Product development of Hybrid Glass Blocks

Rethinking shape, manufacturing process and assembly system

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Course	MSc in Architecture, Urbanism & Building Sciences (Building Technology Track)
Studio	Sustainable Design Graduation Studio
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ACKNOWLEDGEMENTS

My time at TuDelft throughout my Masters in Architecture was the most memorable. I came to TuDelft to study building technology to discover my true passion in the field of architecture. I was initially overwhelmed by the sheer number of new concepts and subjects. It seemed far away at the time since I was struggling to adjust to the new atmosphere I had entered and it was a difficult transition from online to on-campus education. I attempted to focus on courses that I was interested in pursuing while also being intrigued by the seemingly unlimited possibilities that they presented. During the second semester, I was introduced to glass architecture and its future possibilities as a material. I enrolled in a structural design course and designed an observatory in Iceland entirely made of glass.

During this course, I became extremely involved in the use of glass as an architectural and structural material. I researched more into this topic and discovered TuDelft's Glass research group, which has been conducting numerous experiments and developing unique glass products for use in the building industry. I decided to address my mentor, Dr. Faidra Oikonomopoulou, about my intention about collaborating on the ongoing study at the Glass transparency group. She introduced me to the newly emerging concept of Hybrid Glass block, and the opportunities it provided me were enormous since I was interested in building a product through prototyping and experimenting.

Working on this project for the last seven months has been an exhilarating experience for me. I have learned, enjoyed, and appreciated every single moment of the research, designing, and prototyping process. I am proud of the product that I was able to achieve in the end, however, this research would have not been possible if it wasn't for the contribution of some people.

Foremost, I would like to express my gratitude to Dr. Faidra Oikonomopoulou for introducing me to the potential of glass and has been a constant source of encouragement and motivation throughout the entire process. She has been a wonderful mentor who shared her knowledge and expertise in this field and managed to make me passionate about this topic. To my second mentor Dr. Marcel Bilow, has been a great source of inspiration throughout this thesis and especially in the design detailing phase. He has constantly supported and encouraged me with his insightful ideas and experience in the use of innovative materials and connections. His detailed inputs and pragmatic suggestions have not only made the design practical but also unique and innovative.

I am very much grateful to Ir. Telesilla Bristogianni for her commitment, encouragement and support during the designing and prototype manufacturing phase at the Stevin II lab, TuDelft. Her knowledge, valuable inputs on the glass manufacturing process, and hardworking nature have allowed me to push myself beyond my limits.

I would like to thank Dr. James O'Callaghan and Ir. Mariska van der Velden from Eckersley O'Callaghan provided their expertise and practical knowledge for the application of glass blocks in the building industry. Their advice for the structural design of hybrid glass blocks was valuable for concept validation. I would also like to thank Paul de Ruiter from LAMA lab and Bob de Boer from CAM lab who have been helpful with the 3D printing and CNC Milling of the design components.

I would like to thank Shreyas, Sophia and Parikshit for their input, advice, ideas, and most importantly their encouragement through this entire period. Finally, I would like to thank my family, Suchita Sonar and Ulhas Sonar, as well as Akshay and Ruchika for their caring and emotional support throughout my studies.

To all those who believed in me.

Sculpture made of glass shards by artist Marta Klonowska titled 'Lemur' (2011)

ABSTRACT

Keywords:
hybrid glass block, cast glass, shape exploration, interlayer, dry stacked assembly, production methodology, reversibility, recyclability, cross-section study, design considerations & challenges

Glass has been widely used in the construction industry since the early nineteenth century. It was most commonly used in the form of a window, which is a flat glass panel. Glass has natural optical properties and is resistant to weather, making it ideal for use as a facade material. Glass's novel applications in the built environment have led us to go beyond its 2D application of flat glass panels to a solid, 3D component, as seen in recent projects such as Maison de Hermes in Tokyo and Crystal House in Amsterdam.

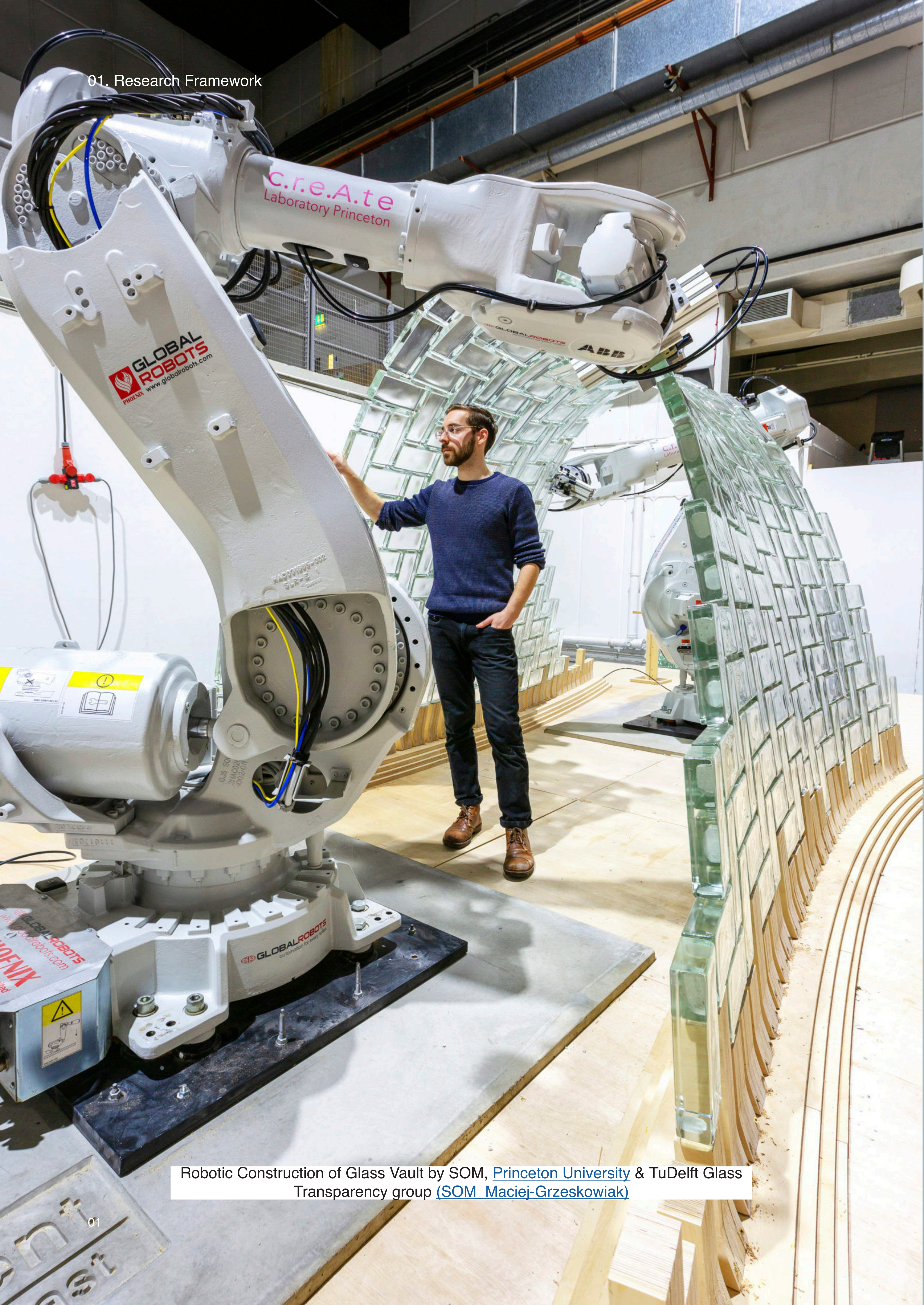
Currently, there are two approaches in glass blocks: load-bearing solid glass blocks with poor thermal properties and hollow glass blocks with optimal thermal properties but no structural performance. Can we combine these approaches and develop a glass block with good load-bearing and thermal properties? Research on Hybrid glass blocks is one such topic that investigates the potential of this unique concept. A hybrid glass block is the combination of solid and hollow glass blocks designed as a single product with good thermal performance and load-bearing capacity.

The existing research on this topic is promising and noteworthy for further development as it conceptualises the rudimentary design guidelines for the system. The output of the existing research is oriented towards the design development of the novel hybrid glass blocks, ideation of the production methodologies, and validation of their thermal performance. Thus the scope for further research and development is actual prototyping of the design concepts, validation of the structural performance, and qualitative analysis. It is observed that the shape of the hybrid glass blocks impacts the structural-thermal performance, production methodology, and desirability of standardisation. Thus, to develop this product a thorough investigation and exploration are necessary.

The research first focuses on developing design guidelines for the innovative hybrid glass system. A product development methodology is formulated to guide and aid the design process of the hybrid glass block systems. Various design concepts are explored in-depth for each design problem based on their relationship with the structural-thermal performance, manufacturing, and assembly process and are then assessed through a set of design criteria to develop a final design concept. The final design concept is further refined based on manufacturing standards and challenges. The final design is then detailed and implemented in the Academy of Arts, Maastricht (case study), and various assembly strategies for dry stacked cast glass systems are formulated.

To validate the design a prototype manufacturing is done by using a kiln casting method. The prototyping challenges, observations, and decisions aid to assess the practicality of the design. A hybrid method of numerical and experimental validation is considered to evaluate the design based on its feasibility for application in the building industry. This research proves to be a guide for developing hybrid glass block systems and provides them with a design development, manufacturing, and evaluation framework to design, develop and assess their concepts.

CONTENTS



Robotic Construction of Glass Vault by SOM, Princeton University & TuDelft Glass Transparency group (SOM_Maciej-Grzeskowiak)

01.

RESEARCH FRAMEWORK

The research framework defines the problem statement and main research questions set-up for this thesis. The scope and limitations are also discussed. To create a connection between various topics and existing research available, a research methodology is discussed in brief along with graduation planning and organization.

01.1

PROBLEM STATEMENT

The use of glass in the building industry over the last few decades has rapidly increased due to its innate optical, thermal, and acoustical properties. Glass possesses such varied properties and has a great potential to be sustainable and energy-efficient material in the contemporary era. The technical advancements in Glass technology have completely changed the perception of its innovative application. Glass's novel applications in the built environment have led us to go **beyond its 2D application of flat panels to solid, 3D components,** as seen in recent projects such as Maison de Hermes in Tokyo and Crystal House in Amsterdam.

Currently, there are **two approaches in glass blocks**: load-bearing **solid glass** blocks with poor thermal properties and **hollow glass** blocks with optimal thermal properties but no structural performance. **Can we combine these approaches and develop a glass block with good load-bearing and thermal properties?** Research on Hybrid glass blocks is one such topic that investigates the potential of this unique concept. A hybrid glass block is the combination of solid and hollow glass blocks designed as a single product with good thermal performance and load-bearing capacity.

The existing research on this topic is promising and noteworthy for further development as it **conceptualises the rudimentary guidelines for the system**. The output of the existing research is oriented towards the design of the novel hybrid glass blocks, ideation of the production methodologies, and validation of their thermal performance. Thus the **scope for further research and development can be actual prototyping of the design concepts, validation of the structural performance, and qualitative analysis**. It is observed that the shape of the hybrid glass blocks **impacts the structural-thermal performance, production methodology, and desirability of standardisation**. Thus, to develop this product a thorough investigation and exploration are necessary.

The Glass Transparency Group at TuDelft is actively researching and developing interlocking cast block systems, which are **dry-stacked glass blocks** that allow for quicker assembly and can be recycled at the end of their life cycle. The system is promising since it makes cast glass blocks more **sustainable**; nevertheless, the type of interlayer and its mechanical qualities have a significant impact on the system's **effective stiffness**. Eccentricities in geometry, for example, can still be predicted, but understanding their behavior under loads necessitates experimental setup and testing. The scope of this research will also include an examination of the dry-stacked assembly system and the relationships between shape, cross-section, alignment, and interlayer to achieve the needed structural performance.

01.2

RESEARCH QUESTION

The scope of this research is to contribute towards the innovation of glass structures by developing Hybrid glass blocks. The main goal is to explore various design concepts, develop (prototype), and experimentally validate the structural & thermal performance of these hybrid glass block designs, from the components, form to an overall structural system. It can lead to partial or fully transparent, self-supporting building envelopes made from a combination of cast glass and float glass components.

The main research question formulated is:

What are the main design considerations and challenges in designing and manufacturing a hybrid glass block system that exhibits good thermal and structural performance?

The research can be divided further into the following sub-questions:

1. What design characteristics influence the load-bearing capacity and thermal performance of glass blocks? What strategies can improve the load-bearing capacity and thermal performance? What are the advantages and limitations of these strategies?
2. What are the structural and thermal properties associated with the performance of hybrid glass blocks?
3. What is the connection between the shape of glass blocks and their structural performance? What are the optimum cross-section thickness and cavity width of glass blocks to improve structural and thermal performance?
4. What are the main design standards that affect the production and assembly process?
5. What are the engineering standards and challenges involved in fabricating the Hybrid glass blocks?
6. What are the design strategies to develop a sustainable (recyclable) hybrid glass block

01.3

OBJECTIVES & LIMITATIONS

Objectives:

1. **Design Guidelines/standards:** The extensive research intends to co-relate various factors that have direct relation to the shape, size, safety, maintenance, structural & thermal properties and derive a set of design standards for development of hybrid glass block.
2. **Manufacturing Standards:** Since the hybrid blocks design is based on combination of cast & float glass, the research will conclude with emphasis on manufacturing process and different engineering standards to make process more efficient and standardised.
3. **Prototyping Observations:** The key observations and conclusions during the prototyping phase for various design concepts, will provide an elaborate overview of challenges and various solutions for further research and exploration.
4. **Structural Validation through Experimentation:** The research is not limited to theoretic validation as it will try to generate real numbers through experimentation.
5. **Innovative Connection Systems:** Innovative connection systems for unit level as well as system level will be explored, considering sustainability aspects.

Limitations:

1. The emphasis of this research is on the exploration of shapes, manufacturing processes for the combination of cast glass & float glass only and reversible assembly system.
2. The sustainability of hybrid glass blocks is limited to reusability and recyclability.
3. Optimization of shape is not the key focus.
4. The structural validation is based on the hand calculations and assumptions derived from the researched literature.
5. The products manufactured are inside a studio with limited resources. The results may differ for the industrial manufacturing process.
6. The thermal performance is based on the extracted findings from researched literature.
7. Economic sustainability of the product is not the key focus of this research.

01.4

METHODOLOGY

The product development of Hybrid glass block is categorised into five phases;

Phase 1: Literature Review and Theoretical framework
The focus lies in extracting necessary information through existing research and available literature related to the chosen topic. This forms the basis for the development of the research framework. A case study of the Academy of Arts, Maastricht (1993) is selected and analysed to provide a realistic scenario in defining structural, thermal, and assembly criteria. The European building codes are studied to define the design guidelines. The in-depth research on glass block technology, its manufacturing and installation process will assist in the formation of design guidelines for the product development of Hybrid glass blocks.

Phase 2: Design Development
The design guidelines formulated in Phase 1 are the basis of the design process. The focus of phase 2 is firstly to formulate a design development methodology. Initially, design aspects are identified and various alternatives are explored. These alternatives will be evaluated based on the specific boundary conditions such as structural and thermal performance along with ease in manufacturing, design for disassembly, aesthetics, sustainability, and problem-specific design criteria set before alternatives exploration. The shortlisted alternatives are combined to form a final design concept. For the evaluation of various cross-sections, basic hand calculations are carried out to identify the structural performance under loading.

Phase 3: Design Refinement
In terms of **manufacturing and constructability**, the final design concept will be developed. To improve the design, the production standards and problems associated with mold fabrication via CNC milling, glass casting and annealing, tolerances, and movements will be considered. Few predetermined risk scenarios, such as structural damage, accidental impact, vandalism, lack of maintenance, vehicle impact, fire, and natural disasters, will be examined, and design solutions to mitigate their impact will be applied for the final design. The final design will be detailed and evolved based on these factors. The final design will be detailed and evolved based on these factors. A manufacturing and assembly sequence will be detailed step by step. This will help with the hybrid glass block prototyping in the studio. This will be a concurrent procedure with the design's details.

The study will investigate the **prototyping** of hybrid glass blocks within the context of an automated, industrial process; however, glass block prototypes will be produced in the glass lab facilities of TuDelft using either the kiln-casting method or/and water-jetting and bonding float glass elements (based on final design) to understand mold limitations, glass flow, and so on.

Phase 4: Design Evaluation
The focus of this phase is to evaluate the final design based on various parameters by numerical and (if permitted) experimental methods.

- Structural: Hand calculations for the compression load, buckling load, deflection, cross-section thickness & stiffness.
- Qualitative analysis of strain concentration by polarisation test (Suggested)
- Thermal: Hand calculations for U-Value on unit and system level
- Hard-body impact and vandalism test (not conducted but considered during risk scenario analysis)
- Design for disassembly: Number of steps involved
- Ease in Manufacturing: Number of processes and their complexities.

Phase 5: Conclusion
The last phase focuses on summarising details of the prototyped hybrid glass block and its application to the case study. The aim is to evaluate the applied design followed by the set of recommendations for future development of Hybrid glass blocks.

An overview of the research methodology can be seen in figure 01.1.

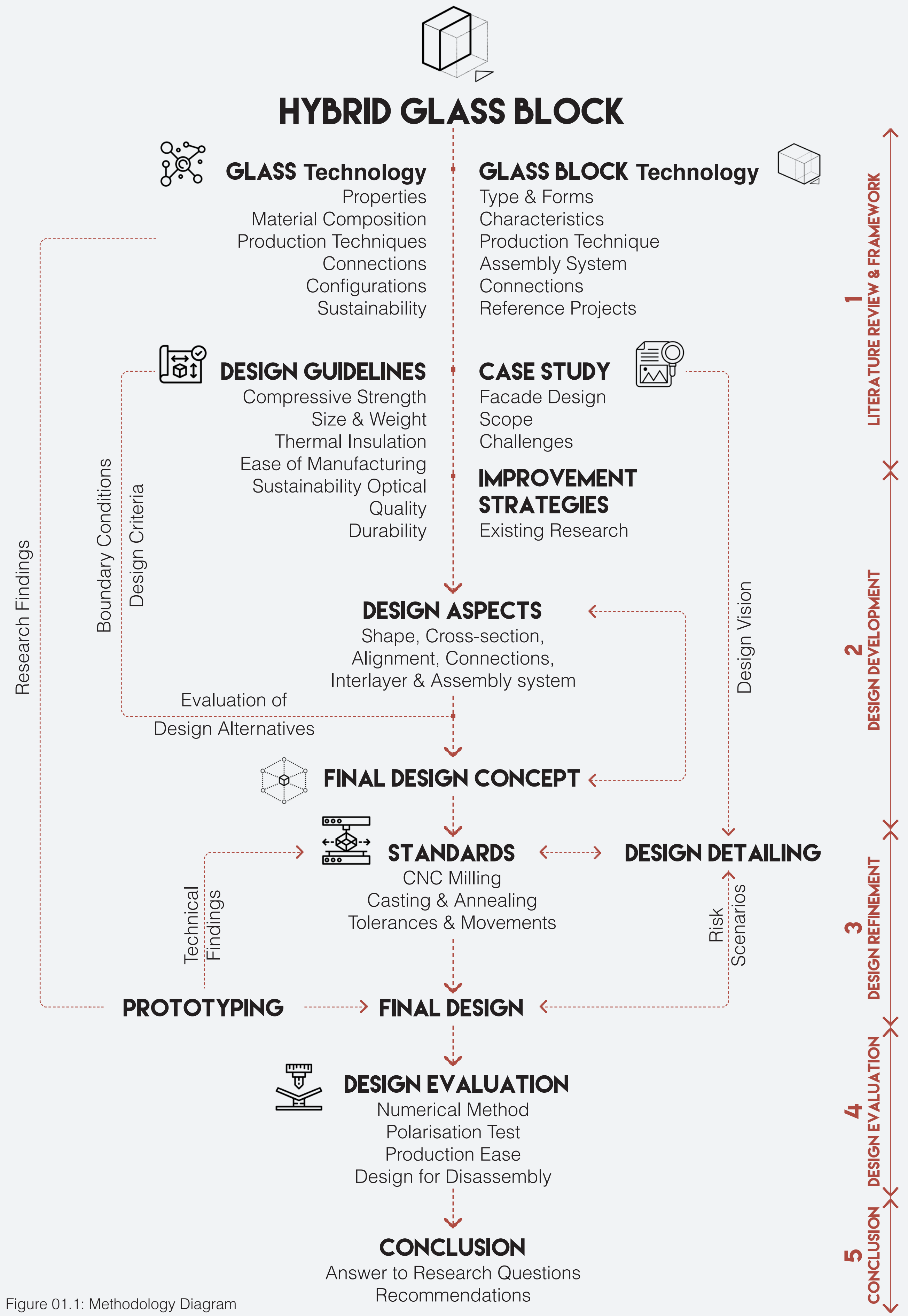


Figure 01.1: Methodology Diagram

01.5

RELEVANCE

Graduation topic and Master Studio

The Sustainable design graduation studio focuses on the **development of innovative design technologies** within the built environment. The material 'Glass' is widely used in the building industry due to its distinctive optical, thermal, and structural properties in various forms, for example, partitions, glazing panels, glass blocks, etc. The existing glass block systems offer either optimal thermal performance or structural stability but neither a combination of both. 'Hybrid glass block' is an innovative concept that endeavours to bridge the gap between the solid glass blocks' thermal performance and hollow glass blocks' load-bearing capacity. Since this is a recently emerged concept, the research will focus on defining design guidelines, manufacturing methodology, and evaluation through design and experimentation along with the freedom of exploration of various design concepts in a realistic case study.

This research will result in an energy-compliant sustainable glass product for application in the building industry. On a broader level, the focus is on **structural design and climate design**, which are two branches of the Building Technology track. The research topic is also related to the ongoing research on **Sustainable structures** in TU Delft.

Scientific and Social Relevance

In the last two decades, the building industry is slowly evolving and transitioning towards designing and creating sustainable environments to meet the global challenges of climate change and scarcity of natural resources. The focus is aligned towards **adaptable building systems** that are energy efficient and have a low carbon footprint. This simply means that every product that goes into the making of the building environment should be energy-efficient, **sustainable**, and have less carbon footprint. The focus is not only limited to a system-level but also on a unit level. Another important aspect is the **circularity and reusability** of building products after their end of function or life-cycle.

"The use of glass in architecture has never been more popular, but the global drive to increase the energy efficiency and sustainability of buildings is posing a challenge to architects, engineers, and manufacturers alike" (James O' Callaghan, 2020)

To ensure the future of architectural glass it is important to push the boundaries of products that provide innovative solutions to meet these g**lobal challenges**. A lot of architectural projects are increasingly using glass in many innovative ways and this will significantly increase in the future since it is circular and recyclable.

The research aims at developing a glass block that adheres to the energy efficiency and sustainability goals by unveiling its true potential. The newly developed glass product and the system will focus on sustainability and a**chieve maximum recyclable components** (e.g. by having a pure glass part, dry-assembly method, etc). The research also focuses on **design for disassembly** so as to reuse the building components at the end of their function or life cycle. This will completely **change the way how glass is perceived in society.** The methodology in which the potential of the glass has been explored relates to the scientific curiosity of developing innovative glass structures that are energy giants and sustainable.

01.6

ORGANIZATION

Time Planning

The graduation studio has been strategically planned in between five presentations as shown in figure 01.2

The first phase focuses on the literature study and data collection which will be presented during P2. Here the topics related to the chosen research will be studied and the inferences drawn out will define the designing phase. The second phase focuses on designing and prototyping the product which will be presented during P3. The third phase will focus on the performance evaluation of the prototypes through possible numeriacal and experimental methods performed in a glass lab. The whole process and findings will be presented during P4. The last phase is for refinement of the research, the findings, and the final report compilation. These will be presented during P5.

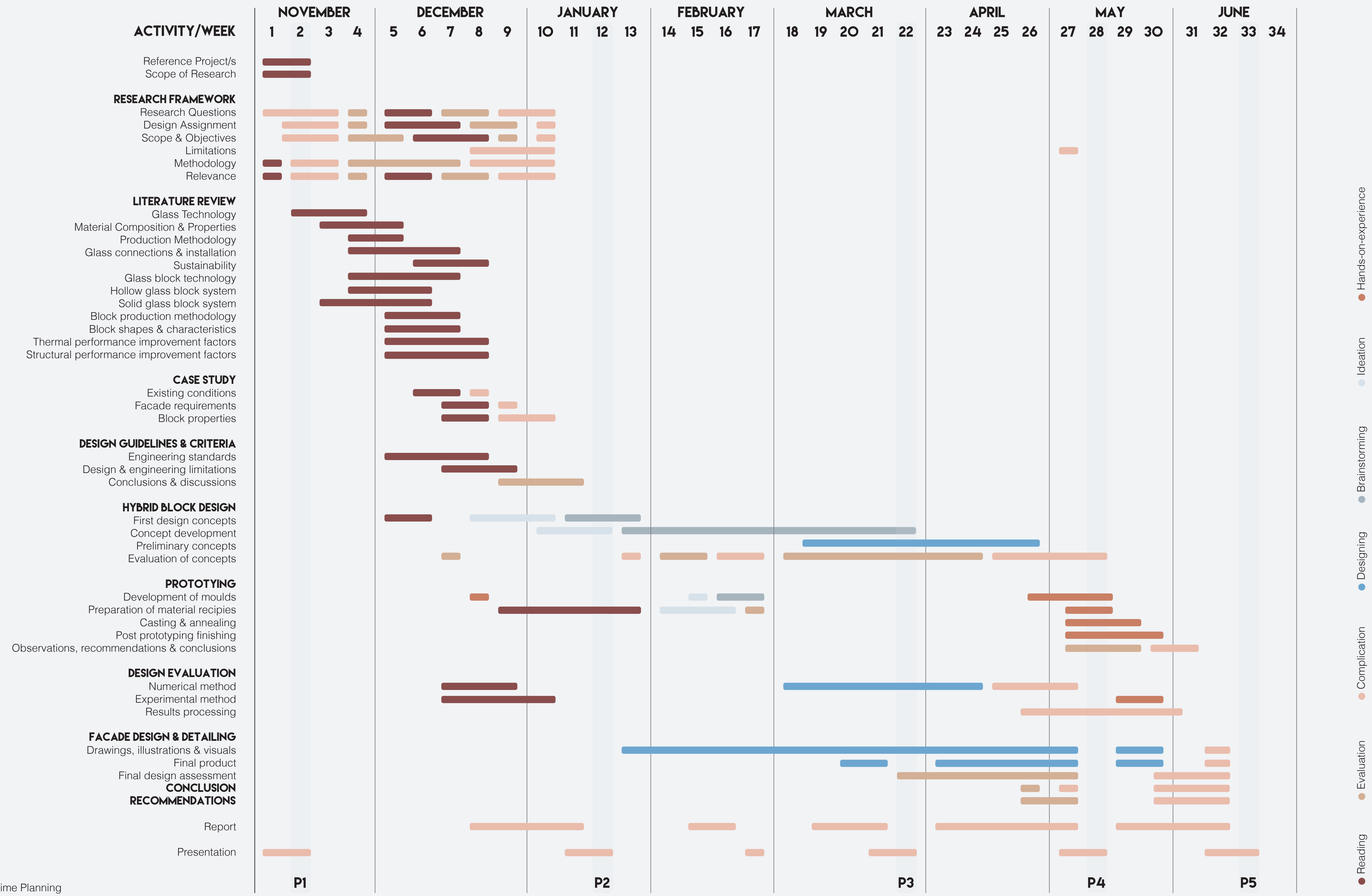


Figure 01.2: Time Planning

Apple Park Visitor Centre by Foster + Partners (Archdaily, 2017)

02.

GLASS TECHNOLOGY

The history of glass, its evolution, and its use in the building industry are thoroughly researched. Various forms of glass are investigated based on their material composition, followed by their material properties and existing production methodologies. This chapter also delves into the numerous connecting technologies utilized to join glass, as well as their immediate impact and structural and thermal performance. The chapter culminates with the glass and manufacturing process considerations that will be explored for the development of hybrid glass block systems.

O2.1

GLASS TECHNOLOGY BACKGROUND

Glass is defined as a hard, brittle, and typically transparent or translucent material produced from sand, soda, and lime by melting them at high temperatures and then rapid cooling. It is used for making windows, bottles, and other objects. (Oxford Dictionary)

The first known architectural application of glass can be seen in the Roman baths, where it was used in the form of a window to trap the internal heat. The use of glass soon became popular due to its optical properties that allow natural light to enter the interiors and provide a view of the exteriors while maintaining thermal comfort. It is a form of transparent screen that connects the indoor with nature. At first, there were limitations to the size of the glass due to limited production techniques, but as the building industry progressed the production methods were developed which allowed good quality and large size of the glass panels. Currently, the largest size of the glass panel available is upto 20 metres long developed by Sedak. Glass can be moulded into any size and desired shape however one of the biggest challenges is its brittle nature. This is due to the production methodology which consists of melting and rapid cooling. The molecular structure of the glass remains unchanged(when cooled down) which is similar to solids and there are gaps that resemble the structure of liquids. This gives rise to an amorphous structure that restricts glass from plastic deformation at room temperature. However, when the glass is heated and reaches its softening point these uneven bonds can be easily broken. (Giezen, C. 2008)

Initially, there were limitations to the size of the glass due to limited production techniques, but as the building industry progressed the production methods were developed which allowed good quality and large size of the glass panels. Currently, the largest size of the glass panel available is upto 20 metres long developed by Sedak. The potential of glass is not only limited to a building skin material but has evolved as a structural material. It is now possible to make glass windows load-bearing and self-supported which has resulted in more thicker cross-sections.

O2.2

MATERIAL COMPOSITION

On the basis of the varied material composition there are six different classifications of glass. These are aluminosilicate, borosilicate, fused silica or quartz, lead, silicate (96%) and soda-lime glass. Each type has varied material properties and thus result in different applications.

Aluminosilicate glass
The aluminosilicate glass is composed of aluminium oxide within the range of 20 - 40%. It has more chemical and heat resistance than the borosilicate glass and can tolerate high temperatures upto 800°c. There are two types of Aluminosilicate glasses that are categorised on the basis of oxide percentage in their chemical composition.

- **Alkaline Earth aluminosilicate glass:** They possess higher softening points due to which they are most commonly used for the production of glass bulbs in halogen lamps.
- **Alkali aluminosilicate glass:** The presence of alkali is responsible for improving their surface compressive strength, making them hard and resistant to scratches. Most commonly used for touch displays and laminated safety glass. (Mills, n.d.)

Borosilicate Glass
Unlike the material composition of traditional glass, Borosilicate glass is made of boron oxide (5%) which is the substitute for soda and lime. The presence of boron oxide demands production at higher temperatures than usual. This results in lower thermal coefficients, higher heat resistance and durability. These properties make Borosilicate glass an excellent choice for a wide range of applications. Mostly used in laboratory equipment as it has good resistance to chemical reactions. Due to higher heat resistance, it does not deform easily and can retain shape at higher temperatures and is therefore used in a wide range of cookware. (Mills, n.d.)

Fused quartz glass: (Fused-silica or vitreous-silica glass)
The Fused quartz glass is produced by the process of electrical or flame fusion by purifying and melting down the natural crystalline silica which results in highly transparent, weather, and shock-resistant glass. The process of fusion occurs at very high temperatures i.e. 1650°c which results in an expensive higher heat resistant glass that can withstand temperatures up to 1400°c for short periods. Due to these properties, it is used in a manned spacecraft as a window where the exterior surface is prone to high temperature. (Mills, n.d.)

High Silica glass
The high silica glass is produced by melting the glass mixture and removing all the non-silicate elements. The absence of fluxing agents results in a deformation temperature of 1700°c and low thermal expansion. It possesses optimum chemical durability, good mechanical and optical properties. Extremely high processing temperatures are a limiting factor in larger-scale production and application. It is used in the manufacture of UV-transmissive lamp tubes, precision optics, refractory tubes, and fibre reinforcers in composites. (Mills, n.d.)

Lead glass: (Lead-oxide or lead crystal)
The Lead glass is well known for its soft nature as it is made from 20% lead oxide. It can be easily cut into various designs with a high refractive index. Because of its lower working temperature and ability to absorb X-rays, it is used in electrical and nuclear applications. However, due to its softness, it has limited resistance to thermal shock and high temperatures and is susceptible to scratching, making it unsuitable for architectural applications. (Mills, n.d.)

Soda-lime glass (Soda lime silica or window glass)
Soda-lime glass is the most common and least expensive type of glass which is produced by melting about 70% silica along with soda, lime, and a few percent of various compounds. The soda lowers the melting temperature of the silica, while the lime stabilises it. It is a chemically stable, easily workable, and softer glass that can be formed into a variety of shapes.

Soda-lime glass is frequently chemically strengthened to increase strength, and it can also be tempered to increase thermal shock resistance and strength. Although it is less scratch resistant it is still widely used for windows. (Mills, n.d.)

An overview of the percentage of material composition , their properties and application can be seen in Table 02.1.

MATERIAL COMPOSITION

M.P. - Mean Melting Point at 10 Pa.s*, S.A.- Softening Point, A.P.- Annealing Point, ST.P.- Strain Point, DE.- Density, C.E.- Coefficient of Expansion 0°C - 300°C, Y.M.- Young's Modulus

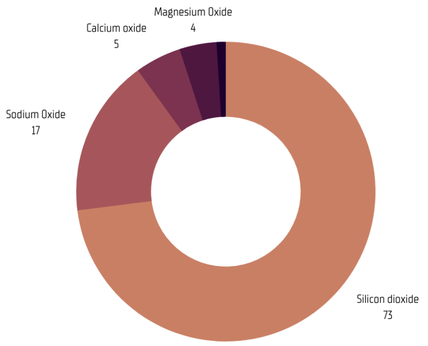
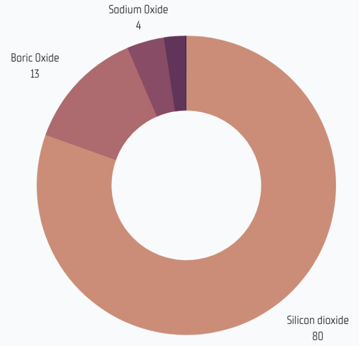
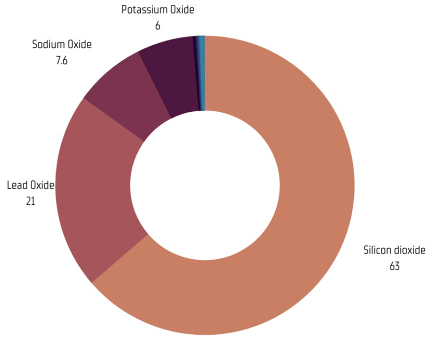
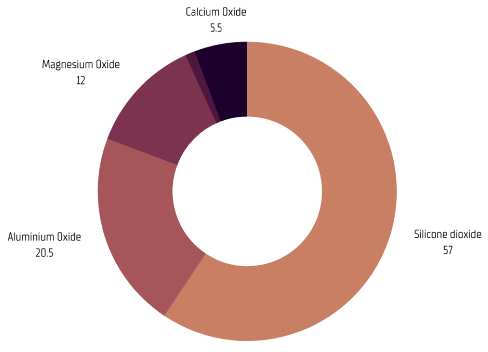
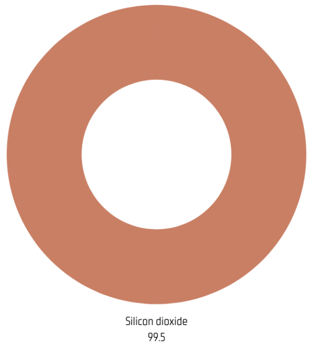
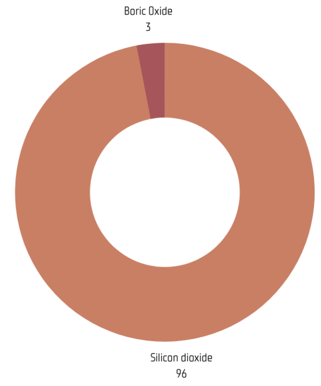
	SODA LIME GLASS	BOROSILICATE GLASS	LEAD SILICATE GLASS	ALUMINOSILICATE GLASS	FUSED-SILICA GLASS	96% SILICA GLASS
GLASS TYPE	 73% SiO_2, 17% Na_2O, 5% CaO, 4% MgO, 1% Al_2O_3	 80% SiO_2, 13% B_2O_3, 4% Na_2O, 2.3% Al_2O_3, 0.1% K_2O	 63% SiO_2, 21% PbO, 7.6% Na_2O, 6% K_2O, 0.3% CaO, 0.2% MgO, 0.2%, B_2O_3, 0.6% Al_2O_3	 57% SiO_2, 20.5% Al_2O_3, 12% MgO 1% Na_2O, 5.5% CaO	 99.5% SiO_2	 96% SiO_2, 3% B_2O_3
OBSERVATIONS	Durable. Least expensive type of glass. Poor thermal resistance. Poor resistance to strong alkalis (e.g. wet cement)	Good thermal shock and chemical resistance. More expensive than sodalime and lead glass.	Second least expensive type of glass. Softer glass compared to other types. Easy to cold-work. Poor thermal properties. Good electrical insulating properties.	Very good thermal shock and chemical resistance. High manufacturing cost.	Highest thermal shock and chemical resistance. Comparatively high melting point. Difficult to work with. High production cost.	Very good thermal shock and chemical resistance. Meticulous manufacturing process and high production cost.
APPLICATIONS	• Window panes • Bottles • Façade glass	• Laboratory glassware • Household ovenware • Lightbulbs • Telescope mirrors	• Artistic ware • Neon-sign tubes • TV screens (CRT) • Absorption of X-rays (when PbO % is high)	• Mobile phone screens • Fiber glass • High temperature thermometers • Combustion tubes	• Outer windows on space vehicles • Telescope mirrors	• Furnace sight glasses • Outer windows on space vehicles
M.P	1350-1400 [°C]	1450-1550 [°C]	1200-1300 [°C]	1500-1600 [°C]	>>2000 [°C]	>>2000 [°C]
S.P	730 [°C]	780 [°C]	626 [°C]	915 [°C]	1667 [°C]	1500 [°C]
A.P	548 [°C]	525 [°C]	435 [°C]	715 [°C]	1140 [°C]	910 [°C]
ST. P	505 [°C]	480 [°C]	395 [°C]	670 [°C]	1070 [°C]	820 [°C]
DE.	2460 [kg/m3]	2230 [kg/m3]	2850 [kg/m3]	2530 [kg/m3]	2200 [kg/m3]	2180 [kg/m3]
C.E	8.5 [10^-6/°C]	3.4 [10^-6/°C]	9.1 [10^-6/°C]	4.2 [10^-6/°C]	0.55 [10^-6/°C]	0.8 [10^-6/°C]
Y.M	69 [GPa]	63 [GPa]	62 [GPa]	87 [GPa]	69 [GPa]	67 [GPa]

Table 02.1: Different Glass types material compositions & properties, adapted from (Shand,Armistead 1958)

* 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

O2.3

PROPERTIES

In the most common form, glass is a mixture of silicon oxides, alkaline oxides, and alkaline earth heated to temperatures greater than 1100°C. It is an inorganic fusion product that has been cooled, resulting in a solid state without crystallisation.

