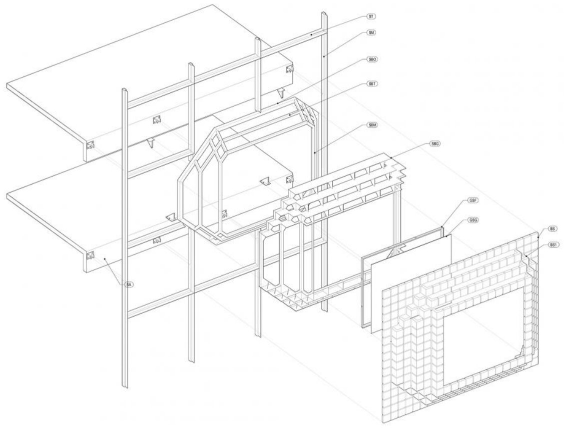


FIGURE 89: Figure showing construction detail of windows of the facade (UUfie, 2015)

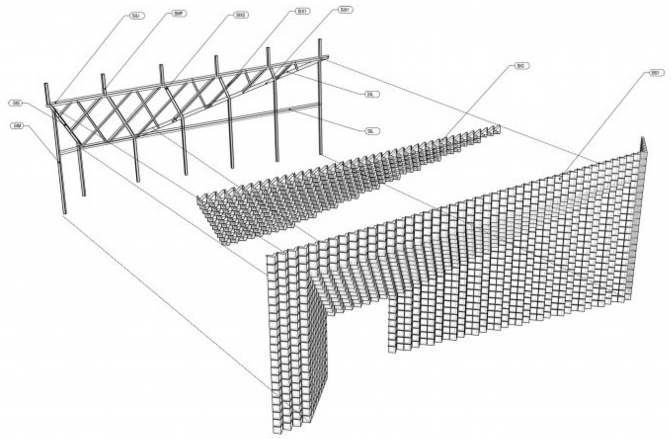


FIGURE 90: Figure showing construction elements of corbeled part of the facade. (UUfie, 2015)

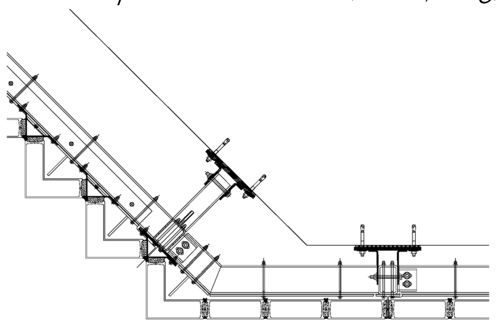


FIGURE 91: Figure showing blown-up detail of the facade system. (Archdaily, 2015)

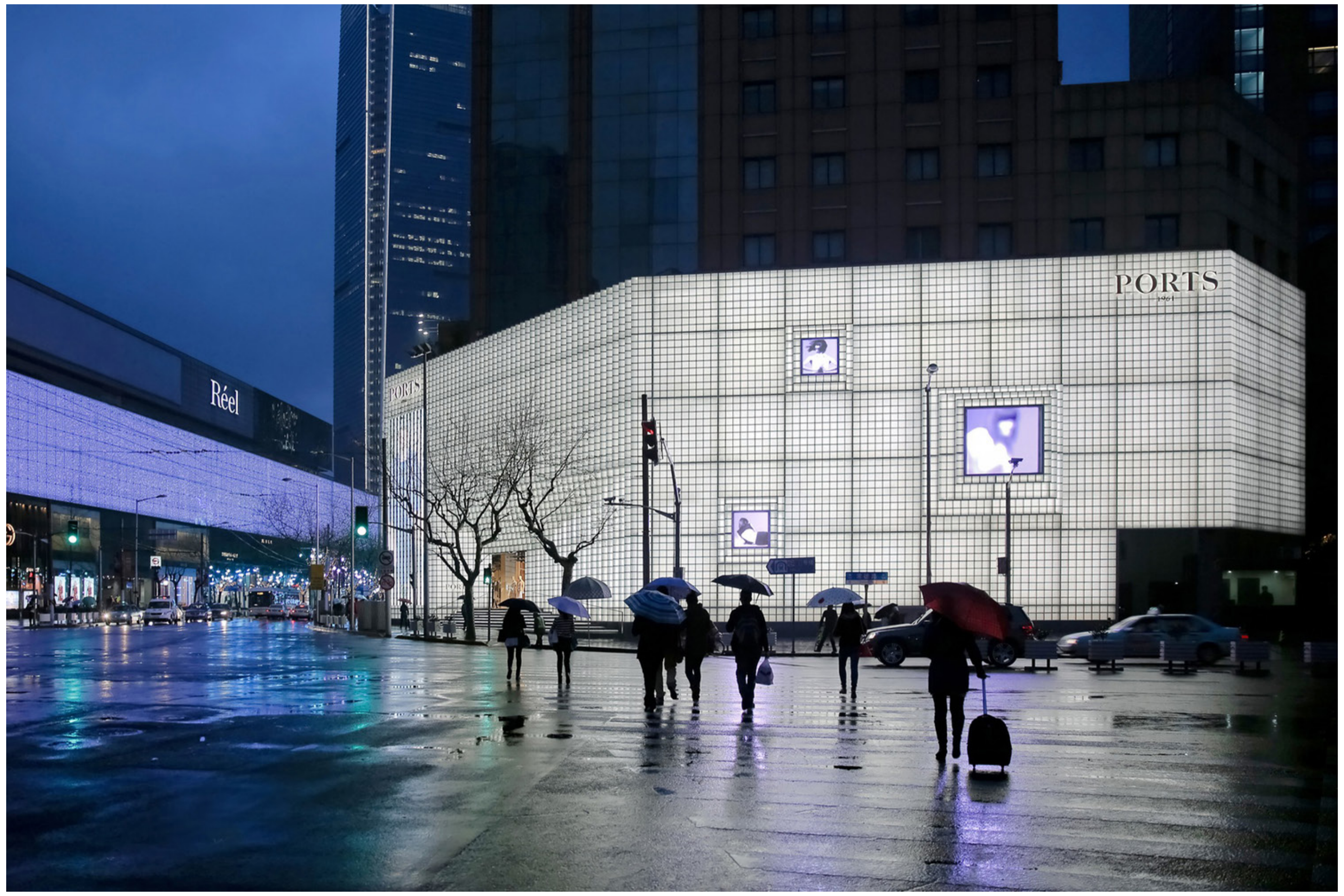
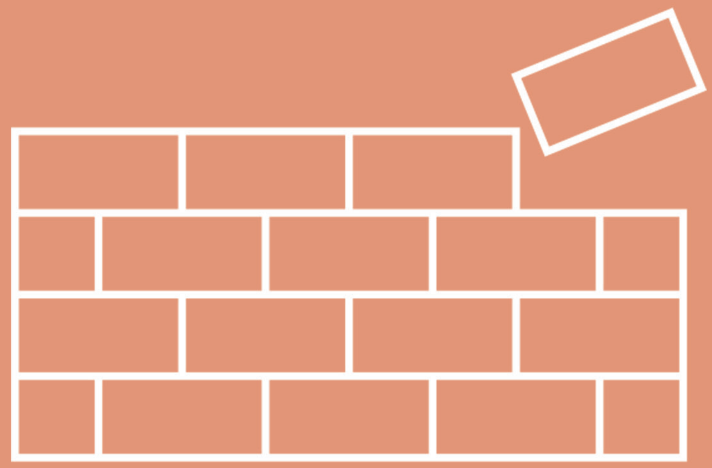


FIGURE 92: Figure showing night view of the building (Archdaily, 2015)

FIGURE 93 Figure showing day view of the building (Archdaily, 2015)



07 Constructability

The main pre-requisite when designing with glass as a structural member is that the design should consider the inherent brittle nature of glass and consequence of failure and post-fracture performance. Therefore, in this chapter first a risk analysis is carried out that offers insight into the damages that can occur in the block and considerations taken for the design to eliminate risks. This also guides the manufacturing process and the connections between blocks. The two design options, manufacturing and assembly process of the block are explained in detail in this chapter.

07.1 Risk Analysis

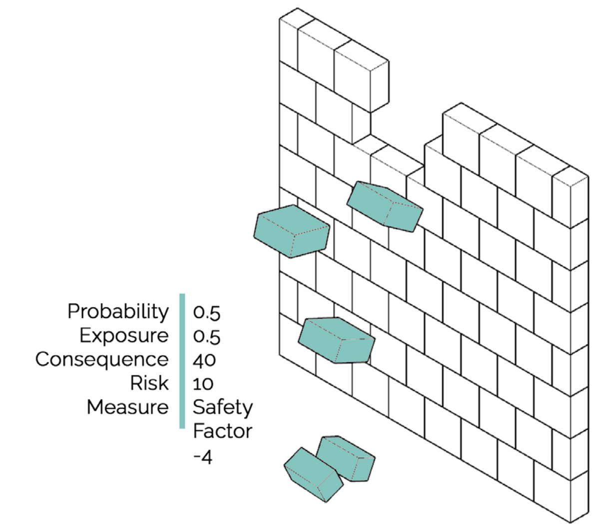
The risk analysis takes into consideration all the possible scenarios that can happen in the façade which might cause damage in the long run. These scenarios are divided into 6 different types namely; Structural damage, accidental damage, impact by vehicle, vandalism, lack of maintenance and natural calamity. There are described in detail below.

Structural Damage: The structural damage of the façade can occur due to excess loading conditions, improper assembly and uneven loading of elements. The probability of this happening is highly unlikely but in case of failure it can lead to serous injuries. Therefore, the blocks should be designed with a safety factor of 4 when assessing it's structural performance. Also the floors do not completely rely on the façade to transfer load therefore the complete failure of the system will not occur.

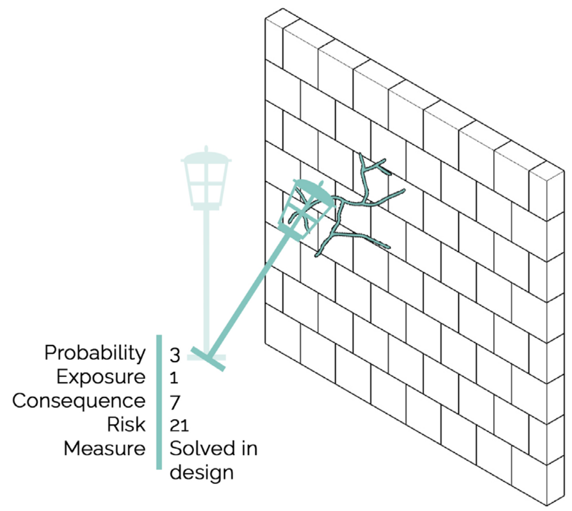
Accidental Impact: This consists of scenarios where the outer or inner surface of the façade is damaged by trees or street lamps in the surrounding. Since our building is a fashion store, the inner part of the façade could also be hit while placing the mannequins in the windows. It can also be accidentally hit by a pedestrian. These scenarios are uncommon but possible, therefore the design of the blocks should be such that there is either a sacrificial layer or redundancy that does not impede the structural performance of the block due to crack development.

Impact by Vehicle: Since the façade form the exterior part of the building, there is always a possibility of it being hit by bicycles or cars especially when the building is located in a busy street. As the bottom part of the façade is very important in load bearing structures as it forms the base therefore special care should be taken for such incidents. This is solved in crystal houses by giving a concrete base till 0.6m where the impact will most likely happen and glass masonry above it. Another method to avoid this from happening is to keep bollards in front of the glass part so that they become

Structural Damage



Accidental Impact



Impact by Vehicle

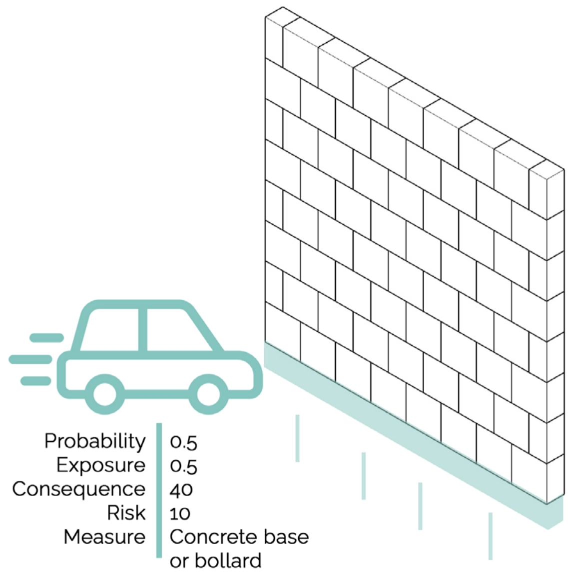


FIGURE 94: Figure showing Risk Analysis

the first point of contact during an impact.

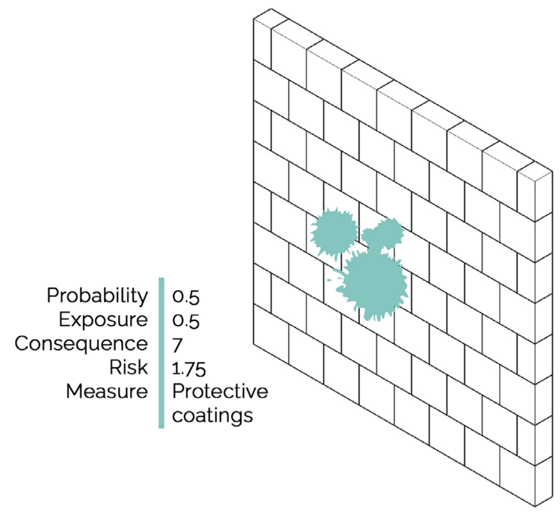
Vandalism: It is an intentional hard body impact or the purposeful damage and destruction of a building element. In facades, it can happen when someone tries to destroy it with hammer or spray paint over it. The chances of this happening are highly unlikely and even then, this can be dealt by treating glass with chemicals or coatings to avoid damage caused by this.

Lack of Maintenance: This can be expected due to negligence and can result in damage of surface finishes, connections etc. As the façade is exposed to sun throughout the day the temperature difference between the inside and outside can result in thermal shocks in the material. These problems will not cause serous injuries but it is important to deal with them in the design process.

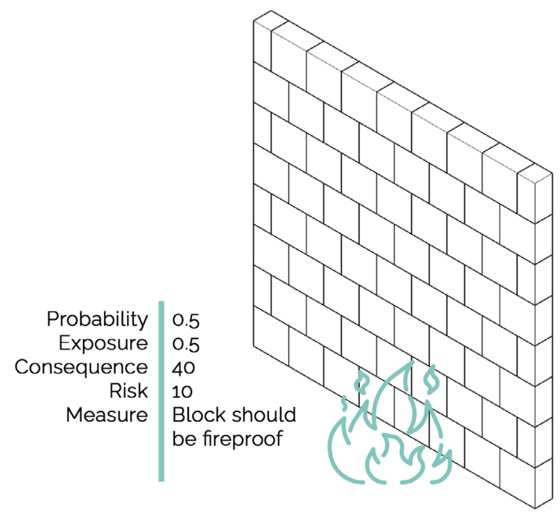
Fire: It is a serious issue when dealing with glass as it tends to burst and can cause serous damage. For fire safety, it is important to ensure that the building is evacuated before the glass breaks, therefore the designed block should comply to the fire ratings. However, the tests for the same are beyond the scope of this thesis. Also, the proposed facade system will be self-supporting and does not carry the load from rest of the building so if the facade collapses, the building will remain standing.

Natural Calamity: Natural disasters like floods and earthquakes can be expected to cause a damage in the building envelop. It is therefore important to deal with them on a building level e.g. addressing the earthquake movement in the support system of the facade to the rest of the building and to the foundation. Another important design consideration would be to make sure that in case of damage to the façade, the entire structure does not collapse and doesn't lead to a catastrophe.

Vandalism



FIre



Natural Calamity

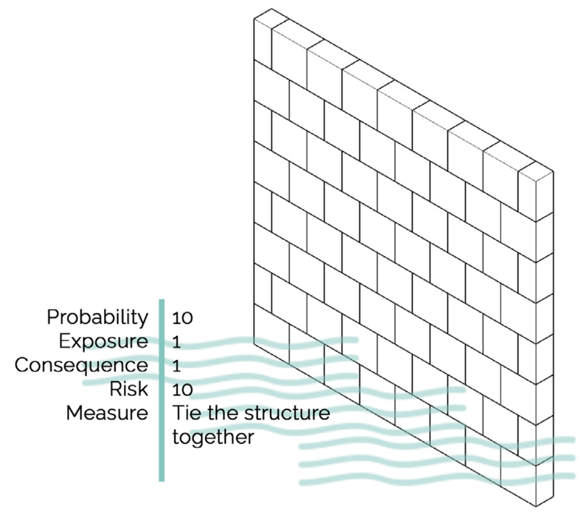
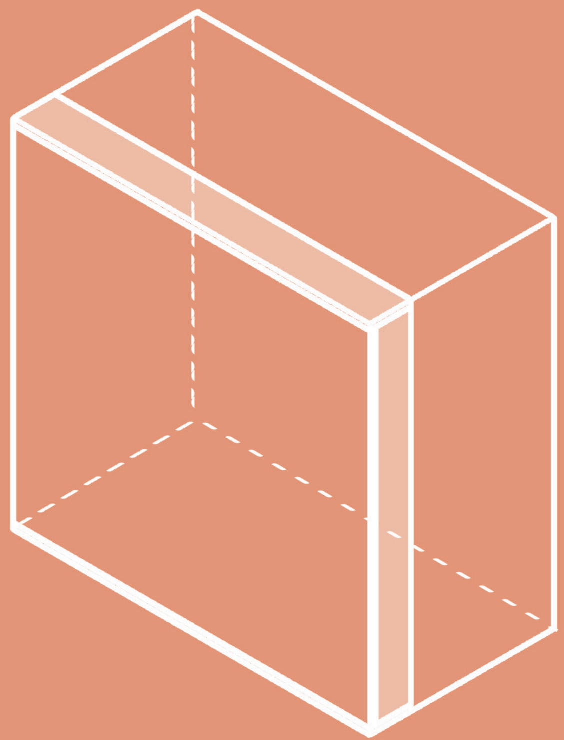


FIGURE 94: Figure showing Risk Analysis



Fusion Block

07.2 Prototyping Blocks

This block was re-analyzed by increasing the cross-section thickness and cavity size to satisfy the U-value norms of Dutch codes. The combination with solid part width 80mm and cavity of 20mm generated a U-value of 1.65 W/m2K and was selected to provide good stability to the overall wall structure with satisfactory thermal performance. This block has two parts; one a solid part to carry the load and the hollow part for thermal performance. The non-load bearing part of the design facilitates a layer of silver coating which in turn makes that part non-recyclable. Therefore, it is important to fabricate the block in a way that the recyclable and non-recyclable part can be separated.

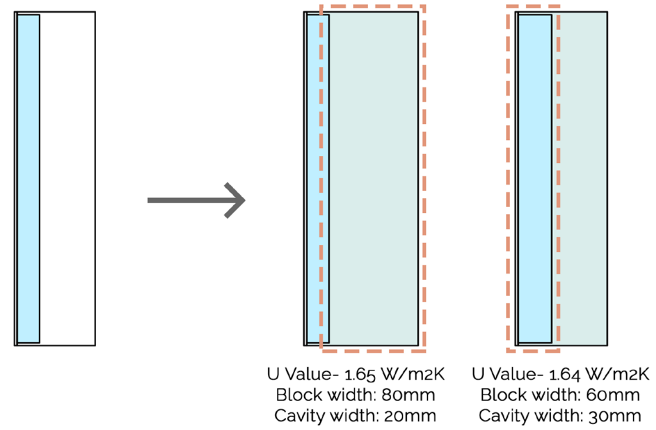


FIGURE 95: Figure showing development of fusion block

The cross-section thickness of the cavity wall was also increased from 2.5mm to 5mm as in the manufacturing process, the molten glass would have not been able to flow easily into the thin 2.5mm part due to it's viscosity. With 5mm thickness, it can easily flow and is also less susceptible to cracking.

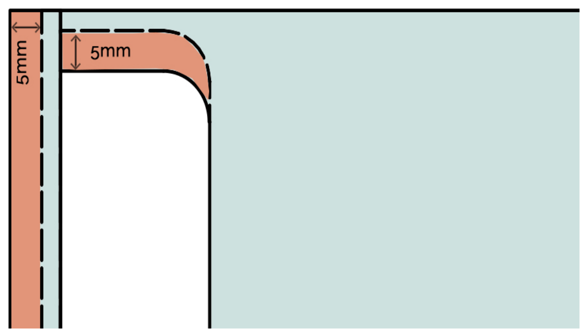


FIGURE 96: Figure showing increase in cross-section thickness of cavity and float glass

The block size used for the solid part is 300mm x 300mm x 80mm and the size of float glass piece used is 300mm x 300mm x 5mm. The float glass piece used here is laminated for safety purposes. The length and height of the block is kept same as the one currently present in the facade.

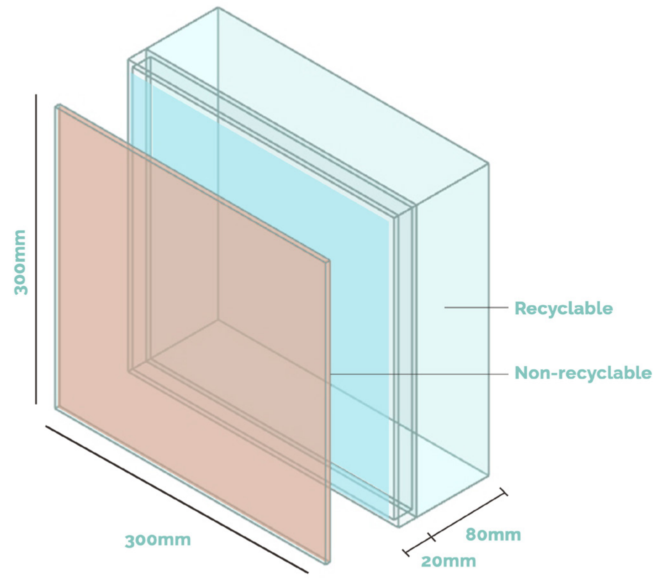


FIGURE 97: Figure showing concept of Fusion block

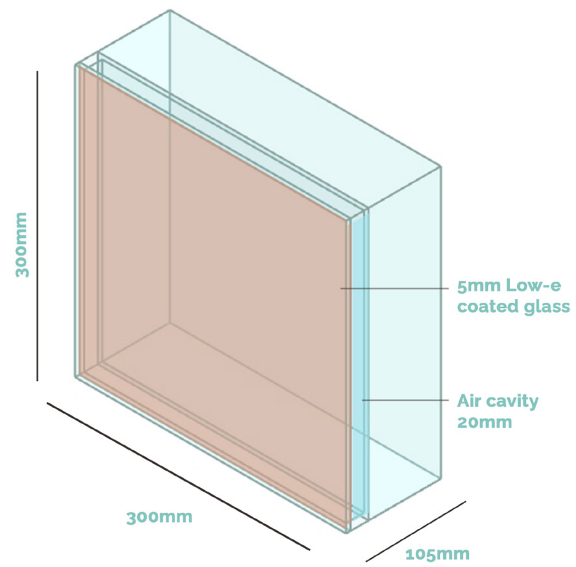


FIGURE 98: Figure showing the design of Fusion Block

07.3 Prototyping Connections

Various connection options in glass were explored for the design of this block. There are basically three different connections (shown in Fig 99) that need attention. Connection Z is just simple vertical edges sealed together locally. For connection X, glued options are not feasible as it will make it impossible to be separated from the entire block. Therefore, option 3 and 4 are preferable. For connection Y, glass to glass interlocking works the best in terms of load transfers, embedded connections may induce additional stresses in the block.