Glass does not possess a fixed melting point due to its rather amorphous chemical composition. Its structural state is similar to that of liquids and molten materials, therefore it lacks any direction-oriented properties. (Weller, 2009)

Transparency
The Optical properties are influenced by thickness, chemical composition, and coatings used. The most noticeable of these is the extremely high transparency within the visible wavelength range [λ=380-750 nm]. Glass is a highly permeable material due to the chemical bonds that transmit, reflect, and absorb radiation. Anti-reflection treatments for low iron, extra-clear glass can be used to reduce absorption for an even more transparent result. Furthermore, the degree of transparency can be influenced by the structure of the glass component. (Barou. L, 2016)

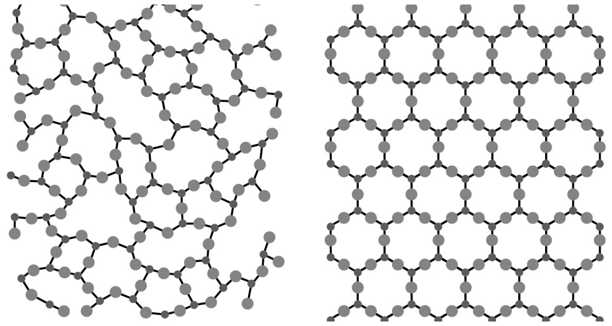


Figure 02.1: Molecular structure of soda lime glass [left] and quartz [right] retrieved from (Fresno)

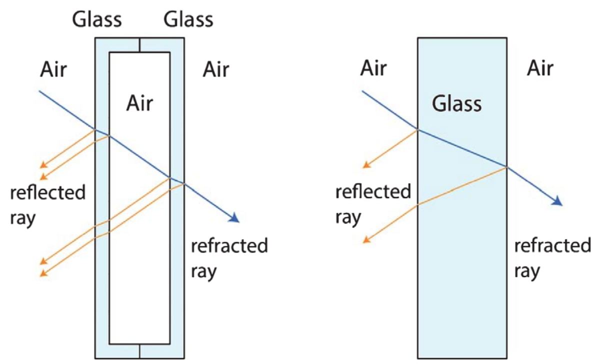


Figure 02.2: Transition of light rays in hollow glass [left] & solid glass [right] (Oikonomopoulou. F, 2019)

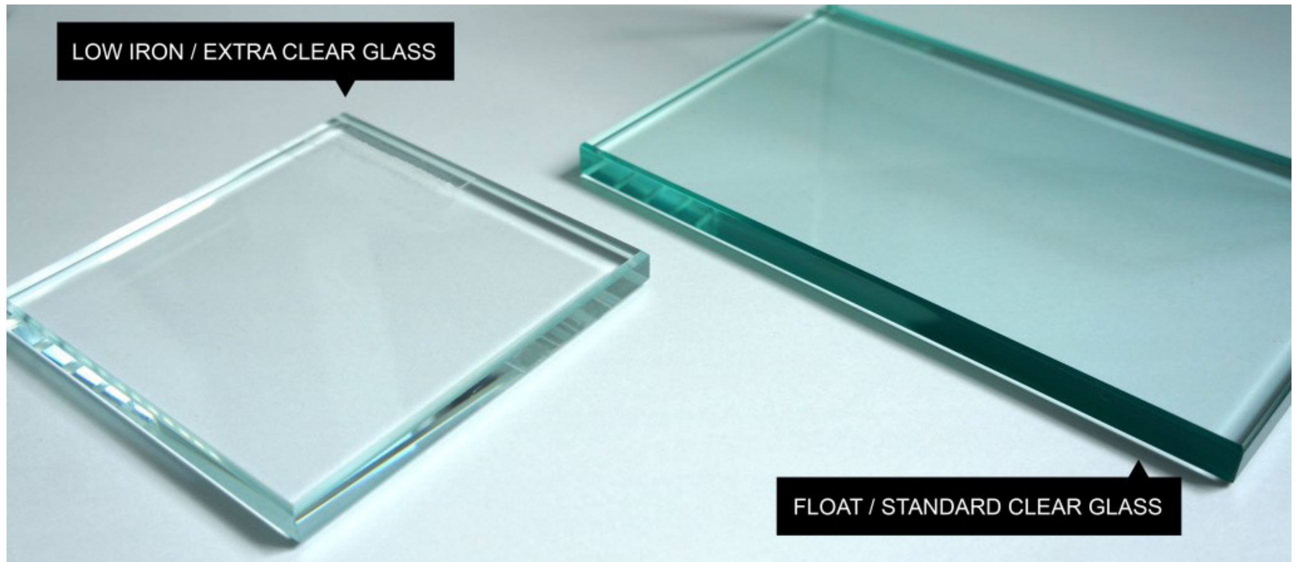


Figure 02.3: Change in glass colour due to the presence of metal oxides retrieved from (Diamond glass)

Brittleness
As glass is brittle it does not yield plastically as steel does. The maximum elongation it can achieve is in the area of 0.1 percent. It is impossible to predict failure as there is no plastic-behaviour zone. (Weller, 2009)

On the molecular scale, the intact atomic bonding forces suggest a glass surface that is perfectly smooth that is capable of undergoing high mechanical strength. Although this is only in theory because the tensile strength of brittle materials like the glass is highly dependent on mechanical flaws on the material's surface. Some minor damages may occur even during the production. According to the "Griffith Flaws," flaws have no effect on overall structural behaviour in compression, but when subjected to tension, they exhibit very high local stresses.(Balkow,1999)

The cracks can be developed over a period of time when they are subjected to loading. The effective tensile strength is lowered when glass is subjected to higher loads for a longer time duration for an existing surface flaw. (Haldimann, Luible et al.)

The tensile strength depends on the type, size and age of the glass pane, duration of the load and surrounding temperature. This is the reason why there is no constant tensile strength.

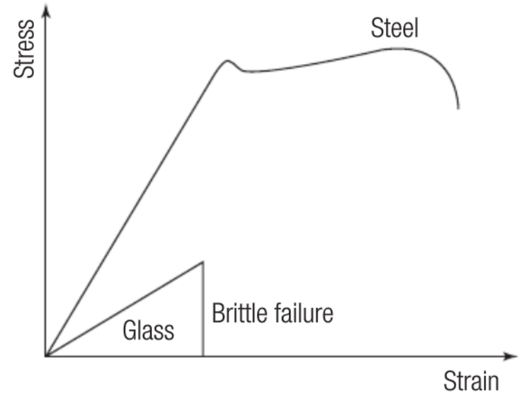


Figure 02.4: Stress / strain graph of glass compared to steel [brittle vs ductile behavior] (Weller, 2009)

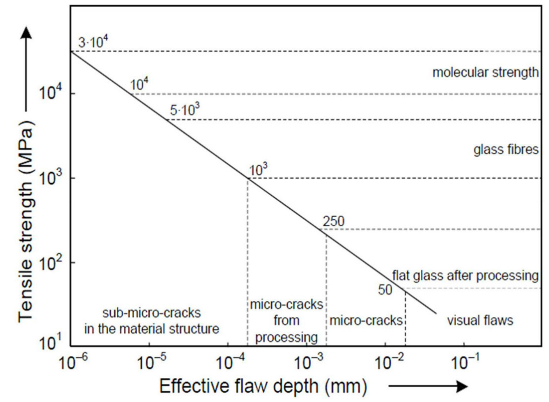


Figure 02.5: Rough estimated ration between tensile strength and effective flaw depth (Balkow,1999)

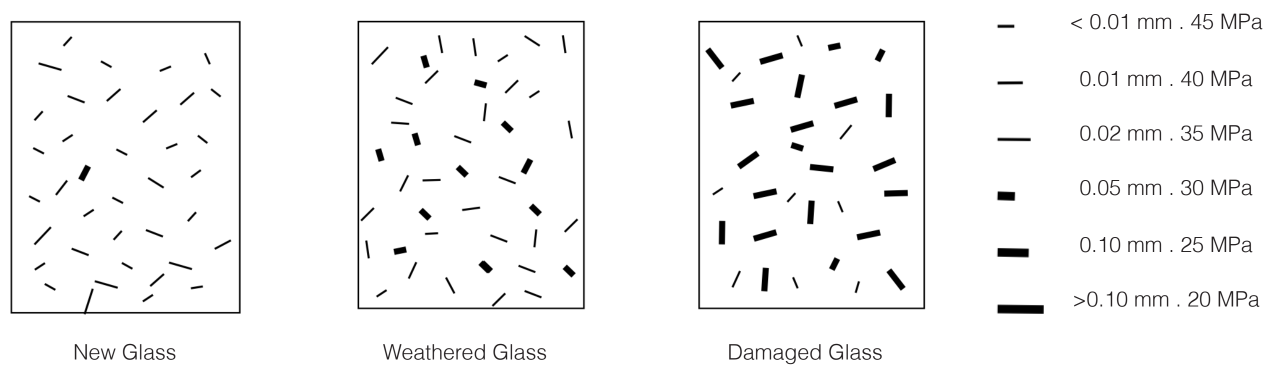


Figure 02.6: Distribution of surface damage and margin of strength (Schittich et al, 2007)

02.4

PRODUCTION TECHNOLOGY

The interesting application of glass in architecture has resulted in the development of various production techniques. Glass can be produced in the form of flat sheets, circular tubes, or any desired shape using a specific production process. To strengthen the glass for its structural application in the form of fins, beams of circular tubes, some complicated processes are undertaken which have impacted traditional ways of manufacturing.

The raw materials, the heat energy required to melt these materials, the technical conditions of a glassworks or factory, and the highly experienced personnel all play a vital role in the production of glass. (Weller 2009). Glass can be produced by the method of float (rolled or drawn), casting, extrusion, or even 3D printing. However, each process has geometrical limitations.

Float Glass
Until the 1960's flat glass was produced using the sheet and plate glass manufacturing method which was quite labour-intensive. An automated system came into place which was designed by Plinkington with the use of an assembly line. This was known as the float glass method which is universally followed for producing high-quality flat glass. Following is the method of production:

- The raw materials used are sand(60%) which is known as a batch, lime dolomite(20%)for weathering glass, soda, and sulphate (20%) to lower the melting temperature, and glass cullets which are recovered from previous manufacturing processes. The glass cullet is used to accelerate the melting process and reduces the energy requirement up to fifth.
- With the help of an automated system, perfect quantities of raw material are fed to the furnace. The mixture is heated at 1550°c inside the furnace for around 50 hours. Here the mixture melts and changes from a semi-molten stage to molten glass.
- The melting, refining, and the homogenising process takes place in separate zones (managed from the control room) and makes the melted glass bubble-free.
- The molten glass leaves the conditioning end of the melting zone at 100°c through a narrow canal.
- The molten glass enters the tin bath where it floats over the tin surface(as tin is denser than glass it goes down). The molten glass spreads out following the flatness of the tin surface.
- The spread molten glass is now passed over a series of rollers, where the thickness (2-25mm range) of the glass is defined. The speed of the roller defines the thickness. Faster the roller speed - less thick is the glass sheet and vice-versa. The glass is stretched out over a roller forming a layer of uniform thickness. Here the glass coming out is hard and free from any damage caused through roller movement.
- Based on the product (tinted, clear, and coated) these glass sheets are carried over conveyor belts for additional layering.
- The hard glass now enters the Annealing lehr where the stresses are removed by a controlled cooling process. The glass enters the system at 600°c and is cooled down to a room temperature of 25°c. The resultant glass is perfect.
- The glass is now snapped in predefined sizes (3.2*6 m max) and the remaining glass cullets are sent back for manufacturing.

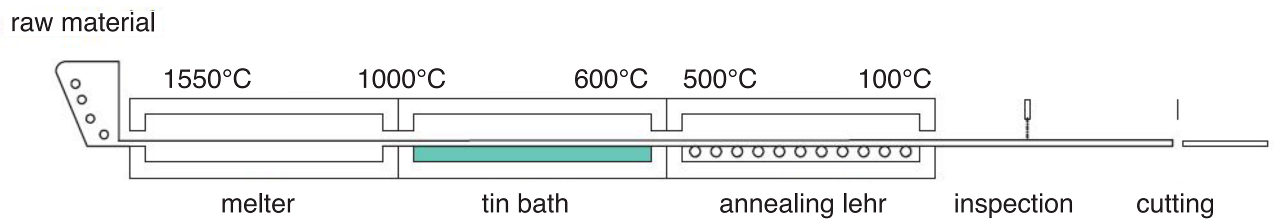


Figure 02.7 : Schematic illustration of the float production process by (Louter 2011) based on (Wörner et al. 2001)

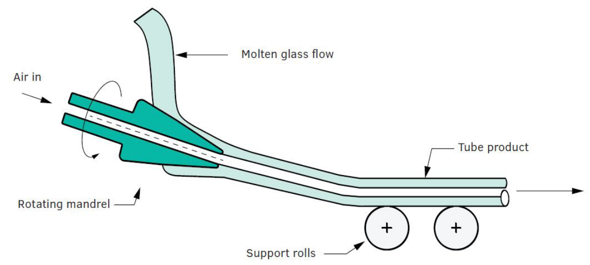


Figure 02.8 : Daner Process for glass production (Oikonomopoulou. F, 2019)

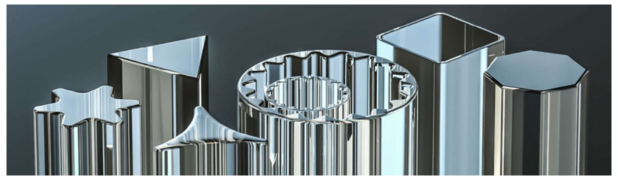


Figure 02.9 : Large variety on profiles for extruded glass products (Schott Conturax)

Figure 02.10 :Arquia Bank office interiors with Borosilicate glass tubes (Archdaily, 2008)

Extruded Glass
Glass extrusion is a method of producing glass profiles with a constant cross-section, such as (thin wall) tubes, rods, or other glass elements. Extruded glass profiles are primarily used in interior architecture, art, design, and lighting. Extrusion can be used for glasses with a steep viscosity curve, a high crystallisation tendency, and/or a very high softening point like silica glass (Roeder 1971).

Extrusion is a cost-effective method for producing full or hollow profiles with sharp-edged cross sections for industrial use (Pfaender 2012).

The Danner process is the most commonly used methodology for extruding a continuous tube.
- Molten glass is continuously poured inside a rotating mandrel which is positioned slightly downwards.
- The air is blown inside the mandrel which results in a hollow space inside the glass. This blown air is drawn out from the end of the mandrel using a tractor mechanism.
- The airflow and speed of the drawing machine are constantly monitored and regulated to achieve a uniform cross-section and diameter.
- A cross-section of up to 10mm is achievable with this process.
- The solidified tube is pulled out using a roller track and then transferred for snapping into desired lengths (typically 1.5m).

(Haldimann et al. 2008)

The extruded glass products have extremely high thermal shock resistance, high optical quality, and tight geometrical tolerances along with a wide geometrical range. (Schott, 2015) The extruded glass is typically borosilicate.

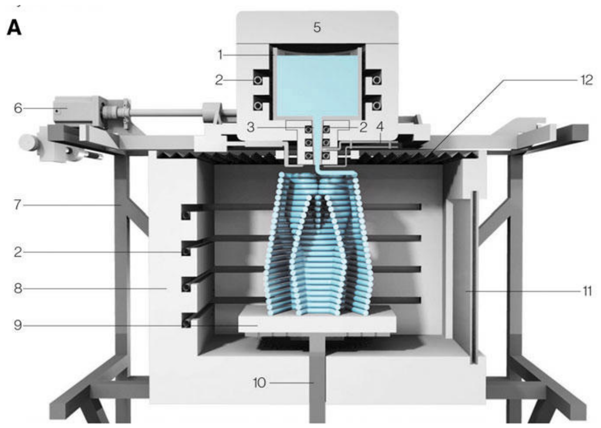
02.4

PRODUCTION TECHNOLOGY

3D Printed Glass
For generating complex geometries and varying degrees of optical transparencies, glass can be 3D printed. It is an expensive and time-consuming process due to which it has limited applications. A research team at MIT named Mediated Matter group has designed and developed a 3D printer that can create interesting geometries out of glass. The printer works on the principle of dual heated chambers.

- The uppermost chamber is heated at 1900°F which results in the melting of the glass. This molten glass is filled inside the kiln cartridge and supplies the flow of glass to 3D print one component.
- The nozzle pours the molten glass in the predetermined layering pattern over the ceramic print plate.
- The temperature in the lower chamber is maintained at 896°F which is just below the annealing temperature.
- The bottom chamber is the print annealer which is responsible for annealing the completed geometry.
- The Annealing process requires a highly controlled environment to cool down the glass by carefully removing the stresses and avoiding cracking. (John et al., 2015)

While 3D printing's precision and detailing allow for mass customization and standardisation of products, the layered nature of the additive manufacturing process influences the transparency of the end product. (Oikonomopoulou. F, 2019)



1. crucible 2. heating elements 3. nozzle 4. thermocouple 5. removable feed access lid 6. stepper motors 7. printer frame 8. print annealer 9. ceramic print plate 10. z-driven train 11. ceramic viewing window 12. insulating skirt

Figure 02.11 : Rendered cross-section of the 3D Printer (John et al., 2015)

Figure 02.12 : 3D Printed glass component (John Klein)

Cast Glass
Glass casting is one of the most traditional ways of shaping the glass into desired shape and geometry. Artists and sculptors practised casting for making beautiful sculptures. In the building industry, it is used for casting solid glass blocks.

The process of casting is straightforward and requires a mould for the glass to take the desired shape. This can be done in two ways;

- **Hot pour:** The molten glass is directly poured inside a mould at 1200°c. To avoid sudden changes in temperatures, the mould is pre-heated at 850°c. The glass is allowed to settle and when it becomes hard it is placed in a kiln for the annealing process. This method is known as sand casting which is mostly used by artists. For commercial manufacturing where standardisation is important, steel moulds are preferred.
- **Kiln Casting:** In this process, the mould is kept inside a kiln throughout the process. The moulds are made of high heat resistant materials such as plaster as they are kept inside the kiln at 1200°c. The glass pieces are filled inside the mould, that after melting cover the whole volume of the mould. The kiln is slowly cooled down to avoid cracking inside the glass. When the kiln reaches room temperature, the mould is taken out and carefully destroyed to get the casted glass block. (Oikonomopoulou. F, 2019)

Figure 02.13 : Casting of Soda-lime glass blocks at Poesia factory in Italy (Oikonomopoulou. F, 2019)

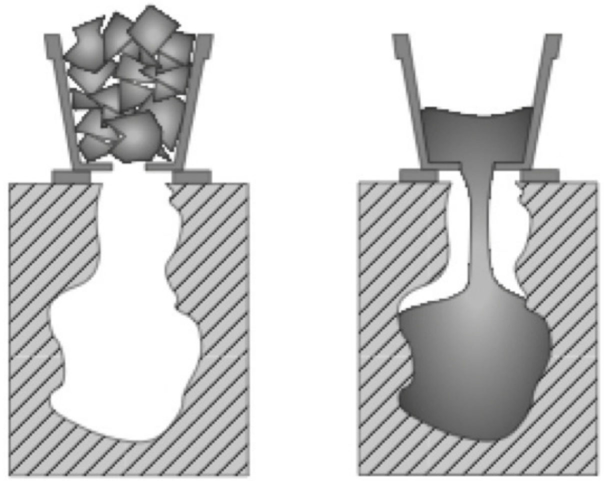
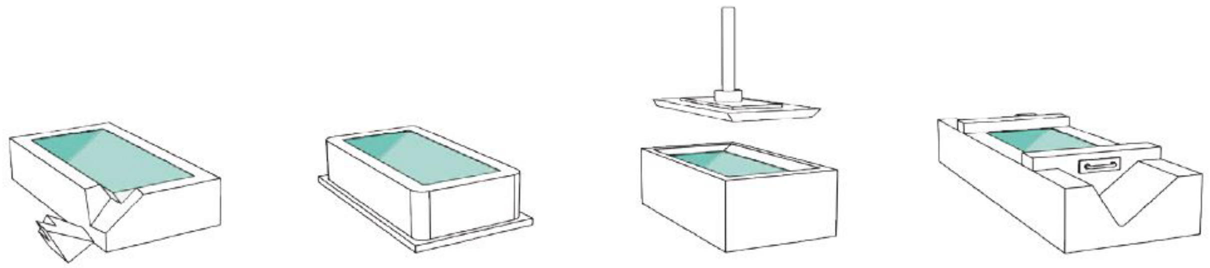


Figure 02.14 : Glass pieces melt and are poured into the mold in kiln casting (Telesilla Bristogianni)



Disposable Mould | Open metal Mould | Press metal Mould | Adjustable metal Mould

Figure 02.15 : Illustration of the mould types. (Oikonomopoulou. F, 2019)

02.5

CONNECTION SYSTEMS

Connections are vital elements in transferring a load of glass to the intermediate support structure. To avoid direct contact of glass with hard materials, intermediate materials like resins, plastics, neoprene, aluminium/fibre gasket, or injected mortars are used inside metal connections. The connections should be strong, stiff, and durable to support the assembly. The connections also define the aesthetic vision of the structures which have resulted in the development of glued connections to create completely transparent building skins. (Haldimann et. al , 2008).

Glass connections are classified as mechanical interlock, friction, or adhesive connections based on their force-transfer mechanism.

Clamped Connection
Clamped connections were created to reduce the visual impact of linear supports. Clamps are used to secure the edges of glass panels to the substructure at discrete locations. The glazing in framed constructions is connected to two or four edges. The edge frame is connected to the glass panel through intermediate material to avoid direct contact and transfer the self-weight towards the edges. The clamps on one side are connected to the glass panel and on the other side to the frame system and are responsible for carrying the lateral wind loads. (Haldimann et. al , 2008)

Following are the load transfer characteristics of clamped connection system:

- Mechanical interlock is used to transfer out-of-plane loads
- Friction forces transfer in-plane loads [such as self-weight] via brackets and blocks.
- The residual load-bearing capacity is directly proportional to clamped surface area and glass embedding
- Clamp connections can be linear, point fixing, or a combination of both and can be fixed at the edges or the corners

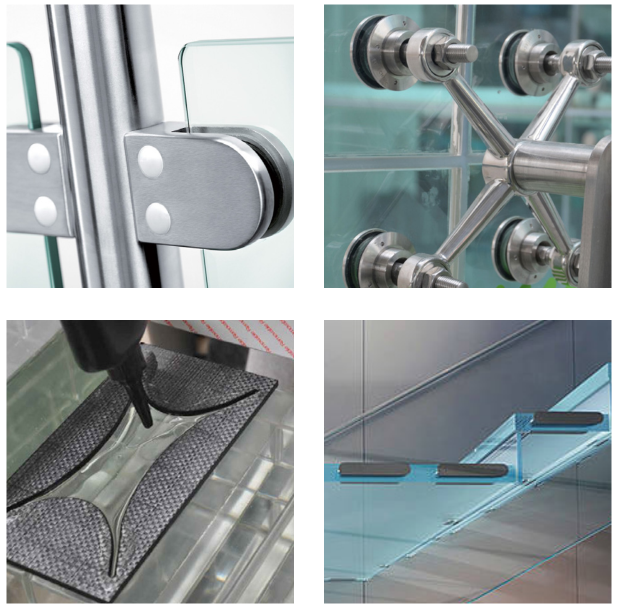


Figure 02.16 : Clamped (top-L) (Q-railing), Bolted (top-R) (Alphaglass), Adhesive (bottom-L) (Oikonomopoulou et. al. 2018), Embedded (bottom-R) (Seele)

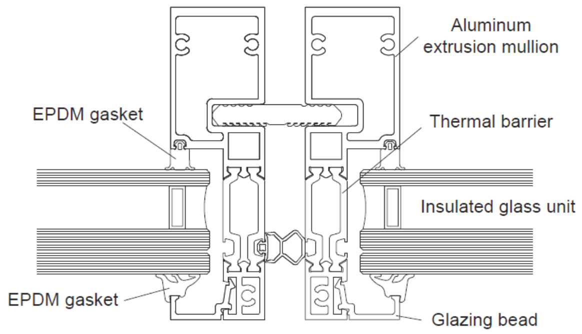


Figure 02.17 : Linear support clamp (Haldimann et. al , 2008)

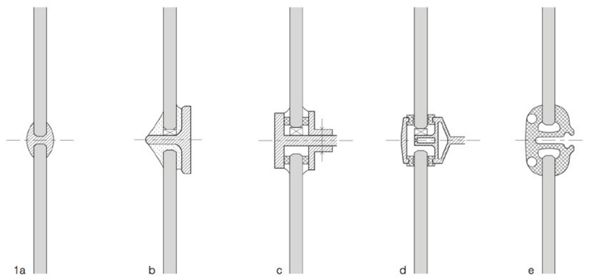
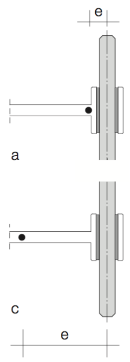


Figure 02.18 : Stages at the development of clamping linear support retrieved from (Weller, 2009)



a. hinge positions with minimal eccentricity
b. rigid support
c. hinge position with large eccentricity
d. hinge roughly in line with the pane of the glass

Figure 02.19 : Possible hinge positions for point fixings (Weller, 2009)

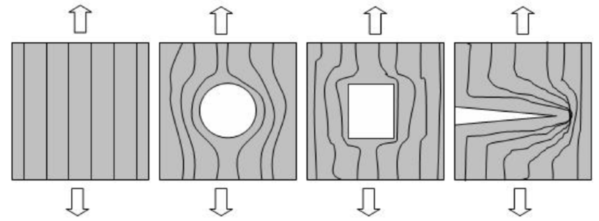


Figure 02.20 : Load distribution around holes in bolted connection (Malinda Zarske 2006)

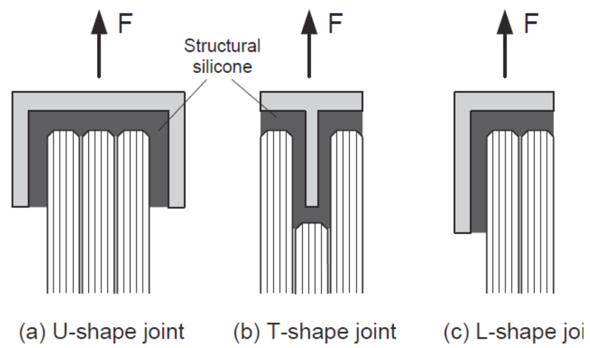


Figure 02.21 : Bolt Adhesive Joints (Haldimann et. al , 2008)

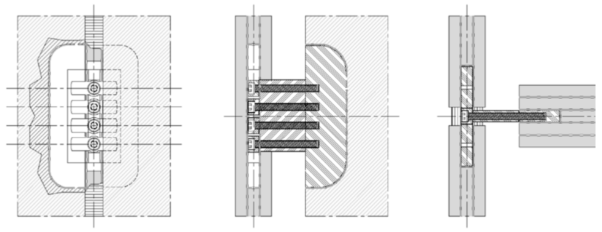


Figure 02.22 :Embedded Connections in Apple cube (Eckersley O'Callaghan)

Bolted Connections
The lateral and in-plane forces are transferred directly to the bolts in bolted connections. The stainless steel bolts are placed over the aluminium bushings, POM, or injected mortars. These intermediate materials avoid direct contact of bolts with the glass surface and reduce the bearing stress concentrations in the glass.(Overend, 2012) Following are the load transfer characteristics of bolted connection system:

- Mechanical interlock is used to transfer loads
- Tempered glass is required
- High local stresses are formed around the bolted holes as the glass surface in that area cannot be tempered
- To reduce the restraint stresses in the glass pane, the fixing can be a hinged point

Adhesive Connections
The adhesive connections are made out of thermosets like U-V cured acrylics, two-component epoxies, etc. These thermosets are more rigid and stronger than structural silicone which transfers the principal loads through either glass to metal or glass to glass. The glass components require to be of precise dimension as the adhesive layer can accommodate thinner tolerances. (Overend, 2012) Following are the load transfer characteristics of adhesive connections:

- The adhesive forces developed at the molecular or atomic level are responsible to transfer loads
- To be strong, the layer must be the proper thickness

Embedded Connections
Embedded connections are a combination of adhesive and bolted types of connection where a stainless steel bolt is embedded inside glass using an adhesive interlayer. Once the adhesive is completely bonded with the bolt, the glass becomes part of the embedded metal which can be bolted to the wall or any desired surface. The embedded bolt is responsible for transferring the principal load to the support frame or wall. (Overend, 2012)

02.6

SUSTAINABILITY

In the last decade, the building industry has shifted its focus to the circular and sustainable use of building materials and components. To address the global challenge of natural material scarcity while reducing the embodied carbon in their production, a circular approach is required. Glass, as a natural material in its purest form, is completely recyclable. The addition of impurities in the form of different coatings, layers, and adhesives is due to the connection system and the need to improve the thermal and structural potential.

An intriguing approach to the circular use of glass components can be found in the Glass research group's Re3 Glass project at TuDelft. They created an interlocking system of cast glass blocks that is simple to manufacture and assemble. The key feature of these interlocking geometries is their reusability, as they can be easily disassembled and reused for other interior or architectural applications.

Because the components are not contaminated by adhesives or coatings, they can eventually be recycled if they are not reused. The traditional use of silicone to achieve dust and waterproof structure is still common due to its recyclability, as silicone can be easily scraped off (or heated) from the glass surface at the end of life. The glass elements in the proposed system can be retrieved intact and reused without having to be re-melted, which adds to the carbon and energy footprint. They can eventually be recycled because they are contaminant-free. (Oikonomopoulou et. al. 2016)

Figure 02.23: Re3 Glass, Small Bone Capsule
(Faidra Oikonomopoulou)

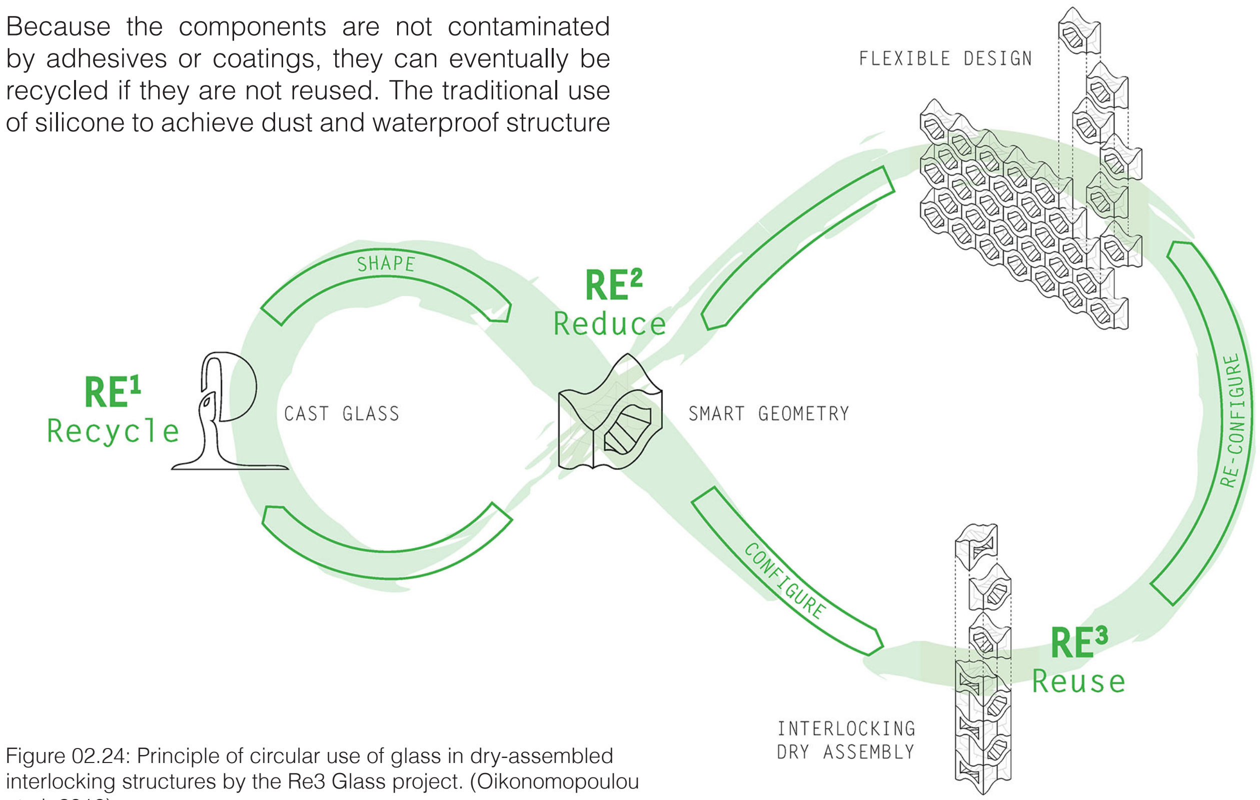


Figure 02.24: Principle of circular use of glass in dry-assembled interlocking structures by the Re3 Glass project. (Oikonomopoulou et.al. 2016)

02.7

CONCLUSIONS & DISCUSSIONS

Type of glass
Based on the previously discussed wide range of glasses in terms of material composition, properties, and applications, soda-lime, and borosilicate glass appear to have a high potential for making hybrid glass blocks. This is because both of these glasses have a lower melting and annealing point in comparison to others. Lead silicate has the lowest values, but it has a poor thermal resistance and is soft, making it unsuitable for making hybrid glass blocks. Because of its high thermal expansion coefficient, lead silicate can exhibit significant expansion, which is undesirable for a structural system, and hence the connections must accommodate these movements.

The soda-lime and borosilicate glass is made using an efficient production methodology that has already been developed. Soda-lime glass has poor thermal resistance (in comparison to borosilicate glass) because of its higher coefficient of expansion whereas borosilicate glass possesses good resistance to thermal shocks and chemicals. Due to the absence of iron, Borosilicate glass has the better optical quality and is very transparent than Soda-lime glass making it more suitable for visual performance.

The annealing time for borosilicate glass production is the shortest due to the lower coefficient of expansion. If cost is not a factor, borosilicate glass is the obvious choice for the production of hybrid blocks due to its high thermal resistance, compressive strength (>200 MPa), and nearly identical young's modulus.

Type of production methodology
Float glass is the most common and widely used method of producing glass. The presence of controlled and automated systems ensures that the quality of the glass produced is high. However, the float glass method is limited to producing thin cross-sections with thicknesses ranging from 2 to 25 mm and sizes ranging from 3.21*6 m. Extruded glass is a popular method for producing hollow glass with a constant cross-section of up to 10mm. These two methods, however, cannot produce 3D blocks. Casting and 3D printing are the only production techniques that can produce 3D shapes in large volumes and sizes. 3D printing is an expensive and still rather experimental process with annealing issues and optical distortion of the final product. Therefore, casting is the only way to make 3D glass elements with large cross-sections and complex geometry that have high optical properties.

Type of connections
The use of glass in architecture is aimed at reducing visual disturbance caused by connections and other substructures. The designers aim to maximise transparency while concealing visible connections that degrade aesthetic quality. Connections are important as they play a crucial role in transferring the loads. The connection systems can differ depending on the desired optical quality, load conditions, and block design. Therefore the choice of connection is important.

For hybrid glass blocks, it is important to understand the role of connections and their priority. In this research, the overall performance under load, unobstructed view, recyclability, and/or reusability of a connection system is prioritised, and the various connections will be evaluated using these criteria.

We already know that bolted and clamped connections cause peak stresses and reduce transparency, but they are reversible. Adhesive-based connections are not recyclable, despite the fact that they are strong under load and provide maximum transparency. Embedded connections perform reasonably well across all of the evaluation criteria mentioned, however, they are less circular as they are laminated making them hard to recycle. The embedded connections also impact the production process as they need to be customised during the glass production. However, it is far too early to finalise and develop a hybrid block solely on the basis of its connection system.

02.7

CONCLUSIONS & DISCUSSIONS

Sustainability Potential
Many interesting interlocking geometries can be developed using the circular use of glass components and their recyclability. Although it may not be possible to make glass 100 percent recyclable (due to contamination from connections and coatings), sensible predetermined design guidelines and a circular approach can lead to maximum glass sustainability.

The key aspect can be a dry assembly system with interlocking glass components designed in a way that it does not require additional substructure for support and can be easily assembled and maintained. Although the use of adhesive connections for solid cast glass blocks can improve transparency, they are not recyclable. As a result, a middle ground must be found where all important aspects meet the sustainability guidelines.

To improve the thermal performance of the glass block, a cavity in the design or the application of e-coatings on the glass's exterior surface is required. E-coatings can help lower the U-Value of glass blocks, but they cannot be recycled since the coating layers are difficult to remove from the glass surface. It is critical to address the issues created by e-coatings at the design stage, and more focus should be placed on including cavities.

EVALUATION OF GLASS PRODUCTION METHODS

METHOD	OPTICAL PROPERTIES	MAIN TYPE OF GLASS APPLIED	STANDARD SIZE (M)	OVERVIEW
Float	Smooth Transparent	Soda-lime	3.12 * 6.0	Limited to only thin glass (2-25mm)
Extruded	Smooth Transparent	Borosilicate, Silica	1.50 - 20 Length	Virtually 2D glass objects(high slenderness ratio)
3D Printed	Layered Transparent	Soda-lime	Upto 30 kgs	Optical distortion due to layer 3D printind
Cast Glass	Smooth Transparent	Borosilicate, Soda-lime, Lead	Upto 20,000 kgs	Freedom in shape & volume, good optical quality

Table 02.2: Evaluation of Production Methods adapted from (Nathani. T, 2021)

OVERVIEW OF GLASS CONNECTIONS

CONNECTIONS	PERFORMANCE UNDER LOADING	TRANSPARENCY	EASE IN ASSEMBLY / DISASSEMBLY	RECYCLABILITY	OVERVIEW
Clamped	+++	++	++++	++++	Susceptible to panes slipping out of fixing.
Bolted	+++	++	++++	+++	Peak stresses due to drilling and point supports
Adhesive	++++	++++	++	-	Uniform distribution of Load
Embedded	+++	+++	+++	-	Uniform distribution of Load Peak local stresses

Table 02.3: Overview of Connections adapted from (Nathani. T, 2021)

Qaammat Pavilion designed by Konstantin Arkitekter, Greenland (Archdaily, 2022)

03.

GLASS BLOCK TECHNOLOGY

This chapter focuses on existing hollow and the solid glass block. The aim is to understand the various shapes, types of these blocks that are currently available in the industry. With the help of some reference projects the chapter will focus briefly on the assembly system, production technology and performance of these varied blocks. The combined research will form the basis for defining the goals for the development of Hybrid glass blocks.

03.1

GLASS BLOCK TECHNOLOGY

1800 · **1900** · **2000**

RENNAISANCE

During the renaissance period the glass blowing technique was discovered. Lot of artists made glass sculptures using this technique. This soon allowed artist to make hollow blocks out of glass

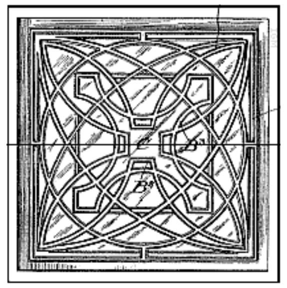
1845 VAULT LIGHT

The vault light made of circular glass plates was patented by Thaddeus Hyatt

Light Vault by Thaddeus Hyatt (Sam Robinson)

1865 PRISMATIC LIGHT

Solid square tiles by Luxfer Prism Company



Luxfer Prism Flower pattern (Frank Llyod Wright)

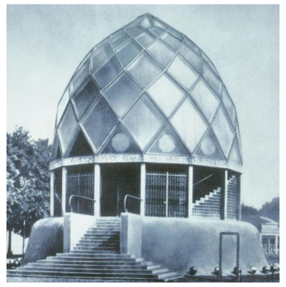
1886 HOLLOW GLASS BLOCK

French engineer Gustave Falconnier patned hollow glass block and made hexagonal or lorenze shaped block. They were popular in staircases, however faced issues of stability and condensation

Blown Glass design by Falconnier (Moma)

1914 GLASS PAVILION

The Glass Pavilion at the Cologne Deutscher Werkbund Exhibition



Glass Utopia (Bruno Taut's)

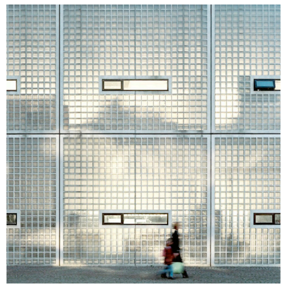
1935 INSULUX HOLLOW BLOCK

Owens -Illinois an american company produced hollow glass block with masonary assembly. The blocks were non load-bearing and patterned. Good sound and thermal insulation

Insulux glass block with Cavity (Owens-Illinois)

1993 HOLLOW GLASS BLOCKS

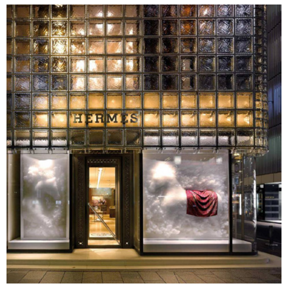
Academy of Arts, Maastricht



Weil Arets Architects (Archdaily)

2001 MAISON DE HERMES

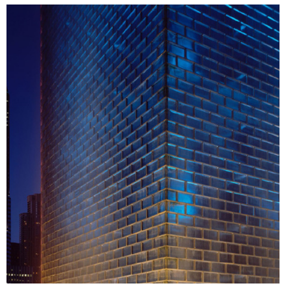
Renzo Piano designed a building out of hollow glass blocks in Tokyo. The curved hollow glass block was produced for the corners by Seves. Here the potential of Glass having load-bearing qualities was realized.



Maison de Hermes (Renzo piano)

2004 CROWN FOUNTAIN

First example of the use of solid glass block



Crown Fountain (Jaume Plensa)

2007 ATOCHA MEMORIAL

First example of load-bearing solid glass block. Interesting interlock geometry and blocks connected using adhesive bonds

Atocha Memorial (EU Mies award)

2012 OPTICAL HOUSE

Dry stacked assembly system

Optical House, Japan (Archdaily)

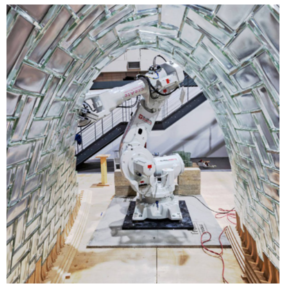
2016 CRYSTAL HOUSE

Completely load-bearing and double heighted facade was explored. The walls were supported by buttresses. The glass block technology stepped ahead by the application of solid glass architraves, cills.

Crystal House, Amsterdam (Archdaily)

2020 LIGHTVAULT ROBOTIC ASSEMBLY

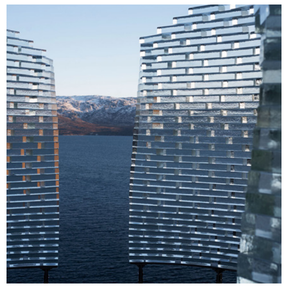
SOM, Princeton & Tudelft



Robotic Assembly of glass blocks (SOM)

2021 QAAMMAT PAVIION

Adhesively bonded soda lime glass blocks arranged in a curved fashion. Designed and developed by Konstantin Arkitekter, TU Delft & Dow for the Unesco site in Greenland



Crystal House, Amsterdam (Archdaily)

Figure 03.1: Glass Block evolution Timeline

03.2

HOLLOW GLASS BLOCKS

Hollow glass blocks are two U-shaped sections of glass that are pressed in metal mould and then sealed together by creating a cavity in between. The cavity in between these two glass panels acts similar to a double glazed glass panel in such a way that it provides good resistance to sound and heat. Therefore these panels are energy efficient. Due to multiple layers of glass panels, these hollow blocks have fascinating responses to natural as well as artificial light. The product offers a great range of thicknesses, sizes and transparency levels depending on the block's pattern and thickness. The multiple layers of glass result in a severe distortion of the objects behind them. The main aim of this product is to invite the daylight inside and provide optimal thermal and sound resistance.

Characteristics

1. Thermal and acoustic insulation
2. Transparent but with optical distortion
3. Non-load bearing, require a substructure for support
4. Produced by casting in press mould and then sealing the 2 halves together
5. The cavity can be filled with air or inert gases (not a standardised process, but still possible)
6. Good fire rating due to presence of cavity
7. Permanent connection system (reinforcement rods and mortar)
8. Available in various patterns, thickness and sizes
9. Not easily replaceable if the single block is cracked

Manufacturing Process

Material Composition: Sand, soda ash & limestone. Recycled glass pieces called cullets are also mixed.

- The raw materials are mixed with the help of a computerised system which portions out each and feeds them into the melter. The batch of ingredients is heated at 1500°c which results in molten glass. The melter pumps out enough molten glass to one half block at a time. With the help of automated sheers (sharp tool to cut off the molten glass) the required quantity is sliced off. This gob of the molten glass is poured into a waiting mould. The plunger (pressing surface made of metal that is usually patterned in the required design) pushes the gob down spreading the molten glass throughout the mould cavity.The plunger surface has various patterns that can be changed based on the glass block design (waffle, tubed, flat). Even distribution is the key so that there is no gap or air bubble inside the gob while shaping in the mould.
- The glass pipes overhead blast ambient air that cools down the molten glass drastically from 1000°c to 600°c in just a few seconds. The retractable arm extracts them from the mould and lays them on a conveyor belt so that they do not lose their shape.
- The two halves are then joined together to form a complete block. The edges are reheated and fused together by pressing in a squeeze station using automated arms. Each piece passes over a series of burners to keep the glass temperature constant. Sudden cooling may crack the glass. The shape of the block changes here.
- Each block now travels into a layer of an oven that cools the glass at regulated temperatures over several hours. This annealing process prevents cracking and allows the glass time to set properly. The glass temperature going in is around 1000°c and while coming out it is around 80°c.
- The blocks are then inspected by a digital alignment tool to check if the two halves are properly flushed. Then the blocks are also checked for distortion in overall thickness. The size and shape is precisely checked.
- Building with glass blocks is similar to building with mud bricks. They are assembled together with mortar. To prepare the glass blocks for mortaring they are placed onto a separate station. Here the blocks are rotated in horizontal direction and the nozzles spray the edges with liquid vinyl. This coating allows the mortar to stick to the glass surface Random blocks are then chosen from a lot for various load testing.

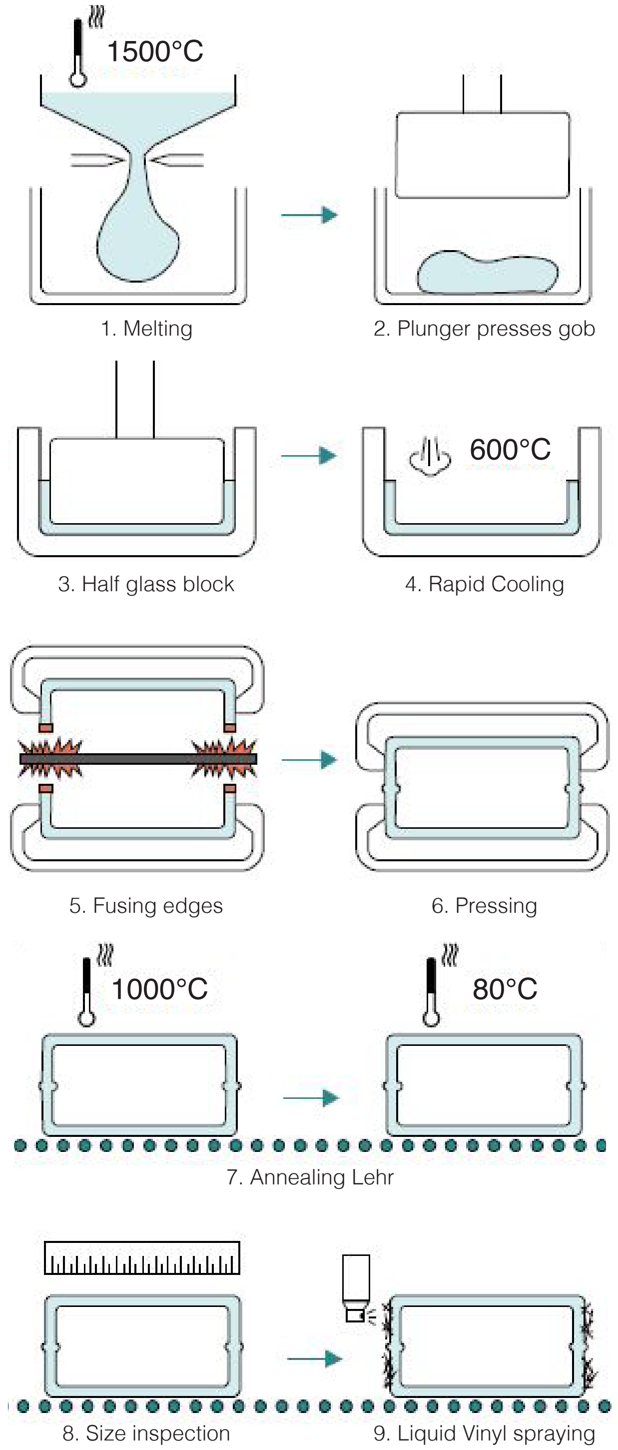


Figure 03.2: Hollow glass block production method (Velden. M, 2020)

Installation Process

The hollow glass blocks are non load-bearing owing to the presence of cavity and thinner glass wall and therefore require a metal substructure to hold the system together. The installation process is similar to mud brick brick construction by using mortar, however, since the hollow glass blocks are brittle they require additional reinforcement in between them. Therefore there are two main components i.e. block structure and bearing structure. Both these components should not come in contact with each other as they need to accommodate the expansion and contraction. The installation process consists of 3 stages;

Preliminary stage

The opening sizes are initially checked for any discrepancies by using rod and measure calculator and ensured that the sizes are as per design. The openings should always be level and square to avoid discrepancies during installation.

- The silicone is then applied to both the jamb and the head. Similar process is followed for the expansion strip that is being held by the silicone.

Installation Stage

- As per the instructions 1 litre of water and 5kg of mortar is mixed in a bucket using a trowel tool. A bed of the vetro mortar is applied over the sill or base surface.
- Starting from either bottom corner the first glass block is placed over the bed by assembling the L and T shaped spacers. The tight is slid against the jamb on the top corner of the glass block. The mortar is applied to the side of the first block. Another T shaped spacer is layed and the next glass block with pre applied mortar on the side is slid in between. The block tight is slid against the top junction of both the blocks.
- A reinforcement rod is vertically inserted in the mortar and ensured that it is straight and levelled. The spacers should always be placed clear to the rod and the block. The similar process is continued until the first course is

03.2

HOLLOW GLASS BLOCKS

finished by ensuring that the mortar fills the joint, spacers are surrounding blocks, rods are straight and the perimeter joint is not filled with mortar.

- The next course is started by laying a bed of mortar on the first course. Holes are drilled in the jambs just above the mortar edge to screw the glass blocks ties. A reinforcement rod is spanned horizontally across the top of ties and covered with another bed of mortar. The next corner glass block is placed over the spacer and tapped down to ensure the joint is filled. The similar process is continued for each course thereafter ensuring each glass block sits on the level of the spacer and uses the spacer support to hold in place. The perimeter is always kept mortar free.
- On the final course L and T shaped spacers are drilled in the jambs and screwed with ties. The glass blocks are slid into these spacers and the mortar is filled in between. The perimeter is left without the mortar to allow expansion.
- The wall is now allowed to dry for 24 hours.

Finishing Stage

- The protruding parts of the spacers are twisted off and removed from the wall. The mixture of veteran altar to the required consistency is prepared and applied to the face of the wall as a grout with a rubber float. Make sure that the glass is not scratched and the perimeter joints are not filled. The excessive grout is removed from the wall using a sponge. The grouting is now allowed to dry for 24 hours.
- The perimeters are sealed off with the silicone to completely watertight the wall.

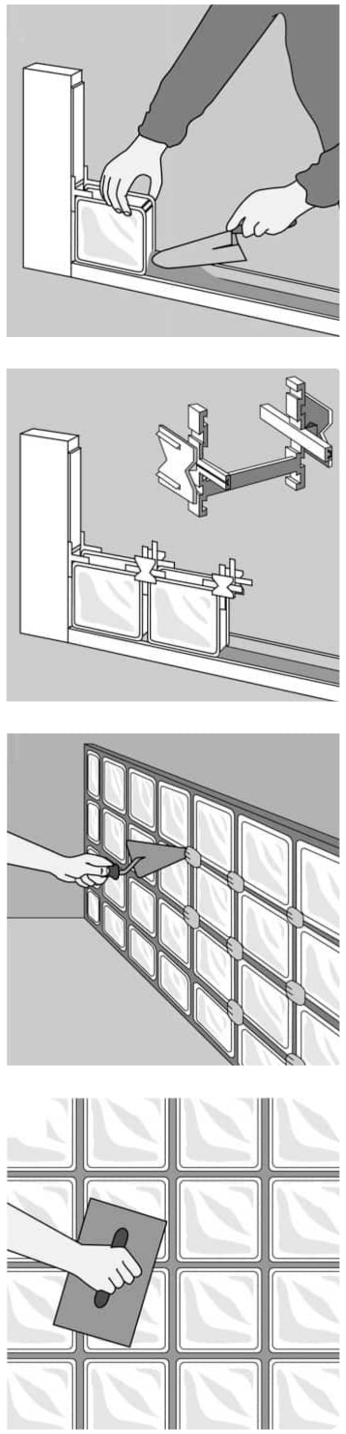


Figure 03.3: Installation of Hollow Glass blocks [(Seves)]

Properties

Hollow glass blocks are widely used in architecture due to their distinctive properties, which are discussed in detail below.

- **Lower heat gain**

They have good thermal resistance due to the presence of cavities. The U-Value of a standard hollow glass block with a clear surface is 2.55 W/m2K (Pittsburgh Corning). The solar reflective units, which are coated with heat bonded oxide, can reduce solar heat gain by up to 80%. The glass fibre insets can further reduce heat gain up to 5%. (Nathani. T, 2021)

- **Light Transmission**

When light rays pass through multiple media in a hollow glass block, the distortion is much greater than in a solid glass block. The patterned blocks provide indoor visual privacy by bringing in as much natural light as possible. Glass fibre insets in the units reduce glare and brightness. (Nathani. T, 2021)

- **Sound, Fire and condensation**

The presence of cavity enhances the sound and fire insulation of the hollow glass blocks. A wall made of 100mm thick hollow blocks can reduce the sound transmission by 40dB with an STC rating of 43-50. The standard hollow glass block has a fire rating of Euro class A1 or 45-minute UL. There is no issue of condensation as the blocks are fused properly through industrial processes. (Nathani. T, 2021)

Figure 03.4: Hollow glass blocks (Falconnier. G, 1886)

Figure 03.5: Hollow glass blocks (Falconnier. G, 1886)

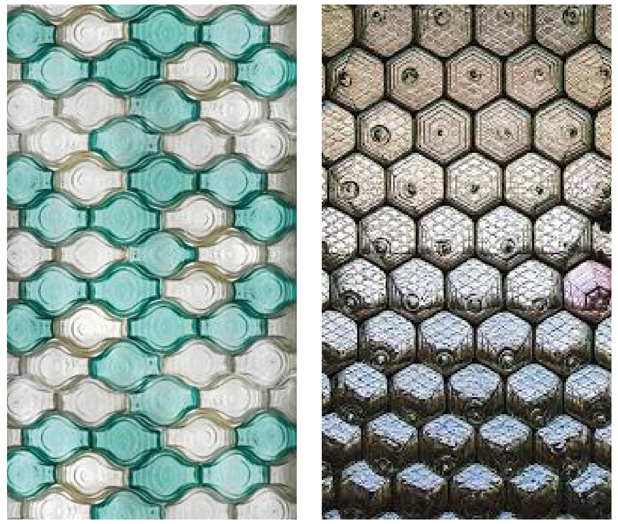


Figure 03.6: Hollow glass blocks (Falconnier. G, 1886)

03.3

SOLID GLASS BLOCKS

The primary goal of developing solid glass blocks was to maximise the structural potential of glass by removing the need for additional substructures. These blocks are made using the casting method, in which molten glass is poured into a mould of the desired geometry. Because these blocks are monolithic, they have high compressive strength and can withstand loads of more than 200MPa. The absence of cavities, on the other hand, results in thermal bridges and poor thermal insulation. Solid glass blocks have less optical distortion than hollow glass blocks but do not provide visual privacy.

Characteristics

1. They are load-bearing and have high compressive strength (more than 200MPa)
2. Poor thermal and sound performance due to absence of cavity
3. Transparent due to less optical distortion. Not suitable for visual privacy
4. Can be cast into desired shape and size
5. No additional substructure required
6. Manual assembly system
7. Easy to maintain
8. The adhesives based connection are not reversible

Manufacturing Process

The solid blocks are manufactured by the casting process. Glass casting is a complex process that must be carried out intricately. Any imperfection in the process can lead to the inhomogeneous distribution of stress that may even lead to failure due to cracking. The manufacturing process is divided into five stages:

- **Mould preparation**

Based on the desired shape and volume the mould is prepared by using a material with high heat resistance (like plaster). Since solid blocks require precise geometry, an open metal or prestressed metal mould is used.

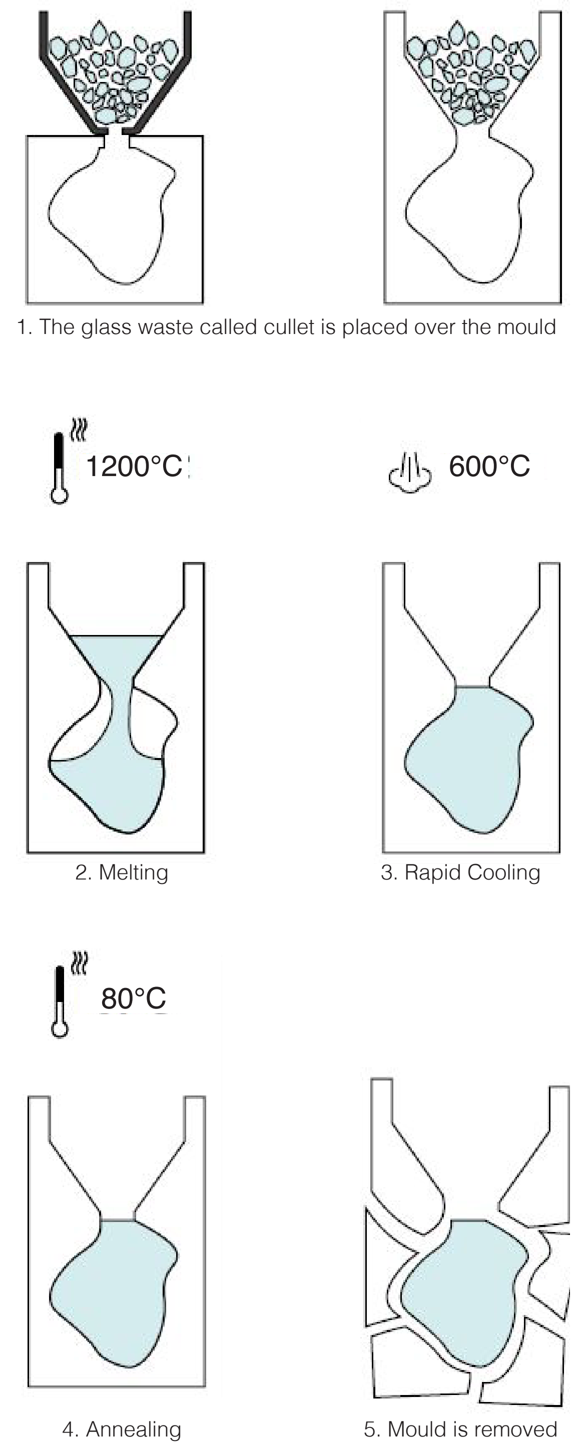


Figure 03.7: Solid glass block production method (Casting) (Velden, M, 2020)

- **Melting & Pouring**

The glass pieces or the raw materials are mixed and heated to around 1200°c. At this temperature, the molten glass is formed which is viscous enough to cast into the desired shape. The molten glass is poured over the mould, which takes the whole volume inside which is further fired in the furnace.

- **Rapid cooling**

During kiln casting the temperature inside the furnace is rapidly reduced so as to avoid temperatures within the crystallisation region to form an amorphous structure. When the temperature of the glass reaches its softening point, it becomes hard enough to retain its shape and not deform under its own weight. In case of hot pour casting the temperature is rapidly reduced outside the mould.

- **Annealing**

The time required for the annealing process depends on the size (more importantly the thickness). This process is crucial as it eliminates the formation of internal residual stresses during the cooling process. During the casting and demolding process differential strain builds up which can be eliminated through annealing.

- **Refinement**

The casted glass is taken out of the mould and the excess overflow is sawn off. In an industrial process there is no excess overflow but due to shrinkage post processing may be required depending on the required accuracy. For eg. in Atocha Memorial where borosilicate glass and press moulds were used there was no need for post-processing, the selected adhesives could accommodate the resulting size deviations. Any defects or imperfections in the glass blocks are sanded out to achieve a smooth and transparent end product. (Oikonomopoulou et. al., 2014)

Installation Process

For solid blocks, no specific installation method has been identified. The installation system is determined by the project requirements. There are three different installation methods based on the options investigated:

With a metal substructure: Optical House, Japan

This installation method is appropriate when the glass blocks only need to perform under compression. The metal substructure is responsible for carrying all tensile forces by providing the necessary stiffness and buckling resistance. The solid glass blocks have holes through which pre-tensioned metal rods pass, absorbing lateral forces and providing a high slenderness ratio. The mesh is held up by a steel beam encased in reinforced concrete. Because the assembly system is completely dry, it is reversible. The deviations are accommodated by the interlayer between the solid blocks. The presence of a metal substructure reduces the overall system’s transparency.

Interlocking units: On-going research, TuDelft

This installation method is effective for a dry assembly system that is completely reusable and recyclable. The solid glass blocks are designed in such a way that they interlock with one another to form an interlocking geometry. The self-weight of the blocks holds them in place and absorbs compression, while the interlocking geometry restricts lateral movement. To prevent friction between two solid blocks, a dry, colourless interlayer (such as PU or PVC) is placed between the surfaces, preventing stress concentration and compensating for dimensional tolerances. This is still a new concept and many interesting interlocking geometries are made by the Glass research group in TuDelft.

03.3

SOLID GLASS BLOCKS

Adhesively bonded brick: Crystal House, Qaammat Pavilion, Atocha Memorial & Lighvault
When complete transparency is required, this installation process is used. The adhesives must form a homogeneous bond with the solid glass blocks so that they perform as a monolithic block when loaded. The mechanical properties of adhesives have a significant impact on structural performance. The most prevalently used adhesives, such as acrylates and epoxies, are used because they can form the highest bond strength with the glass blocks. To ensure maximum transparency, very fine tolerances are allowed, requiring a high precision casting production process.

The Crystal house in Amsterdam is one such project where solid glass blocks are bonded together with high strength, colourless, UV-curing, single component acrylate adhesive named Delo Photobond 4468. Initial mockups suggested that an optimum bonding strength of 0.2-0.3mm and tolerances of 0.25-0.5mm be used. Higher tolerances have an impact on structural performance because they imply that the adhesives are applied unevenly. To achieve a high level of accuracy and transparency, soda-lime glass was used with a high-precision open metal mould. This significantly reduced the production costs as post-processing was required. (Oikonomopoulou. F, 2019)

The installation process consists of three stages:

Preliminary stage

- The opening sizes are initially checked for any discrepancies and ensured that the sizes are as per design. The openings should always be level and square to avoid discrepancies during installation.
- During the installation phase, vertical and horizontal guides are laid to support the assembly.

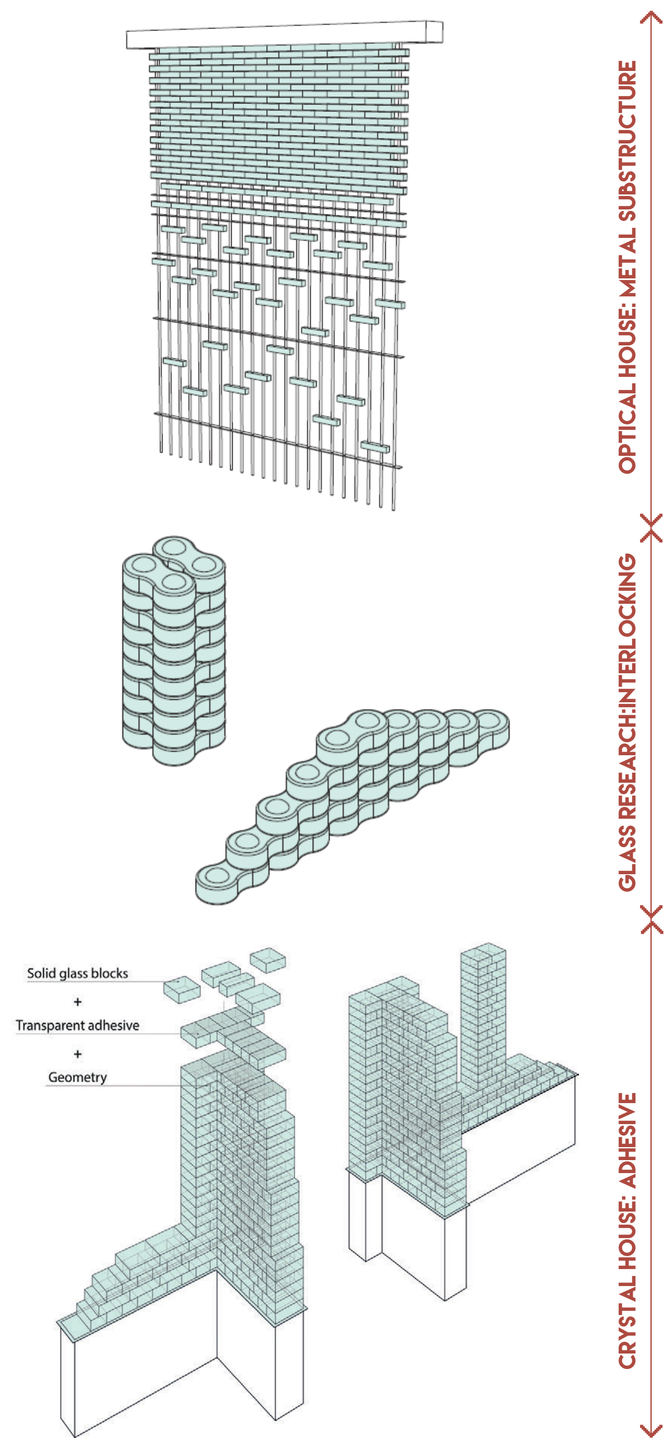


Figure 03.8: Solid glass block Installation methods
(Oikonomopoulou. F, 2019)

Installation stage

- There is no standard process of installation as the application of solid glass blocks is fairly new. The project and architectural vision dictate the type of connection system. Anyone from the metal substructure, adhesive bond, or interlocking system can be used.
- The general process will be similar to brick masonry where the blocks are stacked on each other course by course and an intermediate interlayer or adhesive is applied before placement.

Finishing stage

- Any additional protruding adhesive layer is scraped out (this is not possible in all cases as high precision is required for installation)
- The glass surface and joints are cleaned and the edges are sealed with silicone.

Properties
The use of solid glass blocks in architecture is relatively new. They are currently available in a few standard designs, but they will be used more frequently in the future due to the following distinctive properties:

- **High Compressive Strength**

Solid glass blocks have a very high compressive strength in the range of 300 to 400MPa as they are monolithic(Pittsburgh Corning). They can be used as load bearing blocks. (Nathani. T, 2021)

- **Light Transmission**

Solid glass blocks are completely transparent. When light passes through it there is no distortion as they are monolithic and do not have any cavities. (Nathani. T, 2021)

- **Sound, Fire and Condensation**

Due to thicker cross-section the solid blocks have good resistance to sound with the STC rating in between 43-53. They also perform well in case of fire and condensation.

Figure 03.9: Interlocking cast glass geometries
(Oikonomopoulou. F, 2019)

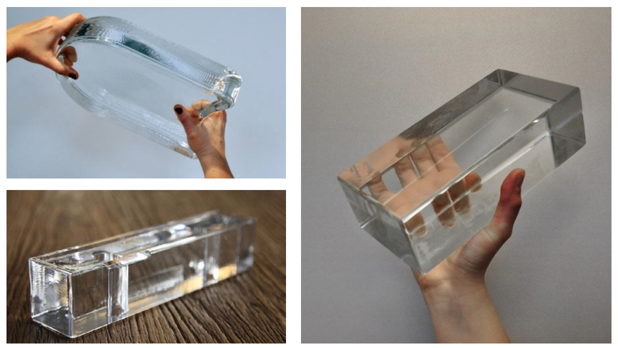


Figure 03.10: (Atocha Memorial 2007) , (Optical House 2012)
(Oikonomopoulou. F, 2019)

03.4

HYBRID GLASS BLOCKS

The Hybrid glass block is a novel product that is developed by a combination of solid glass block and hollow glass. The product shows promising thermal insulation and load bearing capacity. The exploration of various cavity widths and cross-section thickness was done by (Nathani. T, 2021) (Velden. M, 2020). The research findings are extensively considered for the current research and product development.

Characteristics
1. Good load-bearing capacity (15-20mPa)
2. Thermal insulation and low U-Value (1.5-2.2 W/m2K)
3. Sound insulation (50dB)
4. Fire resistant upto 2 hours
5. Ease in assembly
6. Sustainable- recyclable

Types of Hybrid glass blocks
Based on the above-mentioned characteristics two designs for hybrid glass blocks were developed by (Nathani. T, 2021). The thermal performance of these options was validated through TRISCO software. The results were within the desired range (1.5 - 2.2 W/m2K). The designs show a promising hybrid glass block with the potential to further design, prototype, and validate structural stability.

03.4.1

FUSION BLOCK (NATHANI. T, 2021)

Design
The fusion block is a combination of the hollow glass block and solid glass block. There are two components,
1. Solid: The 80mm thick component is made out of cast glass and is responsible for carrying the compressive loads.
2. Hollow: The 20mm thick component with an air cavity and float glass casing. A 5mm silver coating is applied on the external surface of the cavity to insulate thermally.

The presence of silver coating over the float glass surface makes the hollow glass component irreversible. However, the solid component can be completely recycled.

Connection System
Three different types of connections were explored during the design phase. The intent was to connect the separate components together to form one single block and further align and connect the top block. Connection evaluation criteria: Transparency, load distribution, ease in assembly and reversibility
The chosen connection type is a combination of embedded-bolted systems. There are two components,
1. **Embedded:** A steel insert with tungsten coating is embedded in the top and bottom of the solid glass component. The overlap is always 1/4th so the top block always gets connected over the bottom block.
2. **Bolted:** The hollow glass component is connected to the embedded tungsten insert by a rectangular steel connection through bolting.

To avoid friction between two connections a rubber gasket is placed over the junction. The bolted connection has a thermal break on both sides, as the metal has high conductivity. The outer layer of the facade is composed of small float glass pieces. Sealant is applied in between these glass pieces to make them watertight. The outer layer is made of 5mm thick float glass which can be easily replaced through this bolted connection.

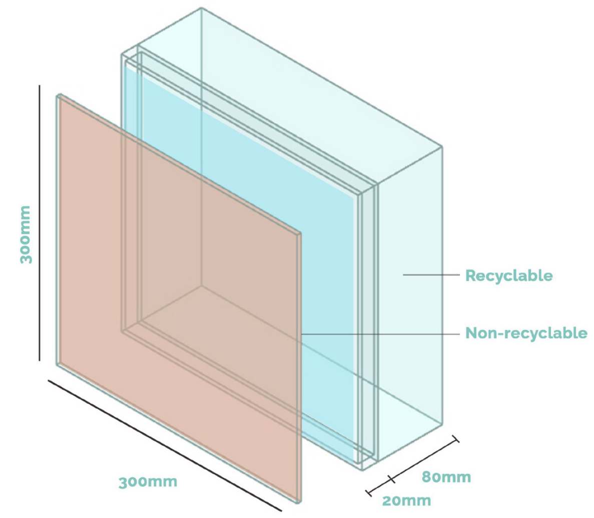
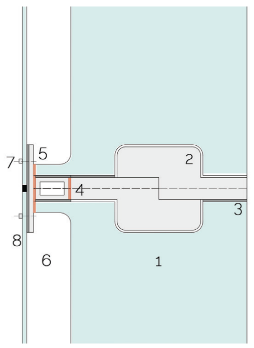
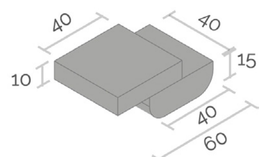


Figure 03.11: Fusion Block Design (Nathani. T, 2021)





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

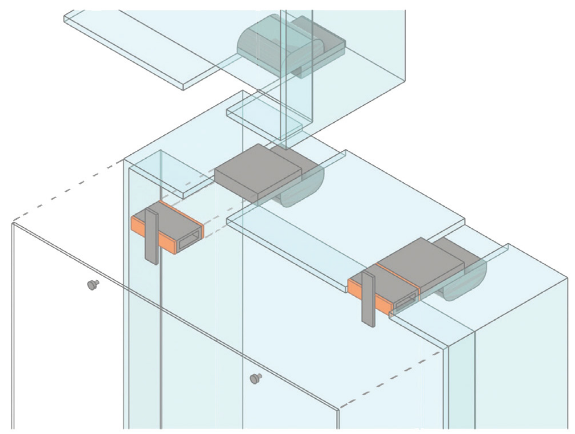


Figure 03.12: Fusion Block Connection (Nathani. T, 2021)

Fabrication
The fabrication method is suggested, however, the blocks were not actually prototyped and there may be certain limitations to this approach. The borosilicate glass is selected for the solid glass component which can be manufactured by the casting process. The flat borosilicate glass can be obtained and cut in the desired shape.
1. **Block Design:** In total there are two different shapes of the block (square-shaped and L-shaped for corbelling detail). The square-shaped block has two different sizes. The L-shaped block is placed on the edges and the combination of these three different types can form six different configurations.
2. **Mould Design:** The solid block which is to be produced through casting has embedded connections. Thus in order to allow these protrusions, a high precision open steel mould will be used. During casting air bubbles are formed and to get rid of those air vents are provided on each surface of the width. The corners are rounded for ease in the annealing process.

The casting and annealing procedures are the same as in the standard process. The metal connections, however, are embedded into the solid block after annealing.