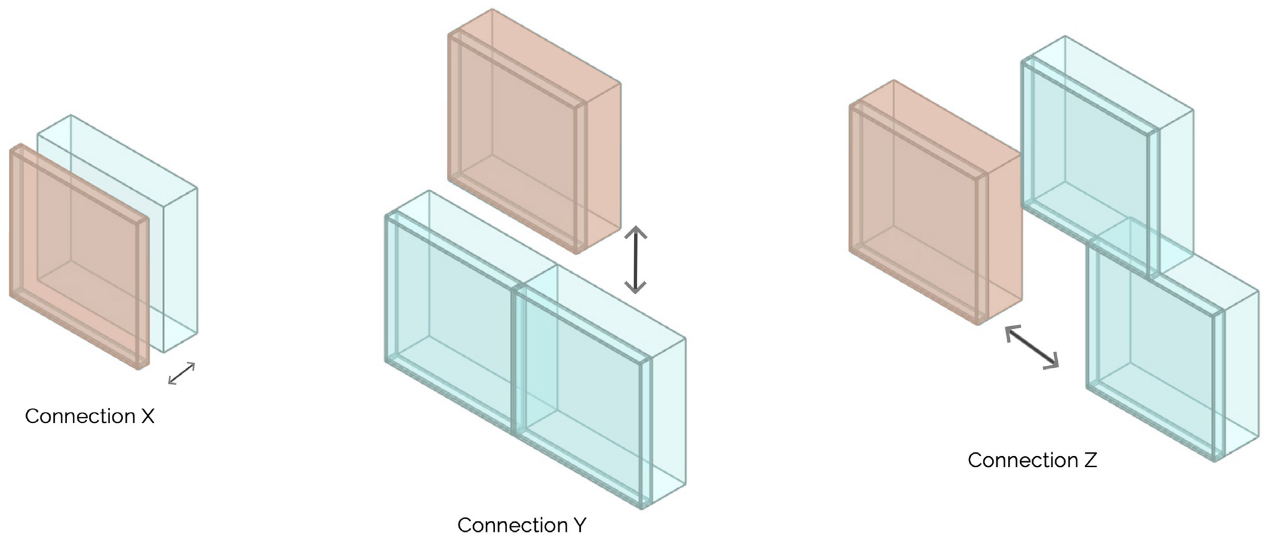


FIGURE 99: Figure showing different connections types

For connection X and Y, the following options were explored. Fig 100 shows connection options for Fusion block. These options are then judged based on unobstructed view, reversibility, assembly ease and load distribution. However, option 3 connection system ensures one system to connect X and Y together, is reversible and easy to assemble as it follows an interlocking pattern. Therefore, for the fusion block, connection option 3 is further developed.

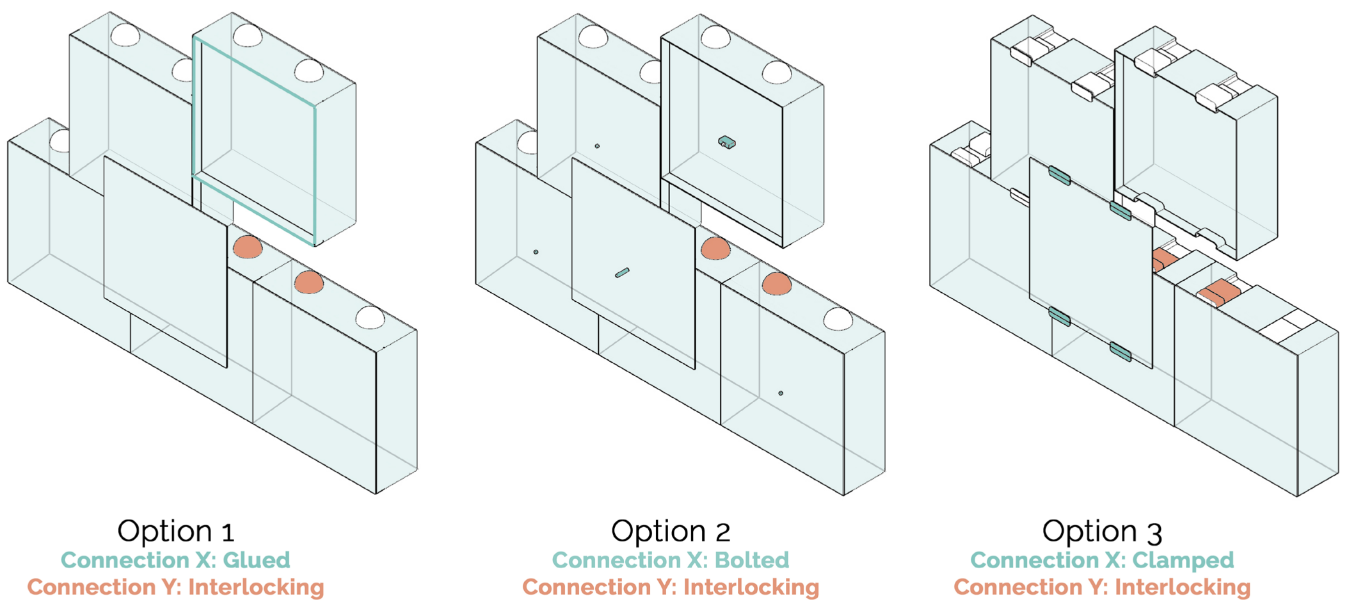


FIGURE 100: Figure showing different connection options for the Fusion Block

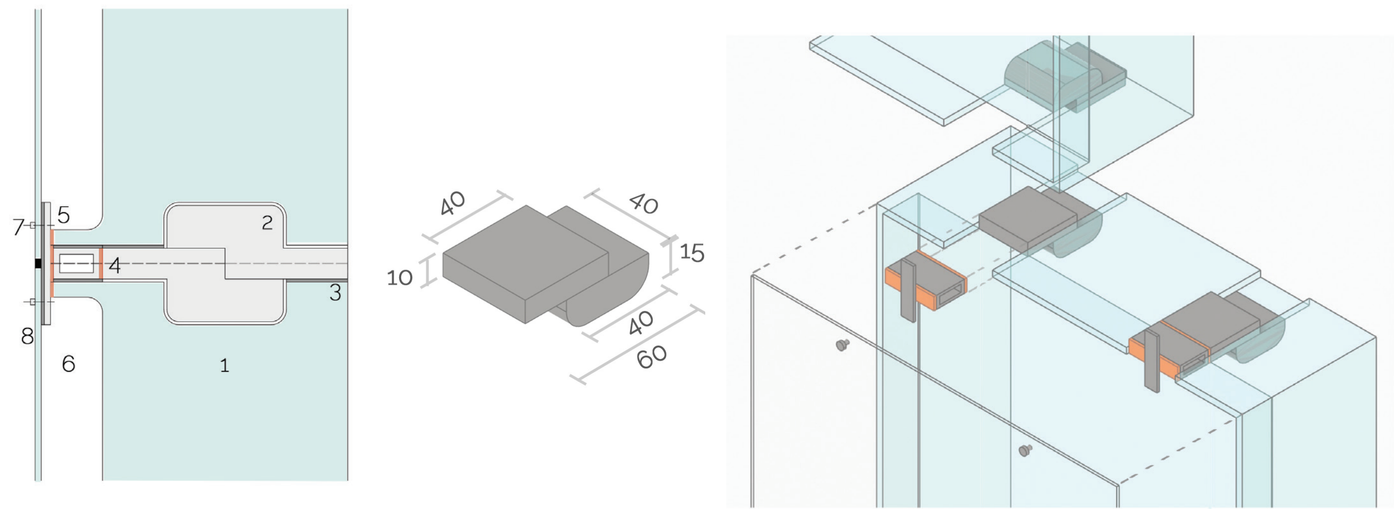
Connection Type		Unobstructed view	Reversibility	Ease of assembly	Load Distribution	Overall
Fusion Block	Glued + Interlock	++++	++	+++	+++	+++
	Clamped + Interlock	++	++++	+++	++	+++
	Embeded Connection	+++	++++	++++	++++	++++

TABLE 15: Table showing scoring chart for different connections for Fusion Block

The connection system used here joins the two parts together and also helps in joining one block to the other. It has two parts one that is embedded in the solid part and the other that holds the hollow part together with the help of bolts. The design of connection is such that it provides movement constraints in two direction and helps in self alignment of the block. Since it is a dry connection, it is also reversible.

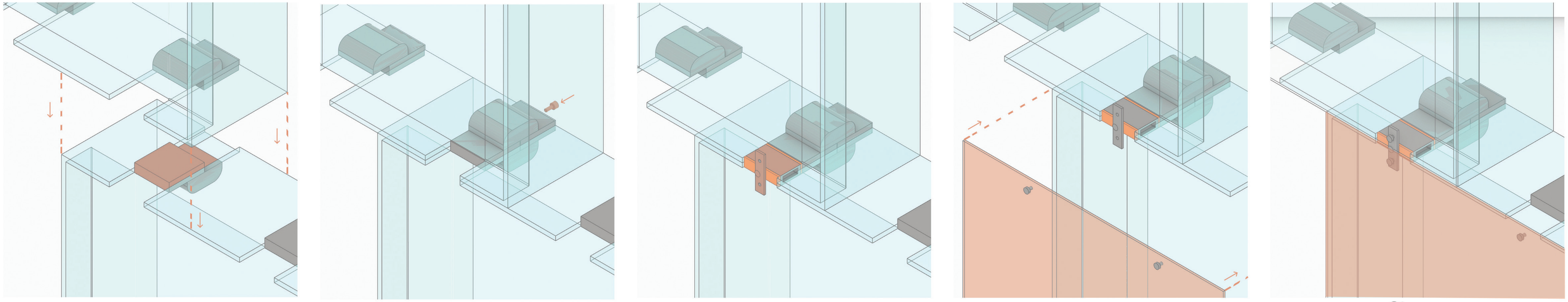
The metal insert is embedded 15mm from the surface of the glass and protrudes out 5mm. There is rubber gasket provided at the junction of the protrusion. The insert can made from Tungsten alloys or Steel coated with tungsten layer because it has similar thermal expansion coefficient as borosilicate glass. This connection is fixed together with a bolt when the blocks are in place. It is then fixed with another rectangular section which connects the float glass to the block and transfer the lateral loads. This rectangular part is made from steel and has a thermal break on both ends. This is done to avoid creation of thermal bridges due to metal inserts in the block as metal has high conductivity.

In this facade the outer layer is composed of small float glass pieces. Thus, the water-tightness is achieved by applying a sealant in between the float glass pieces much like the traditional glass facades. As the outer layer is composed of 5mm thin float glass, in case of accidental damage or vandalism, it can be easily replaced with a new layer. In case of structural damage to the block, the damaged block can be easily slid out and replaced. This is explained in detail further in this chapter.



1. Glass Block 2.Steel Embed with tungsten coating 3. Gasket 4. Thermal Break 5. Steel connection 6. Air cavity 20mm 7. Bolts 8. Laminated float glass 5mm thick

FIGURE 101: Figure showing detail of embedded connection design for Fusion block



Step 1

Place the blocks together.

The metal embeds are designed in a way that this forms a half lap interlocking joint.

Step 2

Lock the connection with the help of screws/bolts.

This is to ensure there is no lateral or transverse movement of the block.

Step 3

Apply the thermal break and fix the external steel connection with the metal embed.

Step 4

Place the external laminated float glass piece.

Step 5

Fix the piece with the help of bolts.

FIGURE 102: Figure showing assembly sequence of block to block connection

07.4 Fabrication

Glass type and Method:
To fabricate this block, the chosen glass is borosilicate (Chapter 3) and the chosen method is casting for the solid part. The borosilicate float glass can be obtained and cut into the desired size.

Block Details:
The facade under study is proposed to be made from three different shapes of block as shown in Fig 103 ; a full brick, a half brick and an L-shape. A major part of the facade is composed of corbeled part, therefore special L-shaped blocks are designed for that segment. These L-shaped blocks can be rotated in the next course to form the corbeled facade following the masonry logic. It also aids in forming the corner junction very easily as described in detail in the installation section of this chapter.

The edges of all the geometry will be rounded to prevent any sharp corners and ensure a smoother annealing process. For the construction process, it is recommended that the weight of the block should not be more than 12kgs to ensure continuous laying process by the workers. Typical masonry blocks weighs on average 3-5 kgs. In our case the weight of the solid part is 16 kgs. This is because the dimensions of the designed block correspond to the original glass blocks used in the facade of the case study building. To ensure, a continuous laying process a time-table for masons can be developed and different masons can be employed at different time.

The embed connections placed in the blocks are of two types. These are identical and the only difference is in their placement. Type 1 has the protruded part at the back face of the block while Type 2 has the protrusion in the front face. These two different types of connections along with three different shapes of blocks generate 6 configurations of blocks used in the facade in total.

Mold Design:
The design of the block has many protrusions and with the interlocking system, it needs accuracy. Therefore, high precision open steel molds are used. Since the entire facade is made out of glass blocks, many molds will be required to produce the quantity of blocks required. As a result, different molds are design for half, full and L-shaped bricks.

The design of the mold is done to take the utmost advantage of gravity and natural flow of glass to take the shape. To ensure, glass reaches in all corners, provisions are made to let the air out and restrict the formations of bubbles/ gaps. For the L-shape block mold, the longer facade is aligned vertically to further aid in the escape of air without formation of air bubbles. The mold is essentially designed in 5 parts, the base as one and 4 walls. Since, it is casted downward, the thin walls are susceptible to cracks, therefore the geometry will be over the base until the glass is sufficiently cool to retain its shape and then put for controlled annealing. The production process and mold design is shown in Fig 104 and Fig 105

The above mentioned method is used to cast the full and half bricks. For the L-shape blocks, a slightly different method can be adopted. To ensure the accuracy of shape, the block can either be placed over an L-shape base when put for annealing process (Step 4a) or the block can be left within the mold and put for annealing (Step 4b). The choice of the process entirely depends on the quantity of bricks required.

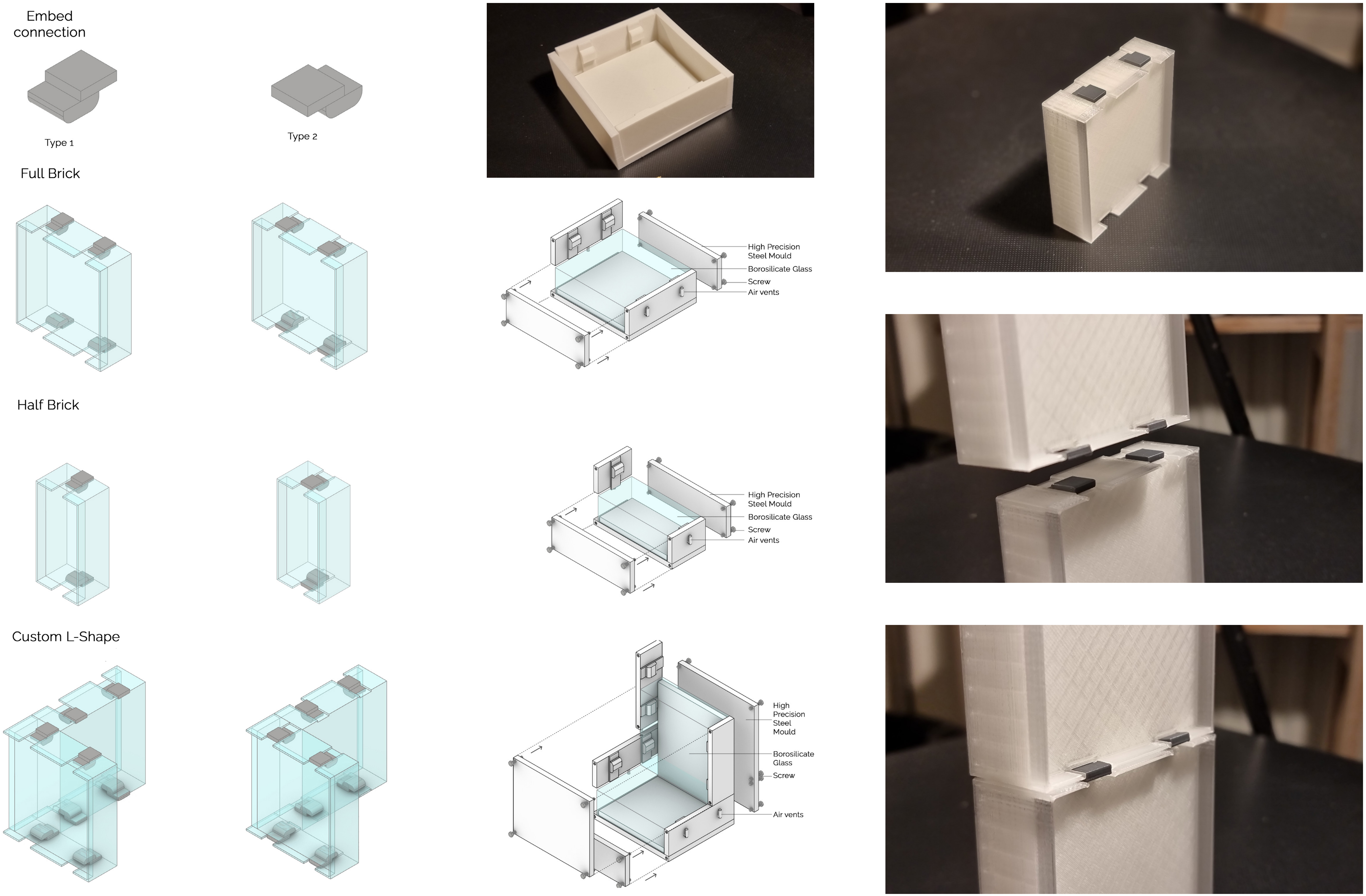


FIGURE 103: Figure showing different blocks used in facade with their respective moulds and 3D printed model

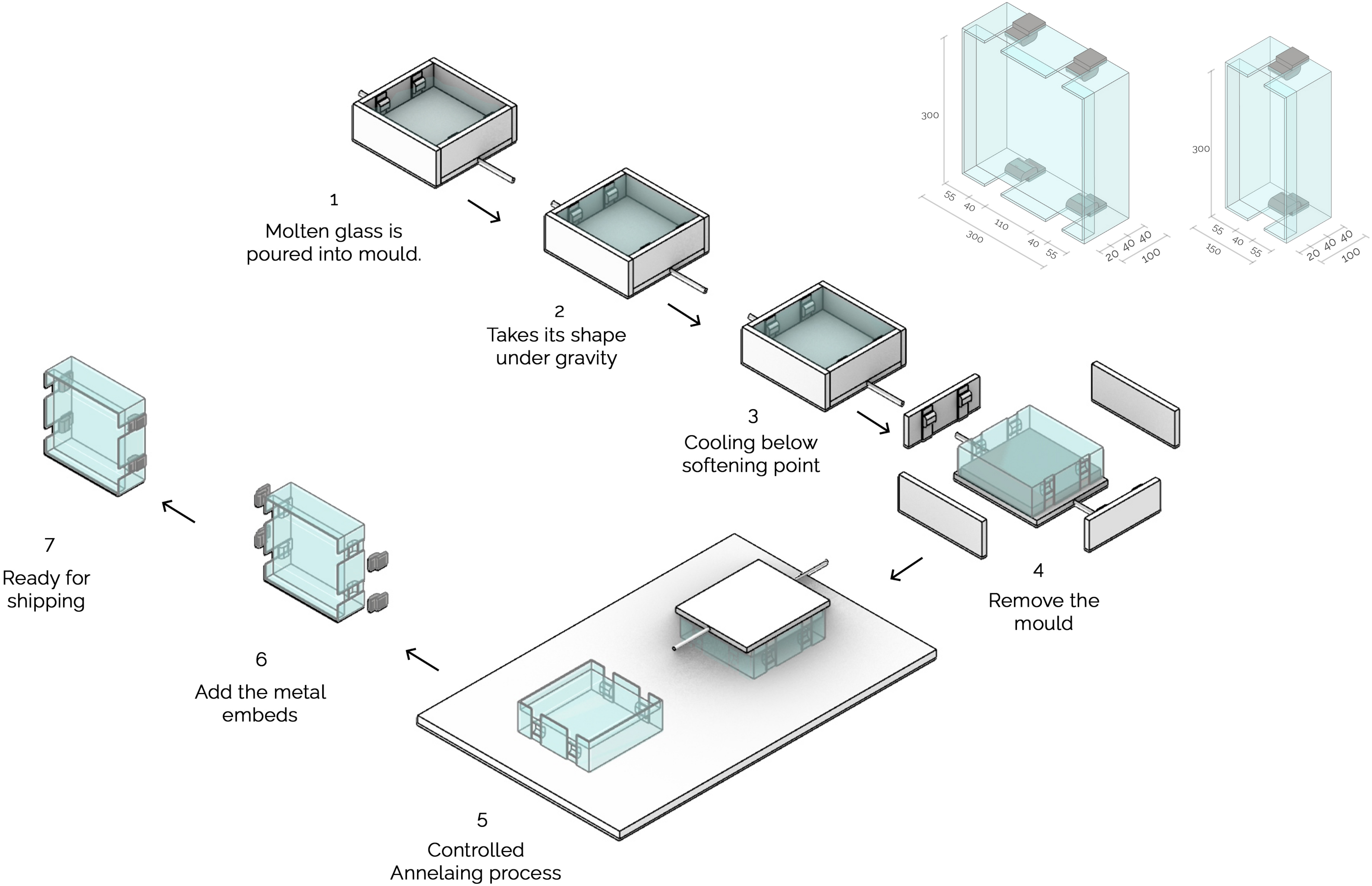


FIGURE 104: Figure showing manufacturing process for half and full brick of Fusion block along with details of half and full brick

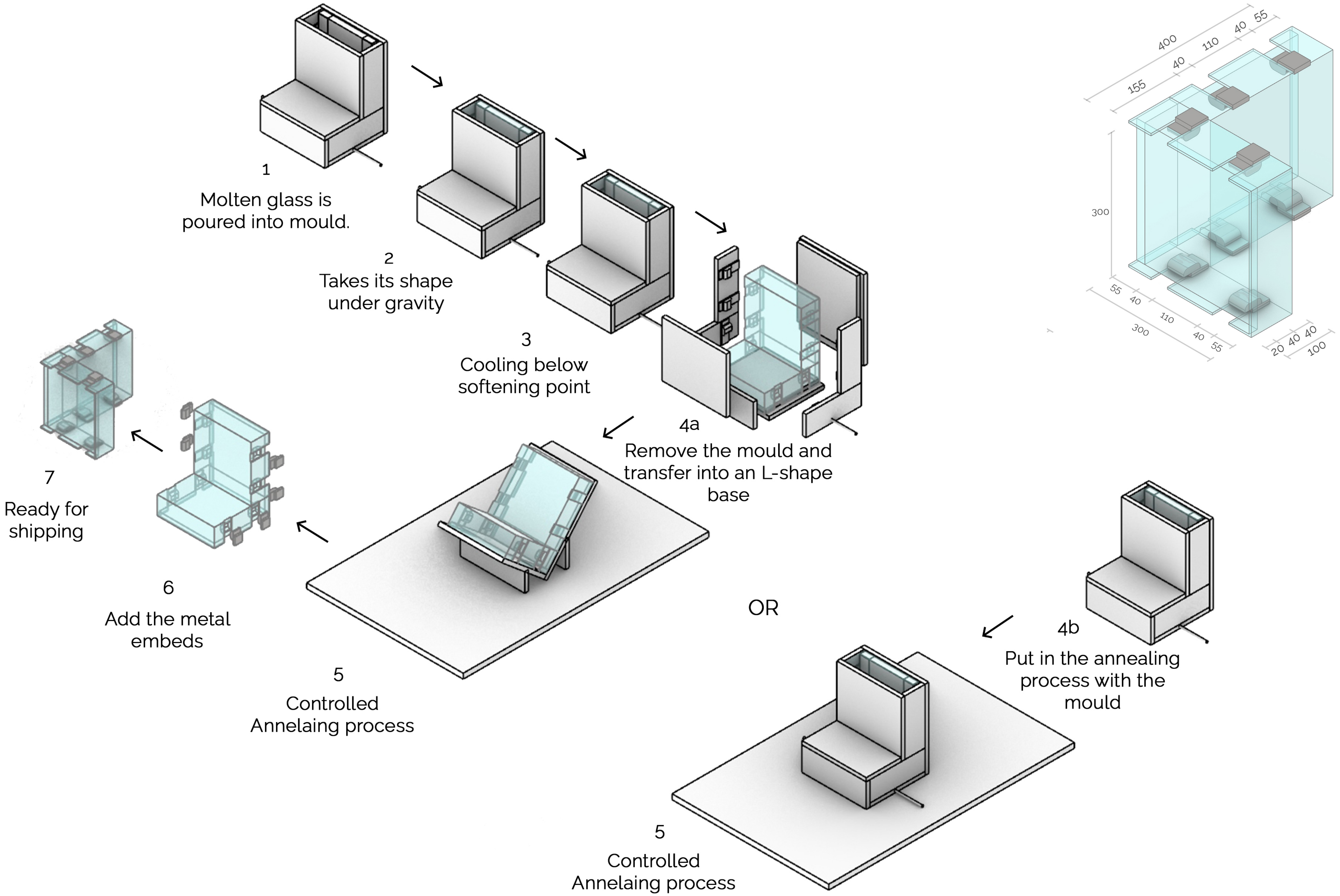


FIGURE 104: Figure showing manufacturing process for L-shape of Fusion block along with details of L-shape block

07.5 Assembly

Bottom Connection

The purpose of the bottom detail is to properly place and align the assembly. To do so, a steel plate is placed over the concrete base. To accommodate the vertical tolerances between steel plate and base, non-shrinkage concrete is added. This also ensures a flat base to start the assembly. Small rectangular tungsten blocks are welded to this steel plate which is then connected to the glass block and fixed together with bolts. Soft rubber layer is added between the glass and steel plate to protect the glass from peak stresses. These separate tungsten blocks along with the soft rubber layer accommodates the dimensional tolerances in the blocks.