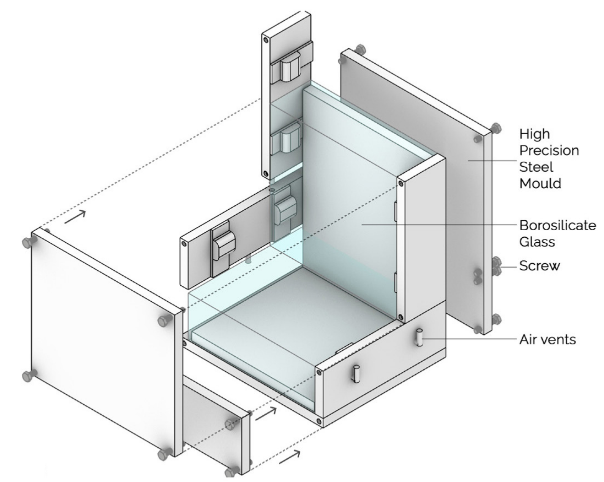


Figure 03.13: Fusion Block L-Shaped Mould Design (Nathani. T, 2021)

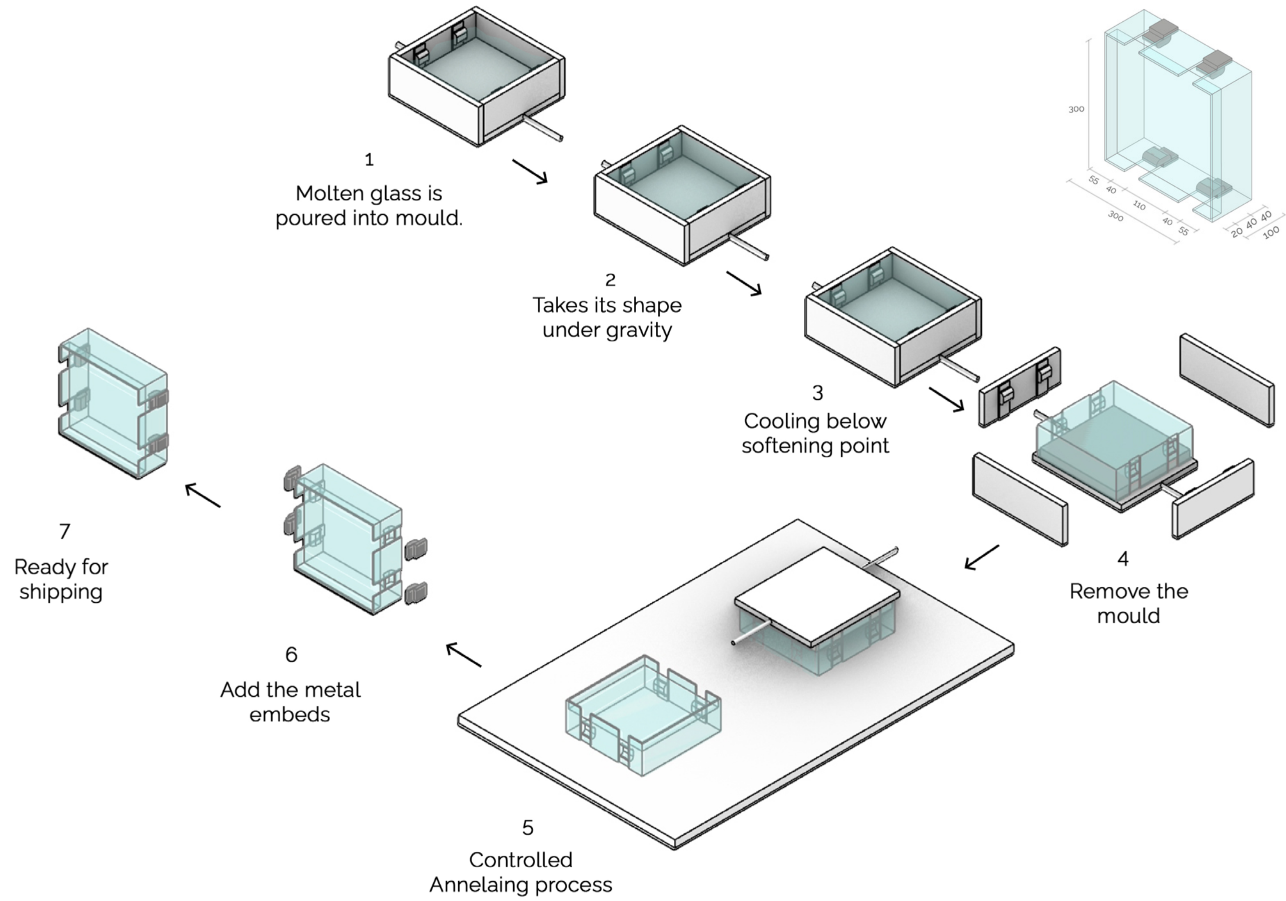


Figure 03.14: Fusion Block, Fabrication Process for square block (Nathani. T, 2021)

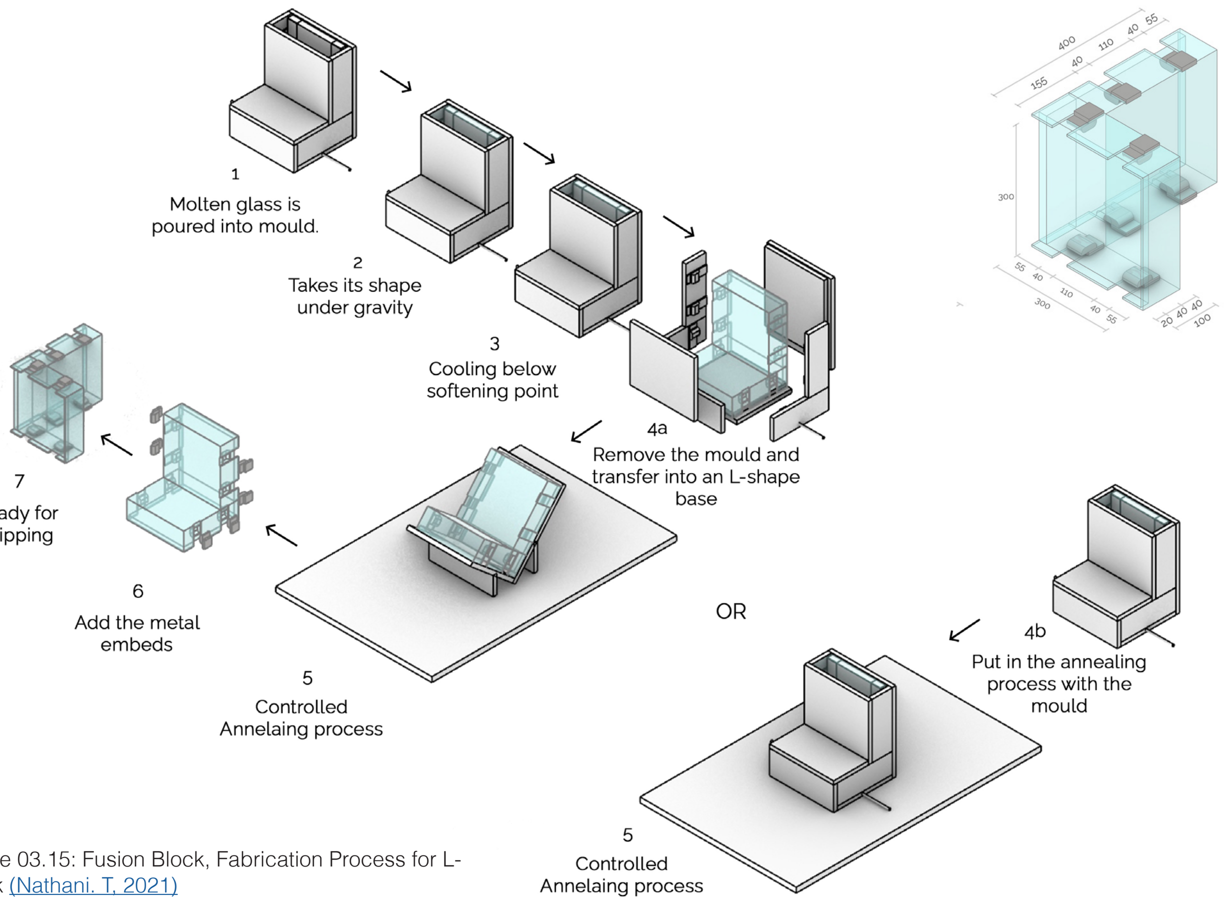


Figure 03.15: Fusion Block, Fabrication Process for L-block (Nathani. T, 2021)

03.4.1

FUSION BLOCK (NATHANI. T, 2021)

Assembly System
Following is the assembly sequence:

1. Bottom Connection:
To align the bottom surface properly a steel plate is placed over the concrete base. In between the steel and base, a non-shrinkage concrete layer is added. The base is ensured to be flat before beginning the assembly process. Small rectangular tungsten blocks similar to the embedded connections are welded on the steel plate. To protect the glass from peak stresses, a soft rubber layer is added between the glass and the steel plate. The glass blocks are now placed over the welded tungsten blocks and bolted together. The first course of solid blocks is completed and the hollow glass component is also simultaneously bolted.

2. Intermediate Floor Connection:
To maximise transparency and get rid of the intermediate frame a steel angle section is bolted to the floor slab. A larger rectangular tungsten block is placed in between the angle section and the solid glass component and bolted together.

3. Top Connection:
Once the final course of the glass block has been completed, the position of the steel frame is aligned in such a way that dimensional tolerances can be accommodated. A rubber layer is introduced to create a thermal bridge between two steel surfaces. The last course of the glass blocks is bolted to the tungsten blocks.

4. Sealing:
Silicone is used to close the air gaps between the glass blocks and the structure to accommodate proper insulation.

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

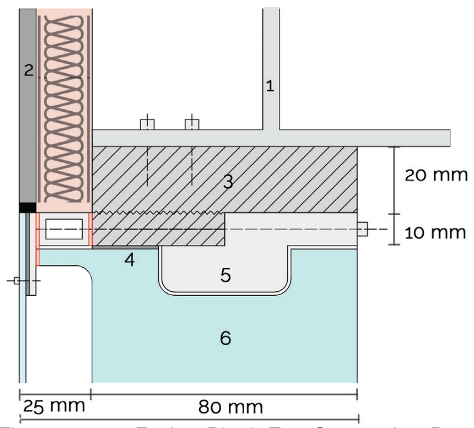


Figure 03.16: Fusion Block Top Connection Detail (Nathani. T, 2021)

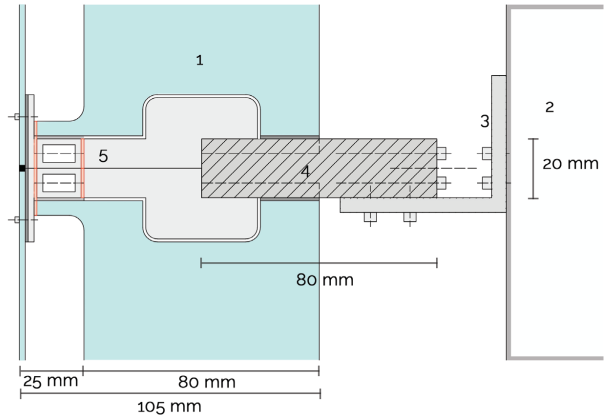


Figure 03.17: Fusion Block Intermediate Connection Detail (Nathani. T, 2021)

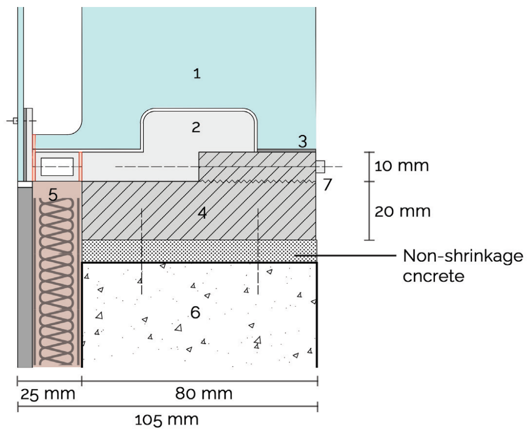


Figure 03.18: Fusion Block Bottom Connection Detail (Nathani. T, 2021)

03.4.2

LATTICE BLOCK (NATHANI. T, 2021)

Design
The lattice block is made up of multiple internal glass partitions that form cavities between them. The design is ideated in such a way that the multiple cavities provide the necessary thermal insulation while the internal partitions increase the glass block's stiffness. Internal partitions can provide alternate load paths in the event of a failure.

There are three components in the lattice block:
1. Outer glass frame of 25mm cross-section
2. Four internal glass partitions of 10mm thickness each
3. Five air cavities of 12mm each

The whole block is reversible and 100% recyclable due to absence of any coating.

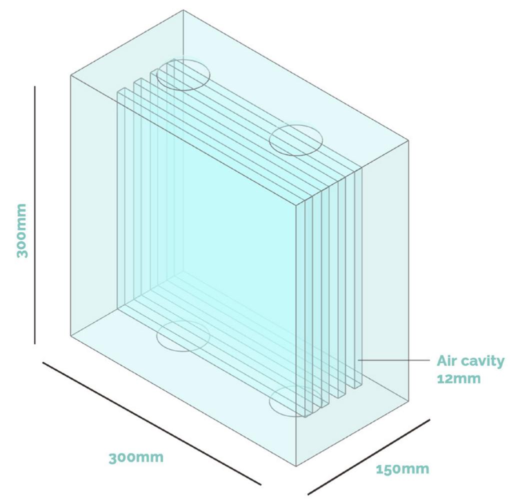
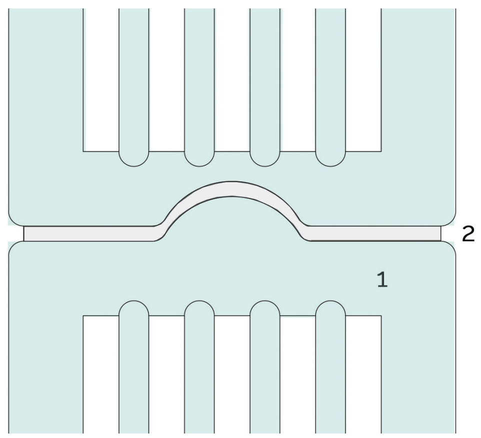


Figure 03.19: Lattice Block Design (Nathani. T, 2021)

Connection System
An interlocking connection system was developed to create a dry assembly system that is both circular and recyclable. During the design phase, three different interlocking types were investigated. The hemispherical interlock was chosen because of its simple mechanism, which is similar to the tongue and groove. The interlock between two glass surfaces is filled with a neoprene interlayer developed by (Dimas. M, 2020). The interlayer is responsible for preventing friction, avoiding stress concentration, and compensating for dimensional tolerances. The self-weight of the blocks holds them in place and absorbs compression, while the interlocking geometry restricts lateral movement.

Connection evaluation criteria: Transparency, load distribution, ease in assembly, and reversibility.



1. Glass block 2. Neoprene interlayer

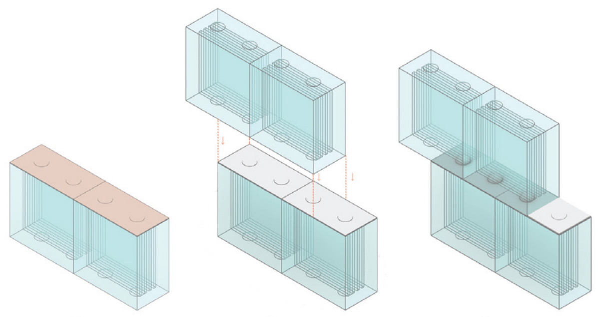


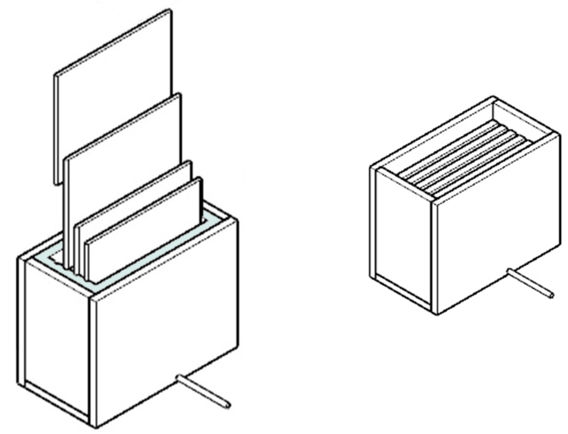
Figure 03.20: Lattice Block Connection (Nathani. T, 2021)

Fabrication
The lattice block can be manufactured in two ways:
- By casting the outer frame as a single piece of borosilicate glass and then inserting float glass partitions. The challenge is to connect the float glass with the borosilicate glass. It can be either fused or glued. Both the processes are labour intensive and time consuming. The presence of glue will influence the recyclability of the glass.
- By casting the entire block with partitions inside mould and keeping one side of the outer frame open. The open frame can be sealed separately. The challenge is to remove the mould easily from the intricate cavities. The mould can be coated with boron nitride, so that the glass is easily removed after casting.

The later method of fabrication is explored
1. **Block Design:**
The lattice block design is similar to standard masonry logic. There are two different sizes of the lattice blocks depending on the edge conditions.

2. **Mould Design:**
A high precision open steel mould will be used. During casting air bubbles are formed and to get rid of those air vents are provided on each surface of the width. The corners are rounded for ease in the annealing process. Two moulds for each lattice block are required, one for the entire block with partitions and another for the top.

The casting and annealing procedures are the same as in the standard process. However, the annealing process is done twice. The second time after sealing the top lid with the entire glass block(just below softening point).



Option A Option B

Figure 03.21: Lattice Block Mould Options (Nathani. T, 2021)

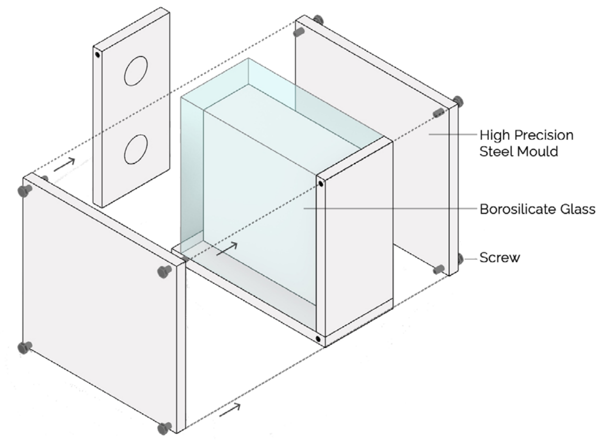


Figure 03.22: Lattice Block Mould Option A (Nathani. T, 2021)

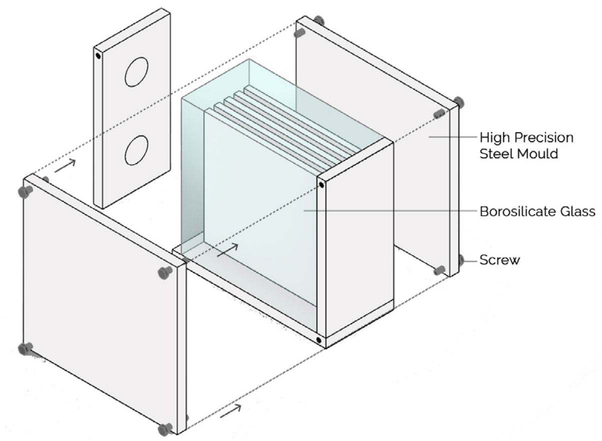


Figure 03.23: Lattice Block Mould Option B (Nathani. T, 2021)

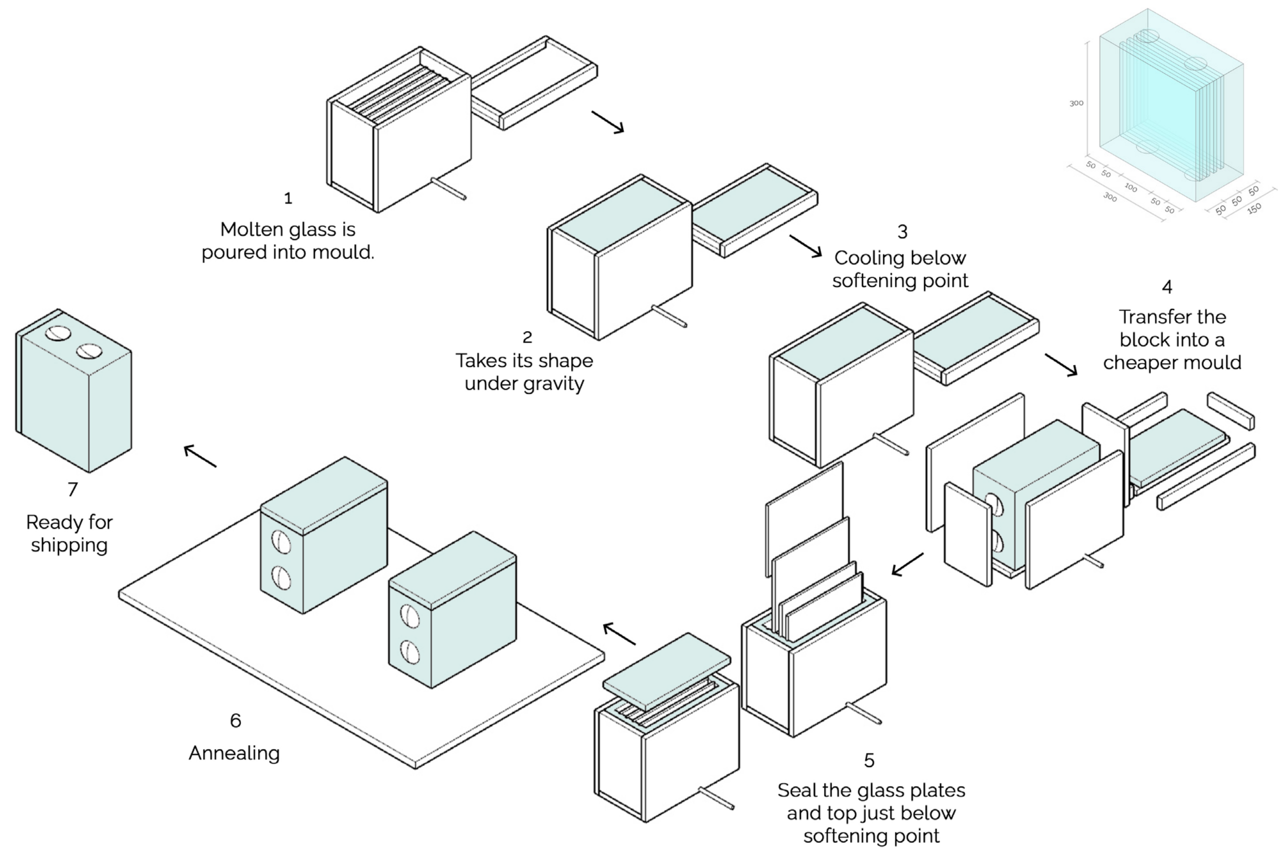


Figure 03.24: Lattice Block, Fabrication Process Option A [(Nathani. T, 2021)](#)

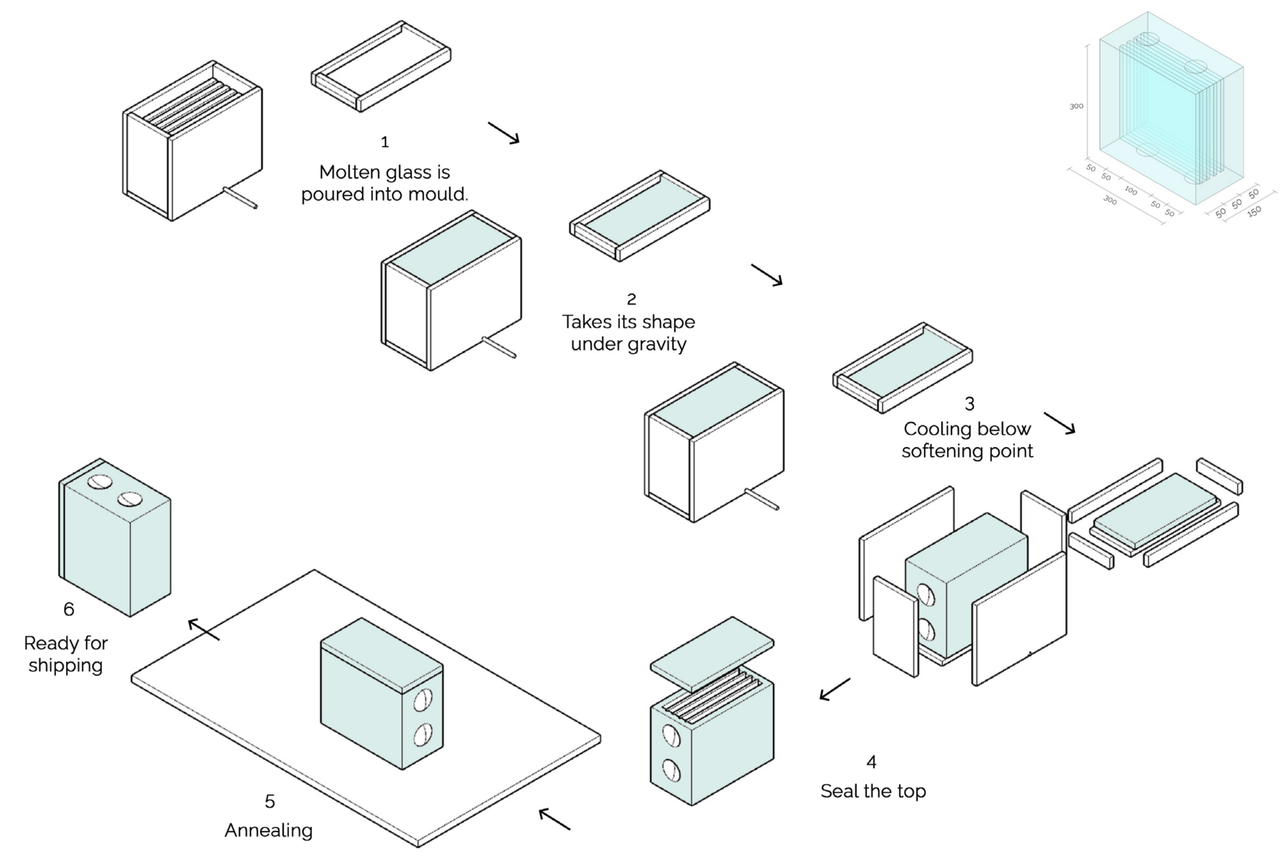


Figure 03.25: Lattice Block, Fabrication Process Option B [(Nathani. T, 2021)](#)

03.4.2

LATTICE BLOCK [(NATHANI. T, 2021)](#)

Assembly System
Following is the assembly sequence:

1. Bottom Connection:
To align the bottom surface properly a steel plate is placed over the concrete base. This steel plate is coated with tungsten and has a hemispherical interlocking face similar to that of the lattice block. In between the steel plate and base, a non-shrinkage concrete layer is added. The first neoprene interlayer is placed over the hemispherical interlocking face of the steel plate and responsible to accommodate dimensional tolerances. The first course of the lattice block is placed and the process is repeated.

2. Intermediate Connection:
The intermediate floor connection is designed in such a way that there is no excess protrusion from the face of the blocks. To accomplish this, the glass blocks are attached to discrete specially milled steel plates with interlocking on both the top and bottom faces, which are then connected to the floor via angle – sections.

3. Top Connection:
Once the final course of the lattice block has been completed, the position of the steel frame (similar to the one placed in the bottom connection) is aligned in such a way that dimensional tolerances can be accommodated.

4. Sealing:
Silicone is used to close the air gaps between the glass blocks and the structure to accommodate proper insulation.

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

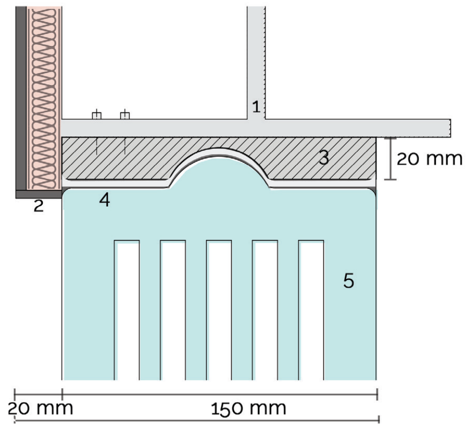


Figure 03.26: Lattice Block Top Connection Detail [(Nathani. T, 2021)](#)

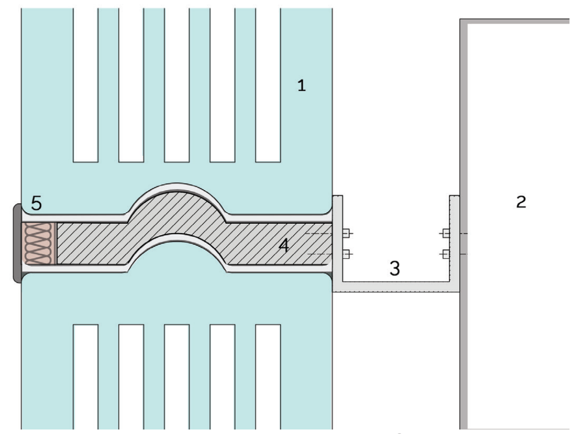


Figure 03.27: Lattice Block Intermediate Connection Detail [(Nathani. T, 2021)](#)

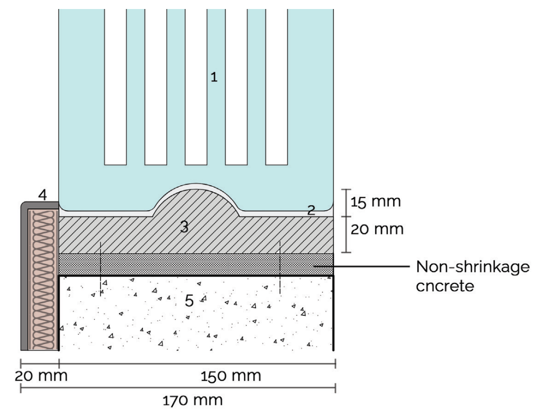


Figure 03.28: Lattice Block Bottom Connection Detail [(Nathani. T, 2021)](#)

03.4.3

INCREASED THERMAL PERFORMANCE OF STRUCTURAL CAST GLASS BRICK WALL (VELDEN. M, 2020)

Another existing research on the subject of the development of hybrid glass blocks is carried out by (Velden. M, 2020) which focused on increasing the thermal performance of the structural cast glass bricks at the unit as well as system level. The research resulted in 7 design outputs on the unit level and 2 design outputs on the system level, which were then further evaluated based on the multi-criteria analysis. On a unit level, an extensive thermal analysis was carried out by using TRISCO software to understand the thermal transmittance of each design. Following are the research findings,

Sustainability of Cast glass and float glass
The issue with laminated float glass is the absence of a sustainable life cycle of the material. A very little recycled cullet is used and the final product is merely downcycled for other usages owing to the presence of coatings, laminations, and other contaminants. Structural cast glass is sustainable if designed wisely, however, poses an issue of thermal performance.

Ways of improving thermal performance
The thermal performance of structural cast glass blocks can be enhanced by adding insulating materials, inert gases, and coatings, but the most simple, inexpensive, and elegant option is to include air cavities. Creating cavities allows for the design and creation of new forms, products, or architectural optimizations. The design of the air cavity may be changed at the system or unit level by modifying the topology of the entire wall or the geometry and cross-section of glass brick. Changing the cavity on a unit level allows for additional design freedom and makes the end product adaptable to numerous system setups. System-level adaptation is more particular to the chosen wall. (Works well in projects with existing wall constraints)

Concerns with air cavities
The more air in the cavity, the greater the glass block's thermal performance. This indicates that cavities with greater thickness and surface area have better heat resistance. The thermal conductivity of the air rises as the overall dimension of the enclosed air rises. Air currents affect convection within the cavities and hence conductivity. Based on the findings of the thermal simulations in TRISCO, it is obvious that the cavity has a significant impact on thermal resistance within the first few millimeters. However, when depth increases, thermal resistance stays constant after a certain point. Multiple air chamber designs will introduce thermal bridges (through the glass), hence continuous glass geometries should be discouraged. However, because a continuous cross-section is vital for structural performance, a compromise between these two approaches is essential. Based on these considerations, the chess and shard brick is intended to extend the heat travel route while maintaining structural integrity. These designs may not be suitable in situations where transparency is critical.

Ways to enhance structural performance
The designed blocks have a combination of float and cast glass components that must be joined to generate cavities without compromising structural integrity. The easiest method is to glue these components together. However, this is not an ideal option since it causes thermal bridges and contamination of the cast glass, making it unsuitable for recycling. Fusing or tack fusing is an alternative approach in which the connection is made at a temperature lower than that of actual fusing and glass nonetheless forms a permanent bond without relaxation or geometric deformation. The shear strength of fusing was determined to examine the critical strength of such tack-fused blocks. Two different series of samples were tack fused at 650°C and one series of glued samples (Delo 4468) was considered. The dirt is trapped in the bubbles, which are imperfections in all of the samples, according to the results of this investigation. DELO creates inaccuracies in the application of adhesive thickness due to its broader spread. The shear strength of the 3 samples are,
Delo 4468 - 11.67 MPa
2 samples - 5.96 MPa & 6.35 MPa

OVERVIEW OF DESIGNS

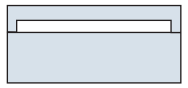
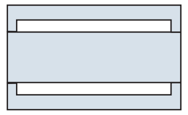
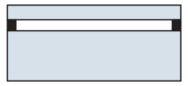
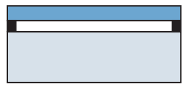
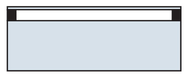
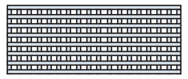
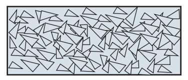
Prototype	Cavity Width	U-Value (W/m2k)	Thermal Performance rating (4)	Sustainability rating (3)	Producibility rating (2)	Aesthetical potential rating (2)	**Total rating**
 Single cavity	10	2.66	0.09	0.68	0.55	0.68	**5.76**
	20	2.54	0.13	0.75	0.55	0.68	**6.14**
	30	2.47	0.15	0.77	0.55	0.68	**6.29**
 Double cavity	5-5	2.66	0.11	0.74	0.30	0.50	**5.04**
	10-10	2.54	0.17	0.75	0.30	0.50	**5.31**
	15-15	2.47	0.20	0.77	0.30	0.50	**5.50**
 Single cavity with spacers	10	1.97	0.32	0.57	0.60	0.38	**5.79**
 Float glass with spacers	10	1.97	0.32	0.41	0.55	0.38	**5.21**
 Thin glass	10	1.97	0.09	0.40	0.40	0.55	**4.29**
 Chess		2.5	0.12	0.77	0.15	0.85	**5.63**
		2.44	0.16	0.81	0.15	0.85	**5.82**
 Shards		1.97	0.37	1	0.30	1	**7.08**
 Double wall	50	1.61	0.45	0.55	0.65	0.63	**6.90**
 Secondary float glass	50	1.75	0.40	0.27	0.75	0.55	**5.91**

Table 03.1: Figure showing analysis of all the design configurations and their performance raitings (Velden. M, 2020)

COMPARITIVE ANALYSIS OF GLASS BLOCKS

	GLASS BLOCK TYPE	HOLLOW GLASS BLOCK	SOLID GLASS BLOCK			HYBRID GLASS BLOCK	STRUCTURAL CAST GLASS
		Seves (HTI WAVE) & Pittsburgh Corning (Thickset 90 VUE)	Seves (VISTABRICK) & Pittsburgh Corning (VISTABRICK)			Developed by Natahani. T	Developed by Velden. M
PROPERTIES	(A) U- VALUE	1.8 - 2.5 [W/m2K]	4.1 - 4.9 [W/m2K]			1.65 - 2.20 [W/m2K]	1.61 - 2.66 [W/m2K]
	(B) COMPRESSIVE STRENGTH	3 - 6 [MPa]	82 - 400 [MPa]			15 - 20 [MPa]	-
	(C) LIGHT TRANSMISSION	70 - 76 [%]	60 - 90 [%]			-	-
	(D) SHGC	0.32 - 0.68	0.52 - 0.78			-	-
	(E) SOUND INSULATION	43 - 50 [STC]	43 - 50 [STC]			-	-
			CRYSTAL HOUSE	ATOCHA MEMORIAL	OPTICAL HOUSE	FUSION BLOCK	LATTICE BLOCK
PRODUCTION METHOD	(E) PROCESS	Casting, Fusing and Annealing	Casting	Casting	Casting	Casting	Casting
	(F) GLASS TYPE	Soda Lime	Soda Lime	Borosilicate	Borosilicate	Borosilicate	Borosislicate
	(G) MOULD USED	Pressed Steel Mould	Open Steel	Pressed Steel	Pressed Steel	Open high precision	Open high precision
	(H) ANNEALING TIME	Unknown	8 - 38 [hr]	20 [hr]	Unknown	more than 20 [hr]	more than 20 [hr]
	(I) BLOCK WEIGHT	2.7 - 3.7 [Kgs]	3.6- 7.2 [Kgs]	8.4 [Kgs]	Unknown	16 [Kgs]	16 [Kgs]
CONSTRUCTIBILITY	(J) SYSTEM	Metal substructure with mortar	Adhesive bonded	Adhesive bonded	Metal substructure	Embedded + Bolted	Interlocking
	(K) LOAD DISTRIBUTION	Not-load bearing. Forces are carried by a metal substructure	Homogeneous load transfer via rigid adhesive	Homogeneous load transfer via rigid adhesive	Tensile forces are carried by a metal substructure	Load bearing. In-plane forces are carried by the glass block & lateral forces (e.g. wind load) is transferred with the help of metal embed.	Load bearing. Homogenous load transfer with interlayer.
	(L) CONNECTION SYSTEM	Blocks are connected through mortar/adhesives	UV- Cured adhesive	Interlayer	Interlayer	Metal Embeds	Interlayer
	(M) ASSEMBLY SYSTEM	Adhesively bonded (mortar)	Adhesive bond	Dry Assembly	Dry Assembly	Embedded + Bolted	Dry Assembly
	(N) TRANSPARENCY	Compromised transparency	High Transparency	High Transparency	Compromised	High Transparency	High Transparency
	(O) REVERSIBILITY	Non-reversible	Non-reversible	Reversible	Reversible	Reversible	Reversible

Table 03.2 Comparitive Study of all the blocks adapted from (Oikonomopoulou. F, 2019) (Nathani. T, 2021) (Velden. M, 2020)

O3.5

CONCLUSIONS & DISCUSSIONS

Glass block technology has advanced significantly over the last two decades. Glass's true potential as a load-bearing material in the building industry is revealed. However, it is too soon to replace glass with traditional masonry because it presents some production and assembly challenges.

Size, shape and weight
Based on existing applications of glass blocks and developed concepts, it is clear that the shape, size and weight of these blocks have a significant impact on facade performance, manufacturing methodology, and assembly system. A minor change in design can have a significant impact on subsequent processes. Because the hybrid block system is a new concept, the relationships between these aspects must be understood and drawn out.

In the designs developed by (Nathani. T, 2021), the shape and size of the hybrid glass blocks were not explored as the architectural vision was to keep it similar to the existing system. As a result, an energy-efficient and load-bearing glass block was created, with a corresponding increase in self-weight (16kgs). This increase in self-weight raises concerns about manual handling on the job site during facade assembly. To accommodate these heavy loads, an embedded metal connection system was developed, which adds an extra process during the production process.

In a fusion block, a combination of the embedded-bolted connection system is designed to connect the two glass components, which results in a complex on-site assembly, but in terms of maintenance and replaceability, it performs well. The casting of the glass for the lattice block is a time-consuming process because it must be annealed twice to seal the top panel. The edges of these hybrid blocks were rounded off to ensure that the annealing process takes as little time as possible. However, due to a lack of actual prototyping, these are design concepts that only work in theory.

There are no specific limitations or guidelines set for the size and shape of the hybrid glass blocks, which makes it possible for the exploration of many options and the determination of the most optimal one.

Desired Optical Properties
Both the hollow and solid glass blocks have similar light transmission properties; however, the hollow glass block has more optical distortion due to the presence of the cavity. Depending on the architectural vision, this optical distortion provides visual privacy that may or may not be required. Nevertheless, the substructure in hollow glass blocks creates division in the facade, resulting in a non-monolithic design. On the other hand, the installation method for solid glass blocks defines the desired transparency level. The adhesive and interlayer connections are the most promising solutions for increasing transparency among the three suggested installation methods.

Before detailing these glass blocks, it is critical to establish a design vision. It will provide a better middle ground for designs where transparency is the most desired evaluation criterion.

Connection & Assembly system
The most promising solutions for the development of hybrid glass blocks are adhesively bonded and interlocking connections. This is because they have the highest levels of transparency in the facade. For ease of assembly, the interlocking connection with the dry assembly system is preferable. It reduces assembly complexity by connecting the glass blocks with an in-between interlayer made of colourless material (such as PU or PVC), making the system completely reversible and recyclable.

The challenge for the hybrid glass block would be the connection of the cast glass with a float glass component. These components can be glued or fused. Glueing can cause inconsistencies and contaminate glass surfaces, reducing their recyclability. They can also be tack-fused as suggested by (Velden. M, 2020)

Production Methodology
The hollow glass blocks have been in the building industry since the mid 20th Century, an automated and standardised process was developed for its production. On the other hand, solid glass blocks which are relatively new are produced by casting methods. This method allows for a great deal of flexibility in the production of solid glass blocks of various shapes and sizes. However, when high precision and mass production of glass blocks are required, the method becomes tedious and time-consuming.

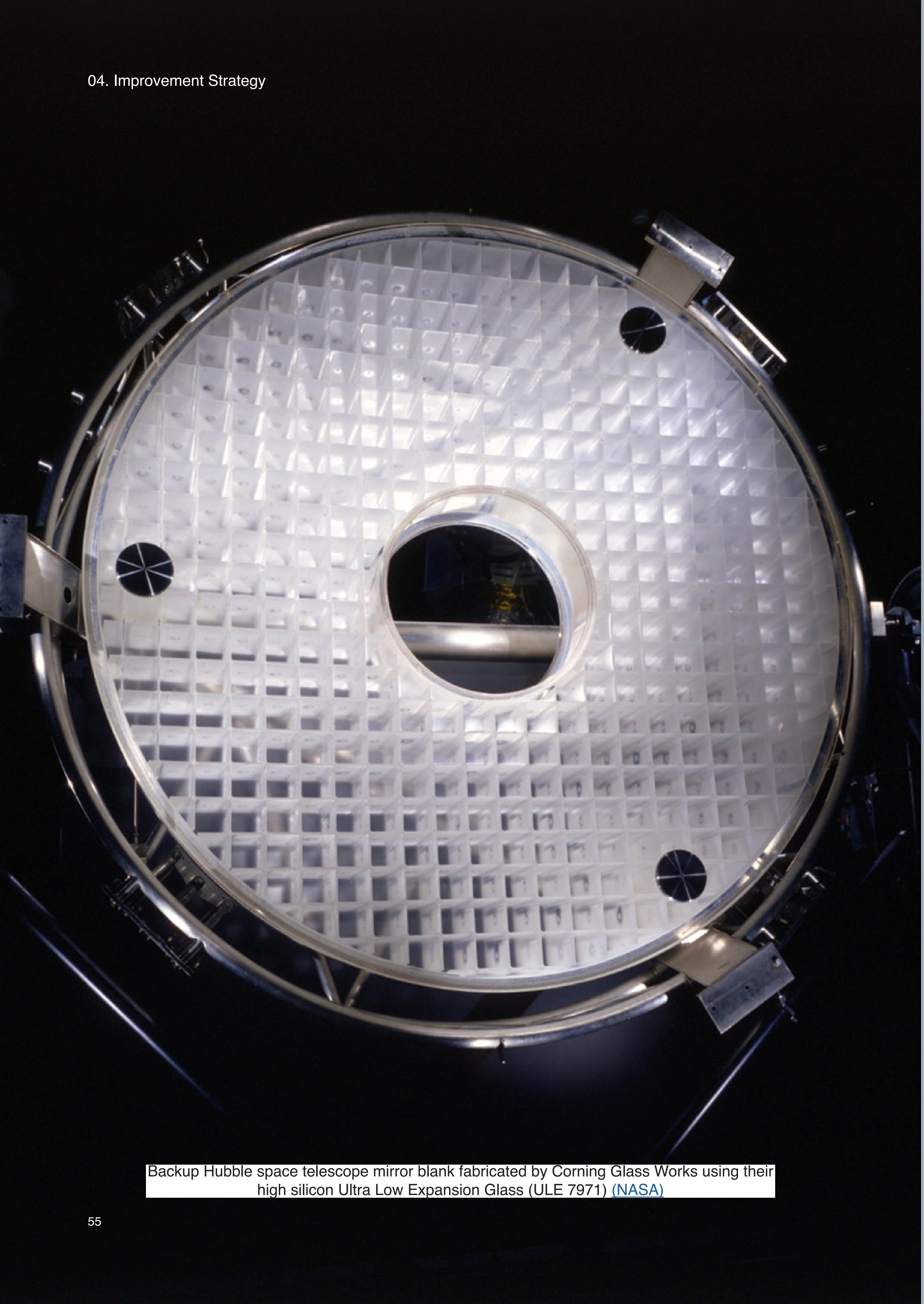
For this research casting method of production is considered as it provides an opportunity to explore various geometries. However, the intent will be to reduce the complexity of the whole process. This can be intervened through mould design and material selection, reducing annealing time by limiting the cross-section and rounding off the edges.

The firing schedule used within a kiln to produce cast glass is determined by the size, form, and, most crucially, thickness of the cross-section. The bonding between two tack-fused connections is temperature-dependent. Longer dwelling time should be explored to increase the strength of the tack fused connection; however, this may result in shape inaccuracies owing to sagging. As a result, each design requires a unique firing schedule that is determined by the form and cross-section thickness. (Velden. M, 2020)

Since the hybrid glass blocks have never been prototyped physically, all the processes in the casting method would be carefully studied. The number of blocks required, the volume and geometry of the block, and the type of mould used are all important factors that influence the production method.

Design Criteria and Practicality
From the overall discussion, it is evident that the shape, size, weight, thermal properties, compressive strength, transparency, and safety are all important criteria for designing the hybrid glass block. As this research aims at exploring various shape options, it is crucial to establish some standard benchmarks for the aforementioned criteria.

To validate the hybrid glass block design a realistic approach and mindset are important. For this purpose, a case study can be selected which will define some boundary conditions and create a design vision.



Backup Hubble space telescope mirror blank fabricated by Corning Glass Works using their high silicon Ultra Low Expansion Glass (ULE 7971) (NASA)

04.

IMPROVEMENT STRATEGY

This chapter researches about the existing improvement strategies in relation to the the structural and thermal performance. These strategies are evaluated on the basis of evaluation criteria, that will allow for the further development of the design concepts of the Hybrid glass block.

04.1

INVESTIGATION TO IMPROVE THERMAL PERFORMANCE

In the past there have been numerous researches carried out to improve the thermal performance of glass blocks and double glazed windows. This section focuses on various design strategies that can be incorporated to improve the thermal performance of glass blocks.

Closed Cavity or change in cavity width
At room temperature and standard pressure, still-air has a good thermal conductivity value of 0.025 W/(mK), but its resistance is reduced by the flow of air within the cavity. The research carried by (Binarti et al., 2014) suggests that the closed cavity within the glass block acts as a true thermal insulator. Based on this, they further developed twelve closed cavity models with varying thickness, cavity width, and cavity number, which were chosen based on mechanical strength, cavity width effectiveness, and production cost.

A medium width (not more than 30mm) closed cavity reduces the solar radiation transmitting through the glass blocks and allows an optimum level of visible light. The thickness of the glass block also influences the SHGC and the indoor surface temperature. (Binarti et al., 2014)

This implies that changes in cavity width can have an effect on heat transmission within the glass blocks. Multiple cavities can act as a barrier and thus improve thermal performance. The challenge here will be to produce cast glass blocks with multiple cavities in an efficient manner. Because of the continuous cross-section, thermal bridge is another challenge. It is also worth noting that this strategy will have an impact on light transmission and result in a distorted optical output.

Additional insulating material
1. Inert Gases:
The insertion of air chambers and cavities is not the only way to improve thermal performance. The resistance can be increased by filling these cavities with inert gases. Even though the air is a good insulator, the cavities when filled by gas like argon or krypton that have lower conductivity can increase the thermal insulation as they do not channelize conductive and convective heat transfers. Inert gases have lower thermal conductivity as they are denser than air. (Velden. M, 2020)

Seves company has developed a high-performance hollow glass block with cavities filled with inert gases which have a U-Value of 1.8W/m2K. This is accomplished by inserting a low-coated glass in the centre, which divides a large cavity into two parts. The argon gas is then pumped into each of these components. This block, however, has a thin cross-section and thus cannot be used for load-bearing applications.(Seves n.d.)

2. Aerogel:
The cavities filled with aerogel (a high absorptivity material) can significantly reduce the U-Value of single cavity glass. Because of the high absorptivity, radiative heat exchange occurs while convective heat transfer is restricted. The study conducted by (Beccali et al., 2010) demonstrates the possibility of lowering the U-Value (1.66 W/m2K is the obtained value) of the hollow glass block. Aerogel is a fragile material, which necessitates a complicated manufacturing process.

3. Phase change materials:
Another recent study that aids in the improvement of thermal performance is the use of phase change material. Based on the heating or cooling requirements the PCM changes their state by absorbing or releasing energy. This is still a new concept that has not been researched yet. The issue with PCM is their transparency as they change properties from one state to another. (Nathani. T, 2021)

Applying coating
The most standardised method of lowering the U-Value is to use various coatings on the external surface of the glass to reduce heat absorption and emissivity of the surface, which affects the conductivity of air cavities. These coatings are applied during the manufacturing process. The heat resistance of a coating is determined by its material properties.

Soft coatings have a low emissivity, a high visible transmission, and excellent optical clarity. The hard coatings are long-lasting and can withstand rough handling, but they do not affect the U-Value. The main disadvantage of using coating is that it is reversible, making it difficult to separate the layer from the glass while recycling.

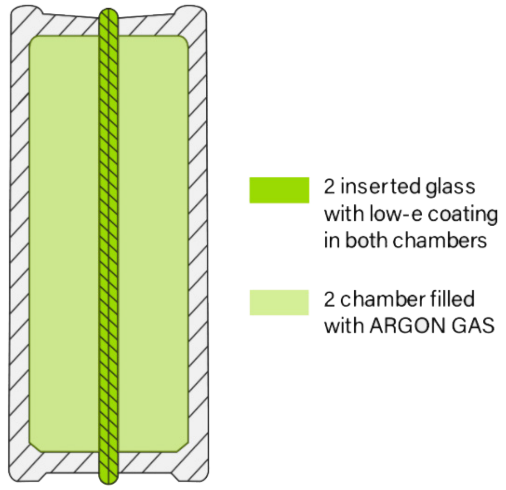


Figure 04.1: Hollow glass block developed by Seves with inert gas infil and 2 glass partitions with low e-coating (Seves n.d.)

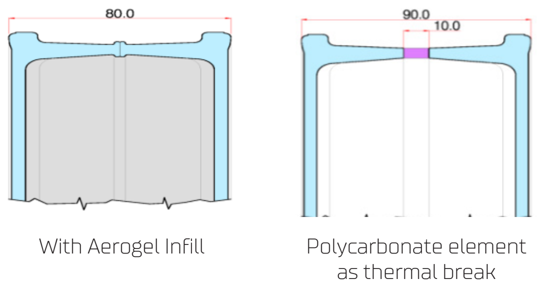


Figure 04.2: Properties of Aerogel & Polycarbonate utilised to improve thermal performance (Beccali et al., 2010)

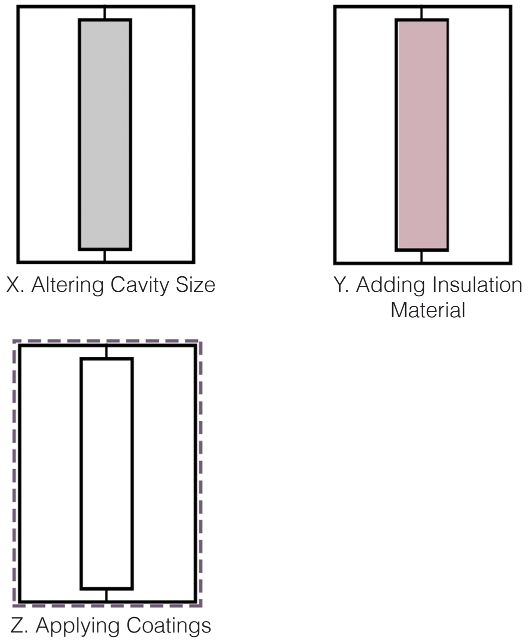


Figure 04.3: Strategies for increasing Thermal Performance (Nathani. T, 2021)

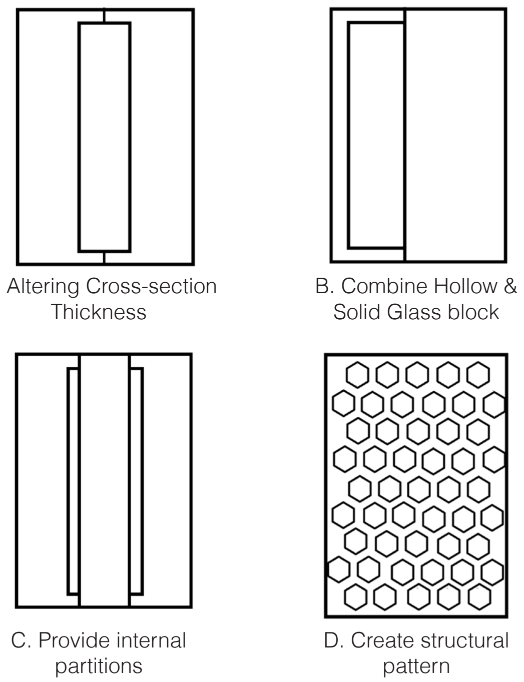


Figure 04.4: Strategies for increasing Structural Performance (Nathani. T, 2021)

04.2

INVESTIGATION TO IMPROVE STRUCTURAL PERFORMANCE

No research directly validates the investigation of the strategies to increase the structural performance of hybrid blocks. However, the research concluded by (Nathani. T, 2021) and (Velden. M, 2020) shows some promising concepts that can be implemented to enhance structural performance.

A. Altering cross-section thickness
A thicker wall, or in this case a thicker cross-section, is required to design a hybrid glass block with load-bearing properties. Because of the larger cross-sectional area, the compressive load over the glass block can be transferred efficiently and without failure (cracking). Since loads are transferred through corners, an optimal cross-section can be determined. According to (Nathani. T, 2021), a cross-section of 75-150 mm is optimal for a glass block of 300*300mm size. However, increasing the thickness has a significant impact on the annealing time, so the thickness can be limited to 100mm.

B. Combination of hollow and solid block
A solid cast glass block is connected to a hollow glass block to form a hybrid glass block, as seen in the fusion block designed by (Nathani. T, 2021) and the Single cavity wall designed by (Velden. M, 2020). The solid component is load-bearing in this concept, while the hollow component provides thermal insulation. The challenge here is to connect both of these components with a sustainable material that will allow the block to be reversible and recyclable.

C. Providing internal partition (Lattice Block)
As seen in (Nathani. T, 2021)'s lattice block, inserting an internal glass partition can significantly increase the surface area for load transfer. The glass partition can be made of float glass with a thermally resistant coating or a single casted block with a top layer that can be sealed by fusing. The difficulty is in the manufacturing method, and the end product will also have optical distortion.

D. Creating structural pattern (Honeycomb or Chess)
By inserting a structural pattern of glass plates inside the cavity of the hollow glass block will increase the surface area for load transfers. The honeycomb pattern (similar to telescope blank) or chess pattern (designed by Velden. M, 2020) is remarkably stable under heavy loadings. This concept introduces various air pockets inside the cavity which will also result in decreased U-Value. The production method of such a block can be investigated.

Redundancy
When glass breaks, there is no indication of cracking or deflection. If one structural block fails in such a circumstance, the neighboring blocks should take on the load-bearing capacity of the damaged or failed block. It is critical to have structural redundancy on both a system and component level. It is critical to consider the situation in case of crack propagation or structural failure in a few design techniques, such as the mix of hollow and solid glass blocks when there is only one structural element in the design. Does the glass block fully fail on a component level, compromising system performance, or will it withstand without compromising structural performance? In both of these circumstances, the immediate impact will be on thermal performance owing to crack propagation and the formation of thermal bridges. As a result, thermal redundancy is necessary at the component level, but structural redundancy is critical at the system level. The connection design should provide for structural failure while having a minimal influence on structural and thermal performance.

04.3

DISCUSSION AND CONCLUSION

The most efficient way to improve thermal performance is to change the cavity. According to research on various cavity widths, a maximum width of 30mm cavity can reduce the U-Value of a double pane glass to 1.66 W/m2K. Theoretically, such a production methodology is available. The challenge will be to minimise optical distortion, which can be accomplished by using smaller cavity widths with less air volume to transfer heat. Although the addition of inert gas fulfils all criteria, the process is non-standard and thus expensive. As a result, the next strategy will be to apply coatings. Even though coatings are not environmentally friendly, they have a significant impact on lowering the U-Value, and the manufacturing process is efficient.

In terms of the evaluation criteria, all of the suggested strategies for improving structural performance perform well. Combining hollow and solid blocks is an intriguing strategy that deserves further investigation. A theoretical validation based on a similar concept is available (Nathani. T, 2021). The existing research on this strategy suggests that there is a lot of room for growth in the future. The change in the cross-section is another important strategy that the study will employ. It is possible to investigate the effects of various cross-sections on load-bearing.

Evaluation of various strategies on the basis of important criteria can be seen in table 04.1

CONCEPTS	THERMAL/ STRUCTURAL PERFORMANCE	EASE IN PRODUCTION	TRANSPAR. OPTICAL DISTORTION	RECYCLABIL-ITY	FINAL SCORE
X. Altering Cavity Size	++++	+++	+++	++++	++++
Y. Adding insulating material	++++	+++	+++	++++	++++
Z. Applying Coatings	++++	++++	++++	++	+++
A. Altering Cross-section thickness	++++	++++	+++	++++	++++
B. Combine hollow and solid block	++++	+++	+++	++++	++++
C. Provide internal partitions	+++	++++	++	++++	+++
D. Create internal patterns	++++	++++	+	++++	++++

Table 04.1: Evaluation of Performance strategies adapted from (Nathani. T, 2021)

Front Facade of Academy of Arts, Maastricht by Wiel Arets Architects (Archdaily, 2012)

05.

CASE STUDY

The case study selected is the Academy of Arts, Maastricht which was built in 1993 and designed by Wiel Arets Architects. This chapter gives a brief introduction to the selected case study and discusses the scope of exploration of the application of hybrid glass block as a replacement over its existing hollow glass block facade system.

05.0

ACADEMY OF ARTS, MAASTRICHT

Architects: Wiel Arets Architects
Location: Herdenkingsplein 12, 6211 PW Maastricht, The Netherlands
Program: School, Educational Institute
Size: 1.300 m2
Date of design: 1989-1990
Date of completion: 1993
Project team: Wiel Arets, Jo Janssen
Collaborators: Lars van Es, Anita Morandini, René Holten, Maurice Paulussen, Paulus Egers
Client: Rijkshogeschool Maastricht
Consultants: Ingenieursbureau Grabowsky & Poort BV, Ir. F.M.J.L. van de Wetering, Laudy Bouw & Planontwikkeling BV

05.1

URBAN CONTEXT

The Academy of Arts is situated on the outskirts of Mastricht's city centre. The school connects the architecture, fashion, fine arts, industrial, and graphic design studios to the existing arts academy. The old building and the new extension are linked by a three-story-high elevated footbridge over the trees. The school is situated in a dense cluster of structures that obscure it from direct view when passing by; it is visible from the city while remaining hidden within it. (Wiel Arets Architects)

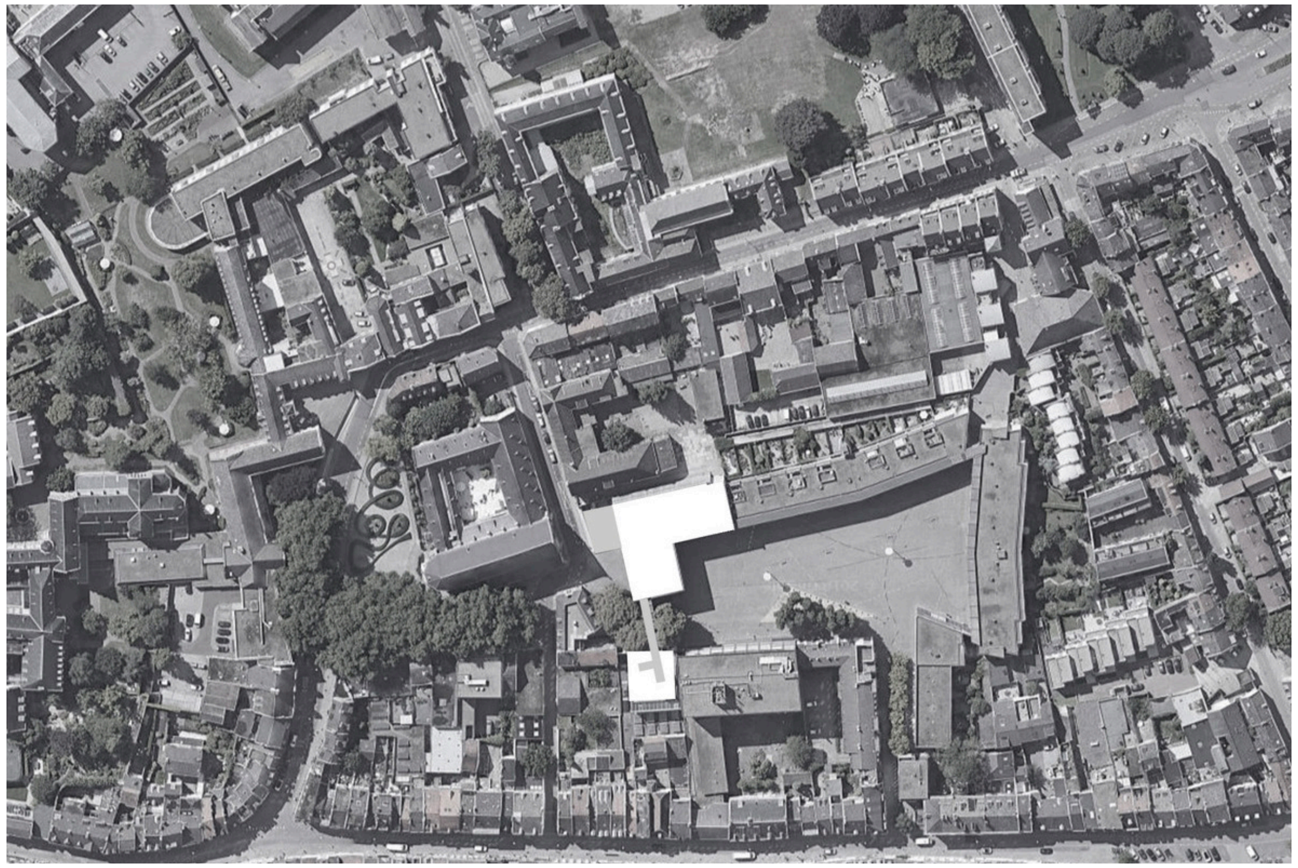


Figure 05.1: Location of Academy of Arts (Wiel Arets Architects)

05.2

THE BUILDING

The school is envisioned to bring in as much natural light inside the interior as possible without losing visual privacy. For this reason, the exterior of the school is covered with a hollow glass block facade that provides a privacy barrier due to optical distortion and allows the students to concentrate throughout the day. The focus of the school is inward-looking. During the night, the glass illuminates from inside the school and casts shadows of the users on the facade envelope. Common spaces such as cafes, libraries, school passages, and auditoriums become the areas of interaction between the students and professors.

Adjacent to the existing arts academy is a series of ramps through which the spaces in the lowermost ground level can be accessed. The ramps guide the users to the ground level from where the enclosed footbridge is seen. The footbridge allows the movement of students from one part of the building to another over a series of trees. The footbridge has a structural shell of concrete with hollow glass block slabs and walls. *"Cocooning students and professors from city life while simultaneously affording them direct access to it; this school is a workshop for artists."* (Wiel Arets Architects)

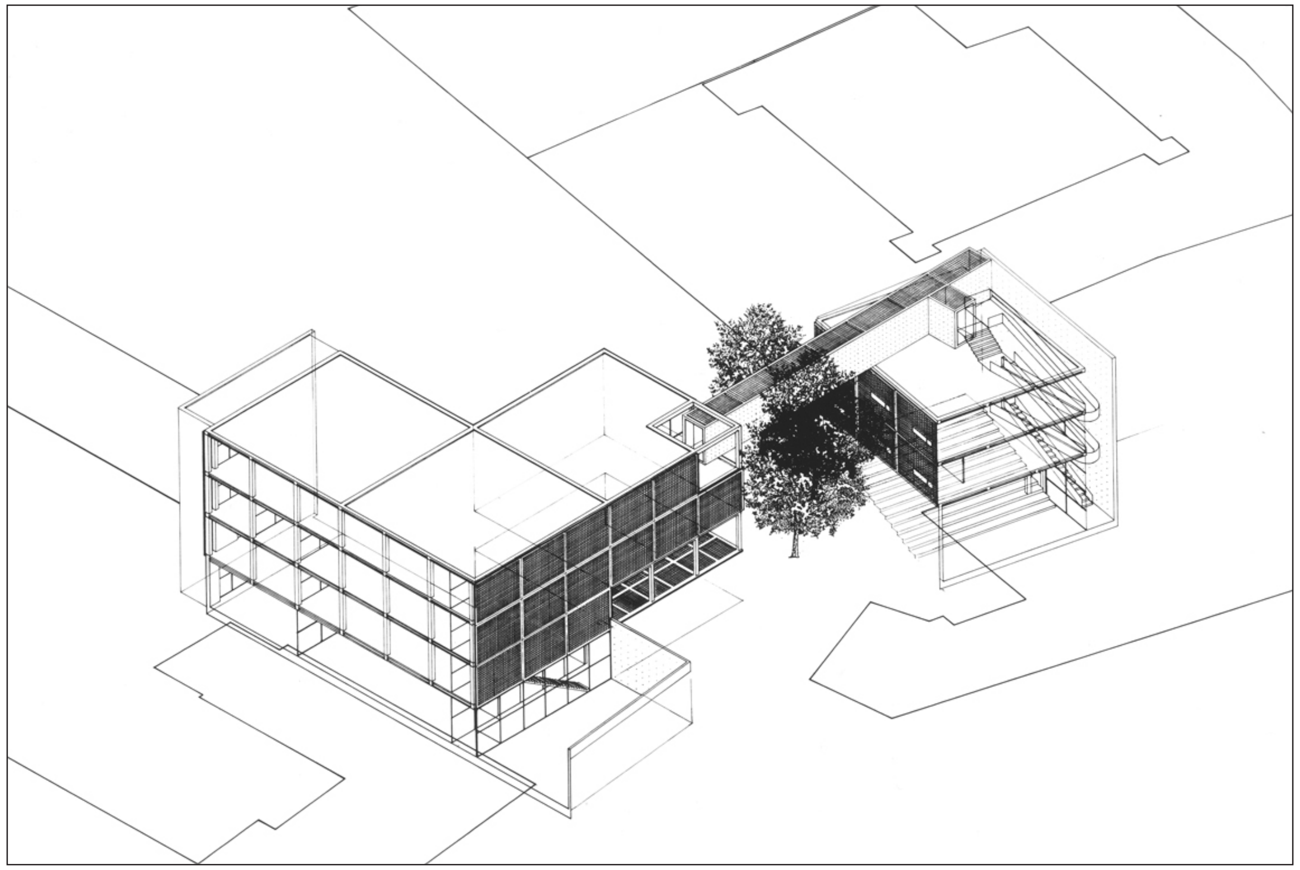


Figure 05.2: Location of Academy of Arts (Archdaily, 2021)

05.3

FACADE DESIGN & INSTALLATION

The building's exterior is wrapped with hollow glass bricks of size 190x190x100 mm. The structural grid is maintained and highlighted on the exterior in the form of precast concrete frames that house these glass blocks from one floor to another. These concrete frames provide structural support to the substructure inside the glass block system. The frames are then anchored on the floor slab using the metal plates. At the corners, the concrete frames are wedged to form a clean detail and are sealed with silicone to make the facade watertight. In spaces where natural ventilation is necessary, an interesting window system with precast concrete frame infill is designed.

Facade specifications

- Floor to floor height- 3140 [mm]
- Precast concrete facade panel- 2380 [mm] c/c
- Precast concrete frame border- 150 [mm] horizontal bands on top and bottom, 120 [mm] vertical bands
- Hollow glass blocks infill size- 2380*2840*100 [mm]
- Window size- 2605*860*100 [mm] (including 120 [mm] concrete frame on all sides)
- Window type- Two paneled. One panel top hung, one panel fixed
- Glass block size- 190*190*100 [mm]
- Mortar thickness- 25 [mm] vertical and horizontal
- Column size- 240*240 [mm]
- Corner column size- 400*400 [mm]
- Overhang ahead of structural edge- 225 [mm]
- Slab thickness- 210 [mm]
- Sunken overhang thickness- 150 [mm] and depth of 60 [mm] from main slab
- Beam depth- 470 [mm]

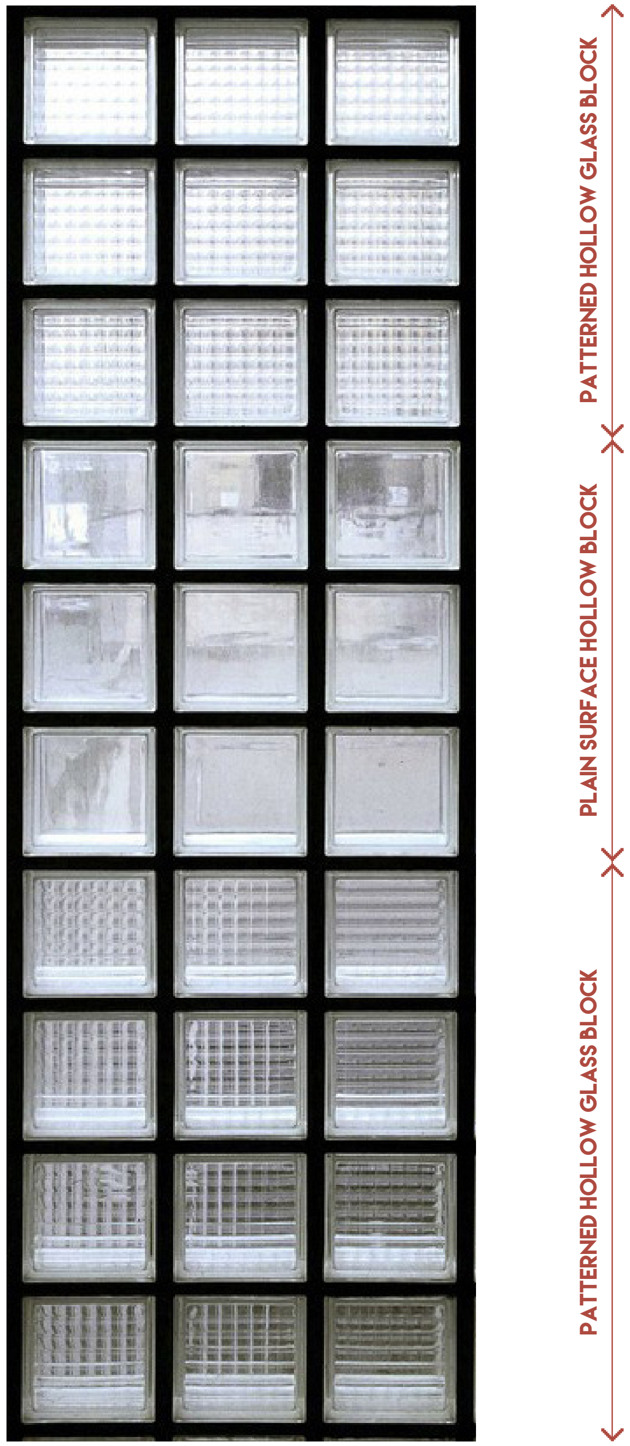


Fig 05.3: Hollow Glass Block Variations (Archdaily, 2012)

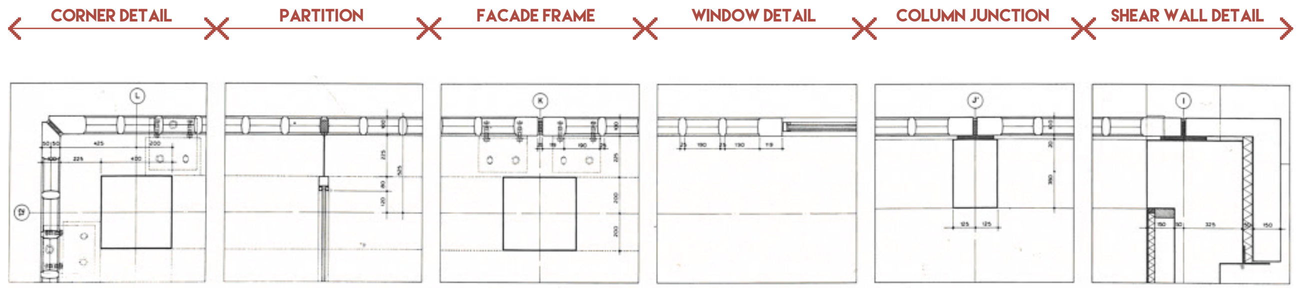


Figure 05.4: Facade Details: Plan (El. Croquis, 1992-93)

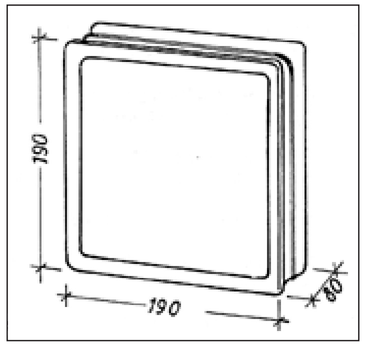


Figure 05.5: Hollow Glass Block (El. Croquis, 1992-93)

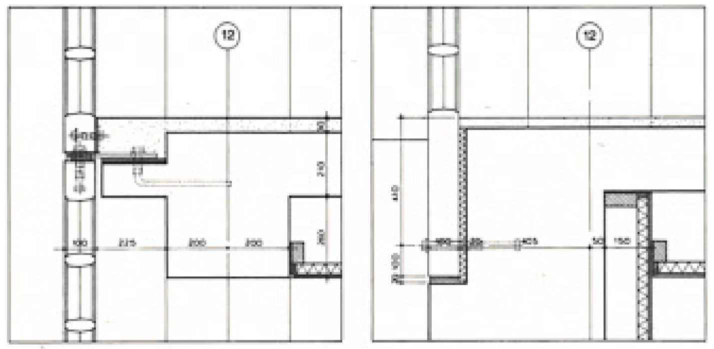


Figure 05.6: Facade Details: Cross-section (El. Croquis, 1992-93)

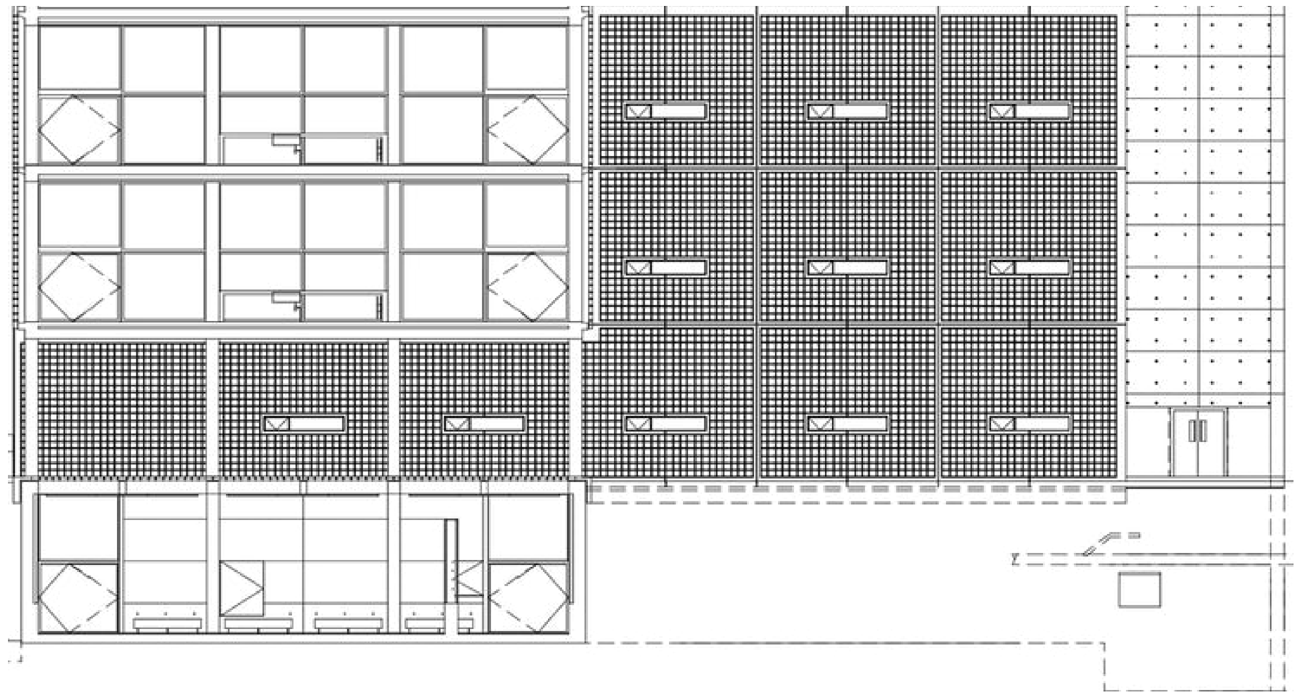


Figure 05.7: Facade Elevation Drawing (El. Croquis, 1992-93)

05.4

DISCUSSION

Architectural Intent
The Academy of Arts, Maastricht is the state-of-the-art combination of architecture and the use of innovative technology to create a dialogue between the interior and exterior. The glass facade is perceived as a transparent screen that welcomes the natural light within the enclosed school corridors and still maintains the sense of privacy within the interior spaces. The hollow glass blocks used are in a combination of patterned and plain surfaces strategically placed in such a way that it creates a harmonious interaction with the exterior environment without losing interior privacy. In the evening, the interior light blooms the facade into a playful well-lit square.

Facade System
The existing facade system is outdated in terms of reusability. The conventional assembly system comprises vertical and horizontal reinforcement rods placed between the hollow glass blocks. The assembly process is tedious and time-consuming as it requires skilled labor. The substructure adds load over the existing primary structure and requires a permanent connection. Therefore, for future renovations or maintenance, the whole facade panel may need to be replaced. Since the hollow blocks are connected with mortar they cannot be reused or recycled. Since the assembly system is completely rigid it does not allow necessary tolerances.