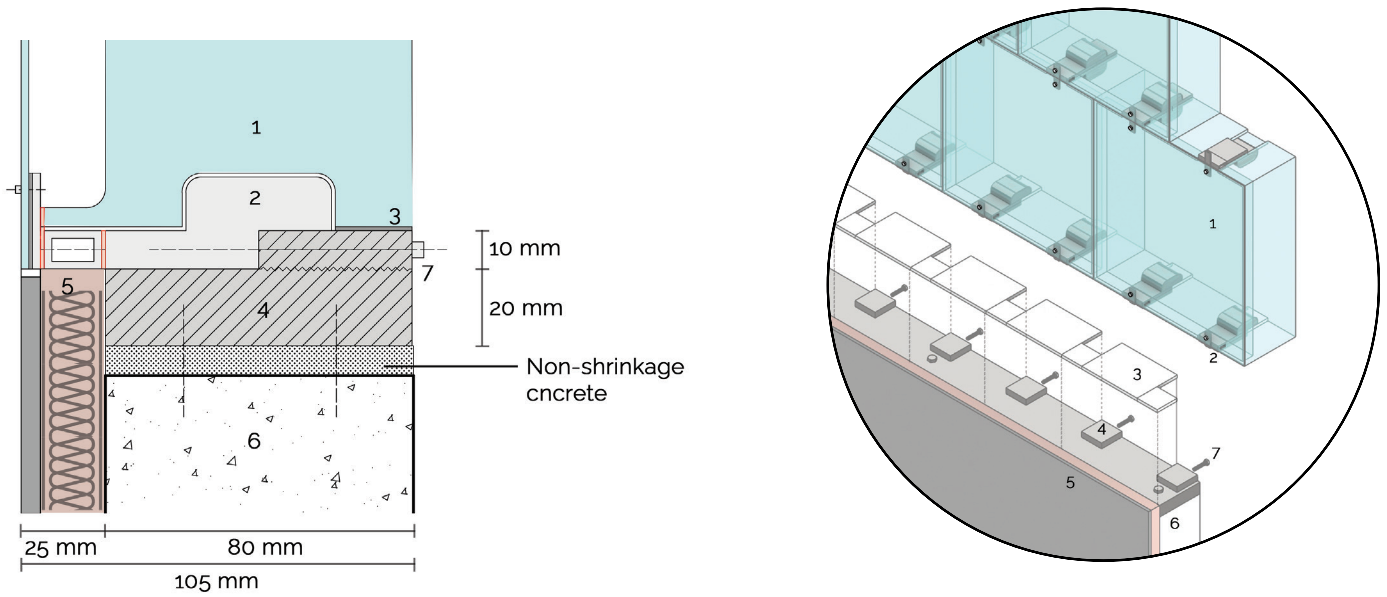
Intermediate Floor Connection

For the intermediate floor connection, the design of connection is done in a way that from outside, there are no breaks visible in the façade. To do this, the glass blocks are tied to discrete rectangular sections which are then connected to the floor through angle – sections.

Top Connection

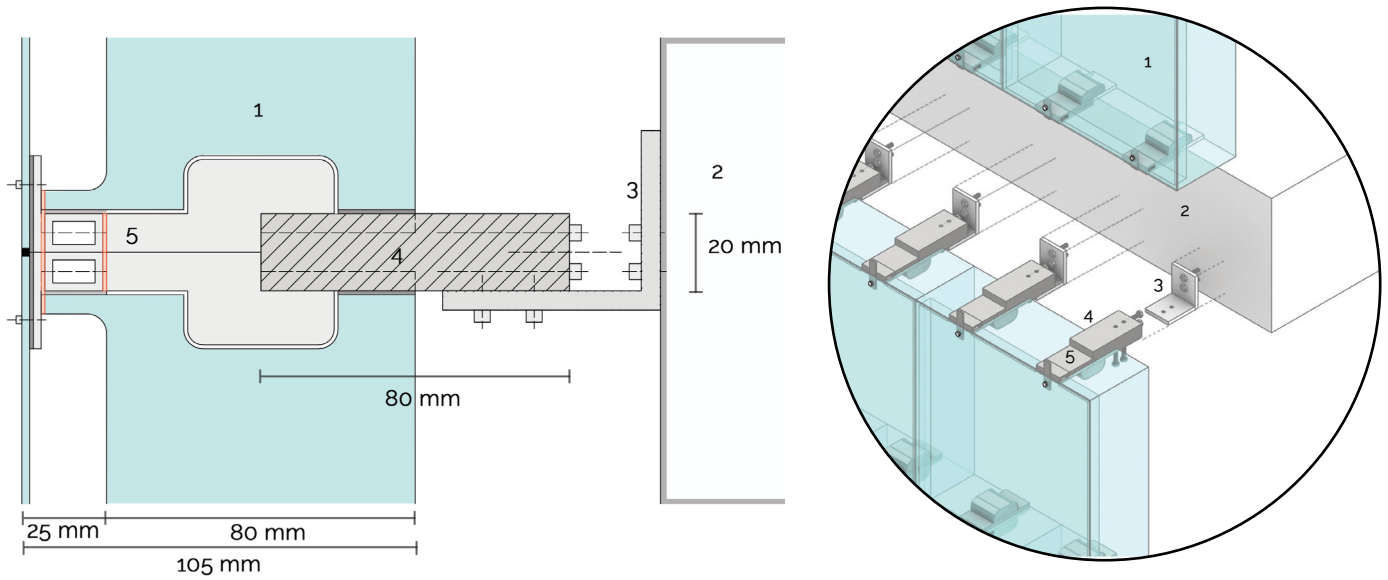
In the top connection, the I-beam can be placed at the position from the start. Once the last layer of blocks is laid. The height of the steel plate along with the rectangular tungsten blocks can be calculated and adjusted on site to accommodate the dimensional tolerances. Again here, the soft rubber layer is provided to break the direct contact between steel plate and glass.

The overall assembly process follows bottom beam – wall – top beam sequence. The beams at the intermediate levels are pushed further into the building allowing for one continuous façade. To ensure thermal performance of the facade at all levels, insulation with wall finished are provided at the bottom and top part to properly seal the joints and building.



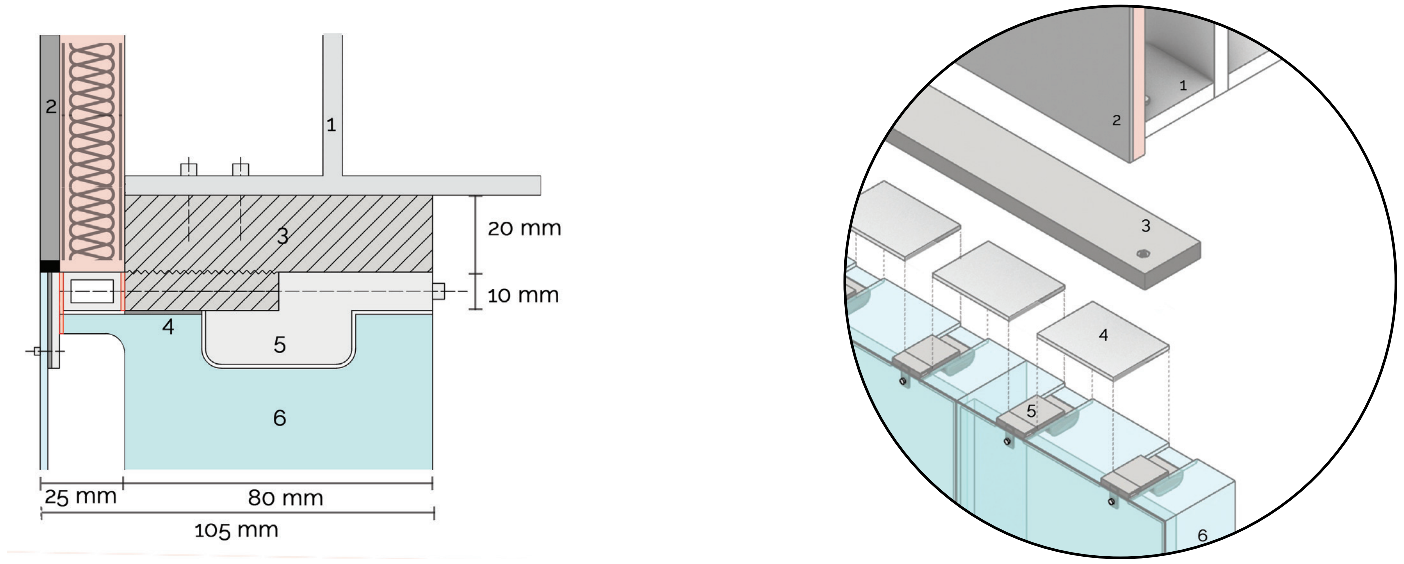
1. Glass Block
2.Steel embed with tungsten coating
3. Soft rubber layer
4.Tungsten rectangular block
5. Insulation with wall finish
6. Concrete base
7. Screw

FIGURE 105: Figure showing (a) section detail and (b) exploded view of bottom connection



1. Glass Block
2. Floor slab
3. Steel angle-section
4.Tungsten rectangular block
5. Steel embed coated with tungsten

FIGURE 106: Figure showing (a) section detail and (b) exploded view of intermediate floor connection



1. I-Beam
2. Insulation with wall finish
3. Steel plate with tungsten coating
4. Soft rubber layer
5. Steel embed with tungsten coating
6. Glass Block

FIGURE 107: Figure showing (a) section detail and (b) exploded view of top connection

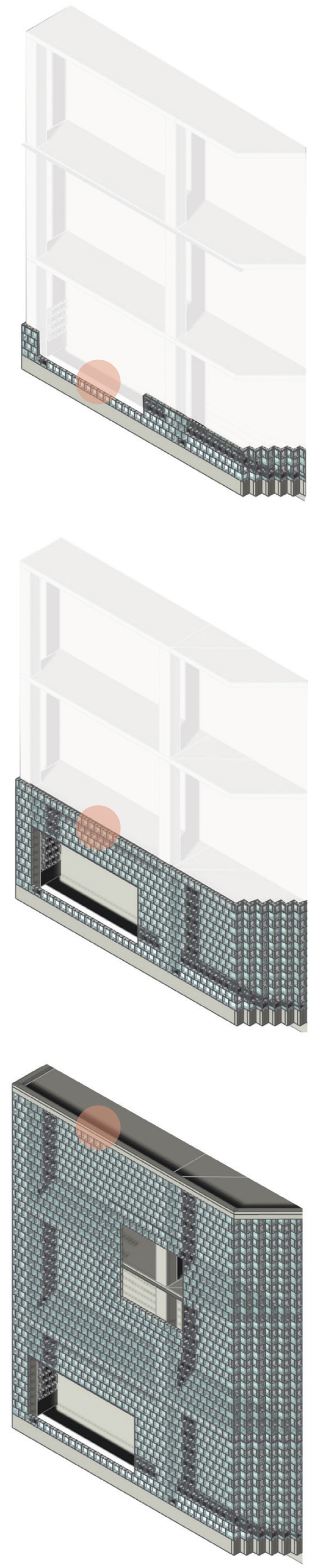


FIGURE 108: Figure showing step by step assembly of building

A. Corner Junction

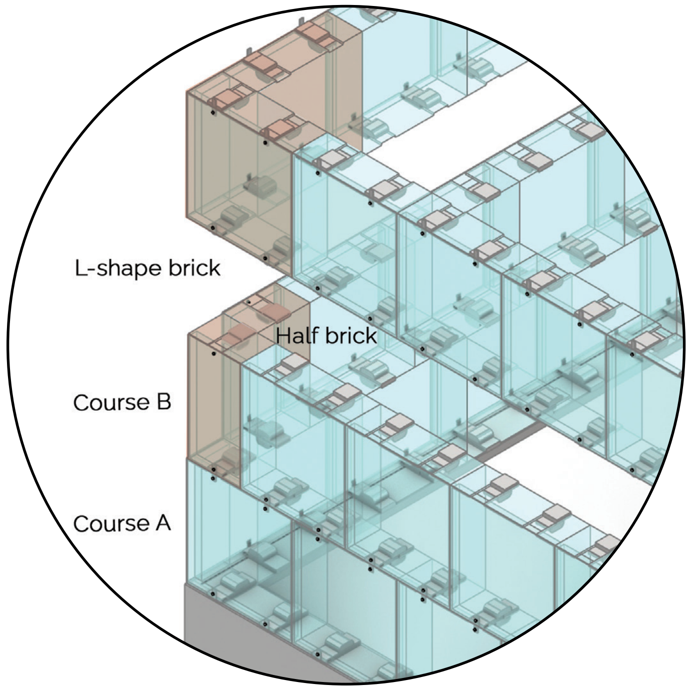


FIGURE 109: Figure showing view of corner junction detail

The corner junction is formed by a special L-shape block over which two half blocks are placed. As shown in figure 109 , course A consists of the L-shape block while course B consists of two half blocks placed on top of this. The special L-shape blocks helps in ease of assembly of this junction and ensures a regular corner with high accuracy.

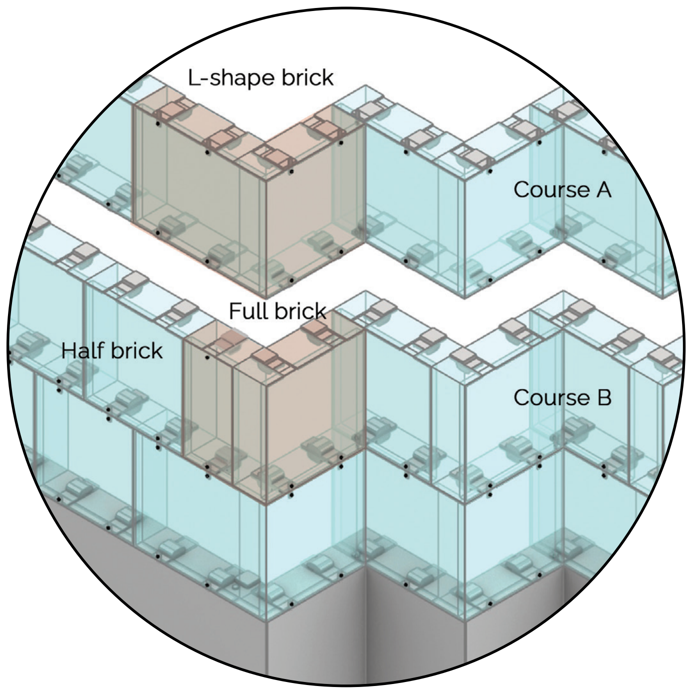


FIGURE 110: Figure showing view of corbel junction detail

Corbel Window

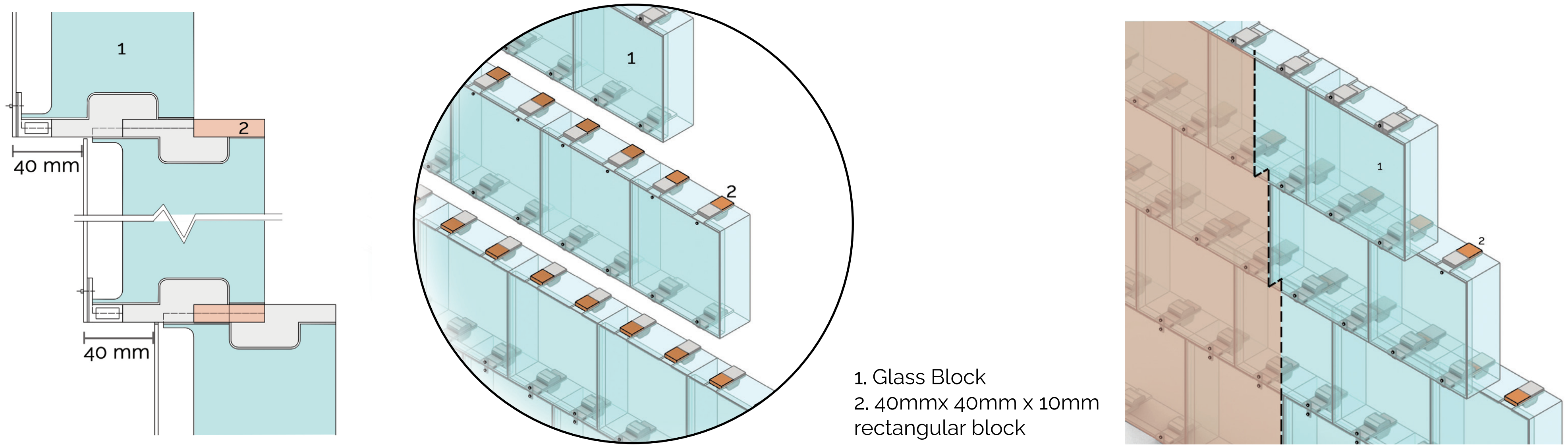


FIGURE 111: Figure showing (a) section detail (b) exploded view (c) view of Option 1 of corbel window detail

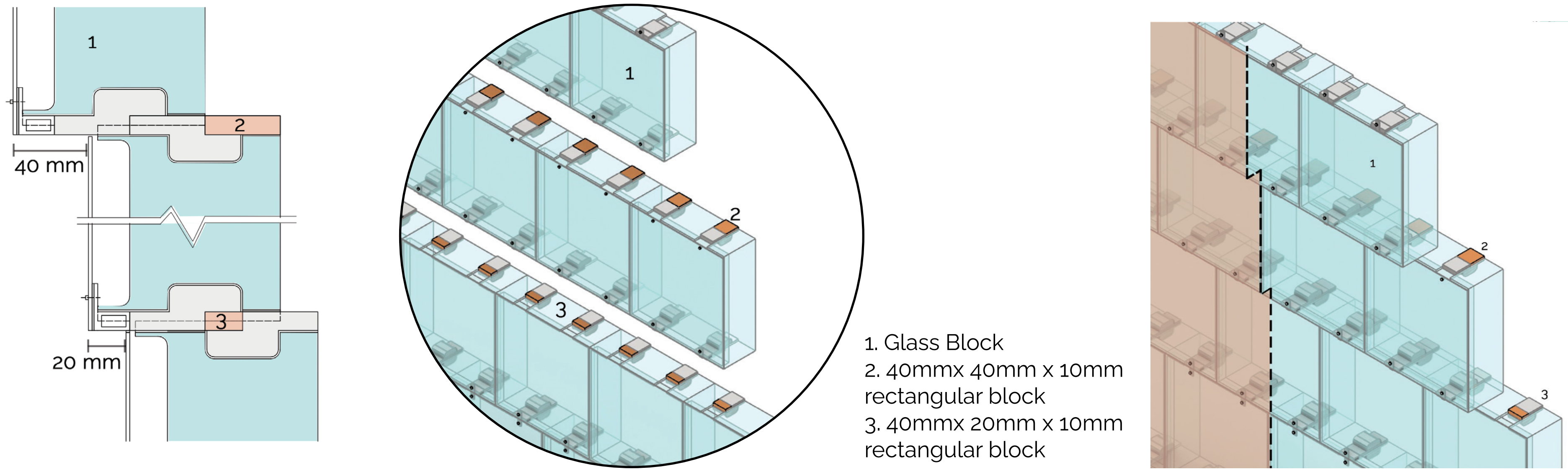


FIGURE 112: Figure showing (a) section detail (b) exploded view (c) view of Option 2 of corbel window detail

B. Corbel Junction

The corbel junction is formed with the help of L-shape blocks and full bricks. In course A, the L-shape block is directly placed one after the other to form the corbeled part. In course B, first a half brick is placed to break the vertical joint and then full bricks are placed. This assembly ensures that there are no weak vertical joints.

C. Corbel Window

To form the corbeled window portion, two options are suggested. Option 1 has a rectangular tungsten block of 40mm that is placed in between the blocks to form the corbeled part as shown in fig: 111

Option 2 follows the corbeled logic for load-bearing masonry structures. Therefore there are two types of rectangular blocks are given. In this, the first corbel part is protruded 20mm while the second is at 40mm as shown in fig 112

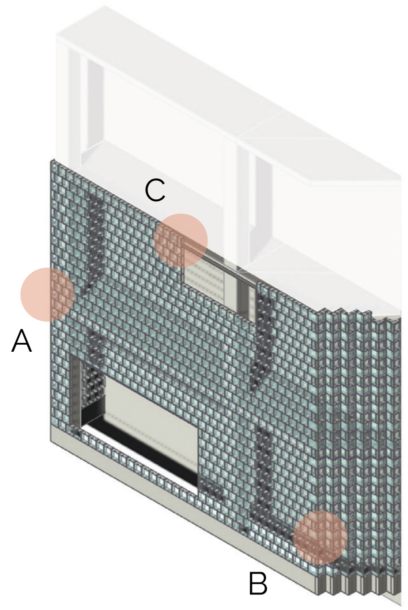
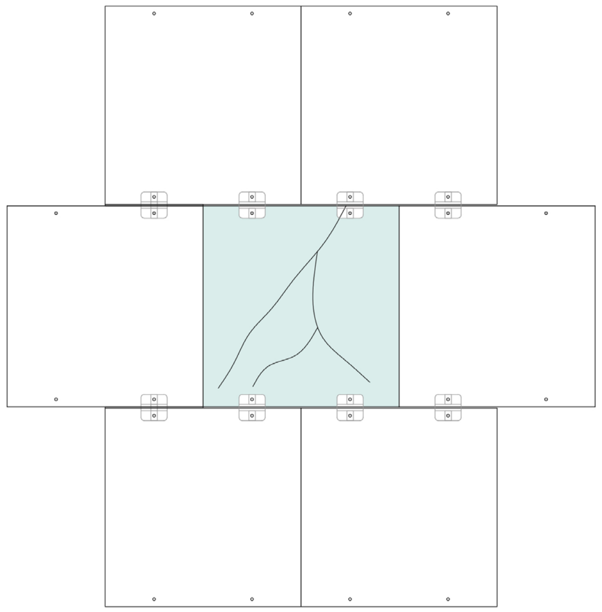


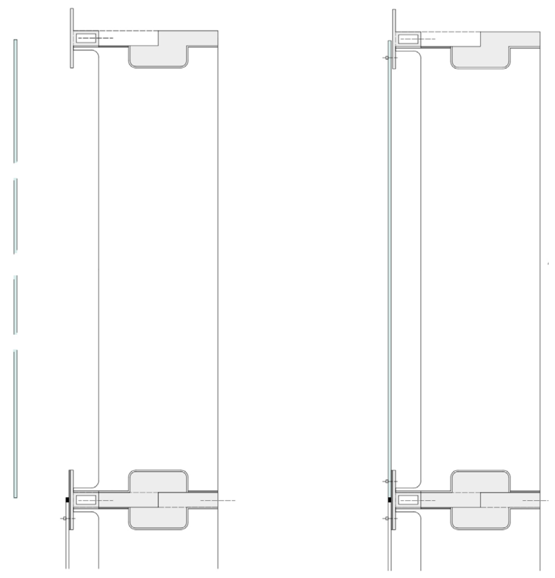
FIGURE 113: Figure showing key detail of building

07.6 Maintenance

Damaged Facade



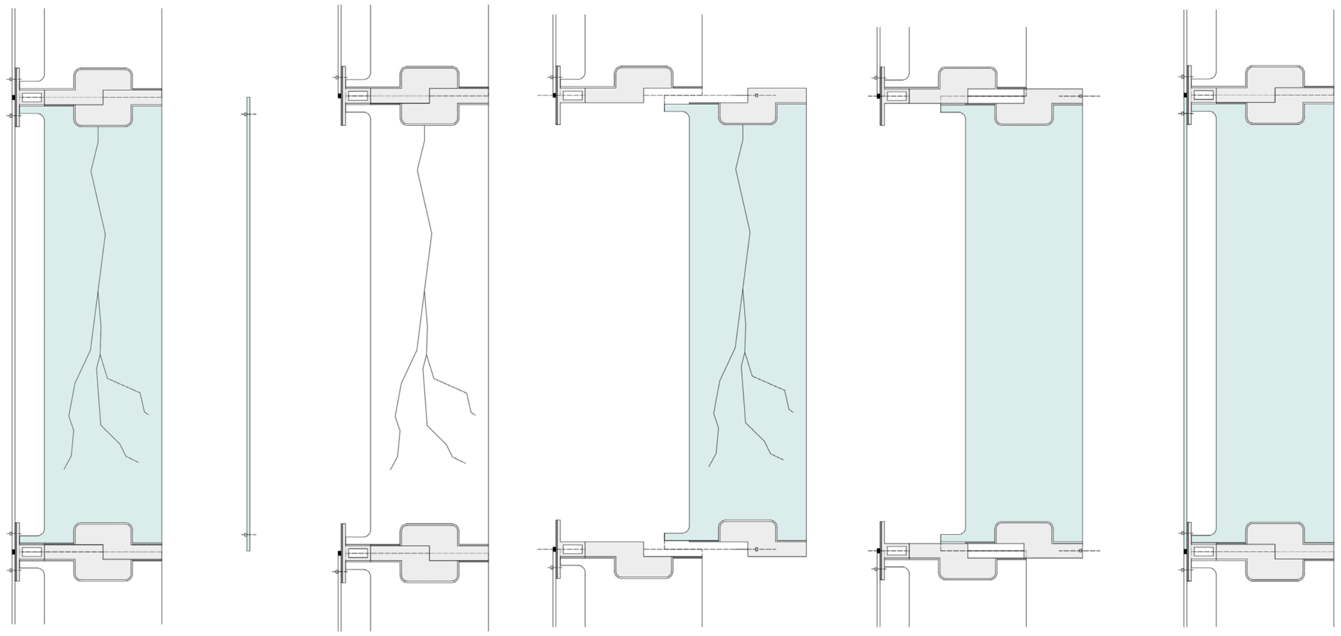
Accidental Damage



Step 1:
Undo the bolts and remove the float glass piece.