Indoor Comfort & Vision
The hollow glass blocks allow abundant natural light within the studios reducing the daylight requirements. The cavity in between these glass surfaces also provides an optimum level of thermal and sound insulation creating a calm environment for education. The strategic placement of windows integrated with the facade allows natural ventilation during summers. Though the facade performs well in terms of energy efficiency, what it reduces is the possibility of complete transparency with reduced distortion. This however may not be the goal of the architect but needs to be explored as the spatial requirements are different throughout the school.

05.5

SCOPE & CHALLENGES

Scope
The aim is to design hybrid glass blocks and apply them to a case study for practical verification. This case study provides a great opportunity to test the various design concepts on the existing building. Some aspects can be explored as follow;

- Maximizing transparency of the facade by getting rid of the steel substructure
- Seamless exterior surface
- Simple assembly system with ease in maintenance and replacement of the damaged portion on unit level
- Circularity considerations of the glass block system
- Maximizing possible recyclability of glass blocks
- Recommendations for future renovations

Challenges
The challenges in the application of a new product on this selected case study are as follows;

- Integration of existing structural system with a revised assembly system
- Load considerations of new glass blocks on existing structural elements
- Corner connections design
- Standardization of block system in terms of size, weight, and shape

The goal is not to evaluate or enhance the performance of existing facade systems but to explore the hybrid glass block design with a practical approach.

Figure 05.8: Interior View of the Studio highlighting Window & facade detail (Archdaily, 2012)

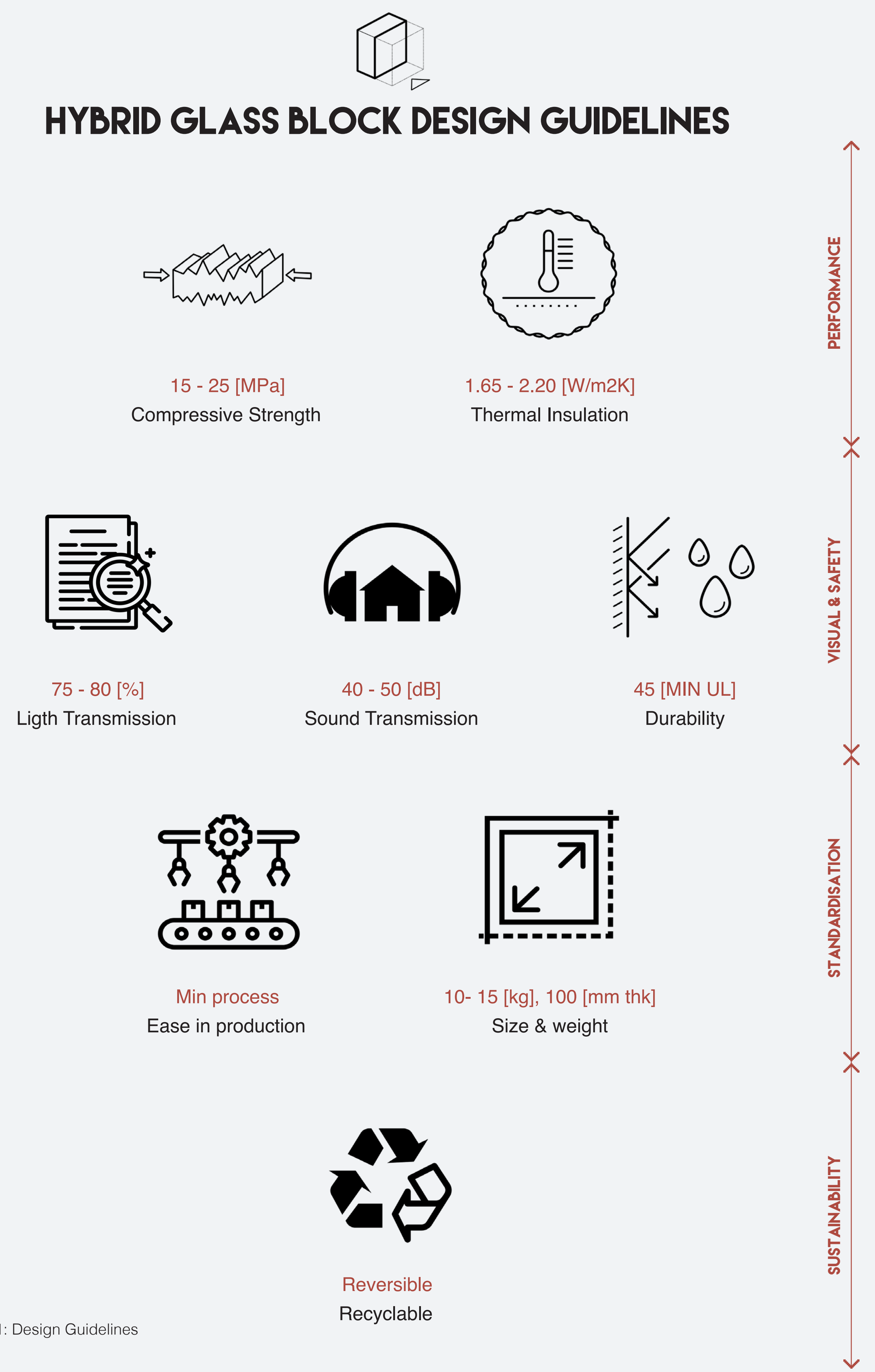


Figure 06.1: Design Guidelines

06.

DESIGN GUIDELINES

The research aims at designing a hybrid glass block which can be applied in architecture in the form of a building envelope or facade component. For a more pragmatic approach in design, a case study is selected which is located in the Netherlands in which the final design will be implemented. For this reason the product needs to adhere to certain building codes and regulations of the Netherlands and/or Europe region.

06.1

DESIGN GUIDELINES

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The main properties that define the Hybrid glass blocks are its compressive strength and the thermal insulation. Thus a benchmark is set that suggests the final product to adhere to the values as suggested in the standards. The Eurocodes, Bouwbesluit and HSE manual handling standards are considered.

1. Compressive Strength
It is defined as “the resistance of a material to breaking under compression.” (Oxford dictionary)

According to the literature, the compressive strength of hollow glass blocks ranges from 2.75 to 6 MPa (Seves n.d.), whereas the compressive strength of solid glass blocks ranges from 82 to 400 MPa (Pittsburgh Corning Corporation, 2007). To establish a standard for “good compressive strength,” references to traditional clay brick used in load-bearing construction are considered. Because compressive strength is affected by material composition, it is never given as a single number but rather as a range. Clay brick has a compressive strength ranging from 6 to 20 MPa (Singhal et al, n.d.). The highest value of clay brick is used as the average benchmark for the compressive strength of hybrid glass blocks. However, the range is set from 15 to 25 MPa.

2. Thermal Insulation
U-value(Thermal transmittance), also known as U-factor, is one of the most important glass performance measures. “It is the measure of how much heat flow or heat loss occurs through the glass due to the difference in indoor and outdoor temperatures.” (Seves n.d.). The standard U-Value of glass should be below 1.6 W/m2K.

According to the literature, the U-Value of hollow glass blocks is in the range of 1.5-1.8 W/m2K (Seves n.d.), whereas the U-Value of solid glass blocks is near 4.0 W/m2K (Pittsburgh Corning Corporation, 2007). Since the design product will be implemented in a case study located in the Netherlands, Bouwbesluit (Dutch Building Code) and Eurocodes are used as standards to set the range. As per the Dutch Building code, the maximum U-Value for a glazed facade is 1.65 W/m2K and as per Eurocodes, it is 2.2 W/m2K. Therefore, for the design of a hybrid glass block, the U-Value of a maximum 2.2 W/m2K is set as a benchmark. During the evaluation of the designs, the values near 1.65 W/m2K will be given more performance points.

Product	U-Value (W/m2K)
Hollow glass block (Seves)	1.5 - 1.8
Solid glass block (Pittsburgh Corning Corporation)	4.0
Eurocode	1.65
Dutch Building Code	2.2
Hybrid Glass blocks	**1.65 - 2.2**

Product	Compressive strength (MPa)
Hollow glass block (Seves)	2.75 - 6
Solid glass block (Pittsburgh Corning Corporation)	82 - 400
Load-bearing mud brick	6 - 20
Hybrid Glass blocks	**15 - 20**

Table 6.1: Comparitive guidelines for compressive strength and U-Value of hybrid glass blocks

3. Light Transmission
It is defined as, “movement of electromagnetic waves through a material medium” (Seves n.d.).

Glass’s transparency is what attracts architects and designers to it as a façade material. As a result, the number of refracting surfaces in the design is used to evaluate it. Every transition from glass to air causes optical quality loss and image distortion. The light transmission of the hollow glass block is in the range of 70 to 76% whereas for solid glass blocks it is near 90%. The suggested descent range of light transmission for the hybrid glass block is 75 to 80%.

4. Ease in production & Standardisation
The amount of material used, the energy required to produce, total cost, mould design, and annealing time are all factors that can have a significant impact on the overall feasibility of the design. The hybrid block’s design should adhere to the concept of standardisation, which means keeping the number of size variations to a minimum. The design can be thought of as a lego block, allowing for multiple iterations with a single defined standardised block. This will significantly improve the standardisation of the production method. It is not possible to calculate the cost of production; however, the significance of additions in the manufacturing process (such as filling inert gases, additional annealing process to seal two blocks, and so on) will be considered as additional costs and may complicate the process.

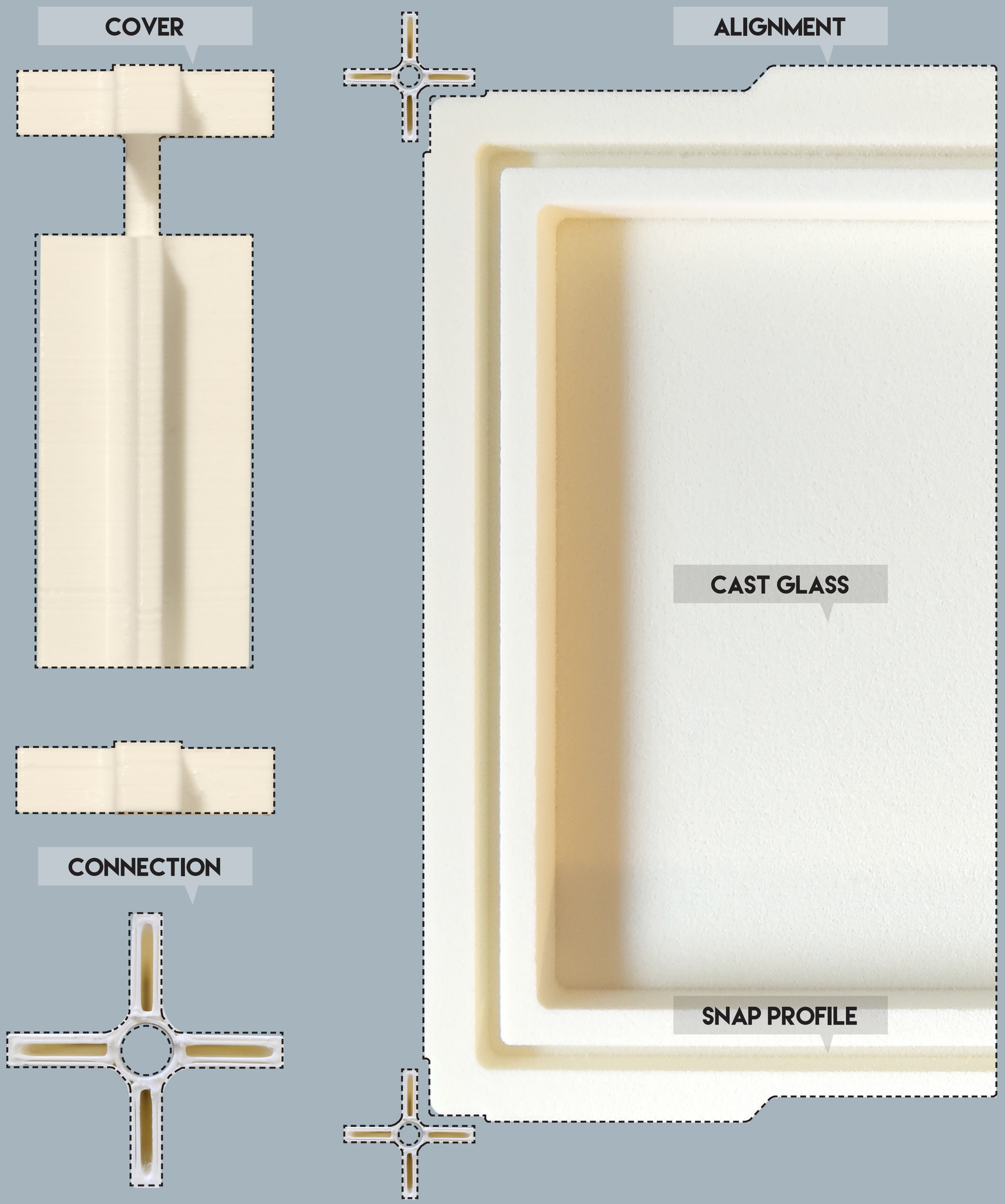
5. Size and Weight
At this point, the glass block in the design has no specific size or weight constraints. The assembly system is considered a manual process, with labourers handling the glass blocks. According to the Eurocode, the maximum manual lifting weight for men is 25 kg (with both hands, until elbow height) and 16 kg for women. The weight of a hollow glass block ranges from 2.7 to 3 kgs (Seves n.d.), whereas the weight of a solid glass block ranges from 3.6 to 8.4 kgs (Crystal house and Optical House). The weight of the hybrid glass blocks designed by (Nathani. T, 2021) is 16 kgs due to the size of 300*300mm.

For ease of assembly, the weight limits for the hybrid glass blocks are 5-7.5 kg (with a single hand) and 7.5-10 kg (with both hands). This is based on the block’s thickness of around 100mm and size of around 200*200mm (based on the block size in the case study). *Thickness of the solid glass component is limited to 100mm considering the longer annealing time requirements for thicker cross-sections.

6. Recyclability
When designing with glass, recyclability is critical. Glass of pure quality can be re-melted and formed into various components repeatedly without losing its quality. However, the presence of coatings renders the block unrecyclable because it is difficult to remove them from the block, preventing the glass from being remelted to form a new shape. (Nathani. T, 2021) This study intends to achieve as much of a recyclable component as possible concerning the other design criteria.

7. Sound transmission
The value for the Hollow block is between 43 and 50 dB, while the value for the Solid block is between 43 and 53 dB. This must be determined experimentally for hybrid glass blocks, which is beyond the scope of this study. (Nathani. T, 2021)

8. Durability
The hybrid glass block system should be fireproof, watertight, and scratch-resistant. Building codes recommend a 45-minute UL or Euro class A1 fire rating. However, verification for the same is beyond the scope of this study.



Final Design Concept Components of Hybrid Glass Blocks

07.

DESIGN DEVELOPMENT

This chapter establishes the design development methodology for the development of the hybrid glass block system. A step by step development of design aspects and criteria are set followed by the design alternatives and evaluation. The chapter results in the development of final design concept.

07.1

DESIGN GOALS

The design guidelines established in the preceding chapter are critical for the hybrid glass blocks to perform in a holistic sense. These criteria serve as minimum standards for the design's development. However, it is critical to building a design vision that is related to the circularity aims on a larger level as well as the scope provided by the chosen case study. The fundamental objective is not merely to create a hybrid glass block, but also to create a system that reacts effectively to this novel product while adhering to current circularity and sustainability standards.

"To develop a hybrid glass block system with good thermal and structural performance, efficient manufacturing process, ease in assembly-disassembly, recyclability and enhanced visual aesthetics "

This vision can be further elaborated in terms of design goals for each of the above-mentioned aspects

Structural and thermal performance
The design is primarily concerned with improving the structural and thermal performance of the hybrid glass block. During the design development phase, parameters such as load transfer, cross-section thicknesses, weight, the center of mass, the number of cavities, the width of the cavities, and the thickness of the glass pane will be evaluated.

Efficient manufacturing
The design is inextricably linked to the manufacturing process. To ensure an effective manufacturing process, it is critical to consider the impact of numerous standardized processes while developing the hybrid glass block. For example, the number of differences in glass blocks will need the fabrication of extra molds, which may have an influence on overall uniformity and lead to customization. The influence can also be dependent on the designed connection system, which may result in additional operations throughout the manufacturing process.

Ease in assembly:
The goal is to create an assembly technique for dry-stacked hybrid glass blocks that is simple and rapid to construct. One of the design parameters for simplicity of assembly is that the weight standards of the hybrid glass block be simple to lift by hand, which is less labor-intensive and removes the need for heavy lifting equipment. These objectives should also guide the design of the connecting system. Finally, the unit-level assembly should be rapid, less labor-intensive, make efficient use of supplementary supports, and minimize the deployment of heavy lifting equipment.

Design for disassembly
The selected case study's existing façade system allows for disassembly, but only on a system level. The standard hollow glass block system is not suitable for block replacement at the unit level. This is because of the wet connection and reliability of the metal substructure. The hybrid glass block intends to give as much flexibility as possible for replacing individual hybrid glass blocks on the unit and at the system level. As a result, thermal and structural redundancy is an important factor that will be evaluated during the design process. The reversibility of connections in the system as well as at the unit level will be emphasized in the design of the hybrid glass system. This is possible by using dry connections and a dry-stacked assembly approach.

Recyclability:
The hybrid glass blocks will eventually attain technical or functional end-of-life. To adapt to new construction methods, it is necessary to address what will happen to the hybrid glass blocks once they have reached the end - of - life. Another design aim is to attain the highest possible percentage of recyclable glass components. To accomplish this, the usage of adhesives and e-coatings to safeguard the glass from contamination could be eliminated. The scope is confined to the glass block since other connecting systems may still be employed after disassembly.

Visual Aesthetics
The final design product will be the facade system over the Academy of Arts building, as well as any other architectural buildings that are newly designed or refurbished in the future. The façade is the building's skin, which not only influences its performance but also expresses innovation and aesthetic appeal. To develop a contemporary character, the combination of materials and facade detailing will be one of the key aspects. However, a thorough visual assessment of the product is outside the scope of this thesis.

07.2

DESIGN METHODOLOGY

Approach
To design a product, it is necessary to create a process that responds to the requirements of various building systems and components and translates them into a cohesive line of inquiry. Architects must be able to construct a methodology that integrates their unique and creative inputs at various stages to follow a modular building system approach and produce a product from its design to actual production.

A systematic approach is essential to identify the most convenient solution to each given design challenge. A lot may be gained from the product development sector, which addresses product design and production procedures analytically and systematically. In the building industry, a comparable analytical and methodical technique may be used to design and produce a product that meets the design goals.

Although the goal of this research is to create a hybrid glass block system, a similar method may be used to develop other components of modular building systems such as connections or assembly systems.

Methodology Sequence
The design development of the hybrid glass blocks system follows an Analytical and systematic methodology that aids to generate various design concepts based on varied design problems.

Following are the systematic steps followed,

1. Identify design aspects
The methodology begins with defining the project's specific design problems. Several design challenges are outlined for this research, including defining the suitable geometry and cross-section for the design of hybrid glass blocks, connection design at the unit and system levels, and facade and assembly system details. Each task has a different level of complication, which can be further elaborated on in the form of criteria.

07.2

DESIGN METHODOLOGY

2. Developing design criteria and boundary conditions
Various criteria that may be considered as guiding principles for design development can be derived from each design challenge. The aspects specified in the design goals are the boundary conditions, however, not all of them must be satisfied or met for the design problems. For example, while designing a cross-section, the emphasis is on structural and thermal performance, including design criteria such as thickness, weight, a center of mass, and cavity thickness. The boundary conditions at this level may cause the aspect of design for disassembly to be disregarded. During the evaluation process, a specific set of boundary conditions and a set of design criteria should be established and prioritized for each task.

3. Developing design alternatives
For each design task design, alternatives are developed. These can be based on existing designs or new design solutions. For a design problem of designing a block-to-block connection, various alternatives are designed based on the set boundary conditions and design criteria set. The main boundary conditions are the design for disassembly, ease in assembly, and performance with criteria like material durability, and redundancy of the system with secondary importance. For the design problem of interlayer design, existing research on the materials is considered and material alternatives are provided.

4. Evaluating design alternatives on the basis of criterias and boundary conditions
To evaluate the design alternatives a systematic way of criteria weightage is developed that results in a specific score for each alternative. The boundary conditions are given equal importance in terms of the weightage, however, for any specific design problem, the average or basic fulfillment of the boundary condition is important. Perhaps there is a tie in the boundary condition score, then the criteria fulfillment scores are considered. Each criterion is given weightage based on its relationship with the design problem and its influence on the guiding boundary conditions.

5. Developing & analysing design concepts
The scores cannot be used entirely to settle on design alternatives. Some design choices with lower scores may also be capable of meeting other essential aspects. As a result, ignoring options with low ratings is irrelevant. Following the design alternative evaluation process, a comprehensive analysis can be performed to generate one or more concepts. Based on the literature suggestions, the shortlisted concepts can be further investigated. Additional criteria for developing a final design idea can be devised.

6. Refining final design concept based on manufacturing and constructibility parameters or actual prototyping
The selected design concept can now be refined based on design standards recommended by the manufacturing process, constructability, or physical prototyping. The goal is to improve the design into a functional final product that meets all manufacturing and constructibility specifications.

7. Design Evaluation
The final design is evaluated by actual prototyping followed by numerical and analytical methods. The prototyping phase focuses on understanding the challenges associated with the casting of the final geometry. All the key observations and decisions are noted down, to aid future research. The structural and thermal performance is evaluated by numerical methods. Hand calculations are implemented to find the compressive strength, buckling load, and U-Value of the hybrid glass block system. The complete design is analytically evaluated for the envisioned design goals based on the research and design development findings. Finally, the design is compared with the hollow and solid glass blocks realized projects and with the existing development of hybrid glass blocks.

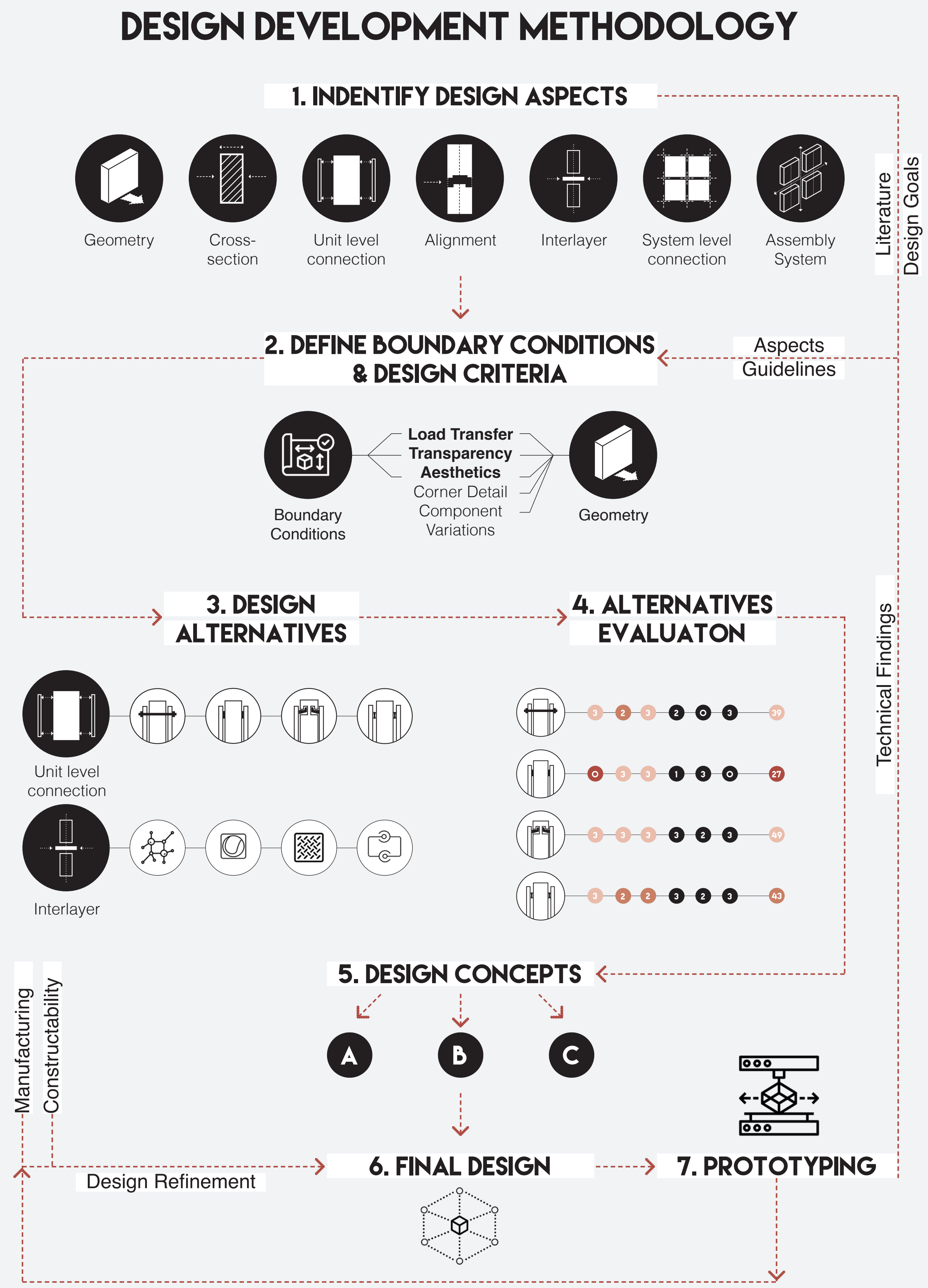


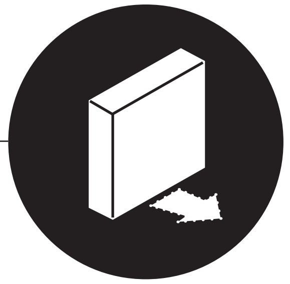
Figure 07.1: Design Development Methodology Diagram

07.3

DESIGN ASPECTS

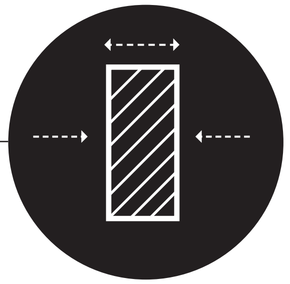
Based on the analytical methodology of product development the design problems are determined. For this particular research, 7 different aspects are to be designed to combine to form a hybrid glass block system. Each aspect is elaborated a bit in detail mentioning the scope and challenges of developing a design alternative.

GEOMETRY



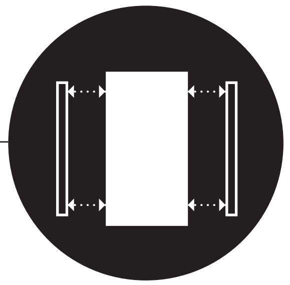
One of the key aspects is the geometry of the hybrid glass blocks. This serves as the starting point for the development of the hybrid glass system. The geometry of the glass block largely influences the manufacturing process and the design of the assembly system. Boundary conditions like aesthetics and transparency are directly dependent on geometry.

CROSS-SECTION



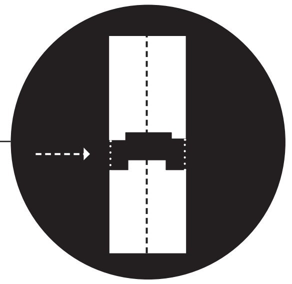
Understanding the relationship between the structural loading and the cross-section thickness of the hybrid glass is a key aspect that requires scientific exploration. The cross-section influences the thermal as well as structural performance and also has a comparative impact on the annealing time. The transparency level and the sound insulation are also dependent on the cross-section design and thickness.

UNIT CONNECTION



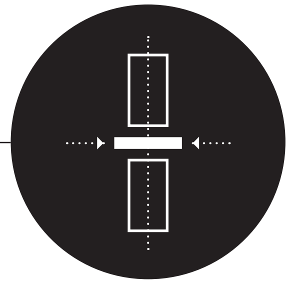
The type of connection used on a unit level is important as it influences the ease of assembly and disassembly. Since the aim is to design dry connection systems, the impact of various types of connections is explored in this aspect. The unit level connection between the cast glass block and the flat glass panel.

ALIGNMENT



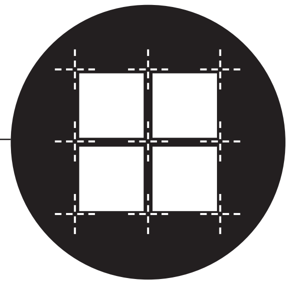
To design a dry-stacked assembly system, the glass blocks are stacked on top of each other in an interlocking fashion. The design of the interlock depends on the alignment design that greatly influences the transfer of load from one block to another. The alignment design should also allow for replaceability in case of any damage to the glass component. The design of the alignment will be also evaluated based on the ease of manufacturing and assembly.

INTERLAYER



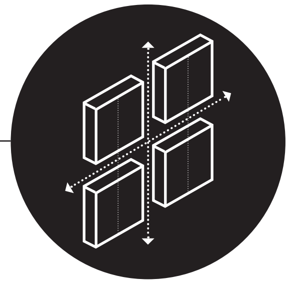
The choice of the interlayer is very essential as it has to do a lot in terms of creating a bond between glass blocks and efficiently transferring loads. The choice of interlayer material has a great influence on the transparency, load, transfer, manufacturing process, and type of assembly system.

SYSTEM CONNECTION



The choice of connection on a system level is an important aspect as it influences the ease of assembly and disassembly, load transfer, and visual aesthetics. The connection between glass blocks also should be durable and resistant to weathering.

ASSEMBLY SYSTEM

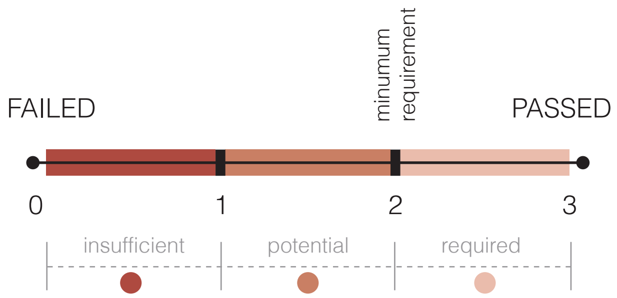


The assembly system largely influences the efficient use of heavy equipment, labor, and material on site. To design a safe, quick, and easy assembly system various scenarios with a modular approach could be designed and considered. The criteria of circularity and reusability on a system level could be achieved.

07.4

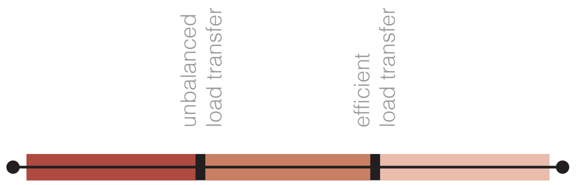
BOUNDARY CONDITION WEIGHTAGE

To assess and evaluate the design alternatives design criteria are developed. Based on the design goals some predetermined boundary conditions are formulated. Each design aspect consists of a few (not all) boundary conditions and specifically applicable design criteria. During the evaluation, the alternatives with a high score in the boundary condition as well as design criteria will be considered. The boundary conditions are given weightage individually based on the failed-passed system (figure 07.2). In total 7 boundary conditions are identified that are important for product development of the hybrid glass block system (figure 07.3).



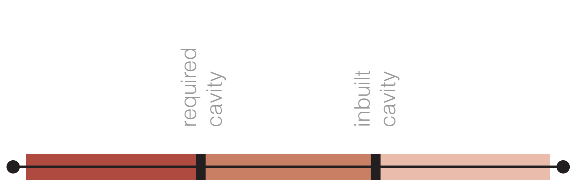
* Weightage of 0-3 is considered and score=weightage*3

Figure 07:2: The weightage system for Boundary Conditions



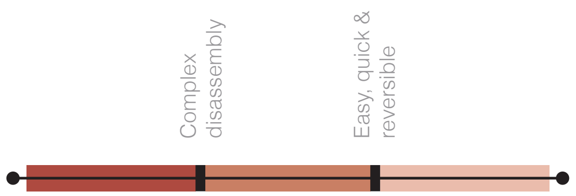
STRUCTURAL PERFORMANCE

The structural performance is primarily associated with the homogenous load transfer. The design aspects such as geometry, cross-section, alignment and interlayer need to perform well under loading.



THERMAL PERFORMANCE

The thermal performance is primarily associated with the ability of the design aspect to resist heat transmission. Strategies such as change in cavity width and number can be implemented in the cross-section design aspect.



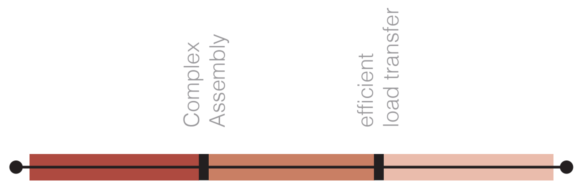
DESIGN FOR DISASSEMBLY

The design for disassembly is primarily associated with easy, quick and reversible connections on system as well as unit level connections. The design aspect of alignment should provide for ease in disassembly.

EASE IN MANUFACTURING

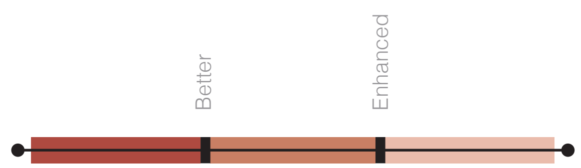
The ease in manufacturing is primarily associated with the efficiency and standardisation of the process. The design aspects like cross-sectio,alignment, unit level connection and interlayer requires easy manufacturing process.

Figure 07:3: Boundary Conditions involved



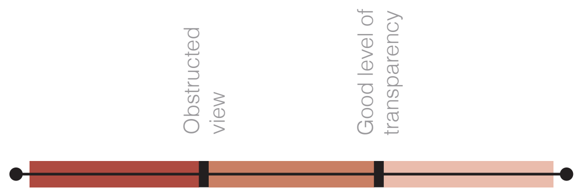
EASE IN ASSEMBLY

The ease in assembly is primarily associated with the complexity of connections and number of steps required for assembly. The design aspects like alignment, connection and assembly system should be easy and quick.



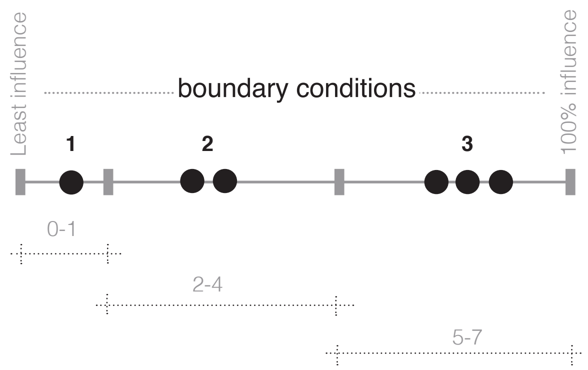
VISUAL AESTHETICS

The visual aesthetics is primarily associated with the look and feel of the designed hybrid glass block system. The design aspects such as geometry



TRANSPARENCY

The structural performance is primarily associated with the homogenous load transfer. The design aspects such as geometry, cross-section, alignment and interlayer need to perform well under loading.



* Weightage of 1-3 is considered

Figure 07:3: The weightage system for the influence of particular design criteria over boundary conditions.

07.5

DESIGN CRITERIA WEIGHTAGE

The design criteria are very specific to the design aspects. Each design criterion is given a weightage out of 3 depending on its importance and influence over the other boundary conditions (figure 7.4). For example in the geometry aspect design criteria like corner detail is more important than the component variations as it influences almost all the boundary conditions. The design alternatives are given a score out of 3. The design scores are multiplied by the criteria weightage as shown in (figure 7.5)

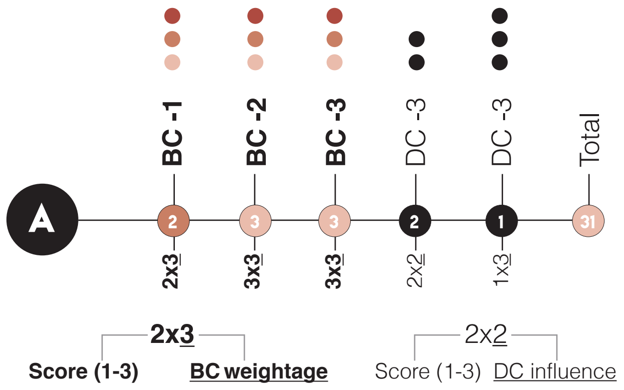
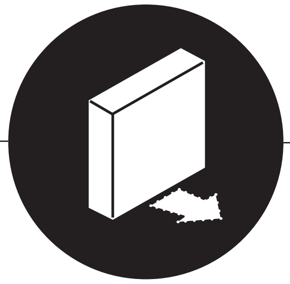


Figure 07:4: The weightage system for design evaluation

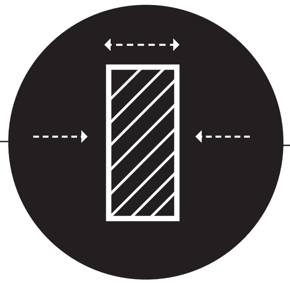
GEOMETRY



Aesthetics
Load Transfer
Transparency
Corner Details
Component Variation

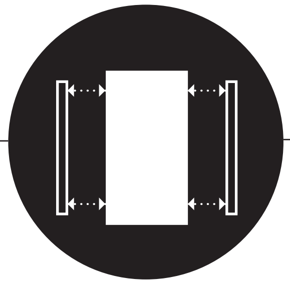
*Bold text highlight the boundary conditions considered.

CROSS-SECTION



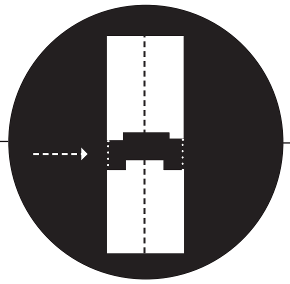
Load Transfer
Thermal Performance
Ease in Manufacturing
Transparency
Ceter of Mass
Weight
Sound Insulation

UNIT CONNECTION



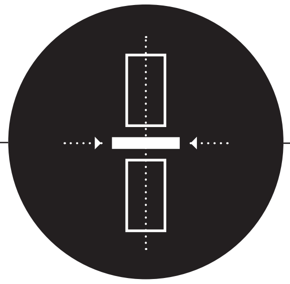
Design for Disassembly
Aesthetics
Ease in Manufacturing
Replaceable on site
Air-tight seal
Dry Connection

ALIGNMENT



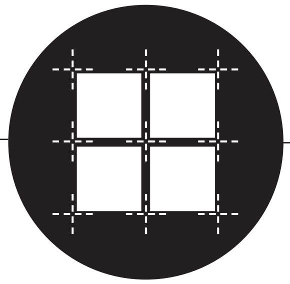
Load Transfer
Ease in Manufacturing
Transparency
Design for Disassembly
Self-Alignment

INTERLAYER



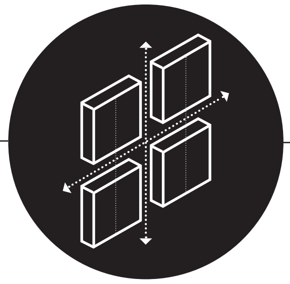
Load Transfer
Transparency
Ease in Manufacturing
Resistance to Creep
Circularity
Thermal Expansion
Durability

SYSTEM CONNECTION



Design for Disassembly
Load Transfer
Transparency
Aesthetics
Ease in Assembly
Durability
Redundancy

ASSEMBLY SYSTEM



Design for Disassembly
Aesthetics
Ease in Assembly
Less Labor intensive
Modular
Replaceable

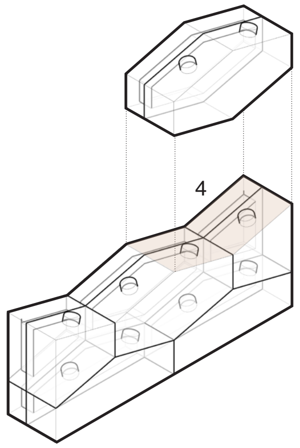
07.6.1 GEOMETRY EXPLORATION

Hollow + Solid

Dry Assembly

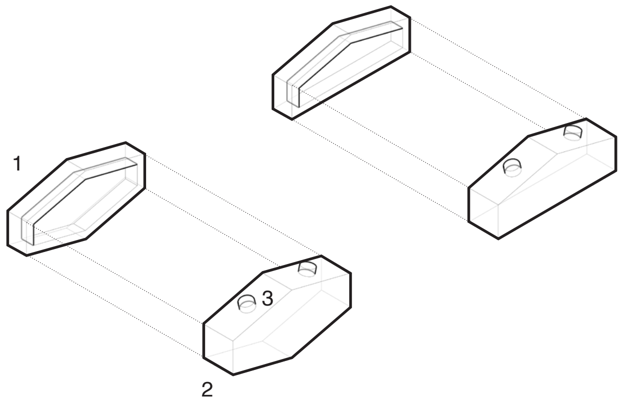
TRAPEZOID

A different type of geometrical shape similar to a hexagon but a bit compressed is designed.



Alternate Stacking

Interlocking is done similar to brick masonry. The top component holds two bottom blocks in one place.



Two components

Varied components stacked together to form an interlocking assembly system

1. Float glass

6mm thk with 5mm e-coating & 20mm thk air cavity, non-recyclable

2. Cast glass

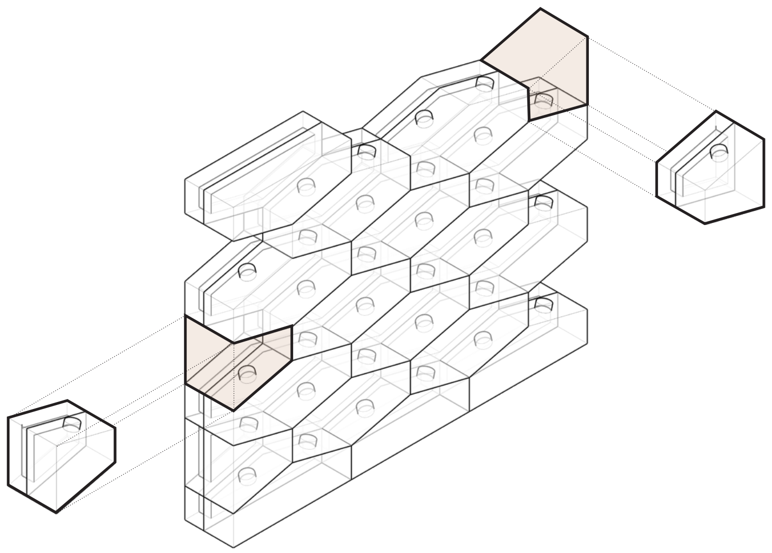
100mm thk borosilicate glass, recyclable

3. Spherical Notch

25mm diameter borosilicate glass, recyclable

4. Interlayer

1-5mm thk made of transparent material



Corner components

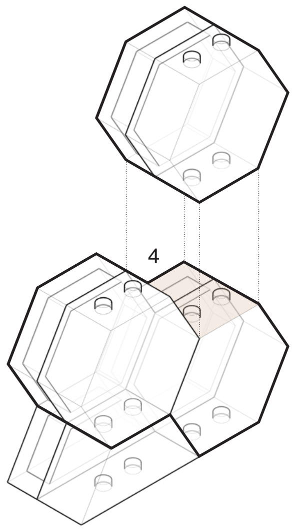
Varied components stacked together to form an interlocking assembly system

HEXAGON

The hexagon or the honeycomb is the most common design shape.

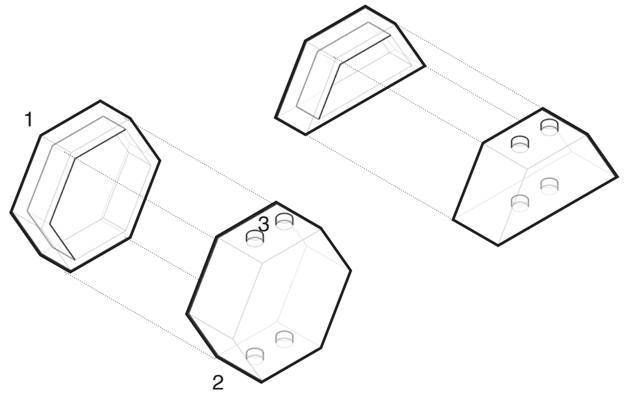
Hollow + Solid

Dry Assembly



Alternate Stacking

Interlocking is done similar to brick masonry. The top component holds two bottom blocks in one place.



Two components

Varied components stacked together to form an interlocking assembly system

1. Float glass

6mm thk with 5mm e-coating & 20mm thk air cavity, non-recyclable

2. Cast glass

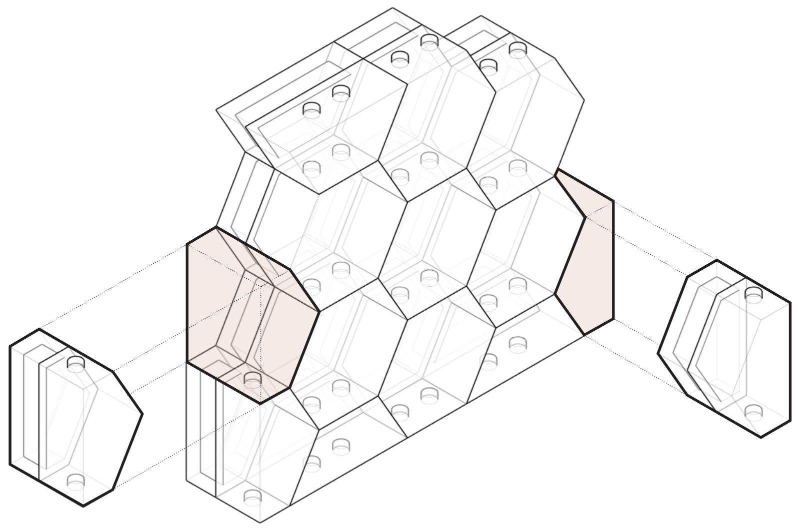
100mm thk borosilicate glass, recyclable

3. Spherical Notch

25mm diameter borosilicate glass, recyclable

4. Interlayer

1-5mm thk made of transparent material



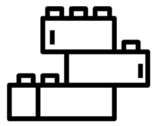
Corner components

Varied components stacked together to form an interlocking assembly system

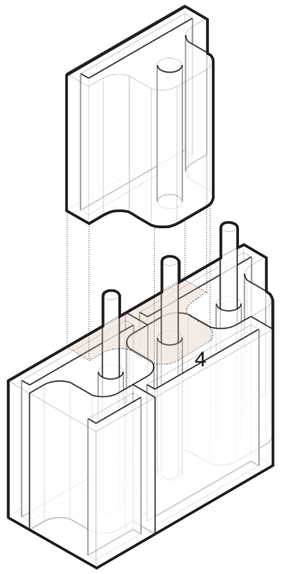
ARMOBLOCK

The armoblock is designed principally similar to the modular concrete block. The interlocking takes place with the guided rod which can be made of extruded glass.

Hollow + Solid

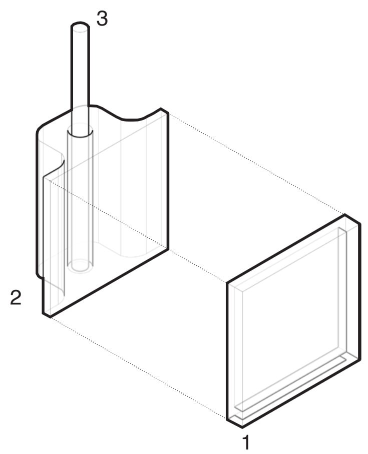


Dry Assembly



Alternate Stacking

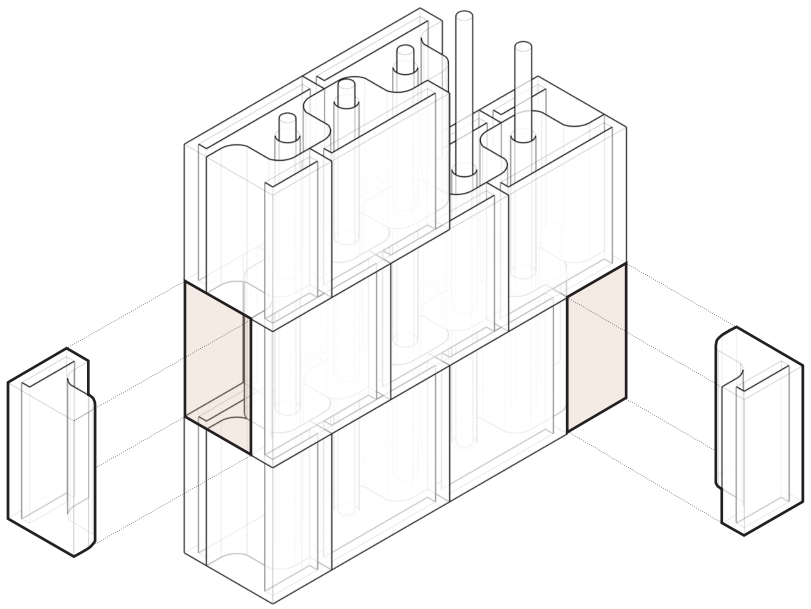
Interlocking is done similar to brick masonry. The top component holds two bottom blocks in one place.



Single component

One Single Component is used in both directions

1. Float glass
   6mm thk with 5mm e-coating & 20mm thk air cavity, non-recyclable
2. Cast glass
   100mm thk borosilicate glass, recyclable
3. Glass rod
   25mm diameter borosilicate glass, recyclable
4. Interlayer
   1-5mm thk made of transparent material

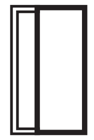


Corner components

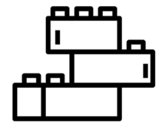
Varied components stacked together to form an interlocking assembly system

FLUET 1

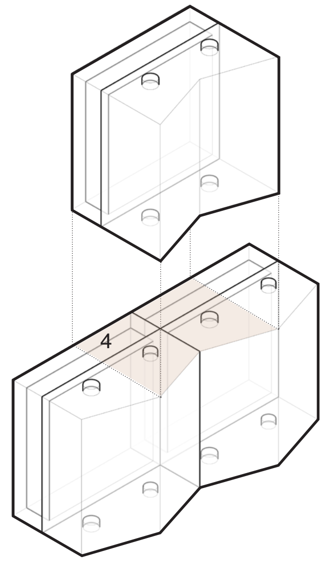
The design of the fluet block is inspired by the wooden fluet profiles for wall decorations. The idea is to reduce or optimize the use of the material



Hollow + Solid

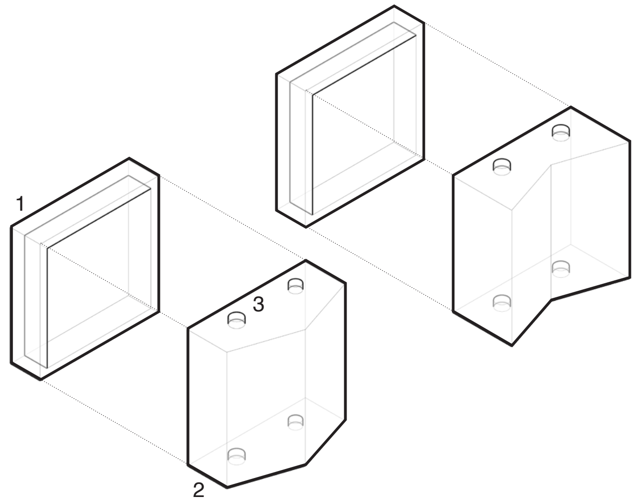


Dry Assembly



Alternate Stacking

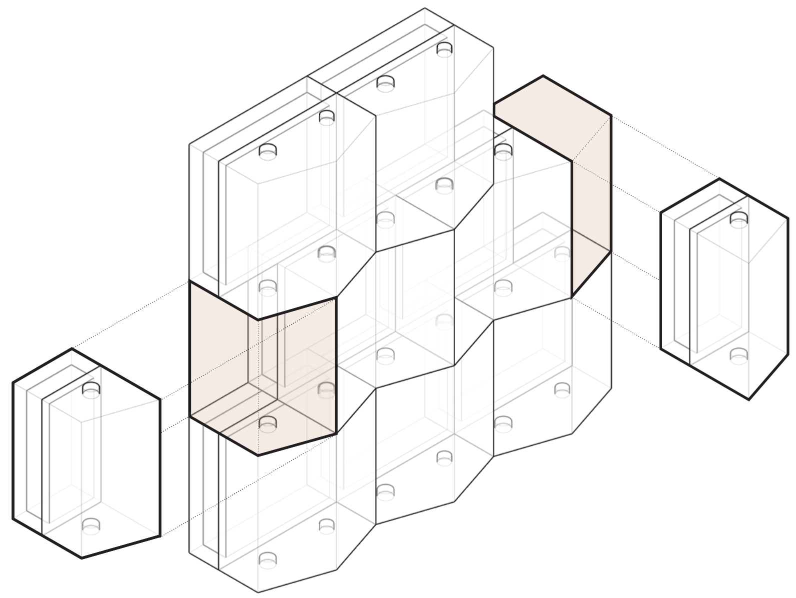
Interlocking is done similar to brick masonry. The top component holds two bottom blocks in one place.



Two components

Varied components stacked together to form an interlocking assembly system

1. Float glass
   6mm thk with 5mm e-coating & 20mm thk air cavity, non-recyclable
2. Cast glass
   100mm thk borosilicate glass, recyclable
3. Spherical Notch
   25mm diameter borosilicate glass, recyclable
4. Interlayer
   1-5mm thk made of transparent material

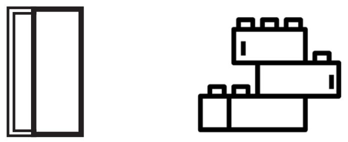


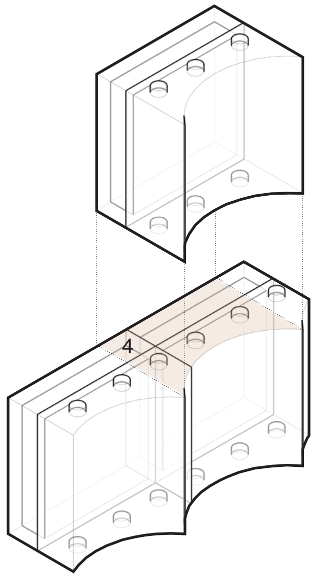
Corner components

Varied components stacked together to form an interlocking assembly system

FLUET 2

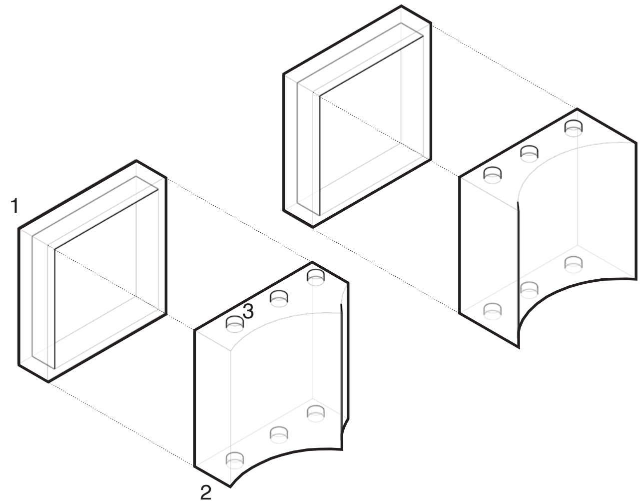
This is similar to the flute 1 design, however, the tapering is at the corner to increase the level of transparency.





Alternate Stacking

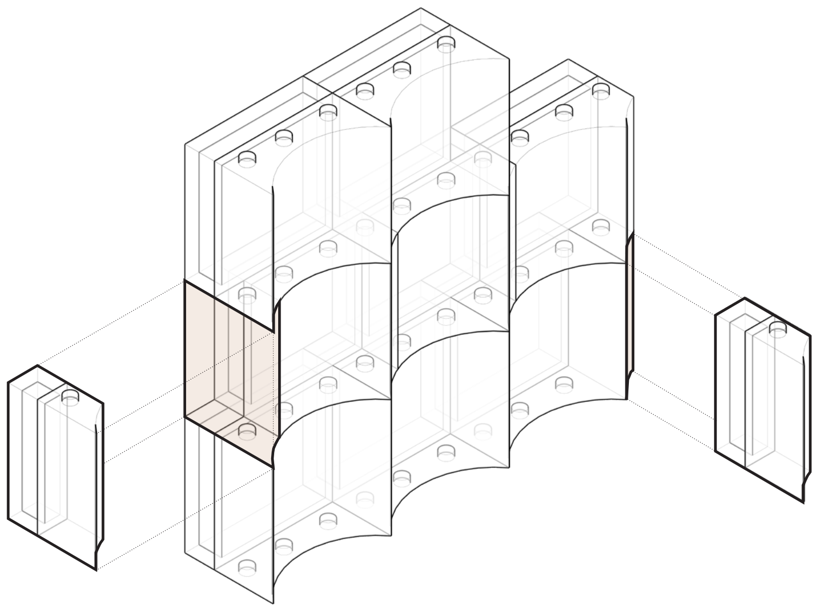
Interlocking is done similar to brick masonry. The top component holds two bottom blocks in one place.



Two components

Varied components stacked together to form an interlocking assembly system

1. Float glass
   6mm thk with 5mm e-coating & 20mm thk air cavity, non-recyclable
2. Cast glass
   100mm thk borosilicate glass, recyclable
3. Spherical Notch
   25mm diameter borosilicate glass, recyclable
4. Interlayer
   1-5mm thk made of transparent material

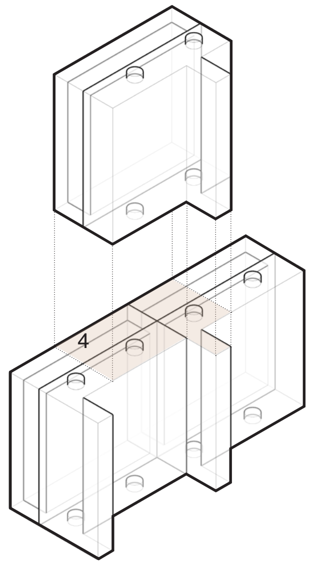


Corner components

Varied components stacked together to form an interlocking assembly system

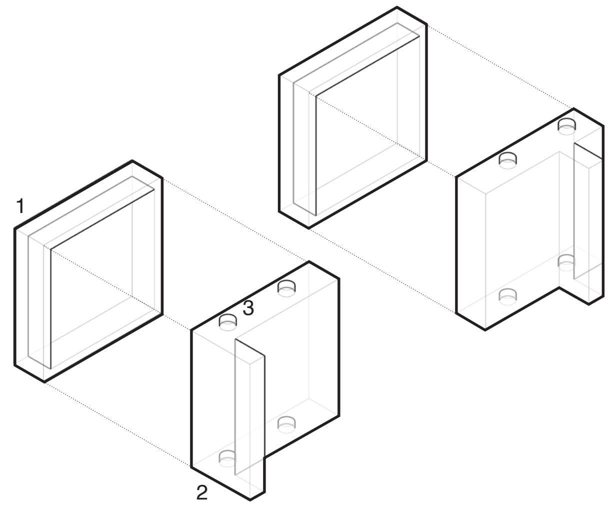
STIFFENER 1

The design of the stiffener is based on optimization of the material and efficient load transfer. The notch extrusion aids the transfer of loads in the vertical direction.



Alternate Stacking

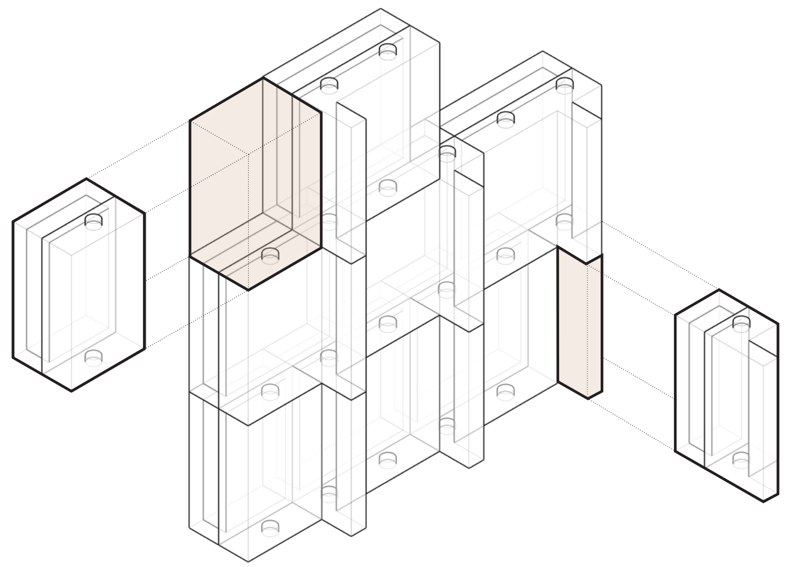
Interlocking is done similar to brick masonry. The top component holds two bottom blocks in one place.



Two components

Varied components stacked together to form an interlocking assembly system

1. Float glass
   6mm thk with 5mm e-coating & 20mm thk air cavity, non-recyclable
2. Cast glass
   100mm thk borosilicate glass, recyclable
3. Spherical Notch
   25mm diameter borosilicate glass, recyclable
4. Interlayer
   1-5mm thk made of transparent material



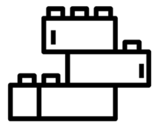
Corner components

Varied components stacked together to form an interlocking assembly system

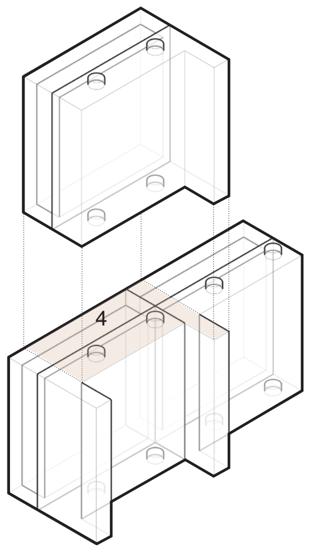
STIFFENER 2

This is the continuation of the previous design which tries to increase the level of transparency by shifting the notch towards the corner.

Hollow + Solid

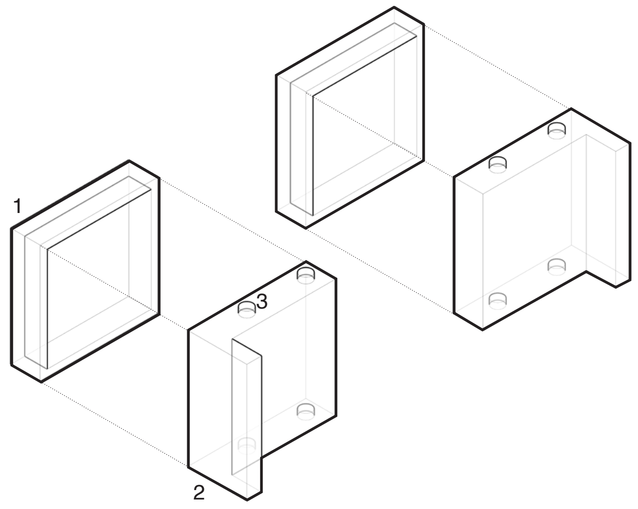


Dry Assembly



Vertical Stacking

Interlocking is done only in vertical direction



Two components

Varied components stacked together to form an interlocking assembly system

1. Float glass

6mm thk with 5mm e-coating & 20mm thk air cavity, non-recyclable

2. Cast glass

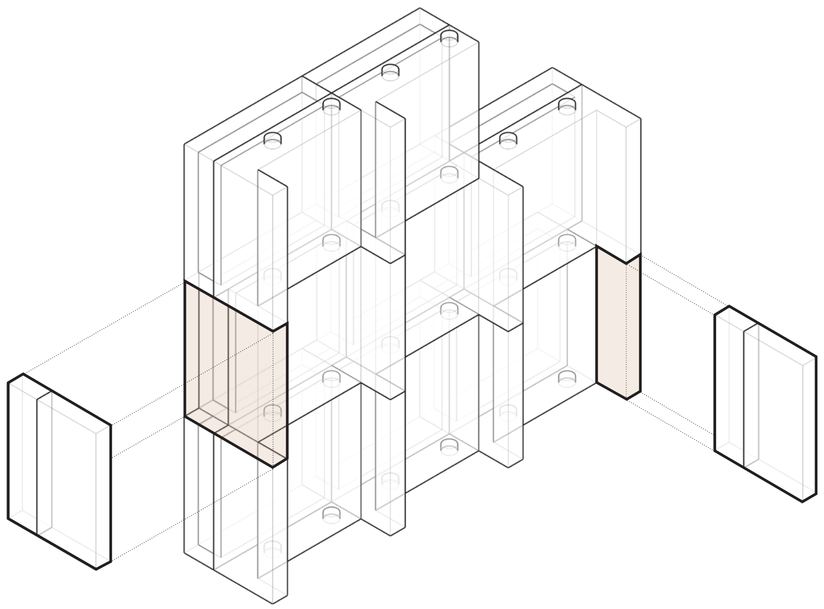
100mm thk borosilicate glass, recyclable

3. Spherical Notch

25mm diameter borosilicate glass, recyclable

4. Interlayer

1-5mm thk made of transparent material



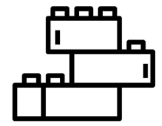
Corner components

Varied components stacked together to form an interlocking assembly system

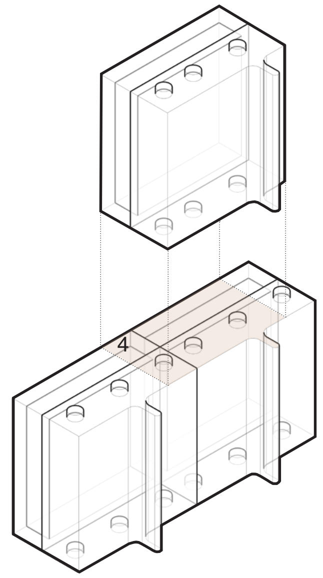
STIFFENER 3

This is the continuation of the previous design with much slender notch which tries to increase the level of transparency.

Hollow + Solid

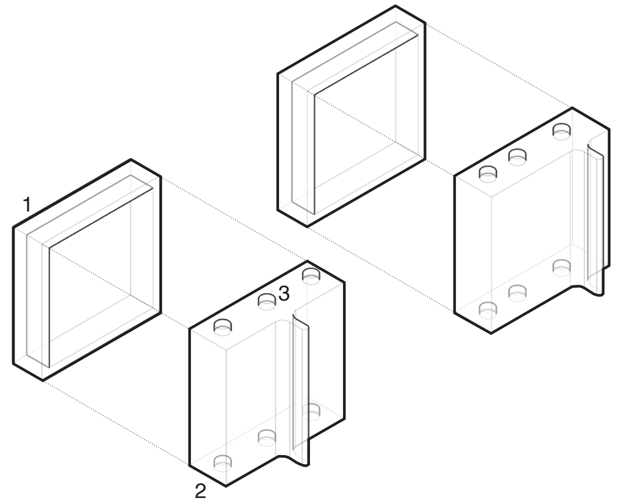


Dry Assembly



Alternate Stacking

Interlocking is done similar to brick masonry. The top component holds two bottom blocks in one place.



Two components

Varied components stacked together to form an interlocking assembly system

1. Float glass

6mm thk with 5mm e-coating & 20mm thk air cavity, non-recyclable

2. Cast glass

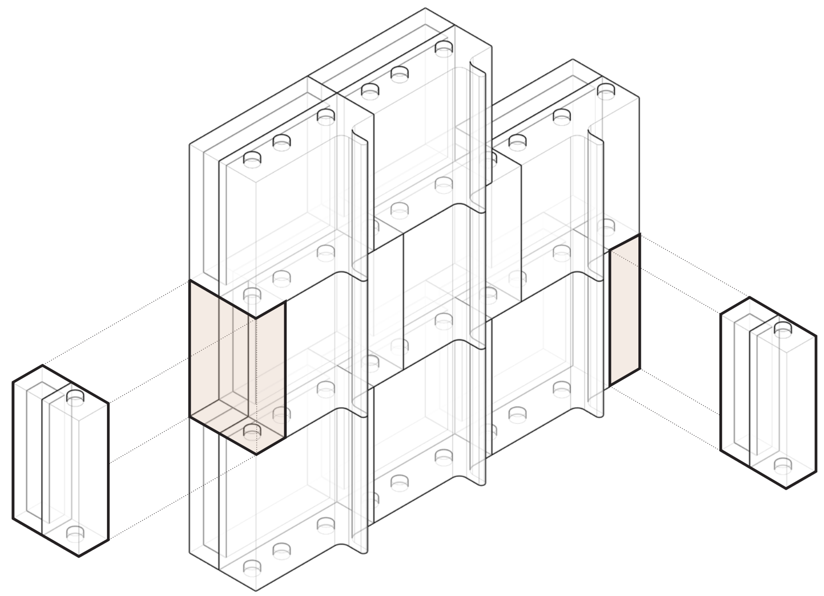
100mm thk borosilicate glass, recyclable

3. Spherical Notch

25mm diameter borosilicate glass, recyclable

4. Interlayer

1-5mm thk made of transparent material



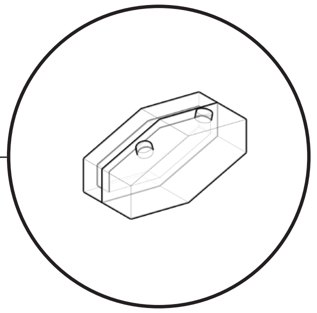
Corner components

Varied components stacked together to form an interlocking assembly system

07.6.2

GEOMETRY: ALL ALTERNATIVES

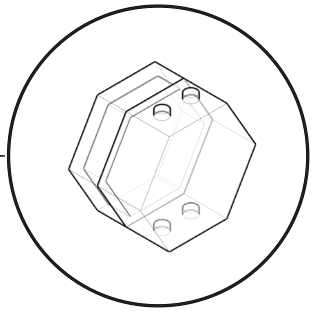
TRAPEZOID



- Efficient load transfer
- An issue with straight corners
- Many edges affect transparency

A different type of geometrical shape similar to a hexagon but a bit compressed is designed. The block performs extremely well under loading as seen from the Falconier's designs. The corner edges are tough to manage due to the presence of a tapered shape. The blocks look aesthetically pleasing, however, do not go with the existing design.

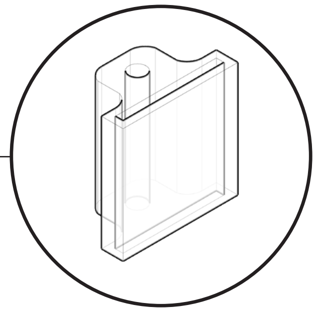
HEXAGON



- Aesthetically pleasing
- An issue with straight corners
- Many edges affect transparency

The hexagon or the honeycomb is the most common design shape. It performs well under loading and transfers load efficiently. The block looks aesthetically pleasing but does not go well with the existing design. The corner junctions are the issue along with the increased number of components. The manufacturing will be a bit time-consuming owing to its additional 2 planes.

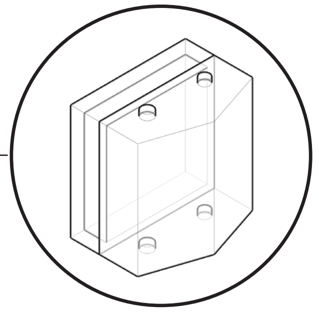
ARMOBLOCK



- Good load transfer & corner junctions
- Poor aesthetics & compromised transparency
- Additional component of rod

The armoblock is designed principally similar to the modular concrete block. The interlocking takes place with the guided rod which can be made of extruded glass. The transparency is affected and the distorted image is developed owing to continuous changes in the geometry. The corner junctions allow a 90-degree connection.

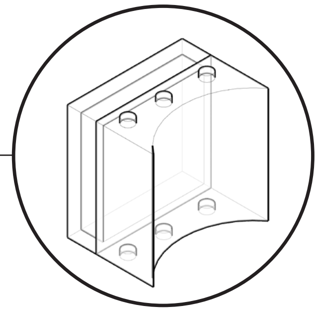
FLUET 1



- Efficient load transfer
- Good level of transparency
- Aesthetics could be better

The design of the fluet block is inspired by the wooden fluet profiles for wall decorations. The idea is to reduce or optimize the use of the material at the junctions where fewer stresses are developed. The tapering junction acts as a stiffener. This geometry however does not work well at the corners and requires an additional set of alternate block designs.

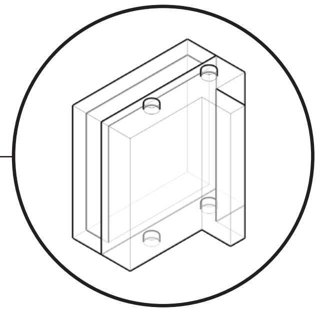
FLUET 2



- Good level of transparency
- Aesthetics could be better
- More number of components

This is similar to the flute 1 design, however, the tapering is at the corner to increase the level of transparency. The corner edges may create challenges during casting. This geometry however does not work well at the corners and requires an additional set of alternate block designs.

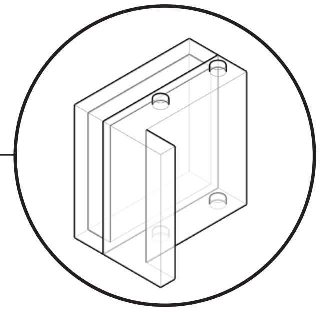
STIFFENER 1



- Efficient load transfer
- Good aesthetics
- Compromised transparency

The design of the stiffener is based on optimization of the material and efficient load transfer. The notch extrusion aids the transfer of loads in the vertical direction. The number of components required is however two.

STIFFENER 2



- Efficient load transfer
- Good level of transparency
- Good aesthetics

This is the continuation of the previous design which tries to increase the level of transparency by shifting the notch towards the corner. The stacking system is vertical and the loads are efficiently transferred. The corner junctions can be designed properly without any additional components.

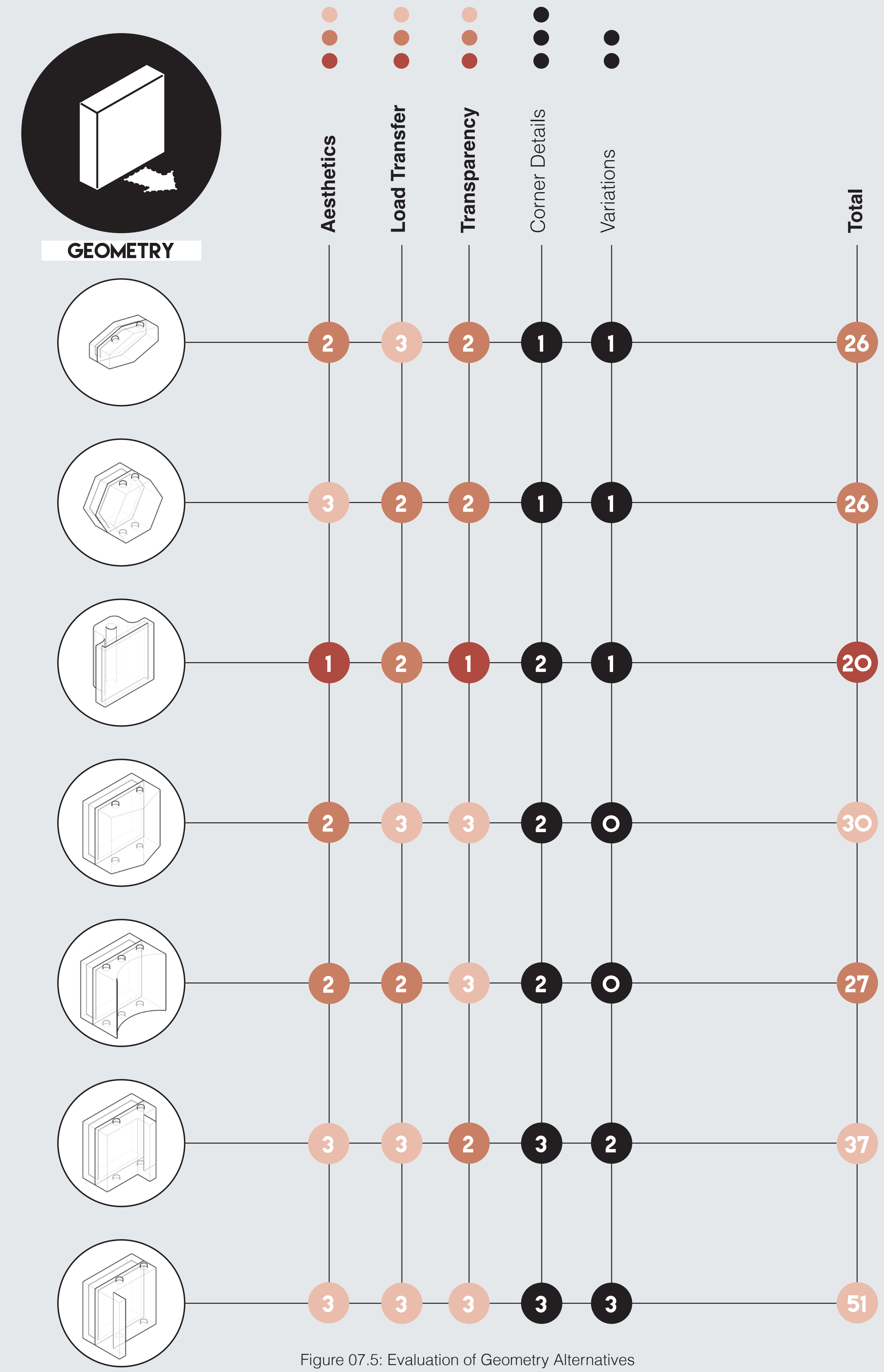
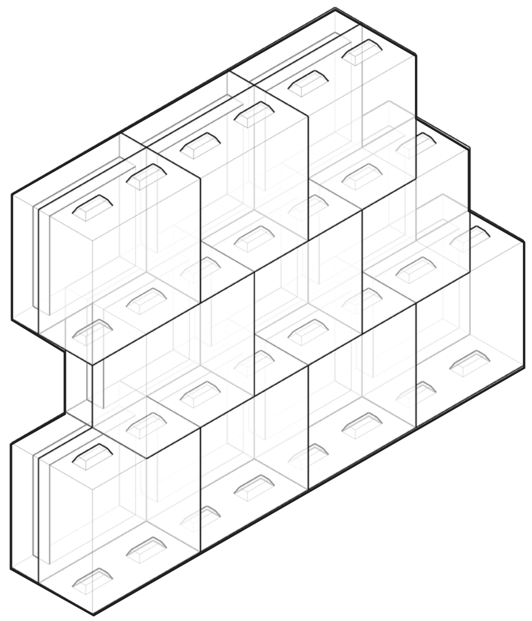


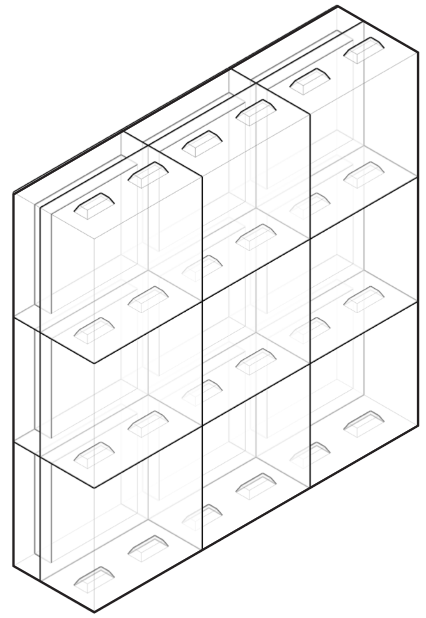
Figure 07.5: Evaluation of Geometry Alternatives

07.6.3

GEOMETRY: CONCLUSION



VS



ALTERNATE STACKING

Interlocking is done similar to brick masonry. The top component holds two bottom blocks in one place.