Step 2:
Add the new glass piece and bolt it.

Structural Damage



Step 1:
Undo the bolts and remove the float glass piece.

Step 2:
Remove the damaged block by unscrewing the connection

Step 3:
Slide in the new block

Step 4:
Bolt the connection and fix the exterior piece of float glass

FIGURE 114: Figure showing maintenance of facade for Fusion block

07.7 Thermal Performance

The initial thermal calculation done in this concept were purely with glass. It did not take into consideration the effect of metal embeds. In the initial analysis, the block dimensions used satisfy the thermal performance criteria set in Chapter 4. Here very thin cross-section of 2.5mm is used.

For practical reasons, such a thin cross-section may break and may not be feasible. Also, because of glass's viscosity it will not get into the thin 2mm gap in the mold, Therefore, a thicker cross-section size of 5mm is considered. This impacts the thermal performance as the size of thermal bridge is increased. Therefore, the analysis was again carried out with the new dimensions and metal embeds.

The size of cavity is 20mm and the cavity is filled with air. The float glass piece on the outside is coated therefore the thermal conductivity of the air in the cavity is 0.038 W/mK. In order to maintain the thermal performance of the block, thermal breaks (with neoprene) are provided at two ends of the metal embed. The thermal conductivity of neoprene is 0.2 W/mK and of tungsten coated with steel is 71.3 W/mK. The other values are also listed in Fig 115

The final U-value achieved for full brick is 2.0 W/m²K and for half brick is 2.2 W/m²K. The blocks comply with European and other building codes except the Dutch regulations. However, this novel technology is aimed at wider application, thus the value is acceptable.

Colours

Col.		Type	Subtype	Physical flow dir.	Geometrical flow dir.	Name	ε1 / ε2 [- / -]	λ [W/mK]	ε [-]	θ [°C]	h [W/m²K]	q [W/m²]	θa [°C]	hc [W/m²K]	Pc [W]	θr [°C]	Standard
1		MATERIAL				air		0.038									
7		MATERIAL				neoprene		0.200									
18		MATERIAL				soda lime		1.000									
24		MATERIAL				tungsten coated steel		71.300									
170		BC_SIMPL	HE			exterior				0.0	25.00	0					EN6946
174		BC_SIMPL	HI	HOR		interior (normal) horizontal heat flow				20.0	7.70	0					EN6946

FIGURE 115: Figure showing boundary conditions and thermal conductivity values for different materials used in the analysis in TRISCO

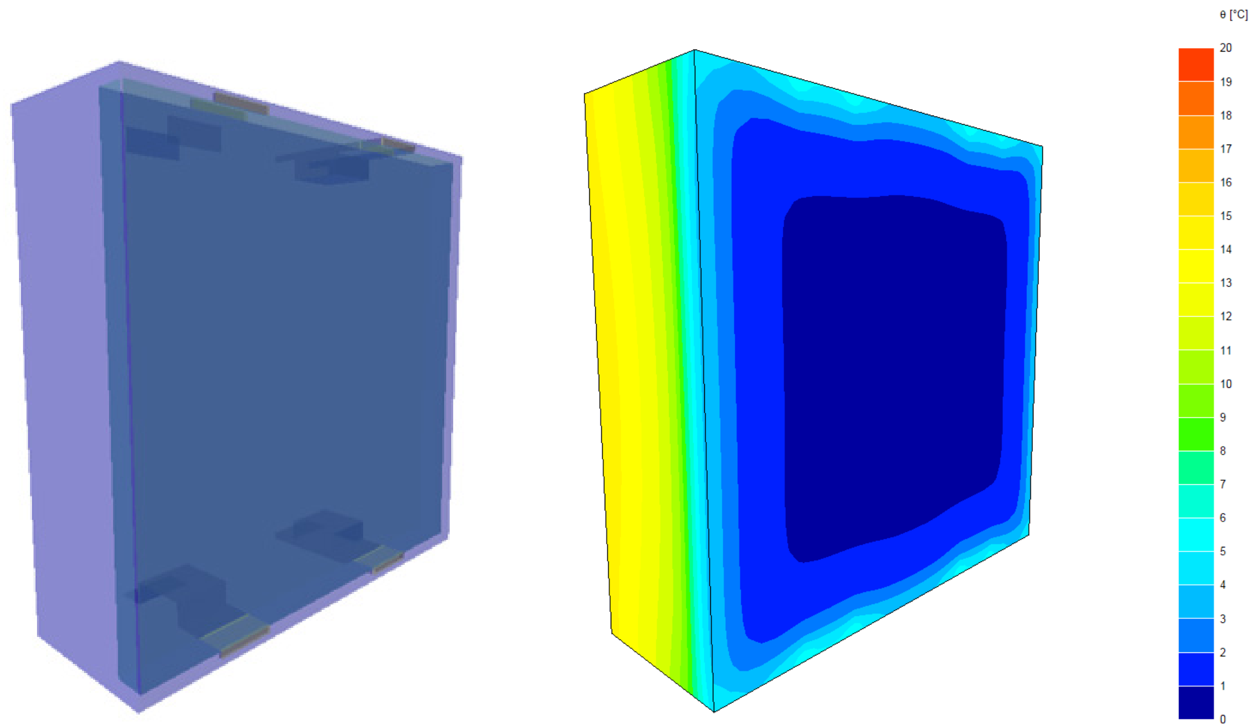


FIGURE 116: Figure showing (a) full brick and (b) temperature graph for full brick

```
TRISCO - Calculation Results

TRISCO data file: Fusionblock_full.trc

Number of nodes = 16184
Heat flow divergence for total object = 2.91787e-05 %
Heat flow divergence for worst node = 0.00586528 %
Equivalent thermal transmittance
Ueq = Q/((ti-te)*(A1+A2+A3)) = 1.194 W/(m².K)
  Q = 3.851 W
  ti = 20.0000°C
  te = 0.0000°C
  A1 = 0.0961 m²
       Xmin=1 Xmax=1 Ymin=0 Ymax=33 Zmin=0 Zmax=33
  A2 = 0.03255 m²
       Xmin=1 Xmax=14 Ymin=0 Ymax=0 Zmin=0 Zmax=33
  A3 = 0.03255 m²
       Xmin=1 Xmax=14 Ymin=0 Ymax=33 Zmin=0 Zmax=0

Ublock = (Q/(ti-te))/A1 = 2.003 W/(m².K)
```

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
1	MATERIAL	air	1.0085	2	23	11	13.0159	6	16	17
7	MATERIAL	neoprene	5.2924	2	9	32	12.5170	6	9	33
18	MATERIAL	soda_lime	0.8969	1	23	11	15.3746	14	16	17
24	MATERIAL	tungsten_coated_steel	8.9219	3	7	1	12.9762	14	11	32
170	BC_SIMPL	exterior	0.8969	1	23	11	5.8605	1	22	0
174	BC_SIMPL	interior_(normal)_horizon	12.8828	14	24	0	15.3746	14	16	17

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
170	BC_SIMPL	exterior		0.0000	3.8506
174	BC_SIMPL	interior_(normal)_horizon		3.8506	0.0000

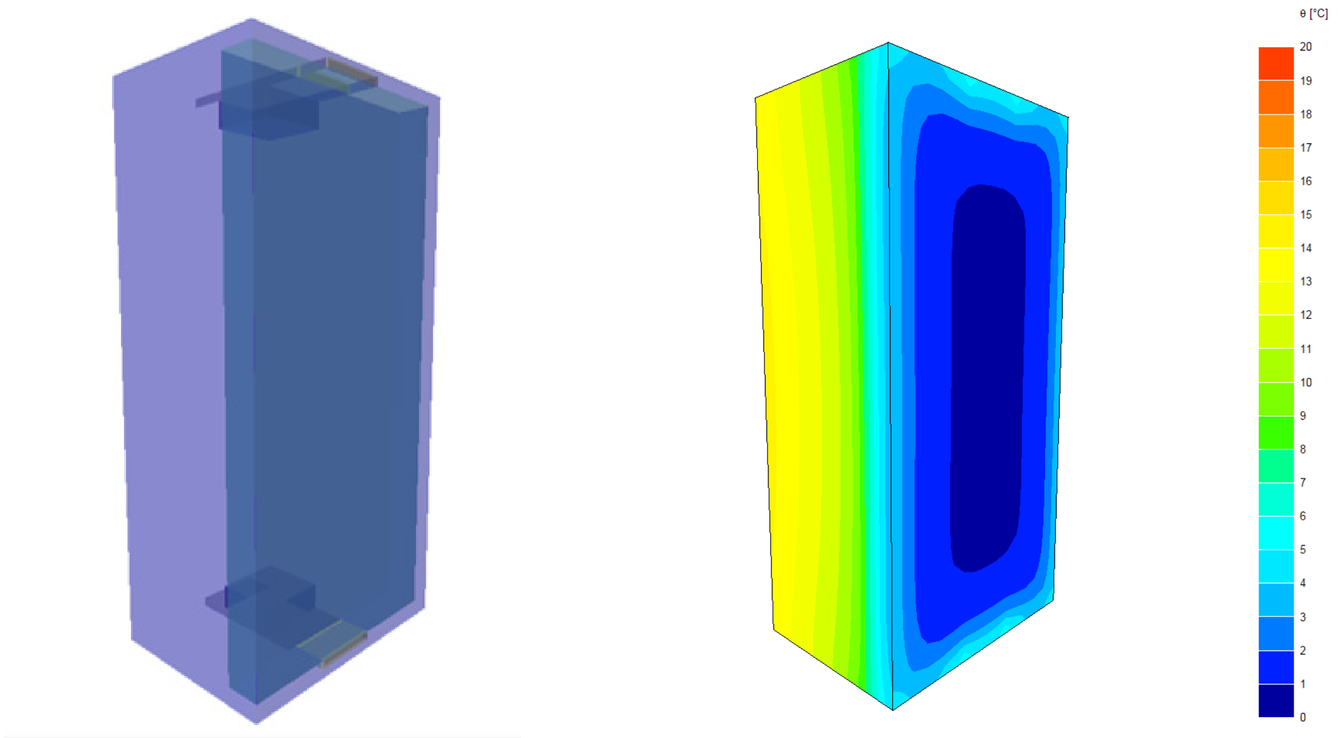


FIGURE 116: Figure showing (a) half brick and (b) temperature graph for half brick


```
TRISCO - Calculation Results

TRISCO data file: Fusionblock_half.trc

Number of nodes = 8092
Heat flow divergence for total object = 1.81964e-06 %
Heat flow divergence for worst node = 0.00166825 %
Equivalent thermal transmittance
Ueq = Q/((ti-te)*(A1+A2+A3)) = 1.111 W/(m².K)
  Q = 2.107 W
  ti = 20.0000°C
  te = 0.0000°C
  A1 = 0.0465 m²
       Xmin=1 Xmax=1 Ymin=0 Ymax=16 Zmin=0 Zmax=33
  A2 = 0.03255 m²
       Xmin=1 Xmax=14 Ymin=0 Ymax=0 Zmin=0 Zmax=33
  A3 = 0.01575 m²
       Xmin=1 Xmax=14 Ymin=0 Ymax=16 Zmin=0 Zmax=0

Ublock = (Q/(ti-te))/A1 = 2.265 W/(m².K)
```

Col.	Type	Name	tmin [°C]	X	Y	Z	tmax [°C]	X	Y	Z
1	MATERIAL	air	0.9598	2	8	11	11.8435	6	8	17
7	MATERIAL	neoprene	5.0664	2	8	32	11.7569	6	8	33
18	MATERIAL	soda_lime	0.8549	1	8	11	14.5295	14	8	17
24	MATERIAL	tungsten_coated_steel	8.4961	3	6	1	12.2243	14	10	32
170	BC_SIMPL	exterior	0.8549	1	8	11	5.5213	1	6	0
174	BC_SIMPL	interior_(normal)_horizon	12.1592	14	8	0	14.5295	14	8	17

Col.	Type	Name	ta [°C]	Flow in [W]	Flow out [W]
170	BC_SIMPL	exterior		0.0000	2.1066
174	BC_SIMPL	interior_(normal)_horizon		2.1066	0.0000

The total thermal transmittance of the facade with these block can be calculated as following:

$$U_{fac} = \frac{U_{full}S_{full} + U_{half}S_{half}}{S_{total}}$$

here,

U_{fac}	W/m²K	Thermal transmittance of facade
U_{full}, U_{half}	W/m²K	Thermal transmittance of full and half bricks
S_{full}, S_{half}	m²	Surface of full and half bricks
S_{total}	m²	Total surface area

The total thermal transmittance of the facade is:

$$U_{fac} = \frac{2.0 \times 101.52 + 2.2 \times 1.8}{103.32} = \mathbf{2.0\ W/m^2K}$$

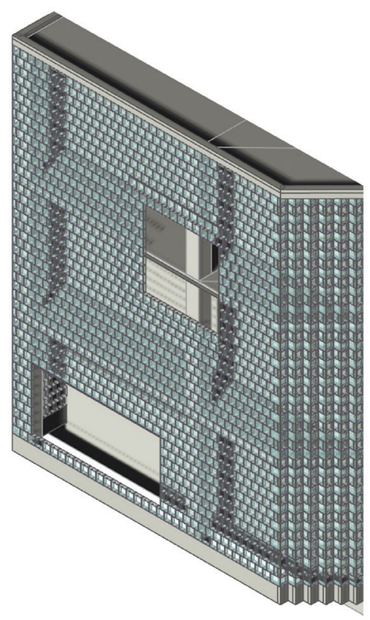
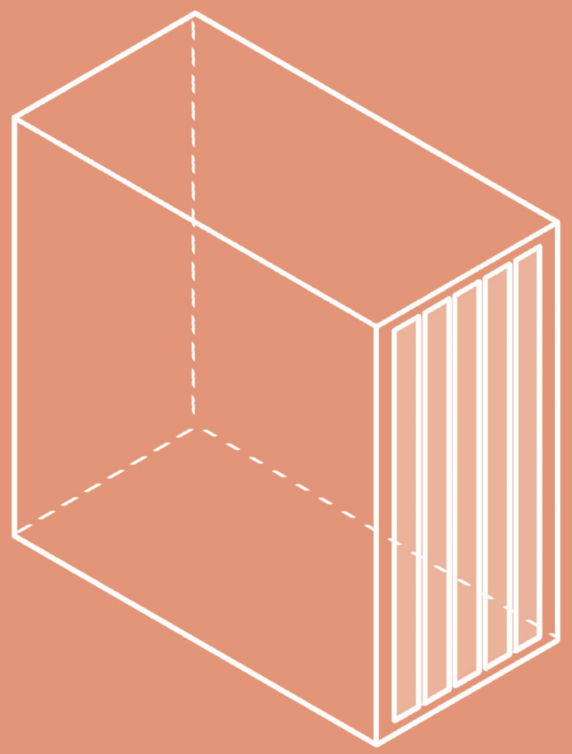


FIGURE 117: Figure showing facade under consideration

Total number of blocks used: 1168
Full brick: 1106
Half brick: 40
L-shape: 22


PORTS
1961
PORTS
EVERMOTION



Lattice Block

07.8 Prototyping Blocks

The Lattice block is developed to have multiple cavities, the advantage of this block is that the in-between layers provide stiffness to the geometry and alternative load path in case of failure so the structural performance is tremendously improved. The thickness assumed for this block previously need to be increased for stability. Since this block follows the proportion of a traditional brick which makes it easier to install, the size and dimensions are not altered instead the cavity sizes are decreased. Thus, the new design block has cross-section of outer frame to be 25mm and the internal partitions of 10mm each. The block size used is 300mm x 300mm x 150mm.

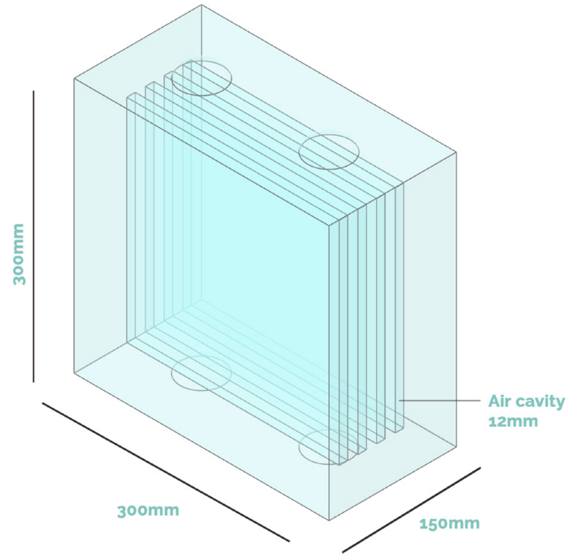


FIGURE 119: Figure showing details of Lattice block

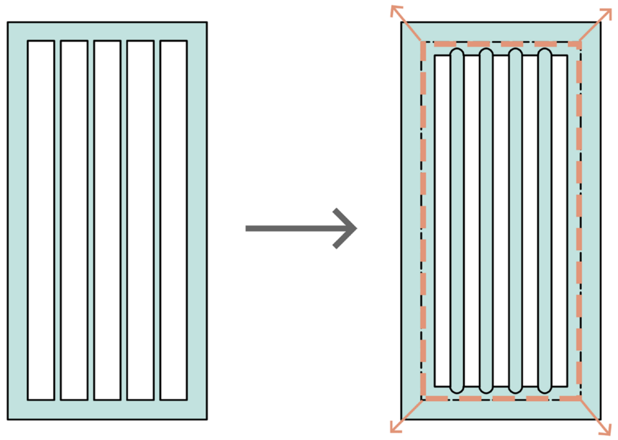


FIGURE 118: Figure showing development of lattice block

07.9 Prototyping Connection

The block-to-block connection here is an interlocking system with an interlayer. For this, different interlocking patters are studied that are shown in Fig 120.

The chosen interlocking pattern is a circular design with neoprene as interlayer as it has good structural performance, low thermal conductivity value than glass, is fire-resistant, water-tight and is cost effective. (Dimas. M, 2020) . The curved interlocking helps in evenly distributing the stresses around the joint. The

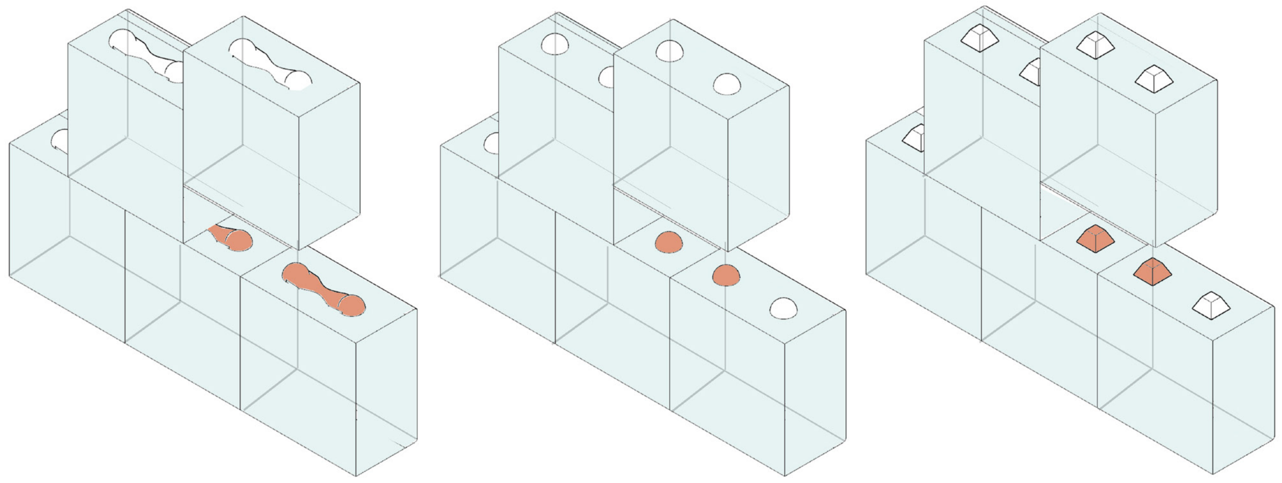


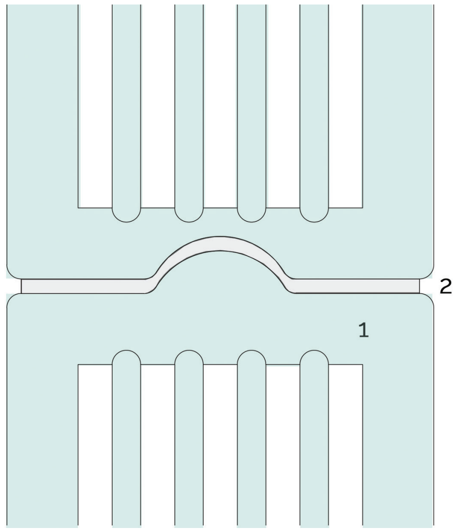
FIGURE 120: Figure showing different connection options for the Lattice Block

Connection Type		Unobstructed view	Reversibility	Ease of assembly	Load Distribution	Overall
Lattice Block	King-Queen Block interlock	++++	++++	++	++	+++
	Hemispherical Interlock	++++	++++	++++	++++	++++
	Lego type Interlock	+++	++++	++++	+++	+++

TABLE 16: Table showing scoring chart for different connections for Lattice Block

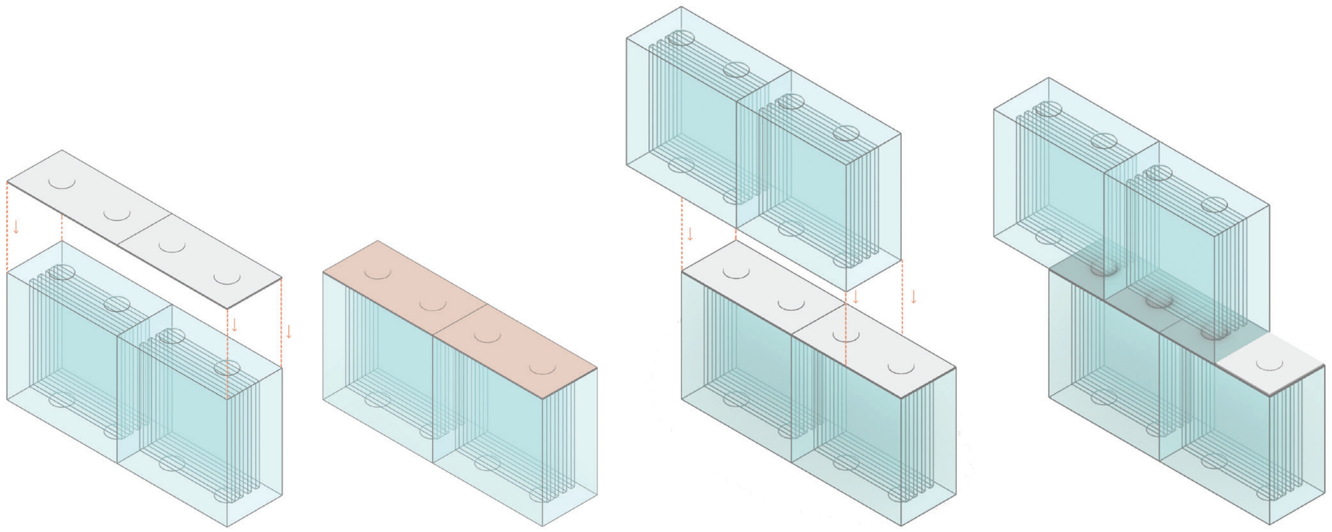
amplitude of the interlocking layer is kept 15mm to ensure a proper lock between the blocks so that the block doesn't slide away.

The connection system used here is a simple tongue and groove hemispherical interlock system. Since the design makes use of non-coated glass and air-cavities, the block can be manufactured as one unit. The design of connection is a reversible dry connection with an neoprene interlayer. Neoprene is produced in sheets which can be easily cut. No additional shaping is required. The flat specimens will be placed on top of the block and will adapt to the interlocking joint merely through compression. The figure 122 shows the installation sequence between two blocks.



1. Glass block
2. Neoprene interlayer

FIGURE 121: Figure showing connection detail for Lattice block



Step 1
Put the block in place

Step 2
Place the interlayer

Step 3
Position the second layer of block in place

Step 4
The interlayer takes the shape under compression

FIGURE 122: Figure showing assembly process of connection between two blocks for Lattice concept

07.10 Fabrication

Glass type and Method:
The fabrication of this block can be done in two ways. One is to cast the outer frame as one and insert the float pieces and seal the block. The challenge is to make sure that the glass doesn't sag when joining these pieces together. Since the glass used here is borosilicate, it is possible to locally heat the glass using flame torch and weld the pieces together. Another way would be to use the 3M DP 610 glue to join them together. (Fig 123a)

The other way (Fig 123b) is to cast the entire structure with the plates together in one mold and seal the block. The challenge with this is that the mold needs to be properly coated with either boron nitride or something similar so that glass can be easily separated from the mold.

Block Details:
The façade under study is proposed to be made from two different shapes of block as shown in Fig 124; a full brick, and a half brick. Since this block follows proportion of a traditional brick, the corbeling and corner junctions can easily be made following the masonry logic as explained in detail in the assembly section further.

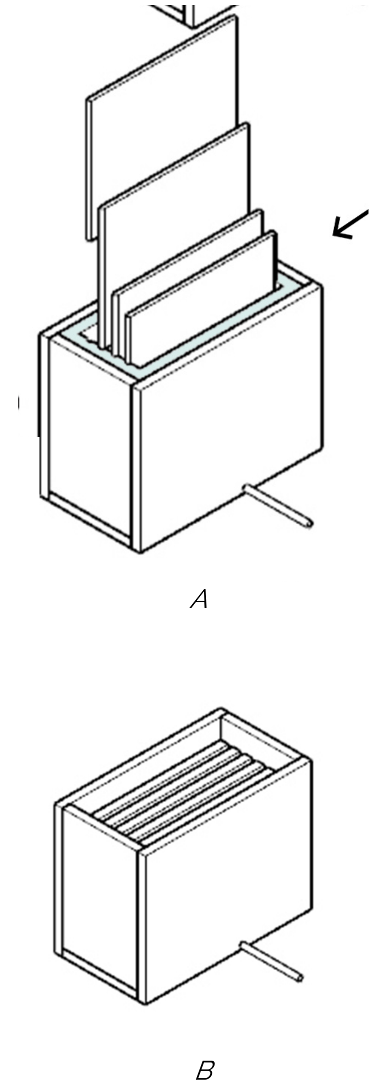


FIGURE 123: Figure showing development of lattice block

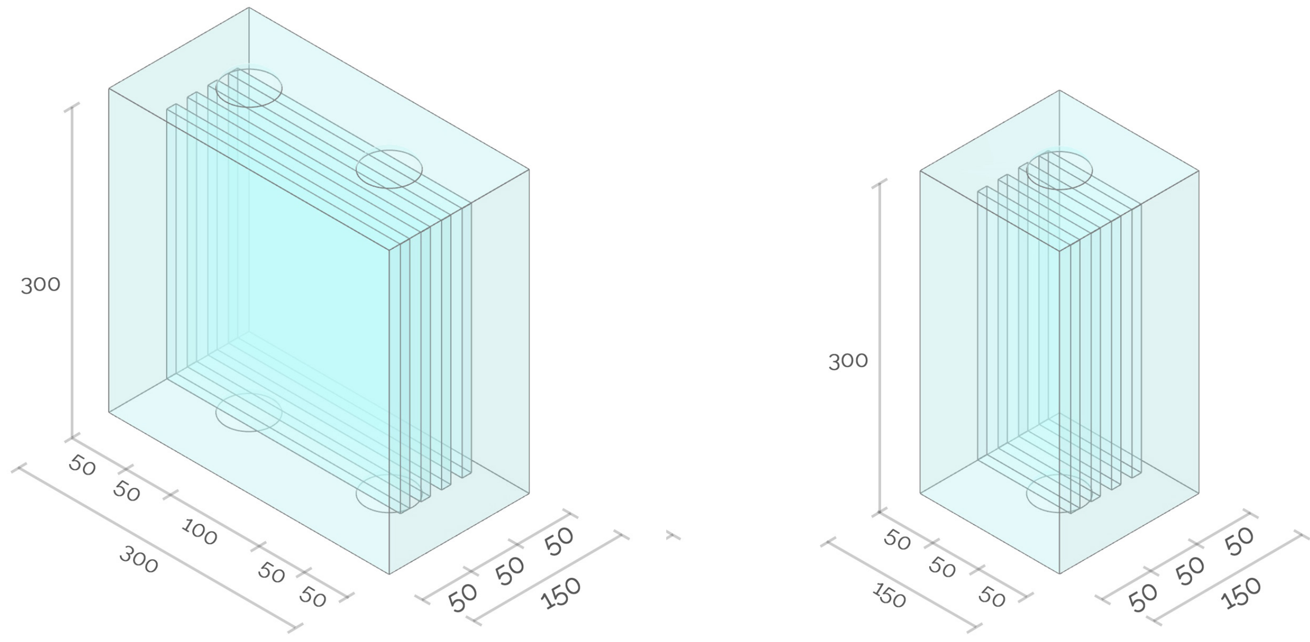


FIGURE 124: Figure showing details of full and half brick of Lattice block

The edges of all the geometry will be rounded to prevent any sharp corners and ensure a smooth annealing process. In this case as well, the weight of the block is 16 kg and can be accounted for in the managerial aspects of the project to ensure, a continuous laying process.

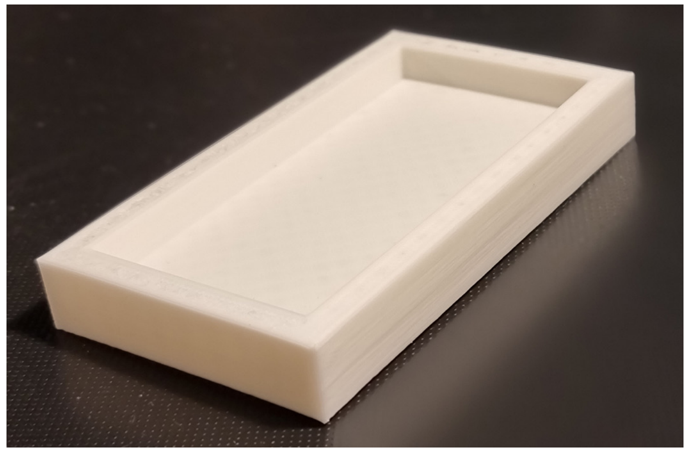
Mold Design:
High precision open steel molds are used here as well for accuracy and cost-effective purposes. Since the entire façade is made out of glass blocks, many molds will be required to produce the quantity of blocks required. As a result, different molds are design for half bricks, full bricks and their respective tops. In this design too, care is taken to ensure no bubbles are formed and glass takes the shape of the mold naturally under gravity.

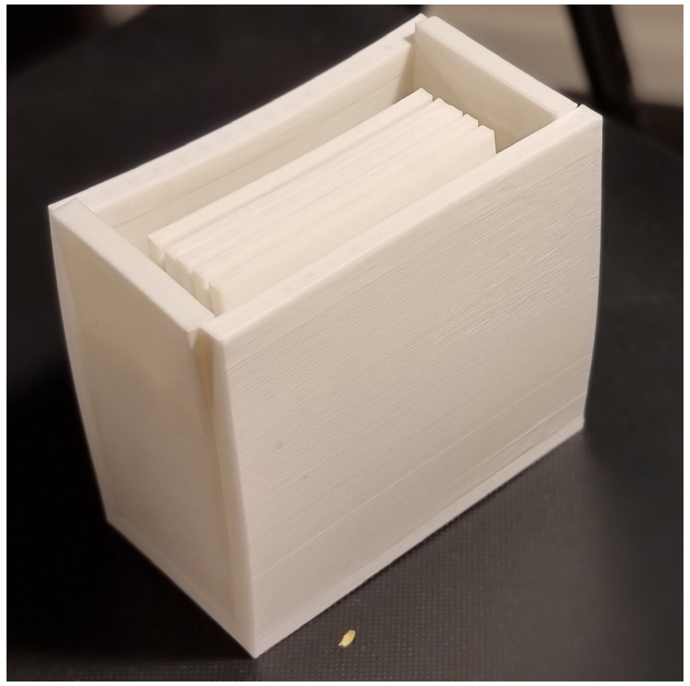
For the above-mentioned casting methods, different molds would be needed as the processes are different. Therefore, for option 1; the mold is essentially designed in 5 parts, the base as one and 4 walls. It is casted downward so that the base can be rotated and the block can be shifted to another cheaper mold which will be pre-heated to avoid sudden thermal shocks.

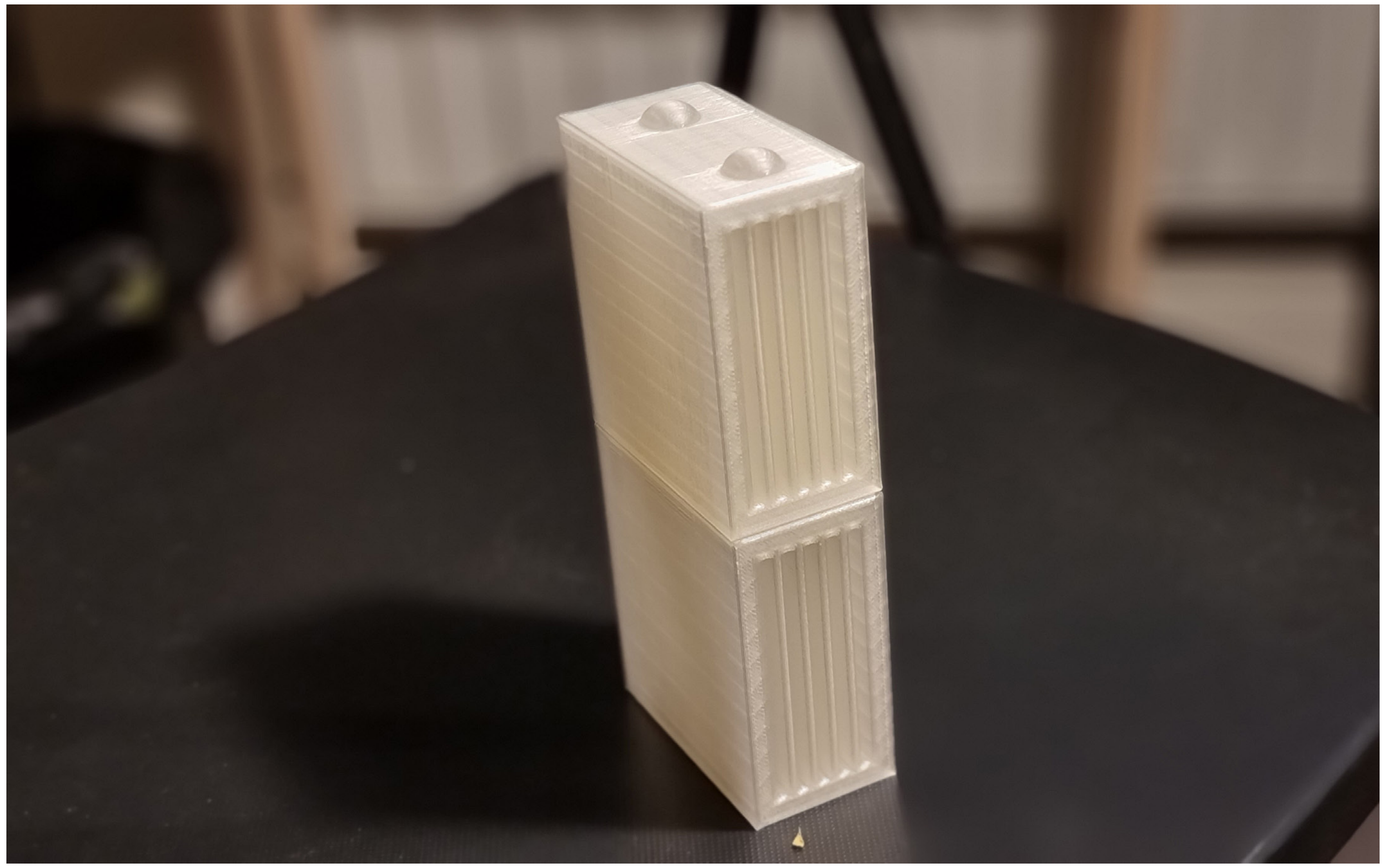
This mold will accommodate the block during the softening and annealing process to ensure there is no sagging in the hollow part. The thin float plates are either locally welded or glued just below the softening point temperature while keeping the frame in the mold. The entire geometry is then sealed with the top part and put for annealing. Since it involves two molds and a welding process, the method can increase the production cost.

For option 2, the mold is designed to accommodate the thin float plates together with the outer frame. The entire geometry with base is casted as one and the top is separately sealed later below softening point temperature. The mold for this can be made with 5 parts; a base and 4 walls. The mold can be removed for the annealing process. Careful consideration in coating the mold need to be taken when casting with this method as the glass might stick to the mold and won't come out. This is a challenging aspect, however more complicated shapes with glass have been casted before therefore, it is possible to manufacture the glass block with this method.

The different types of molds along with their respective manufacturing process is shown in Fig 126 and Fig 127.







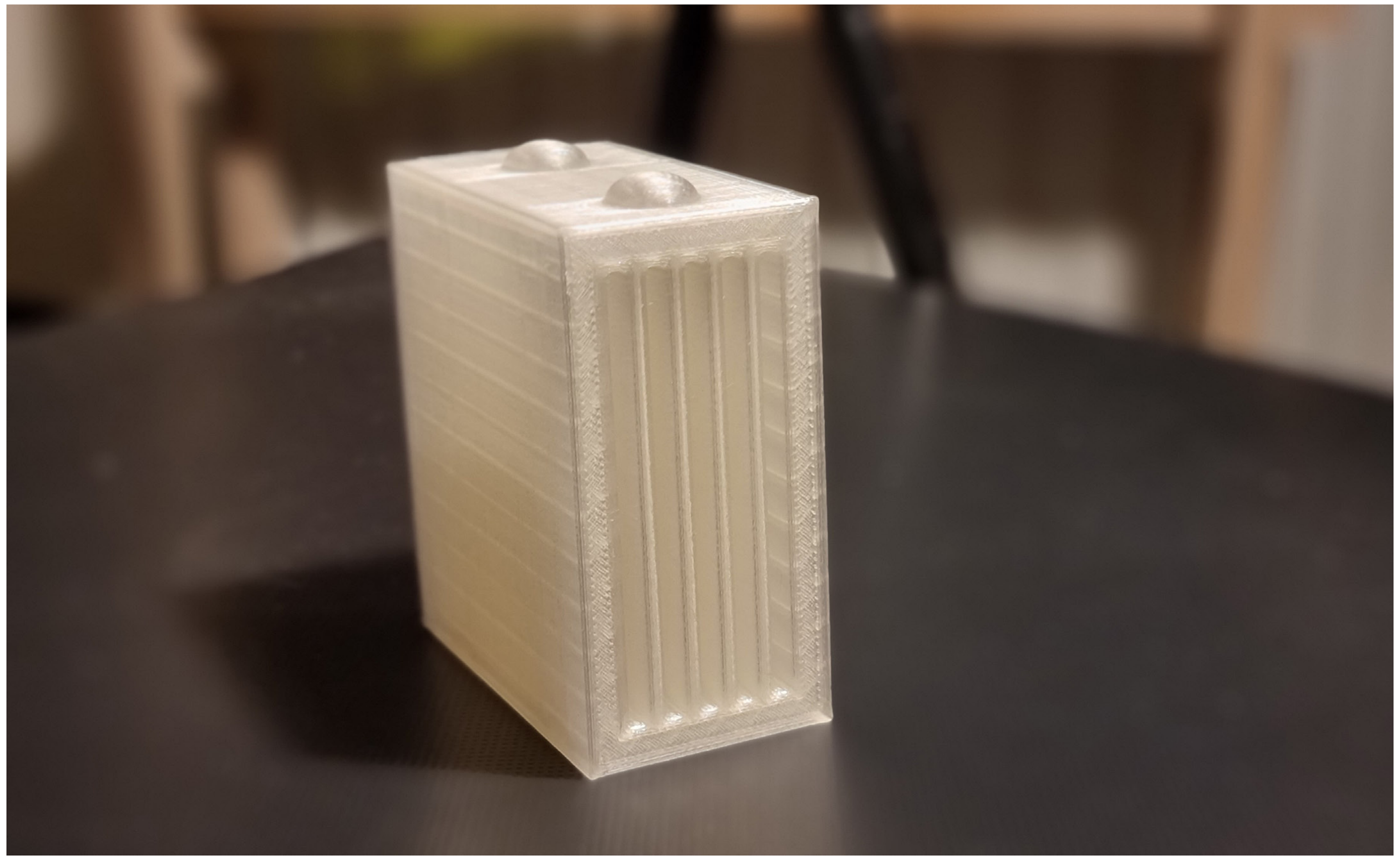


FIGURE 125: Figure showing 3D print of mould and block

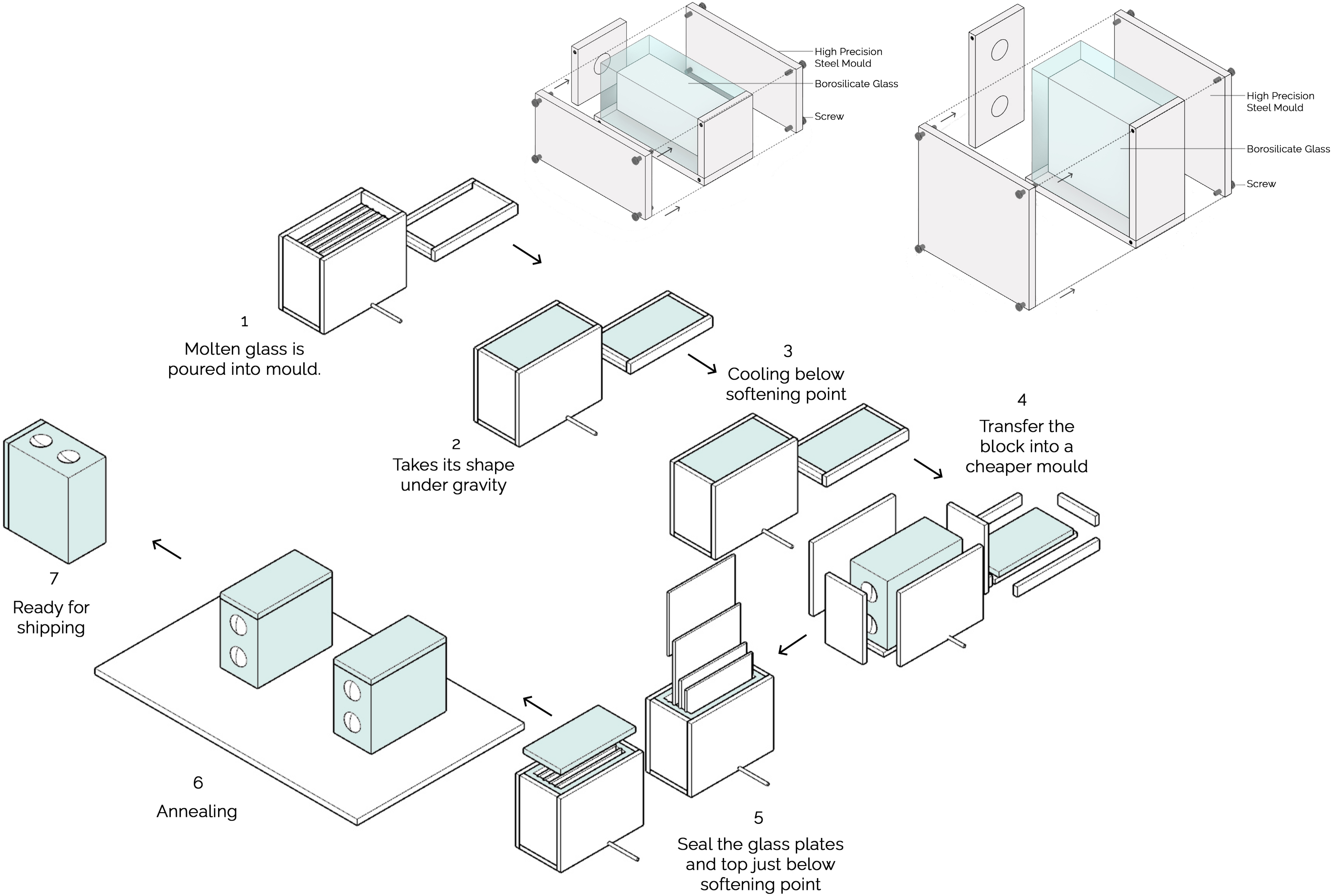


FIGURE 126: Figure showing manufacturing process option 1 for Lattice block with respective mould details

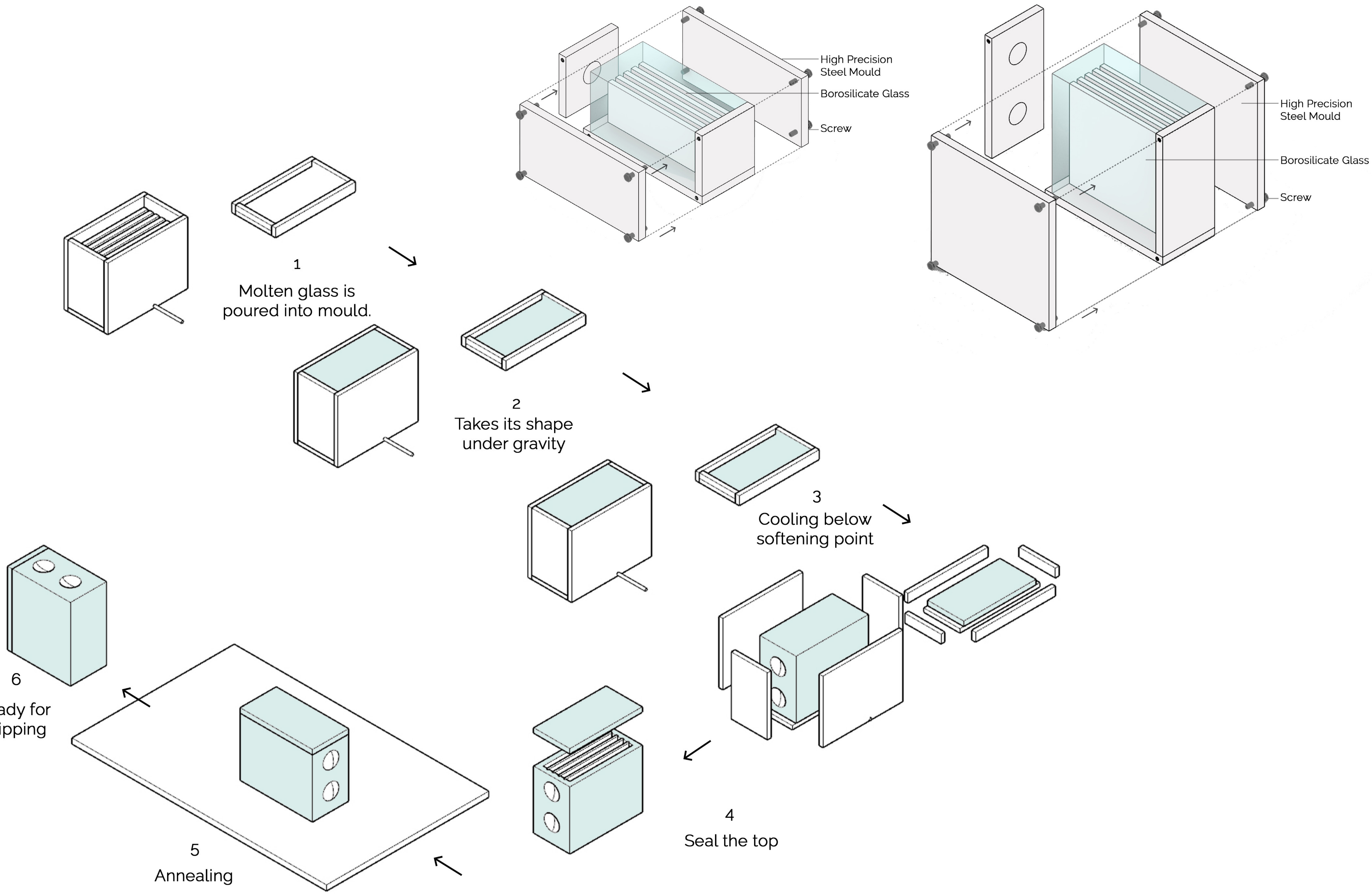


FIGURE 127: Figure showing manufacturing process option 2 for Lattice block with respective mould details

07.11 Assembly

Bottom Connection

The purpose of the bottom detail is to properly place and align the assembly. To avoid casting an additional block, tungsten coated steel plates are milled into shape with their top face interlocking which are placed over the concrete base. Over this neoprene interlayer in placed to avoid the direct contact between steel and glass. Then the glass blocks are placed. To accommodate the vertical tolerances between steel plate and concrete base, non-shrinkage concrete is added. This also ensures a flat base to start the assembly. The dimensional tolerances between glass blocks is taken care by the interlayer.

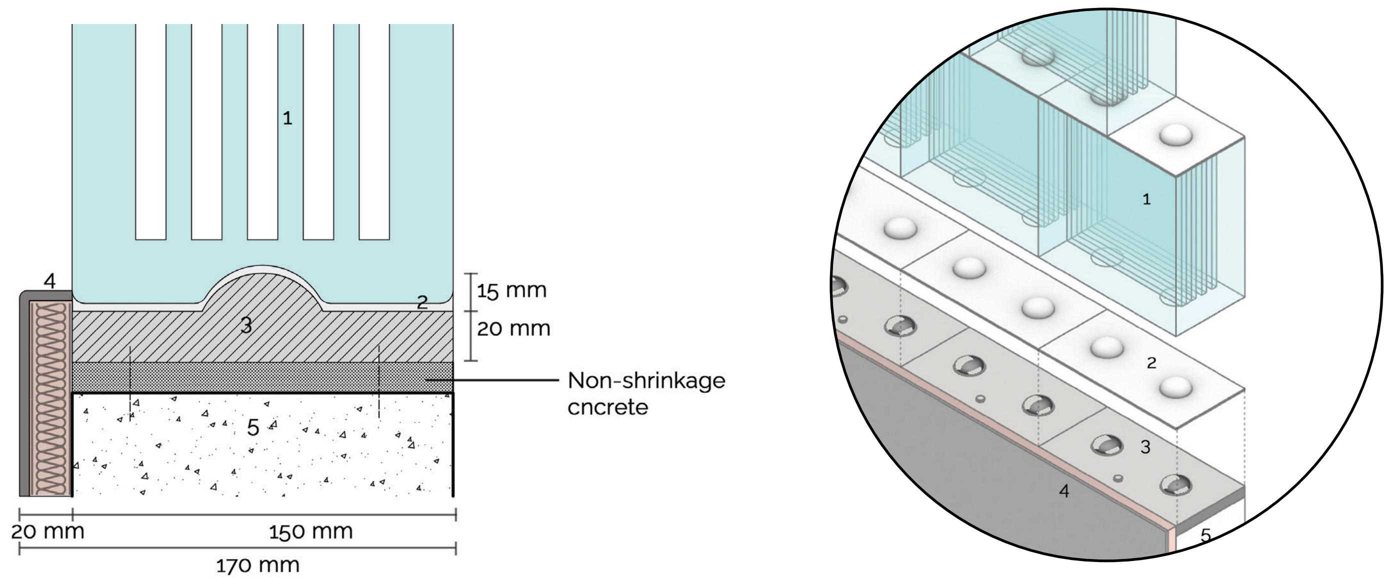
Intermediate Floor Connection

For the intermediate floor connection, the design of connection is done in a way that there are no excess protrusion from the face of the blocks. To do this, the glass blocks are tied to discrete specially milled steel plates with interlocking on both top and bottom faces which are then connected to the floor through angle – sections.

Top Connection

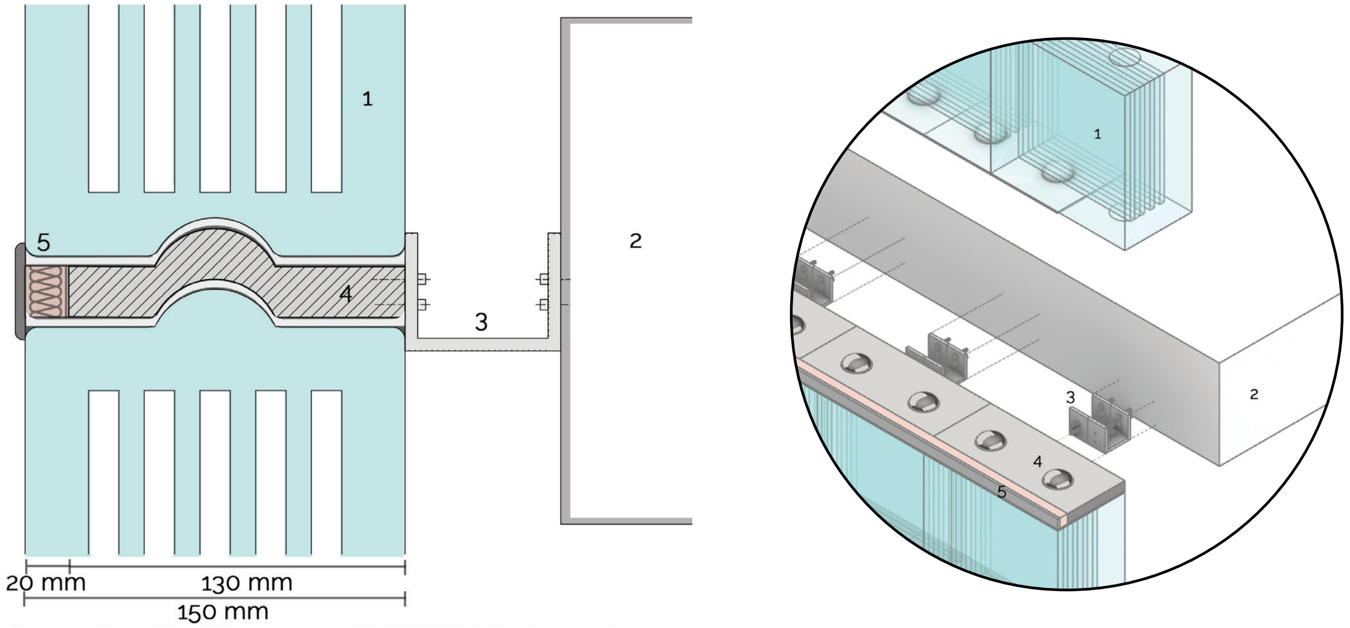
In the top connection, since neoprene has a tendency to creep, therefore the I-beam at the top needs to be placed at a higher position and then lowered and secured, at a height suitable for the desired compression. Here too tungsten coated steel blocks are screwed on to the I-section as in the bottom detail. The height at which the beam is placed depends on the amplitude of interlocking system. In our case that is 15mm, thus the beam is placed at 25 - 35mm higher for the worker to place the last row and place the interlayer. The beam is then finally lowered and secured in its final position. Any tolerances that occur can be accounted for by the repositioning of the beam.

The overall assembly process follows bottom beam – wall – top beam sequence. To ensure thermal performance of the facade at all levels, insulation with wall finished are provided to properly seal the joints and building.



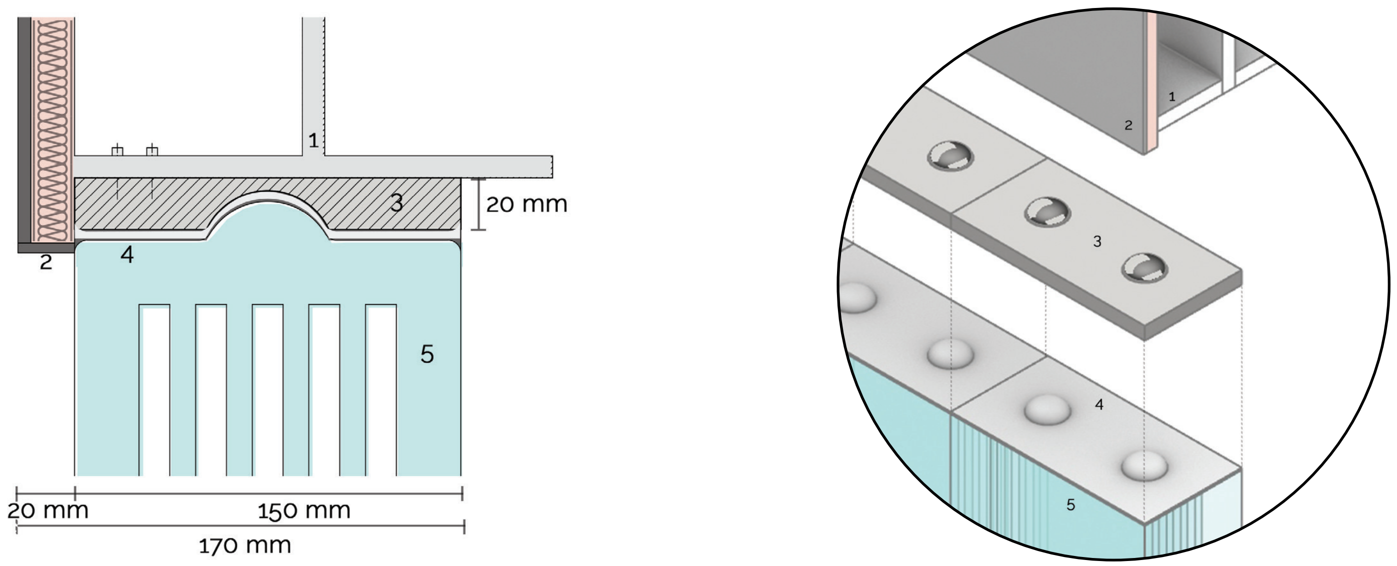
1. Glass Block
2. Neoprene interlayer
3. Steel plate coated with tungsten
4. Insulation with wall finish
5. Concrete base

FIGURE 128: Figure showing (a) section detail and (b) exploded view of bottom connection



1. Glass Block
2. Floor slab
3. Steel angle -section
4. Steel plate coated with tungsten
5. Insulation with wall finish

FIGURE 129: Figure showing (a) section detail and (b) exploded view of intermediate floor connection



1. I-Beam
2. Insulation with wall finish
3. Steel plate coated with tungsten
4. Neoprene interlayer
5. Glass block

FIGURE 130: Figure showing (a) section detail and (b) exploded view of top connection

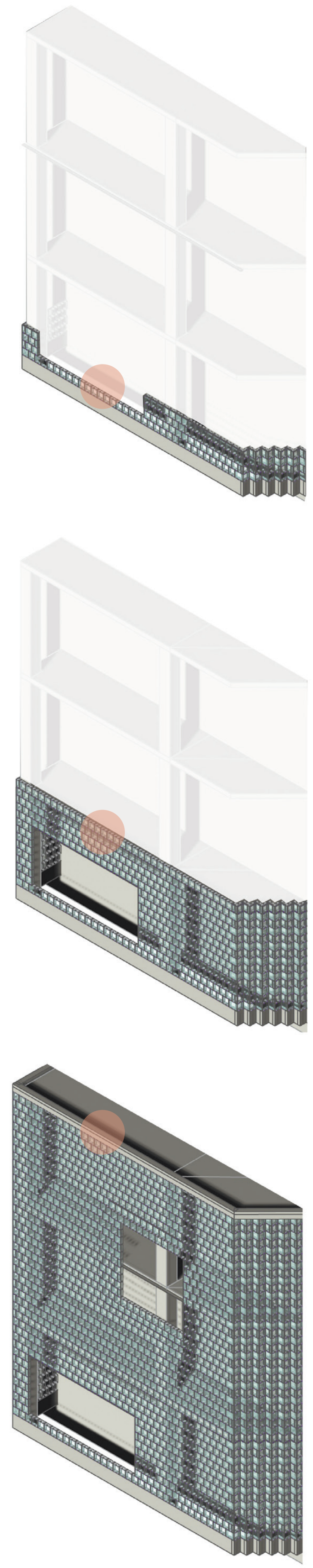


FIGURE 108: Figure showing step by step assembly of building

A Corner Junction

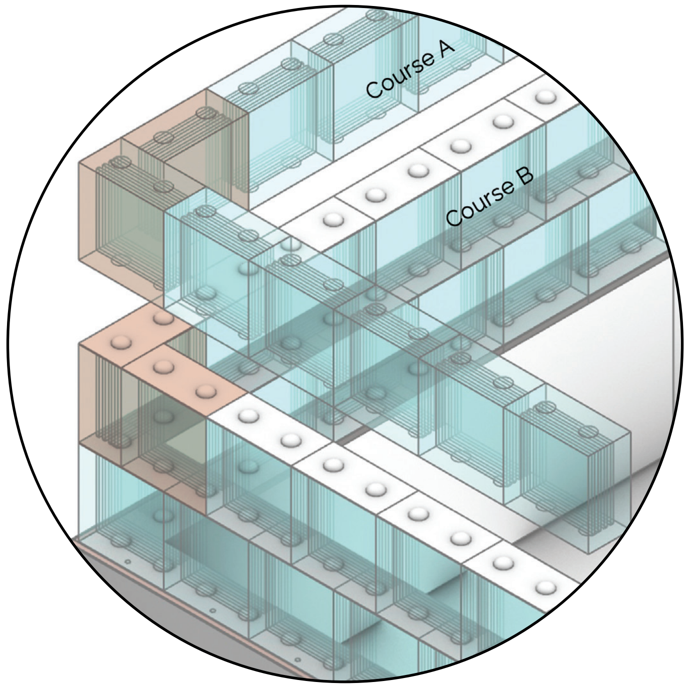


FIGURE 131: Figure showing view of corner junction detail

The corner junction is formed by placing the full bricks alternatively to each other. This ensures that there are no weak vertical joints in the system. The logic is similar to the L-junction in terracotta brick masonry systems.

Corbel Window

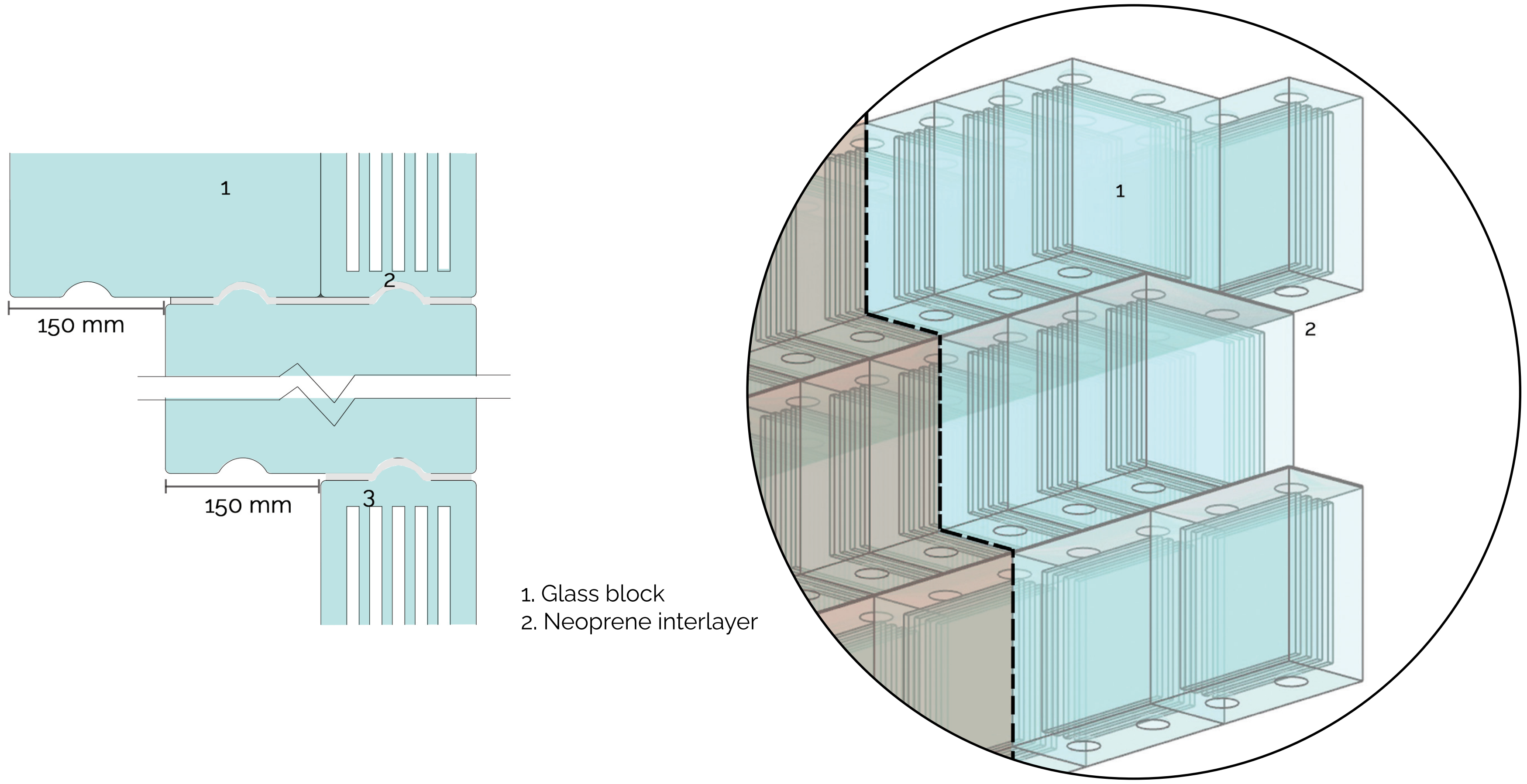


FIGURE 133: Figure showing (a) section detail (b) view of corbel window detail

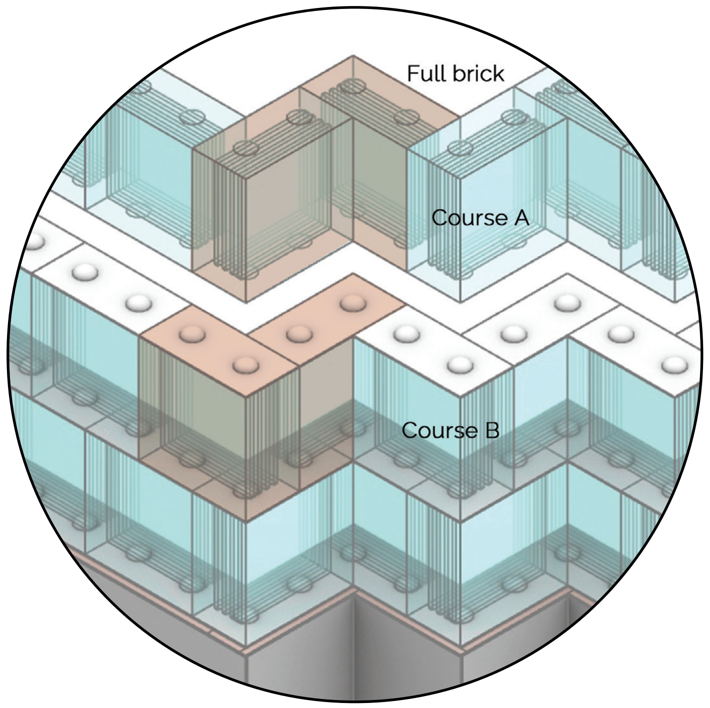


FIGURE 132: Figure showing view of corbel junction detail

B Corbel Junction

The corbel junction is also formed by alternating between full bricks in the two courses. It is ensured here as well that there are no vertical joints in the system.

C Corbel Window

To form the corbeled window portion, in the first course, the bricks are rotated by 90 degrees and placed. This ensures a protrusion of 150mm. In the second course, the bricks are placed exactly on top of each other but the second half accommodates series of full bricks in regular way that provides stability to the system.

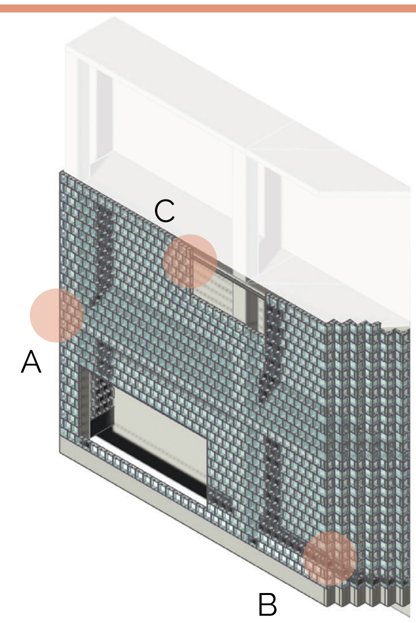
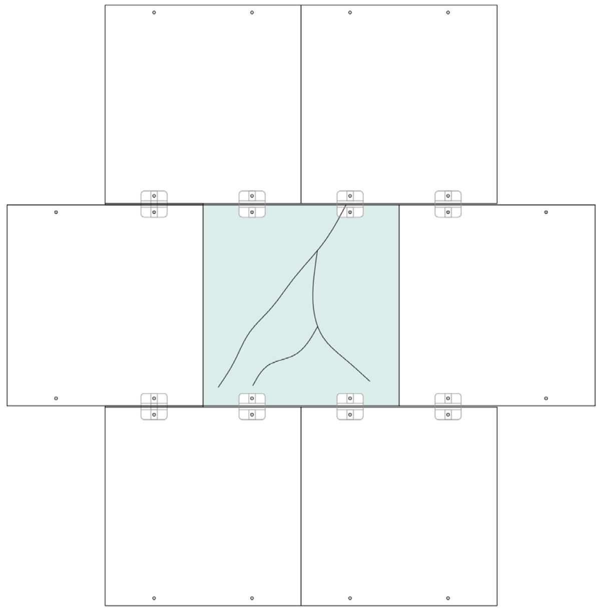


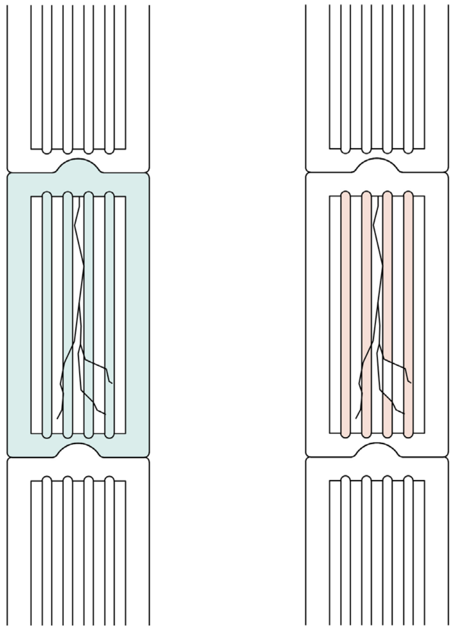
FIGURE 113: Figure showing key detail of building

07.12 Maintenance

Damaged Facade



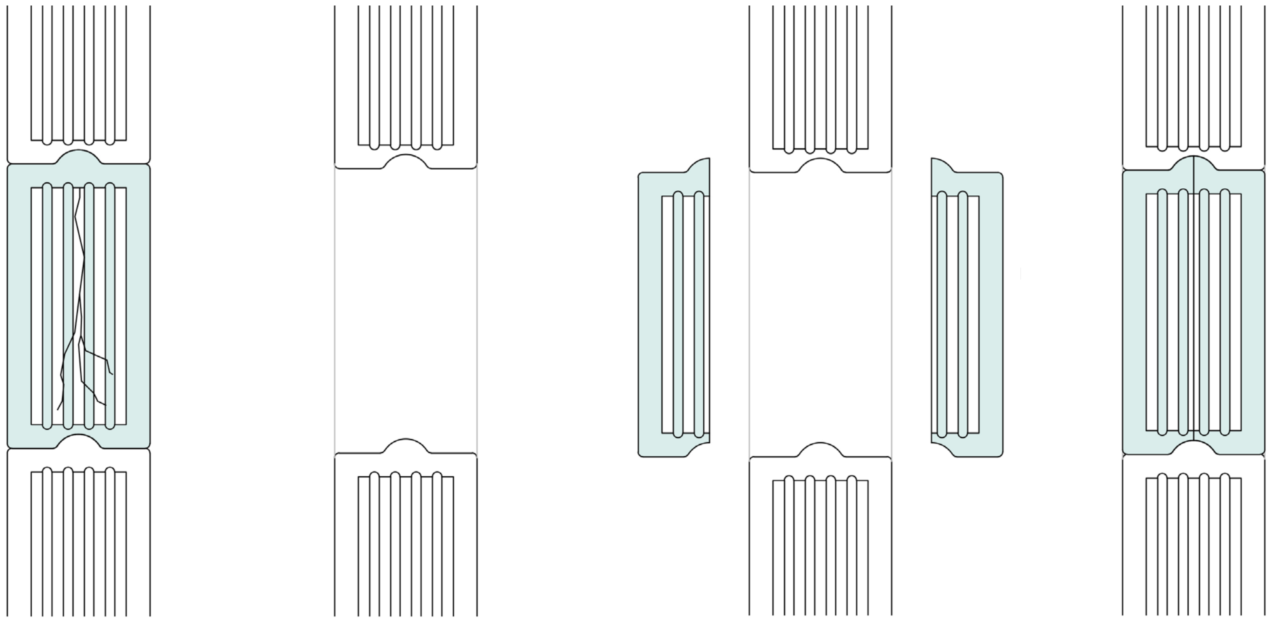
Accidental Damage



Step 1:
No need to remove the block

Step 2:
Additional load paths can carry load

Structural Damage



Step 1:
Remove the glass by breaking it

Step 2:
Clean the part where block needs to be fixed

Step 3:
Slide in the new block in two halves and locally fuse them together

FIGURE 134: Figure showing maintenance of facade for Lattice block

07.13 Thermal Performance

The thermal calculation done prior to this has a thin cross-section of the outer frame as well as the float glass plates and the cavity size were larger. After working out the glass design for structural safety, the cross-section thickness was increased leading to formation of larger thermal bridges. Thus, the analysis was carried out again.

The size of each cavity is 12mm and it is filled with air. The thermal conductivity of air in this cavity width is 0.074 W/mK. There are total 5 cavities of 12mm each.

Col.		Type	Subtype	Physical flow dir.	Geometrical flow dir.	Name	ε1 / ε2 [- / -]	λ [W/mK]	ε [-]	θ [°C]	h [W/m²K]	q [W/m²]	θa [°C]	hc [W/m²K]	Pc [W]	θr [°C]	Standard
1		MATERIAL				air		0.074									
18		MATERIAL				borosilicate		1.000									
170		BC_SIMPL	HE			exterior				0.0	25.00	0					EN6946
174		BC_SIMPL	HI	HOR		interior (normal) horizontal heat flow				20.0	7.70	0					EN6946

FIGURE 135: Figure showing boundary conditions and thermal conductivity values for different materials used in the analysis in TRISCO

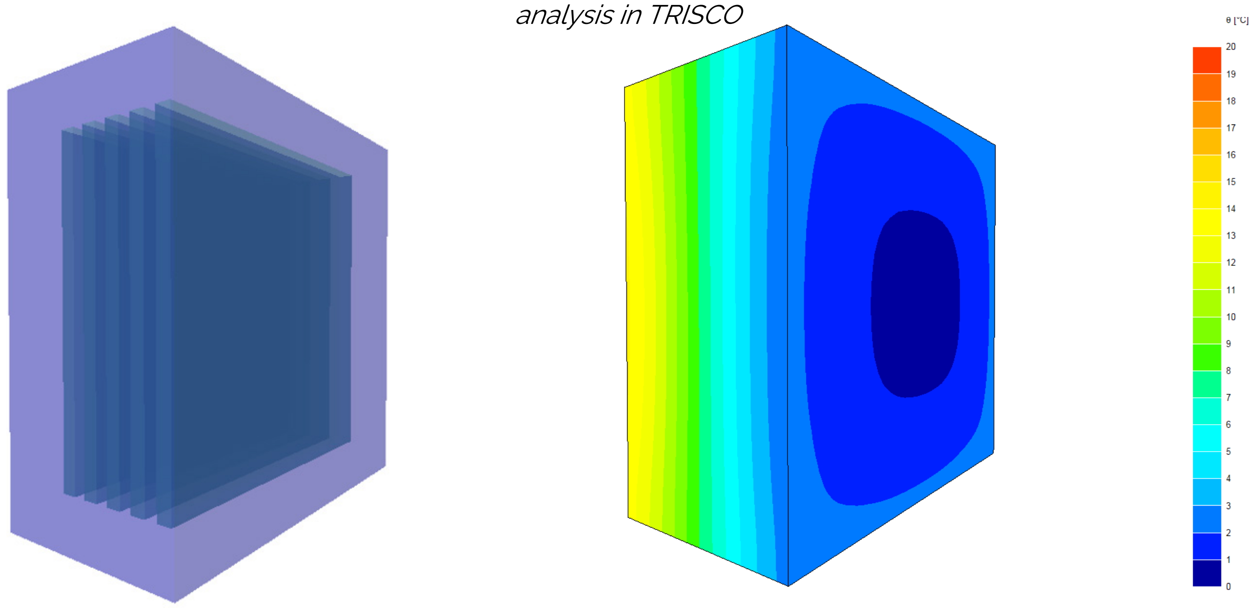


FIGURE 136: Figure showing (a) full brick and (b) temperature graph for full brick

```
TRISCO - Calculation Results

TRISCO data file: Lattice Block.trc

Number of nodes = 21504
Heat flow divergence for total object = 5.20586e-10 %
Heat flow divergence for worst node = 1.53904e-05 %

Ublock = (Q/(ti-te))/A1 = 1.937 W/(m².K)
  Q = 3.486 W
  ti = 20.0000°C
  te = 0.0000°C
  A1 = 0.09 m²
       Xmin=22 Xmax=22 Ymin=0 Ymax=31 Zmin=0 Zmax=31
```

The final U-value achieved for full brick is 1.9 W/m²K, for half brick is 2.3 W/m²K and for brick rotated 90 degrees is 1.7 W/m²K. This lower U-value for rotated brick is because the path length for heat transfer increases and the U-value is reduced with a similar cross-section of the thermal bridge. The block complies with European and other building codes except the Dutch regulations. However, this novel technology is aimed at wider application, thus the value is acceptable.

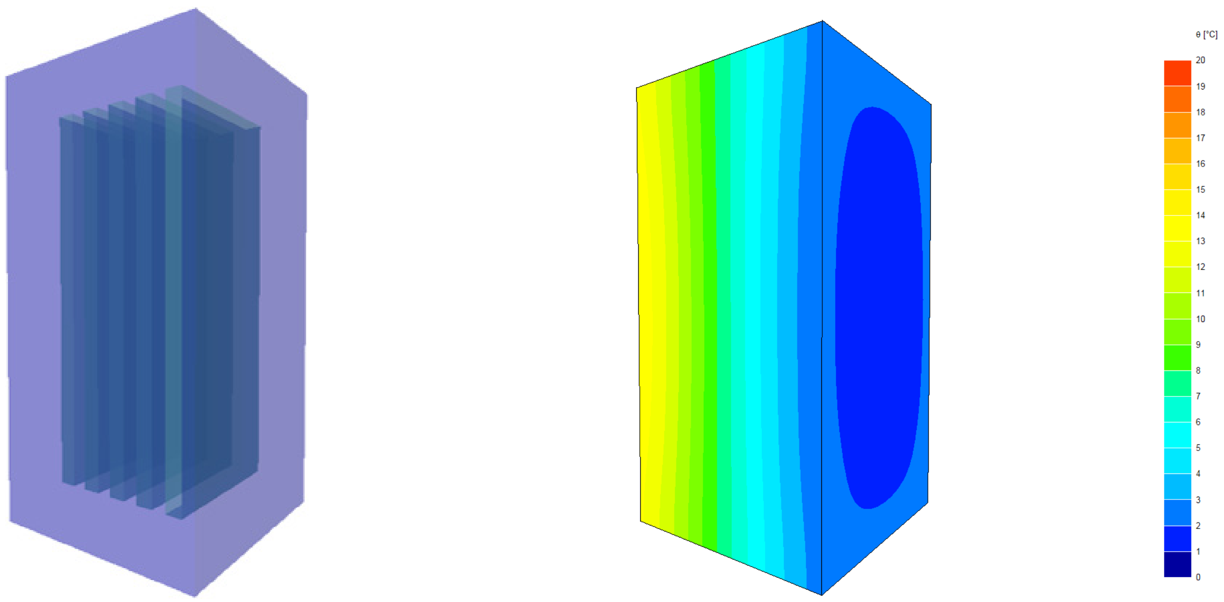


FIGURE 137: Figure showing (a) half brick and (b) temperature graph for half brick

```
TRISCO - Calculation Results

TRISCO data file: Lattice Block_half.trc

Number of nodes = 11424
Heat flow divergence for total object = 1.15294e-05 %
Heat flow divergence for worst node = 0.00234768 %

Ublock = (Q/(ti-te))/A1 = 2.312 W/(m².K)
   Q = 2.081 W
   ti = 20.0000°C
   te = 0.0000°C
   A1 = 0.045 m²
        Xmin=22 Xmax=22 Ymin=0 Ymax=16 Zmin=0 Zmax=31
```

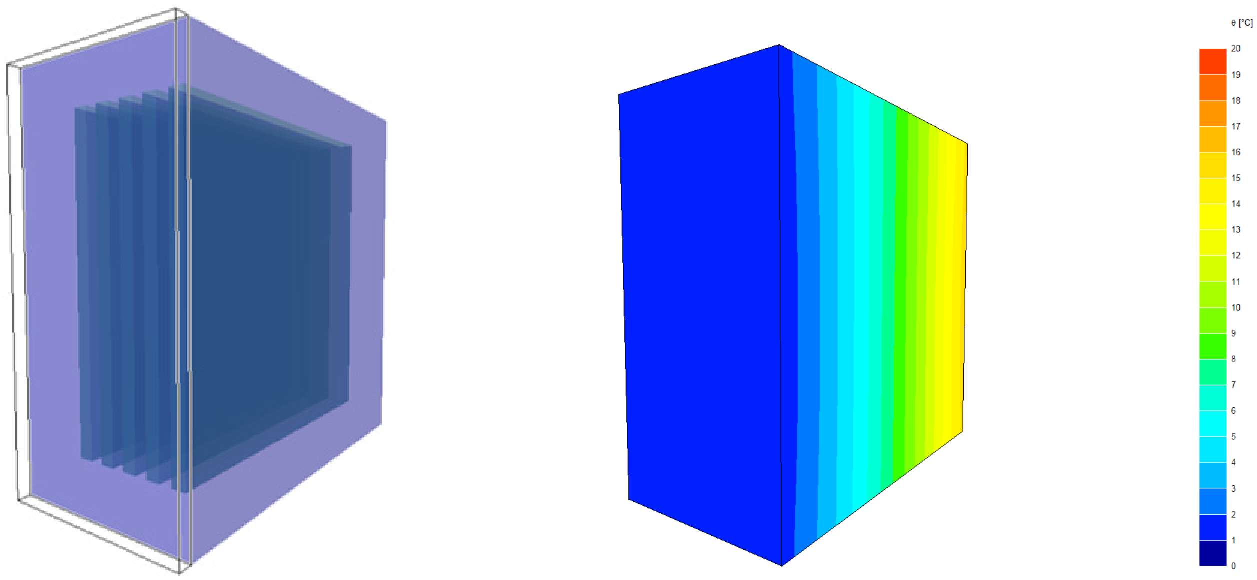
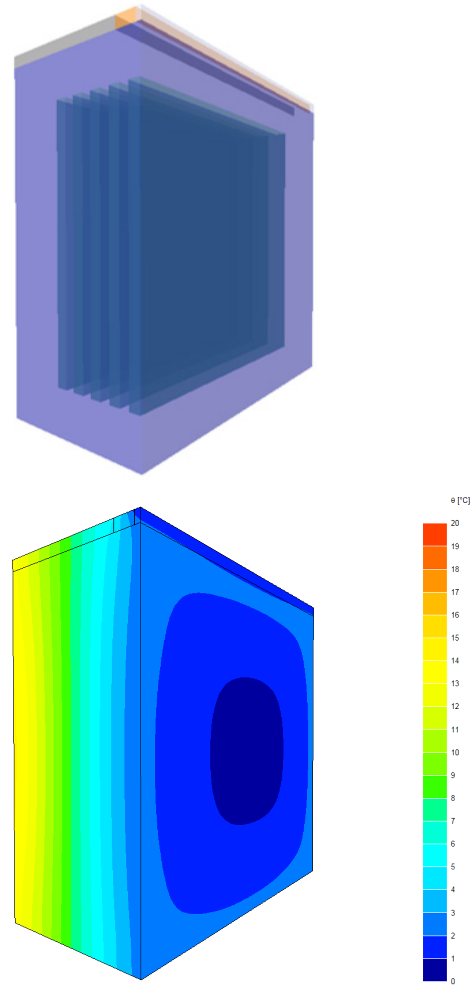


FIGURE 138: Figure showing (a) full brick corbeled part and (b) temperature graph for full brick corbeled part



```
TRISCO - Calculation Results

TRISCO data file: Lattice Block_corbel orientation.trc

Number of nodes = 21504
Heat flow divergence for total object = 1.01119e-07 %
Heat flow divergence for worst node = 0.000935515 %

Ublock = (Q/(ti-te))/A1 = 1.709 W/(m².K)
   Q = 1.538 W
   ti = 20.0000°C
   te = 0.0000°C
   A1 = 0.045 m²
        Xmin=32 Xmax=32 Ymin=0 Ymax=20 Zmin=0 Zmax=31
```

```
TRISCO - Calculation Results

TRISCO data file: Lattice Block_connection.trc

Number of nodes = 22176
Heat flow divergence for total object = 4.35678e-05 %
Heat flow divergence for worst node = 0.0508777 %

Ublock = (Q/(ti-te))/A1 = 2.343 W/(m².K)
   Q = 4.217 W
   ti = 20.0000°C
   te = 0.0000°C
   A1 = 0.09 m²
        Xmin=22 Xmax=22 Ymin=0 Ymax=31 Zmin=0 Zmax=31
```

FIGURE 139: Figure showing (a) full brick with steel connection and (b) temperature graph for full brick with steel connection

The total thermal transmittance of the facade with these block can be calculated as following:

$$U_{fac} = \frac{U_{full}S_{full} + U_{half}S_{half} + U_{corbel}S_{corbel}}{S_{total}}$$

here,

U_{fac}	W/m²K	Thermal transmittance of facade
U_{full}, U_{half}, U_{corbel}	W/m²K	Thermal transmittance of full, half and corbel bricks
S_{full}, S_{half}, S_{corbel}	m²	Surface of full and half bricks
S_{total}	m²	Total surface area

The total thermal transmittance of the facade is:

$$U_{fac} = \frac{1.93 \times 93.78 + 2.3 \times 0.9 + 1.7 \times 9.16}{103.32} = \mathbf{1.92\ W/m^2K}$$

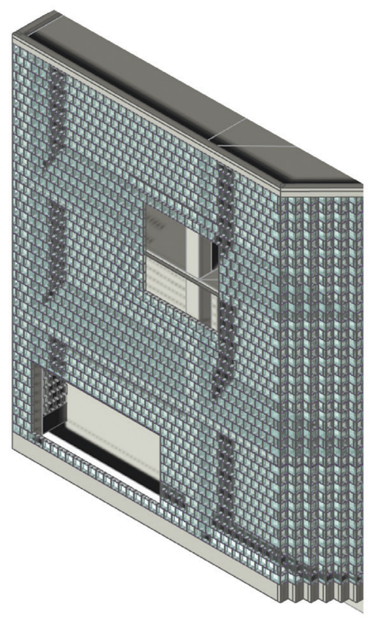


FIGURE 117: Figure showing facade under consideration

Total number of blocks used: 1266
Full brick: 1042
Half brick: 20
Corbel brick: 204


PORTS
1961
PORTS

07.14 Comparative Analysis

Introduction
The case study of Ports 1961, Shanghai building was chosen to understand the main differences between using a conventional hollow glass block system and a hybrid glass block system. This particular case study building also had all faced of the facade from glass blocks with a corbelling part which also posed a challenge as multiple different junctions were required to be tackled. But this challenge was used as an opportunity to design these different junction details that led to wider applicability of this system.

Thermal Performance
The hollow glass blocks used in the façade have a U-value of 2.6 W/m2K due to presence of single air cavity, The Fusion block with the metal embeds and single air cavity has a U-value of 2.0 W/m2k while the Lattice block with 5 air cavities has a U-value of 1.9 W/m2K. These values are in correspondence with the European codes as well as the Chinese national building regulations. Thus, the hybrid system performs much better thermally than the traditional hollow glass block.

Fabrication
The process of manufacturing hollow glass blocks is standardized as it has been present in the building industry for long now. On the other hand, the cast glass blocks have been used in very few buildings and so their process is not standardized. The cast glass blocks also require much more annealing time than the hollow glass blocks owing to their thick cross-section. Both Fusion and Lattice block requires roughly 20h to fully anneal.

Assembly
The assembly process of the Fusion and Lattice blocks appears to be more effortless and cleaner as compared to the hollow glass block in the façade. The existing systems makes use of steel supports that divide the blocks into groups of 64. This steel support is iturn tied with the structural system of the building. The blocks are tied together with the use of mortar. The use of mortar makes the system non-reversible and contaminates the glass block for future uses. On the other hand, the proposed system for both Fusion and Lattice block works on the principle of interlocking geometry and is a dry-stack system. In case of Fusion block, the metal embeds form the interlock with an additional connection to ensure separation of the coated float glass from the main assembly. And for the Lattice block, the simple round interlock with neoprene interlayer forms the assembly. The façade is then tied with the building through simple metal connections elaborated in this chapter earlier. Apart from being easy to assemble, both these systems are reversible so at the end of life, the structure can be disassembled and re-purposed or recycled.

Optical and aesthetical qualities
The appearance of the two systems also present distinctions. The most dominant feature of the hollow block assembly is the mortar grid. The thick grout line with rectilinear arrangement of the façade result in a very strict and visually heavy arrangement. Also, the glass block used here has a satin finish which diminishes the transparency of the façade. Contrary to this, the proposed system of interlocking hybrid glass blocks seems much more fluid and playful. The transparency of the Lattice block is less than that of the Fusion block due to the presence of multiple cavities. However, both these blocks present better optical qualities than the existing hollow block on the façade.

The corbeled window portion of the existing system is very dominant as the bock rest on a steel support system. However, in the proposed options the corbeling is done with the masonry logic and therefore, the protrusion is not much.

Load Bearing capacity
The structural role of hollow glass blocks and hybrid glass blocks are not comparable as the conventional hollow block system serves as a non-load bearing element that fills the space between the structural frame. On the contrary, the monolithic cast glass system is load bearing and therefore can be considered for a wider range of applications.

Design criteria	Ports 1961, Shanghai	Fusion Block	Lattice Block
Properties			
Compressive Strength	+	++++	++++
Thermal Performance	2.6 W/m2K	2 W/m2K	1.9 W/m2K
Manufacturing			
Process	Casting and fusing	Casting	Casting
Glass Type	Soda-lime	Borosilicate	Borosilicate
Mould Type	Pressed steel mould	Open high precision mould	Open high precision mould
Number of Moulds	4 (2 per block)	3 (1 per block)	4 (2 per block)
Annealing Time	unknown	more than 20h	more than 20h
Weight per block	3 - 5 kg	16 kg	16 kg
Constructability			
System	Metal substructure	Interlocking metal embed connection	Interlocking with interlayer connection
Load Distribution	Not-load bearing. Forces are carried by a metal substructure	Load bearing. In-plane forces are carried by the glass block and lateral forces (e.g. wind load) is transferred with the help of metal embed.	Load bearing. Homogenous load transfer with interlayer.
Connection system	Blocks are connected through mortar/adhesives	Metal embeds	Interlayer
Assembly type	Adhesively bonded (mortar accomodates size deviations)	Dry-assembly (Metal embeds accommodates size	Dry-assembly (Interlayer accommodates size
Transparency	Compromised transparency	High transparency	High transparency
Reversibility	Non-reversible	Reversible	Reversible
Number of Blocks	2 (full brick and custom-metred block)	3 (full brick, half brick and L-shape)	2 (full brick and half brick)
Optical Quality	+	++++	+++

TABLE 17: Table showing comparative analysis between hollow glass block of Ports 1961 building, Fusion block and Lattice block

FIGURE 140: Figure showing zoomed in view of existing hollow glass block

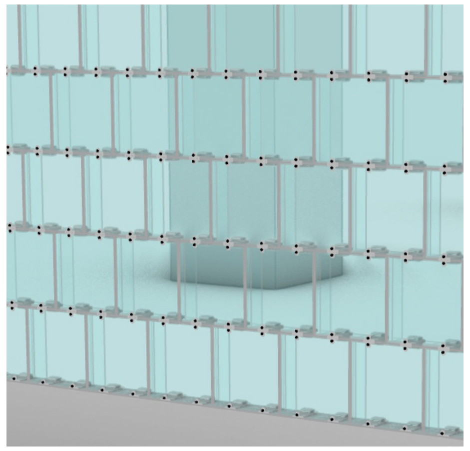


FIGURE 141: Figure showing zoomed in view of Fusion block on the facade of Ports 1961 building.

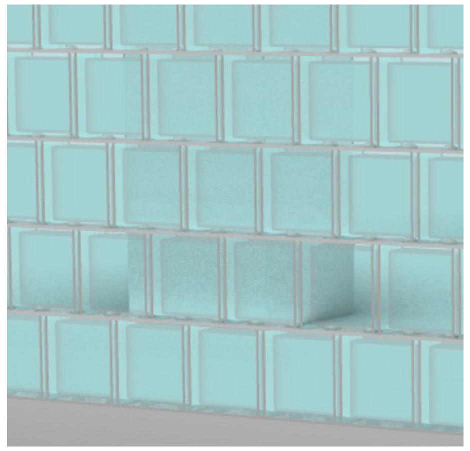


FIGURE 142: Figure showing zoomed in view of Lattice block on the facade of Ports 1961 building.

FIGURE 143: Figure showing facade of Ports 1961 building.

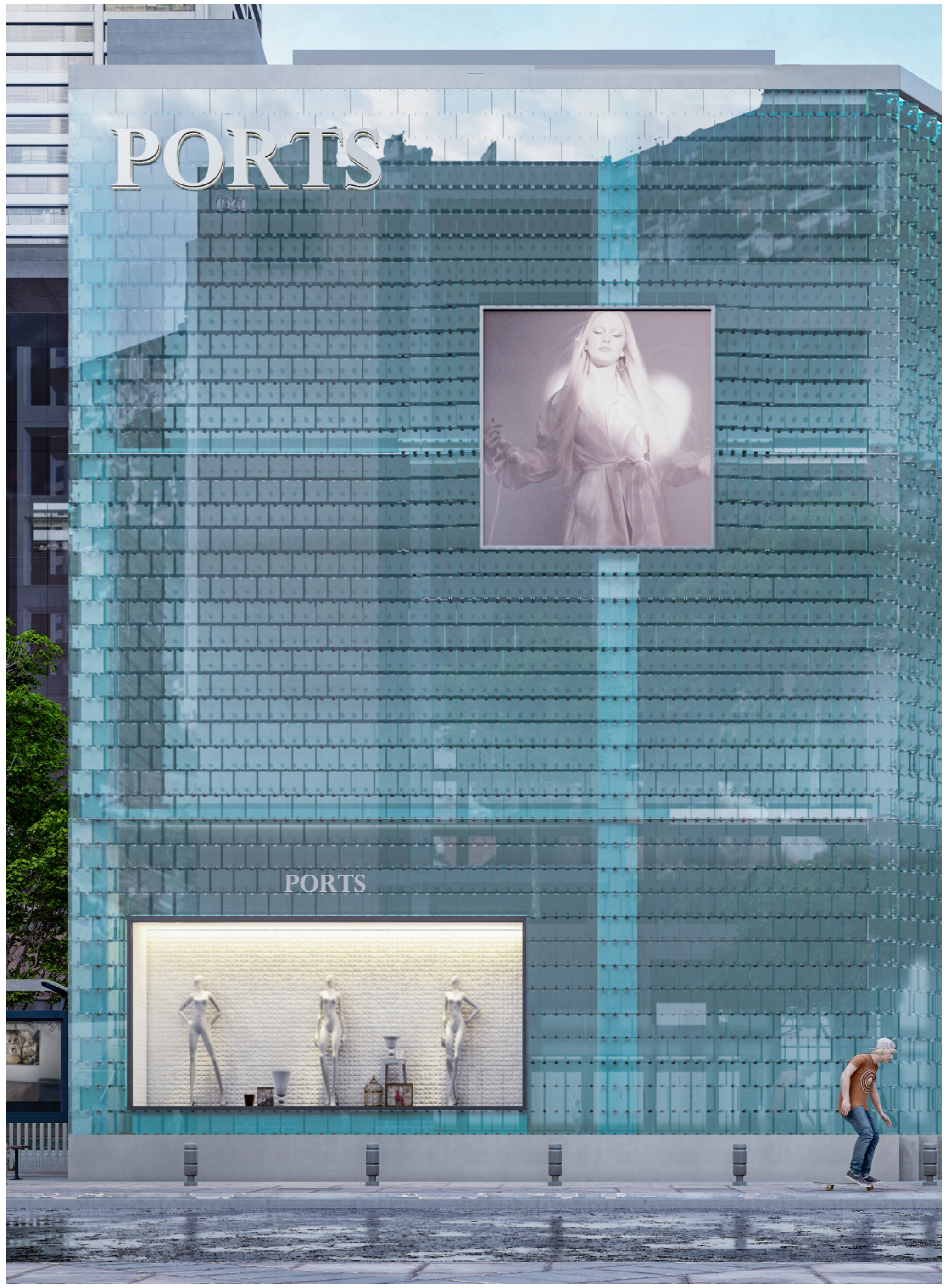


FIGURE 144: Figure showing impressions of Fusion block on the facade of Ports 1961 building.

FIGURE 145: Figure showing impressions of Lattice block on the facade of Ports 1961 building.

08 Conclusions

08.1 Introduction

The thesis aims to explore a novel idea of having thermally performing and load bearing cast glass system. This chapter summarizes the results found by answering the sub-questions and main research question. It also discusses the constraints associated with the development of the technology and suggests recommendations for future development.

What are the main engineering criteria and challenges involved in the development of Hybrid block? (Chapter 2 & 3)

The studies conducted into the current technologies of hollow blocks suggested that the thermal performance is credited to the air cavity present in it while the structural performance of solid blocks is due to it thick cross-section, design and material property of glass to perform well under compression. Various studies suggested that it's possible to further improve the thermal performance of the block. Therefore, the various design options proposed and analyzed during the research focused on combining these two ideas into one design. It was also important to make sure the developed design has good optical quality as it is of great importance when working with a material like glass. The recyclability potential and ease of manufacturing of the block were also crucial to generate a feasible design solution in correspondence with the circular economy.

One of the main challenges of this technology is the unavailability of standardized data or guidelines for construction with cast glass therefore, it becomes crucial to validate the calculations and design through experiments. Also, the thermal performance can be improved in many ways as discussed in Chapter 3. To keep the fabrication process and geometry simple, cheap and elegant the design options developed in this thesis taken into account the effect of air cavities which limits the overall performance of the system.

Another important challenge lies in the manufacturing process of this technology. Since the cast glass structures till date have used custom design of blocks, there are no standards available for size, mould or type of glass. Each design is catered with different parameters and thus differs vastly from each other. One of the main limitation is the prolonged annealing time required for these blocks. This is due to the thick cross-sections which is essential for load bearing strength.

What are the main factors influencing the thermal performance of the system? What methods can be employed to increase the efficiency and what are the advantages and limitations of these methods? (Chapter 5)

The thermal performance of the system is measured by its thermal resistance and the main factors that affect it are the size of the block, size of cavity, number of cavities, material property and the path length that heat flows. In this thesis, the heat resistance is analyzed by incorporating multiple air cavities, filling it with argon gas and applying coatings.

The effective thermal conductivity of air increases with the total size of the cavity. However too large cavities can lead to the flow of air currents and cause convective heat transfer which impedes the performance. Through the simulations presented in Chapter 4, it can be observed that the increase in cavity width till 30mm tremendously influences the thermal performance while the convective transfer starts happening from a cavity width of 35mm. The analysis also suggested that multiple air cavities are much better than single air cavities and it drastically reduces the thermal conductivity as can be seen in the two concepts C3 and C4 where similar block size of 100mm had different U values. Introducing multiple air chambers lead to formation of thermal bridges which impedes the thermal performance of the system. However continuous glass frame is necessary for structural performance. In fusion and lattice block, the initial cross-section of these thermal bridges is very less, however to keep the structural integrity these were increased which had a great influence on the resulting thermal resistance. Also, multiple cavities

result in a greater optical distortion and low optical quality.

The addition of an insulative material in the cavity can further aid in improving the thermal performance. Studies done with noble gas and aerogel prove beneficial, however the addition of aerogel takes away the transparency of the entire system. Noble gas like argon causes a change in heat transfer through the cavity and improves the performance. Nevertheless, the production of the unit with argon filling is quite complicated and becomes expensive. It is therefore not taken forward in this research.

A common method to improve the thermal resistance is applying coatings on the glass surfaces. These coatings change the emissivity value of the surfaces, thereby altering the material property and impact the heat transfer through radiation. This positively influences the total thermal resistance values. These coatings can be applied either on the inside surface of the outer glass or outside the inner glass surface, depending on whether it is applied to stop heat from entering or retaining it inside the room. However, these coated glasses are difficult to recycle and therefore is not sustainable. In the design option of In Fusion block, a dry connection system with bolts is suggested instead of the common gluing method so that the non-recyclable part can be easily separated. This way a majority of the block can be recycled or melted to be re-used in other forms.

Which are the main factors affecting the manufacturing process of these blocks? What methods can be employed and what are the advantages and limitations of these methods? (Chapter 7)

The factors that affect the manufacturing of the blocks are the size and geometry of component, design of connection and its fabrication process.

The geometry and size greatly influence the overall stability of the structure. In the two explored designs; Fusion block and Lattice block, changes were made in the geometry to achieve the required stiffness. In Fusion block the small horizontal part that joins covers the cavity from all sides was assumed to be 2.5mm in the initial thermal calculations. This was then changed in the final design to 5mm to reduce the chances of it cracking.

In Lattice block, the cross-section of the outer frame was increased from 15mm to 25mm in order to avoid sagging during the manufacturing process due to presence of a large hollow part in the center. Also, the additional glass members in between were also increased from 5mm to 10mm to provide stiff additional support. A curved geometry helps in distributing the stresses more evenly throughout the component. Its also preferable to have round edges for smoother annealing process.

The overall dimensions and cross-section thickness greatly influences the annealing time of the component. Both the blocks have similar annealing time in spite of Lattice block having nearly double overall width than Fusion block. This is because lattice block is formed as a hollow geometry and therefore anneals faster than blocks of similar dimension. Prolonged annealing time can negatively impact the feasibility of a design. Also, very complex shapes can lead to intricacy and accuracy in mould design which can further increase the costs of the production.

The fabrication process depends on the choice of glass, size of the component, geometry and mould design. For the hybrid glass block research, casting method was chosen as it is the only method currently available to generate components of substantial cross-section and complex geometry with high optical qualities. The glass chosen was borosilicate over the common soda-lime glass as the former is resistant to thermal shocks and due to the lower thermal expansion coefficient requires less time for the annealing process. For the industrial production of these blocks, open high precision steel molds are suggested as they are comparatively cheaper than the other moulds.

What are the main practical implications and challenges of employing Hybrid blocks in an existing structure what impact will it have on the existing structural, thermal and aesthetical value? (Chapter 7)

The main practical challenge of employing this novel method is the absence of standard guidelines. Therefore, experimental validation is of utmost importance when employing it in real life structures. To understand the impact on aesthetical, structural and thermal value, a case study was chosen. The chosen building was Ports 1961 store in Shanghai which is done entirely in hollow blocks. Hollow blocks have a standardized fabrication and installation process owning to their wide usage for many decades. The cast glass blocks on the other hand have been incorporated only recently and yet do not have a standardized process but these blocks show brilliant load bearing performance.

The research presents two different designs for the hybrid glass block; Fusion block and Lattice block. The two different designs required two separate connection systems. The design of connection between two blocks and other parts of the building is crucial as it should be able to transfer loads evenly without causing stresses in glass. In this thesis two types of connections are explored in detail; one an embedded connection and the other an interlocking pattern. Both connections generate a dry assembly system which is reversible and easy to maintain. The design of both connections facilitates in ease of assembling the structure. They also compensate for size deviations.

For an embedded connection, it is important to make sure that the material used for the insert has similar thermal expansion coefficient as of the used glass. This is essential to avoid cracks induced due to stress caused by heat. In our case, since thermal performance was crucial, the connections needed to be designed so as to not impede the heat resistance of the facade. Using a metal insert in an embedded connection posed a challenge as metal has high conductivity value. Therefore, thermal breaks were introduced in between the joints to make sure that the façade is properly sealed. The interlocking system with an interlayer, generates a highly transparent façade. It is important to note that the size and amplitude of interlock influences the rigidity of the connection. It should not be too small so that the block can slip away. Another important factor is the geometry of the interlock, in lattice block a hemispherical geometry Is chosen for an even distribution of load and stresses but as per the user and design requirements, other geometries can also be explored.

There are two types of assembly process for the hybrid blocks that are suggested in this research; the embedded metal interlock and the glass interlock. Both these appears to be simple, effortless and clean. However, the initial system of rails and guides to position the block is much more elaborate in comparison to the hollow blocks. The interlocking system leads to a dry-assembly which is a big advantage against the existing methods of hollow and solid glass block construction. This system is reversible and the components can be dis-assembled easily and recycled at the end of life.

The thermal performance of the blocks achieved are well within the European building regulations as well as the local regulations of Shanghai. The hollow block currently used in the building is expected to have a U value of 2.6 W/m2K while both the proposed design have a U-value less than 2 W/m2K which is an improvement from the existing performance. Though the design of the blocks does enhance the thermal performance, it is however unable to achieve the value set by Dutch regulations (1.65 W/m2K) just with simple air cavities and no coatings.

Apart from the improved structural and thermal performance, the appearance of the system is also enhanced. The most dominant feature in the existing system is the steel grids and thick mortar joints between the blocks that generate a very heavy appearance. The proposed system being load bearing removes the need for the additional steel supports and

the interlocking connections removes the need for the thick mortar joints rendering the system more fluid and lightweight. The loss of transparency due to the presence of cavities is acceptable here as original block used has satin finishes on both sides which renders the block opaque. The only aesthetical challenge with the proposed system is that corbeling in windows present in the existing structure is not possible with the same dimensions. Nevertheless, options are proposed to have corbeling following load bearing principles which are discussed in detail in Chapter 7.

08.2 Main Research Question

"How can we develop a Hybrid glass block that exhibits good structural, thermal and optical properties and how will it be fabricated and manufactured?"

The main objective of the research is to contribute towards the innovation of glass structures by developing a novel block that can solve the challenges of the modern time by being structurally sound and thermally comfortable. The current technologies of hollow block and solid blocks suggested that there is potential in developing a hybrid system by combining the properties of both the blocks. Prior to this research, limited explorations have been done concerning the combination of these two aspects as the load bearing cast glass system in itself is a recent innovation. The limited available engineering data required to develop a set of guidelines for this novel technology.

The research begins by defining the design criteria that the new hybrid system should satisfy. These are specified by carefully studying the existing performance of the hollow and solid blocks and also the different building codes. The main contribution of this research is the development of two distinct systems; an embedded connection interlock of glass block and an interlocking system with dry interlayer. Both these systems show great potential of this technology and can be further validated with experiments for real life applications.

In the research, the thermal performance of the system is measured by its thermal resistance and is analysed by incorporating multiple air cavities, filling it with argon gas and applying coatings. Through the simulations presented in Chapter 5, it can be observed that the incorporation of cavity greatly influences the thermal performance. The presence of multiple cavities also enhanced the performance but compromised the optical quality of the block. The presence of continuous glass cross-section is important for structural integrity which generated thermal bridges that negatively impacted the thermal performance. However, the thermal performance of the block was still within the limits of European and National building codes. The addition of another insulative material like Argon improved the overall performance but complicated the fabrication process. However, concepts can be explored with argon gas as infill as it enhances the overall performance and in turn compensate for the excess manufacturing costs. In one concept the effect of coatings was also simulated and was found to be successful in reducing the thermal conductivity. Although, coated glass posed a challenge in the recyclability of the system therefore a dry connection system with bolts is suggested instead of the common gluing method so that the non-recyclable part can be easily separated.

The detailing and fabrication of the blocks was carefully done considering the overall stability. The size of the blocks and cross-sections were increased to account for structural performance and to counter the sagging effect. Moulds were carefully designed to ensure a smooth and cost-effective production. The glass chosen was borosilicate over the common soda-lime glass as the former is resistant to thermal shocks and due to the lower thermal expansion coefficient requires less time for the annealing process. One of the challenges with the proposed designs is the total weight per block which is around 16kgs and may interrupt the continuous laying of the bricks. However, this can be accounted for in the management part of the assembly process. For the two designs, two separate connection systems are employed; one an embedded connection and the other an interlocking pattern. Both connections generate a dry assembly system which is reversible, easy to assemble and easy to maintain. For an embedded connection, care was given in choosing the material for the metal inset as it should have similar thermal expansion coefficient as of the used glass to avoid cracks induced due to stress caused by heat. As metal has high conductivity than glass, thermal breaks become crucial to include at the junctions to avoid losing the thermal performance of the system. The interlocking system generates a highly transparent façade. The size, geometry and amplitude of the interlock are common factors that affect the rigidity of the connection.

Concerning the assembly process, different details are adopted for the two different options proposed in the research. The fusion block has an embedded metal connection that is used to join it with the beams at the top and bottom. This beam is then connected to the main structure so that the façade becomes part of the building and doesn't fall out. The corner junction and corbelled part are formed by a special L shaped block that aids in an easier assembly of these details. For the corbelled windows, two separate details are made and is left up to the reader to decide on one as it is merely a matter of preferred aesthetical quality. For the lattice block, the assembly process is fairly simple as the proportions of the block correspond to the traditional brick proportions. Therefore, the corner junction and corbelled details are also fairly simple. The bottom and top connection however is done using special steel blocks. Both these systems require additional formwork than the traditional hollow block system but they improve the overall aesthetical qualities of the façade.

The present research does not conclude in a single suitable design option but rather two concepts that are then detailed to be applied in an existing scenario. The exploration of different concepts for thermal performance results in a general understanding of the parameters that affect the development of this technology. The further research into the structural and fabrication process also gives insights about the practical challenges in realizing this technology. To realize the proposed system, fire safety and acoustics still need to be carefully considered and additionally this need to be validated experimentally to derive statistical data for its safe application. Nonetheless the performance values indicate a great potential in the technology.

Recommendations

1. A promising and potential concept to be developed further is to design a cavity wall between solid cast glass bricks as the load bearing member and float glass with cavity to provide the thermal performance. It is an extrapolation of the Fusion block from a unit level to an element level. This can help in reducing the thermal bridges formed right now in every block which can help in further improving the thermal performance.

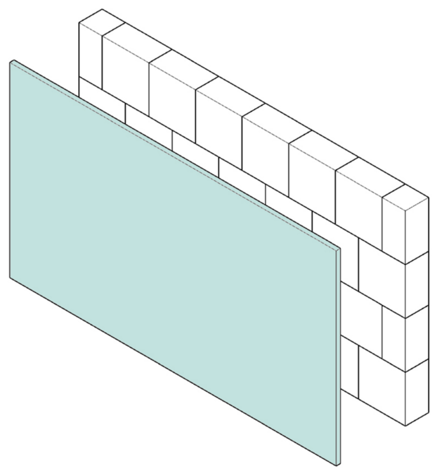


FIGURE 146: Figure showing illustration of recommendation 1

2. Another important development is to explore the horizontal connection between the blocks in both systems which is not dealt with in this thesis. To achieve a good thermal performance, it is important for the façade to be properly sealed therefore, this connection is of great importance.

3. Research could further be done on the life cycle assessment of the two blocks, as well as a detailed study of their structural performance.

4. In the research one challenging aspect was the block weight which is due to its size derived from the existing block in façade. A potential research could be done to study the thermal performance in standard sizes of blocks used for masonry structures. This can result in wider application of this technology.

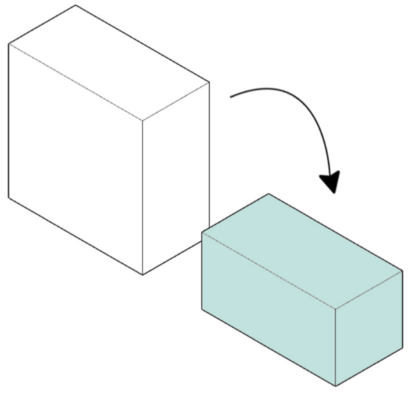


FIGURE 146: Figure showing illustration of recommendation 4

5. The honeycomb concept of the Lattice block can also be further explored in two directions; one keeping the same design as now and exploring the effect of different colors and textures of glass on dispersion of light and varying degrees of transparency. The other could be to develop this block computationally to find the most optimum solution for the hybrid system.

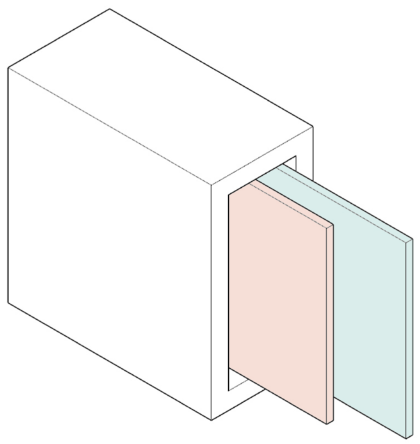


FIGURE 146: Figure showing illustration of recommendation 5

6. Finally, if this is to be applied, additional investigation of fire safety and acoustics should be carried out along with the experimental validation of structural and thermal performance.


PORTS
PORTS

PORTS
1961
PORTS

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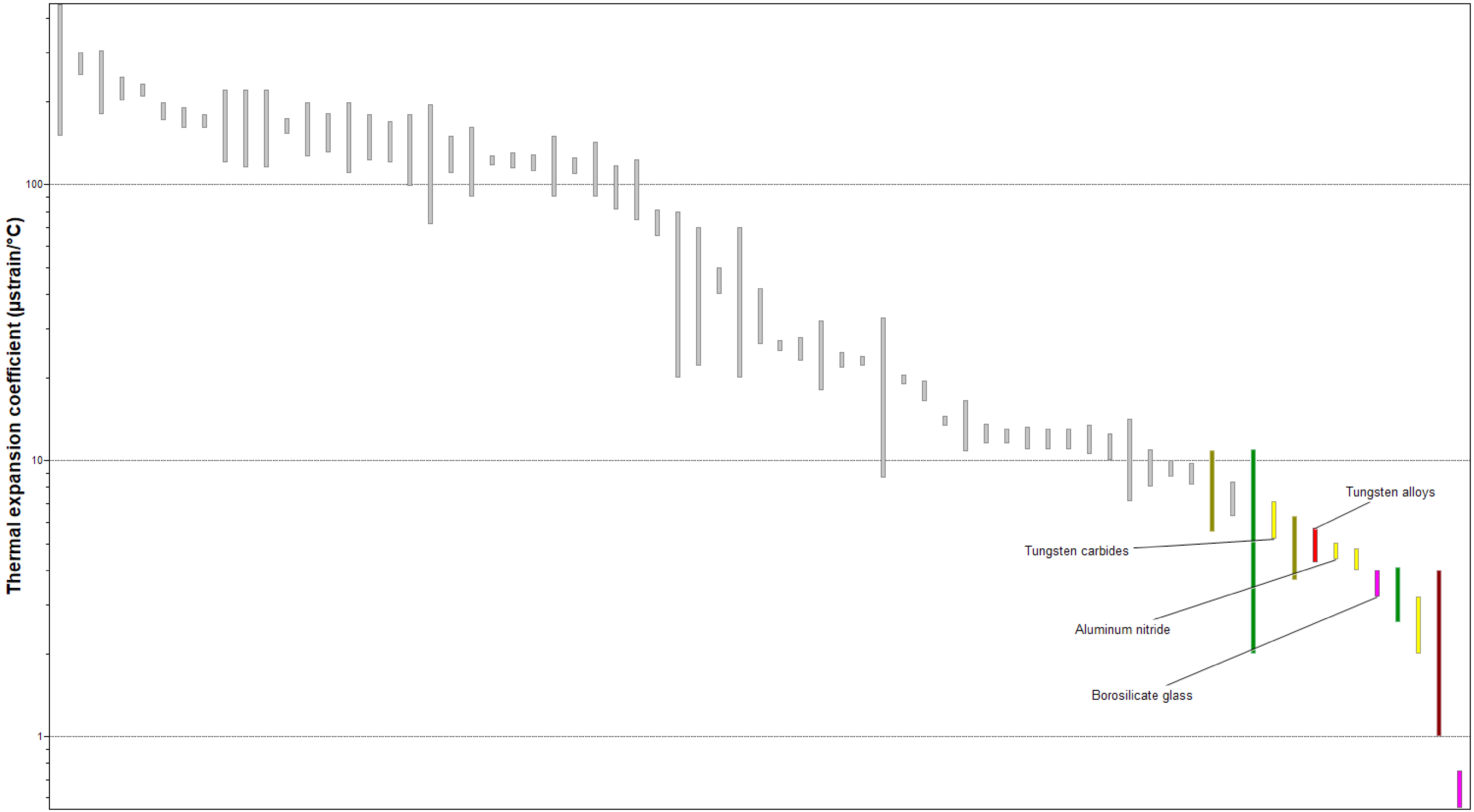
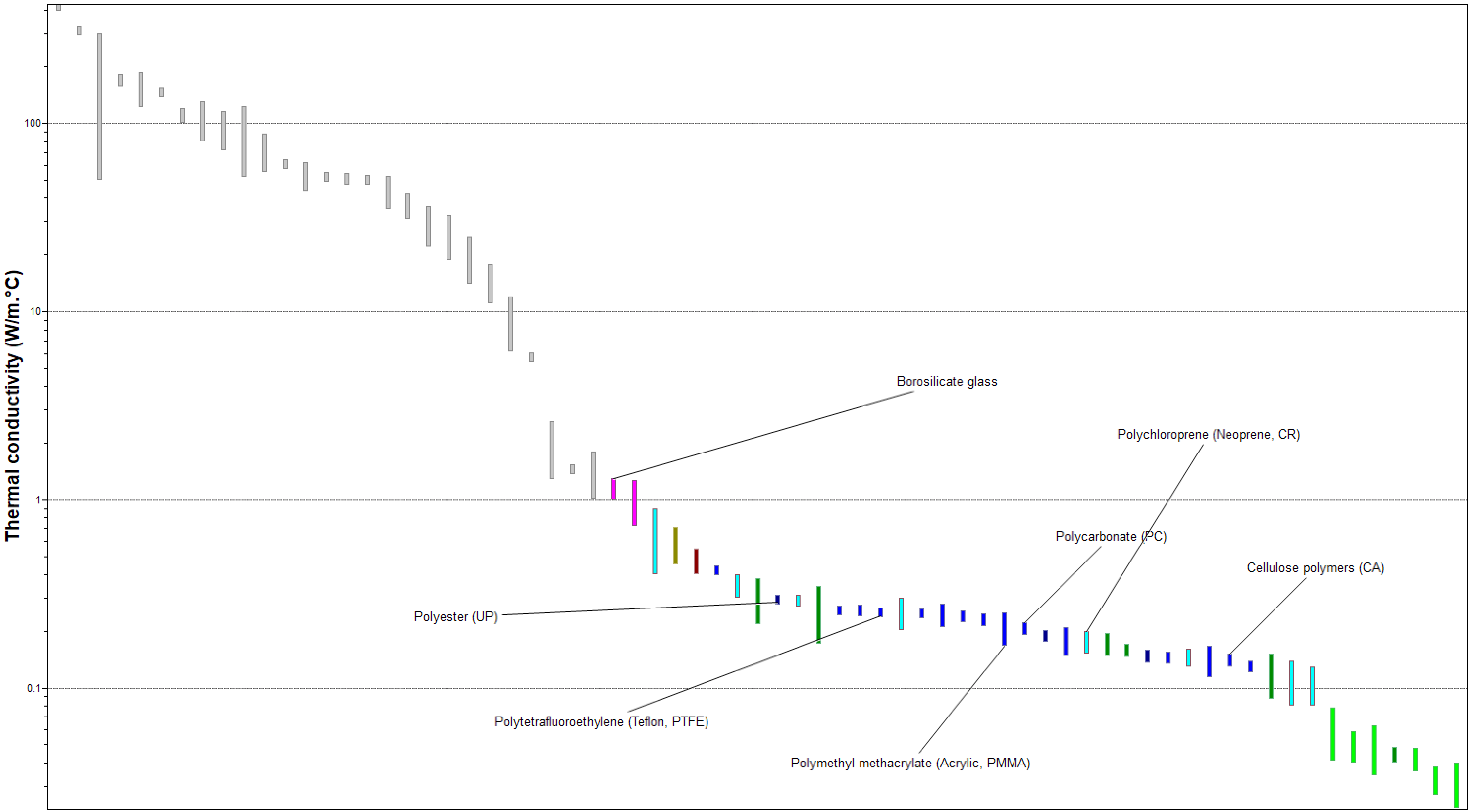

Thermal expansion coefficient (µstrain/°C)
100
10
1
Tungsten alloys
Tungsten carbides
Aluminum nitride
Borosilicate glass


Thermal conductivity (W/m.°C)
100
10
1
0.1
Borosilicate glass
Polychloroprene (Neoprene, CR)
Polycarbonate (PC)
Cellulose polymers (CA)
Polyester (UP)
Polytetrafluoroethylene (Teflon, PTFE)
Polymethyl methacrylate (Acrylic, PMMA)