VERTICAL STACKING

Interlocking is done only in vertical direction

Based on the results of the comparison of the alternative, it is clear that the stiffener designs function well with all of the boundary conditions and specific design criteria. The stiffener-2 design allows for easier corner junctions as well as material consumption and further cross-section optimization. The amount of transparency attained is satisfactory; however, this can be improved by removing the notch.

The stacking approach may be developed on a comparison of both of these geometries. The aesthetic result for these geometries is shown in diagram (00).

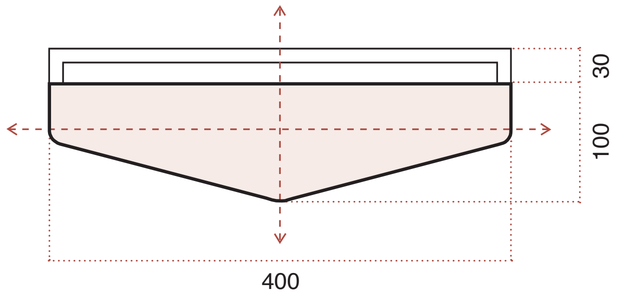
Vertical stacking was chosen because it allows for more flexibility in corner junctions while also resembling the current facade system of the Academy of the Arts building. The hollow glass structure resembles a grid within a grid, which has colossal importance in the Dutch architectural epoch of the early 1990s. It was critical to retain the historical and majestic picture of the existing facade system when making this deliberate decision.

07.7.1

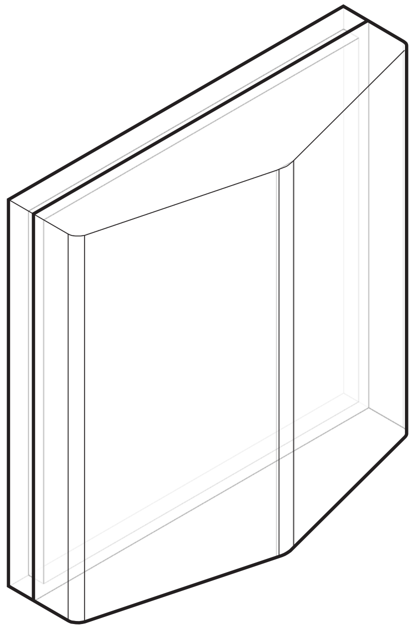
CROSS-SECTION EXPLORATION

TRAPEZOID - 1

Block dimension: 400*400 [mm]
Maximum Thickness: 100 [mm]
Cavity Size: 18 [mm]
U-Value: 2.6 [W/m2K]
Area of the Cross-section: 0.030[m2]
Volume: 0.012[m3]
Mass of the block: 26.76[kg]
Force: 262.51[N]
Compressive Strength: 0.009[MPa]



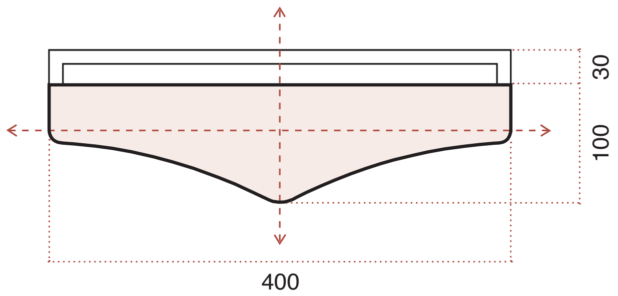
Plan



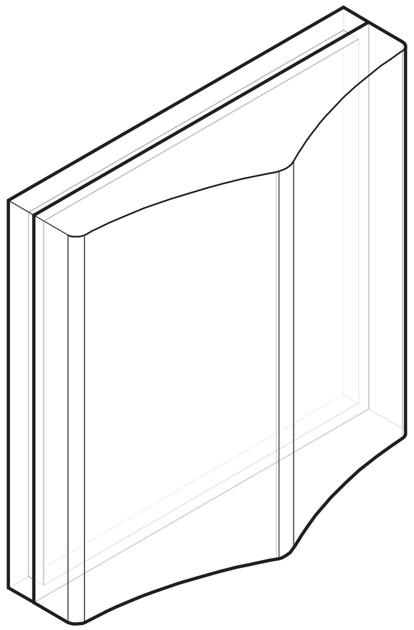
Isometric View

TRAPEZOID - 2

Block dimension: 400*400 [mm]
Maximum Thickness: 100 [mm]
Cavity Size: 18 [mm]
U-Value: 2.6 [W/m2K]
Area of the Cross-section: 0.026[m2]
Volume: 0.010[m3]
Mass of the block: 23.19[kg]
Force: 227.51[N]
Compressive Strength: 0.009[MPa]



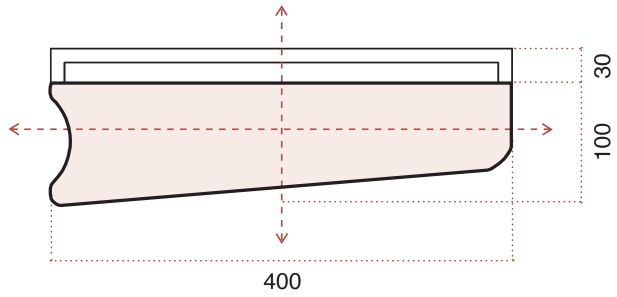
Plan



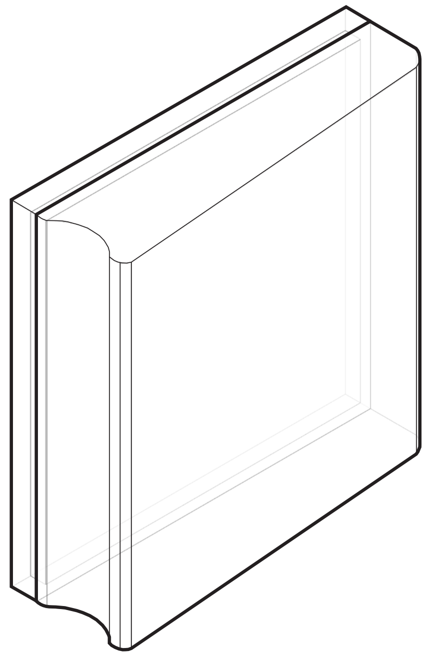
Isometric View

TRAPEZOID - 3

Block dimension: 400*400 [mm]
Maximum Thickness: 100 [mm]
Cavity Size: 18 [mm]
U-Value: 2.6 [W/m2K]
Area of the Cross-section: 0.034[m2]
Volume: 0.014[m3]
Mass of the block: 30.32[kg]
Force: 297.58[N]
Compressive Strength: 0.009[MPa]



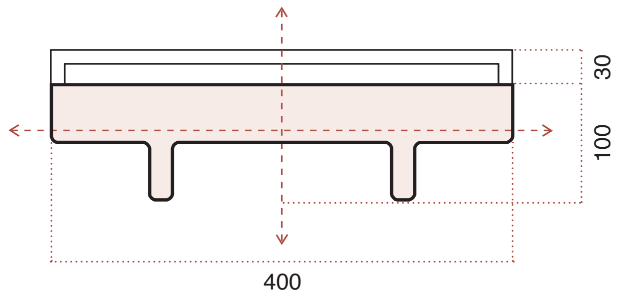
Plan



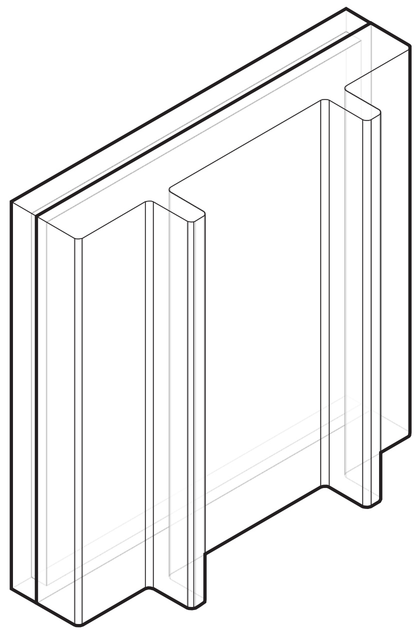
Isometric View

T-SHAPED

Block dimension: 400*400 [mm]
Maximum Thickness: 100 [mm]
Cavity Size: 18 [mm]
U-Value: 2.6 [W/m2K]
Area of the Cross-section: 0.022[m2]
Volume: 0.009[m3]
Mass of the block: 19.62[kg]
Force: 192.51[N]
Compressive Strength: 0.009[MPa]



Plan



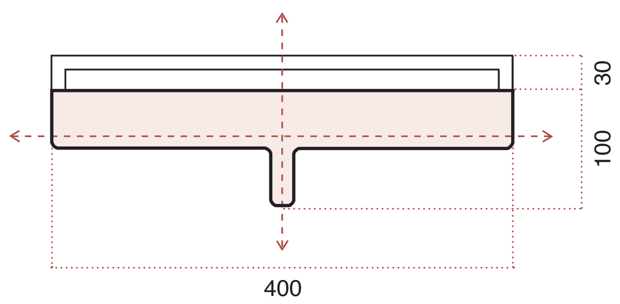
Isometric View

07.7.1

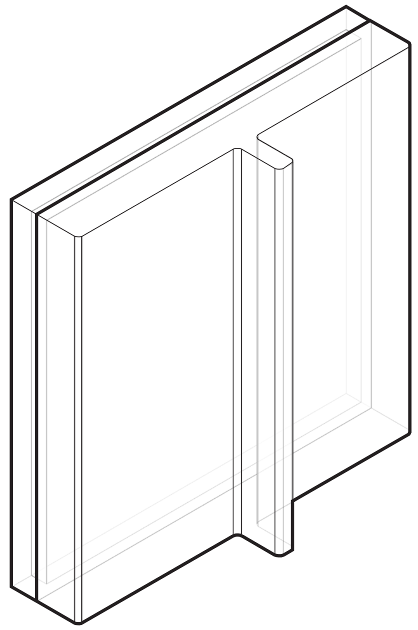
CROSS-SECTION EXPLORATION

T-SHAPED

Block dimension: 400*400 [mm]
Maximum Thickness: 100 [mm]
Cavity Size: 18 [mm]
U-Value: 2.6 [W/m2K]
Area of the Cross-section: 0.021[m2]
Volume: 0.008[m3]
Mass of the block: 18.73[kg]
Force: 183.76[N]
Compressive Strength: 0.009[MPa]



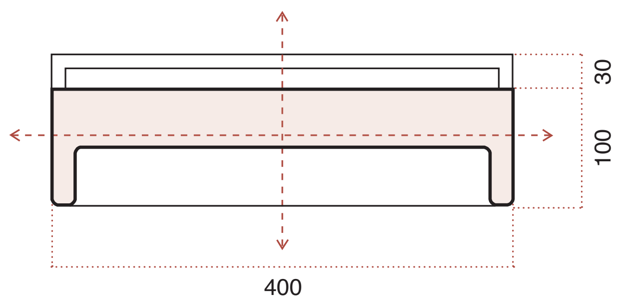
Plan



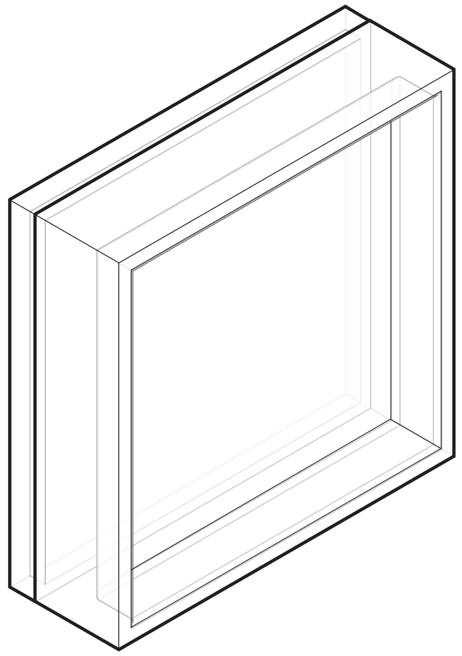
Isometric View

C-SHAPED 1

Block dimension: 400*400 [mm]
Maximum Thickness: 100 [mm]
Cavity Size: 18 [mm]
U-Value: 2.6 [W/m2K]
Area of the Cross-section: 0.040[m2]
Volume: 0.013[m3]
Mass of the block: 29.90[kg]
Force: 293.317[N]
Compressive Strength: 0.007[MPa]



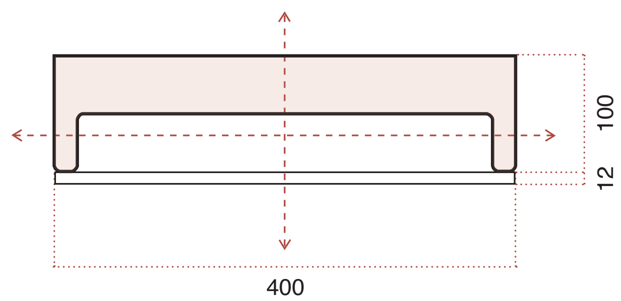
Plan



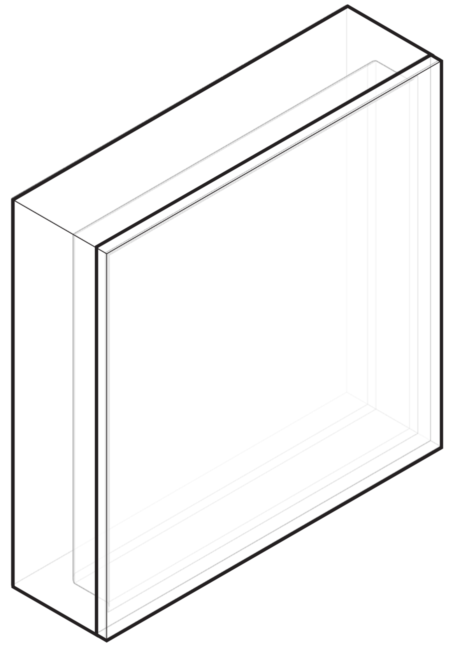
Isometric View

C-SHAPED 2

Block dimension: 400*400 [mm]
Maximum Thickness: 100 [mm]
Cavity Size: 18-2 [mm]
U-Value: 2.63 [W/m2K]
Area of the Cross-section: 0.040[m2]
Volume: 0.013[m3]
Mass of the block: 29.9[kg]
Force: 293.31[N]
Compressive Strength: 0.007[MPa]



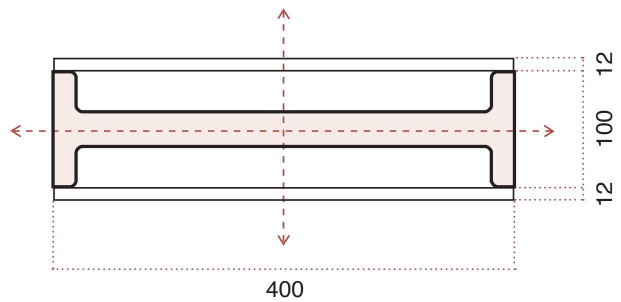
Plan



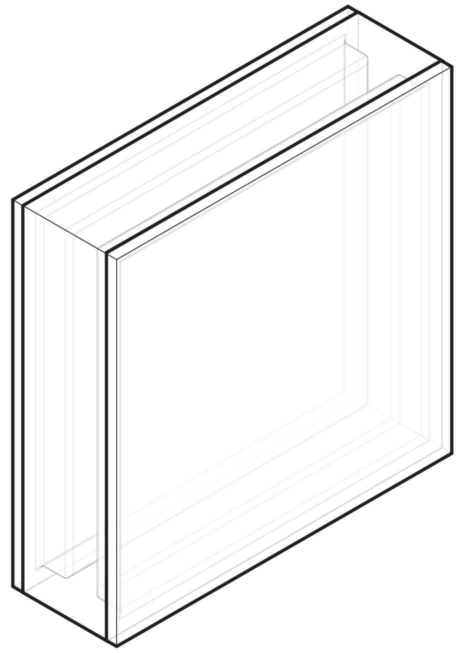
Isometric View

I-SHAPED

Block dimension: 400*400 [mm]
Maximum Thickness: 100 [mm]
Cavity Size: 18-2 [mm]
U-Value: 1.71 [W/m2K]
Area of the Cross-section: 0.040[m2]
Volume: 0.011[m3]
Mass of the block: 24.12[kg]
Force: 236.61[N]
Compressive Strength: 0.006[MPa]



Plan

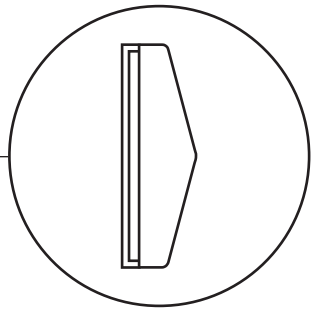


Isometric View

07.7.2

CROSS-SECTION: ALTERNATIVES

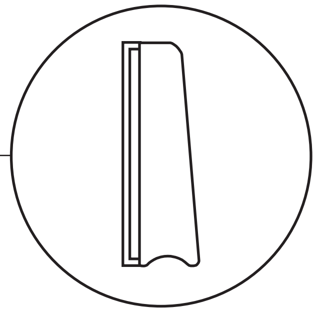
TRAPEZOID 1



- Good level of transparency
- Average load transfer and thermal performance
- Issue with weight

The designed cross-section is the translation of fluet-type geometry. This cross-section has a good level of transparency, however, the load transfer and thermal performance are average. The sound insulation is good owing to its thickness, however, the weight of the cross-section is the issue.

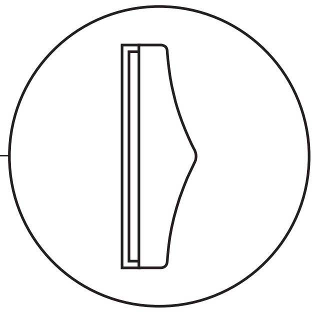
TRAPEZOID 3



- Issue with load transfer
- Issue with mass distribution
- Issue with the weight

This cross-section is designed to check how such irregular-shaped designs work under loading and mass distribution. Even though this design adheres to the casting process, the load transfer is slightly imbalanced. Transparency is not highly compromised, but weight is an issue.

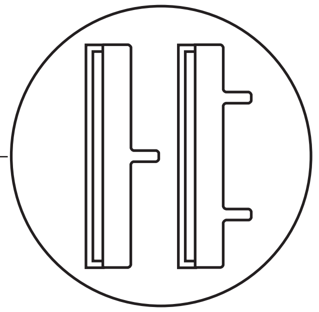
TRAPEZOID 2



- Good level of transparency
- Works good in casting process
- Average load transfer and thermal performance

This cross-section works similarly to the previous design, however, the curved surfaces allow ease in casting due to the sagging process and are possible for weight reduction. The thermal and structural performance is similar. The transparency is good. There is a scope for further optimization however the weight will remain the issue.

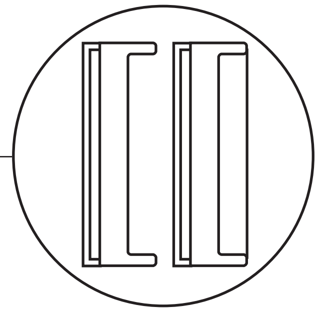
T-SHAPED



- Average load transfer
- Average thermal and sound insulation
- Compromised transparency

Potentially this cross-section is the most promising design, however, it has average performance under all the boundary conditions and design criteria. The notches provide a great level of stiffness, but the key issue is with the center of mass being near the thinner notch. Stress can be easily developed.

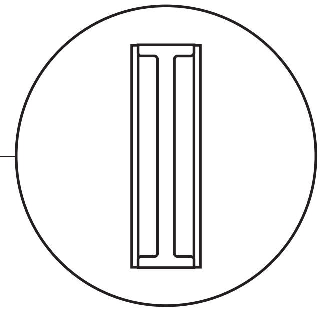
C-SHAPED 1



- Efficient load transfer & ease in manufacturing
- Enhanced transparency
- Unbalanced mass distribution

Two variants of these cross-sections are designed. The first one is C-type but in the vertical direction and the next one is in all directions. The cross-section works well for load transfers however the thermal performance is similar to previous designs. The transparency is enhanced.

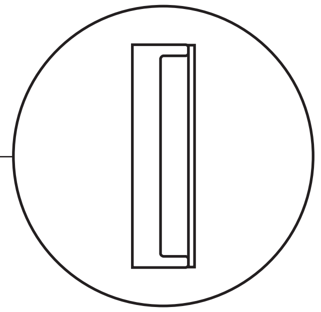
I-SHAPED



- Efficient load transfer & thermal performance
- Ease in manufacturing
- Transparency compromised - more glass layer

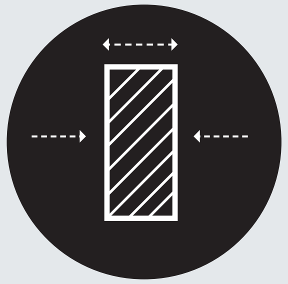
The I-type cross-section is designed with the consideration of a symmetrical design which results in equal mass distribution and the possibility for thickness and weight optimization. The design naturally creates two cavities that aid the thermal performance. The sound insulation is also better due to the presence of two cavities.

C-SHAPED 2

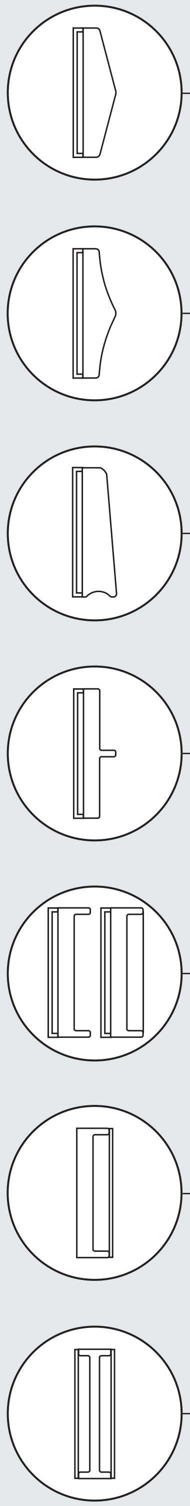


- Efficient load transfer & ease in manufacturing
- Enhanced transparency
- Unbalanced mass distribution

The C-type cross-section is the evolution of the previous cross-section with a slight change in the location of the flat glass plate. This design works well in all the boundary conditions, however, the mass is not distributed due to the asymmetrical design. Due to only one cavity, the thermal performance and sound insulation are similar to the previous design. The transparency is good.



CROSS-SECTION



Load Transfer	Thermal Performance	Manufacturing	Transparency	Center of Mass	Weight	Sound Insulation	Total
2	2	2	3	2	1	2	34
2	2	3	3	2	2	2	40
1	2	2	3	1	1	2	31
2	2	2	2	2	2	2	33
3	2	3	3	2	2	2	43
3	2	3	3	2	2	2	43
3	3	3	2	3	3	3	48

Figure 07.6: Evaluation of Cross-section Alternatives

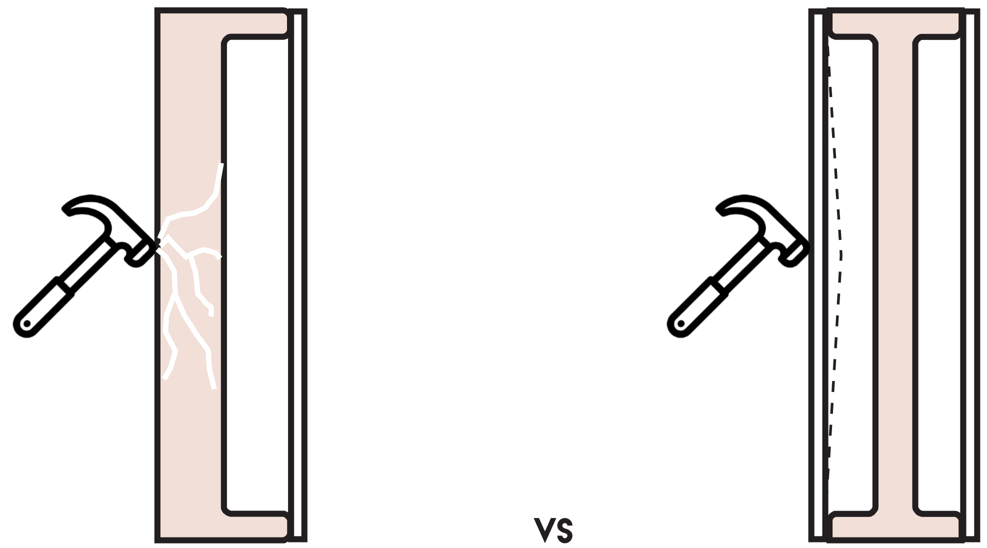
07.7.3

CROSS-SECTION: CONCLUSION

According to the results of the alternative comparison, the two cross-section designs (I & C) are efficient in terms of the stipulated boundary conditions and design requirements. Both of these cross-sections use their natural shape to create a niche that results in a cavity and improves thermal performance. More emphasis is placed on the cross-section that functions well under loads, and theoretically, the cross-section with a symmetrical cross-section will be more stable.

The comparison of the mass of these two designs reveals that there is a lot of space for weight reduction. The weight optimization (Appendix .1) is accompanied by changes in cross-section thicknesses. This also contributes to increasing the cavity depth and allowing for significantly better heat resistance in the design.

Finally, the I cross-section works better than the C cross-section in the risk analysis since the structural component is always safe with two glass plates covering it. Eventually, I cross-section is considered for additional detailing.



C TYPE CROSS-SECTION

1. The structural cast glass component & flat glass plates are prone to structural damage during vandalism or any risk scenario

2. The natural shape of the C type cross-section aids in the development of a single cavity

3. The mass distribution of the cross-section is oriented in one direction.

I TYPE CROSS-SECTION

1. The structural cast glass component is never prone to structural damage. The flat glass plates are prone to damage during vandalism or any risk scenario

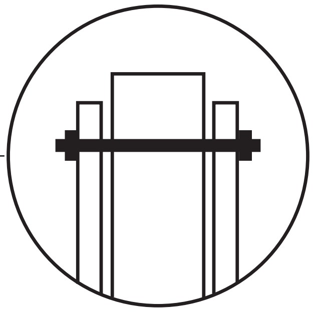
2. The natural shape of I type cross-section aid in the development of double cavities. In comparison to the C type, the thermal performance will be better.

3. The mass is equally distributed due to a symmetrical cross-section

07.8.1

UNIT CONNECTION ALTERNATIVES

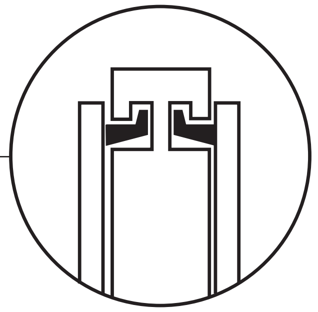
BOLTED



- Good for disassembly and manufacturing
- Average aesthetics and replaceability
- Issue with air-tightness

A mechanical type of connection is considered to connect the two float glass panels to the inner cast glass component. The metal or glass screw goes through the blocks and is bolted on both sides due to the presence of a continuous hole in the cross-section at 4 different locations, the thermal bridges are created and airtightness is also an issue.

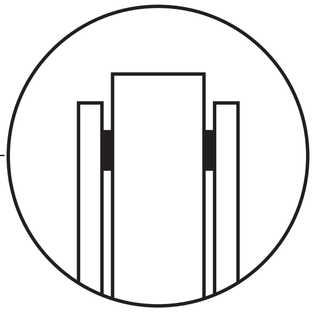
SNAP-FIT



- Good for disassembly and replaceability
- Ease in manufacturing
- May have issue with air-tightness

These are pre-existing connecting systems that are used to connect geometries. Plastic or thermoplastic materials can be used. Plastics avoid thermal bridging; yet, the snap-fit should be able to produce airtightness in the cavity to prevent moisture accumulation.

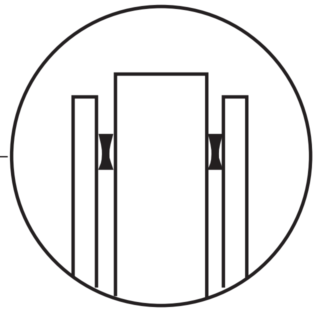
ADHESIVE



- Good aesthetics and ease in manufacturing
- Good for air-tightness
- Issue with disassembly and replaceability

Using Adhesive or silicone is the most traditional way to connect glass components. It creates an airtight cavity and no thermal bridges. The issue is the disassembly, replicability, and contamination of the cast glass surface.

SUCTION



- Good for disassembly and replaceability
- Manufacturing can be challenging
- May have issue with air-tightness

This technique is already relevant to lifting glass panels using suction plates. A similar approach can be used to connect two glass components. The connection is completely dry, however, it is not known how much pressure is required to create the required bond between glass surfaces to hold them together.

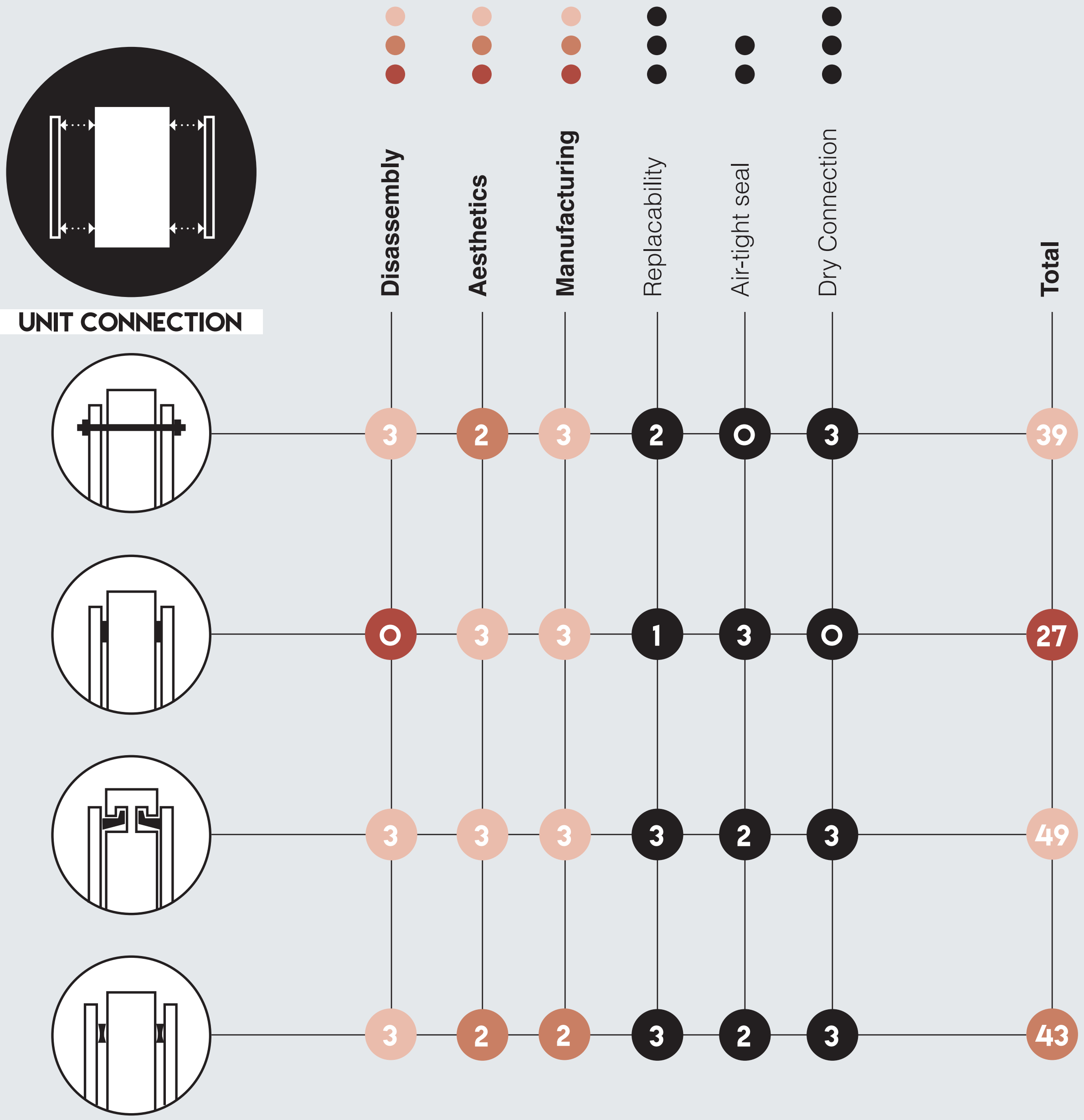


Figure 07.7: Evaluation of Unit Level Connection Alternatives (Author)

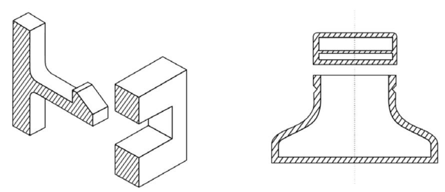
07.8.2

SNAP-FIT CONNECTIONS

Snap-fit joints use interlocking characteristics to connect two 3D-printed components quickly and easily. They are not only a low-cost, time-saving connecting method, but they may also minimize the number of parts required in an assembly. Furthermore, they allow for quick construction and disassembly. The premise behind all forms of snap joints is that a projecting element of one component, such as a hook, stud, or bead, is displaced quickly during the joining procedure and catches in a groove (undercut) in the opposite element. (Hubs) Following the joining process, the snap-fit elements must be stress-free. Depending on the form of the undercut, the joint may be detachable or inseparable; the force required to separate the components varies substantially depending on the design. When constructing snap joints, it is especially crucial to keep the following things in mind:
1. Mechanical stress during the assembling process.
2. Assembly necessitates the use of force. (Hubs)

Snap joints can be designed in a variety of ways. Plastics are often extremely ideal materials for this connecting process due to their high level of flexibility.

The cantilever joint is the most typical snap-fit junction, consisting of a protrusion at one side of the beam and a structural support at the other. This protrusion deflects when it is put into a cut-out or slot. When fully entered, the protrusion bends back to secure the connection. Cantilever snap-fits are simple to design and simple to utilize during assembly and removal. In many circumstances, this is the cheapest approach to connect two elements.

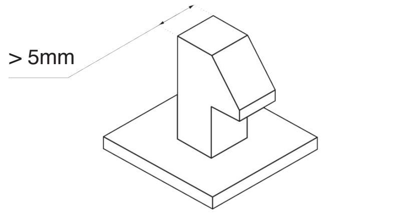


Cantilever   Annular

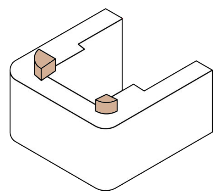
Figure 07.8: Snap-fit types (Hubs)

07.8.3

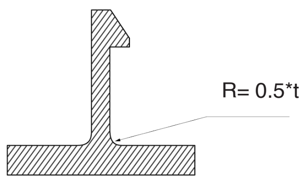
SNAP-FIT PRACTICES



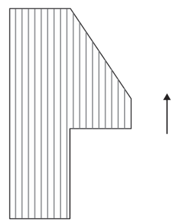
Increase Width of the clip



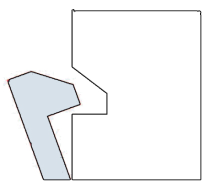
Add Lugs for alignment



Fillet the base of cantilever for stress distribution



Consider build direction



Deflect only during assembly

Figure 07.9: Snap-fit practices (Hubs)

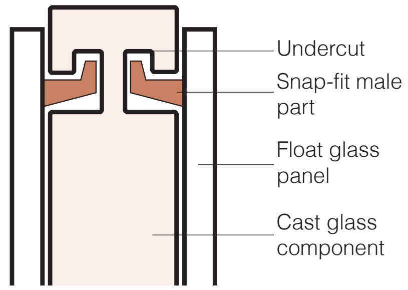
07.8.4

UNIT CONNECTION: CONCLUSION

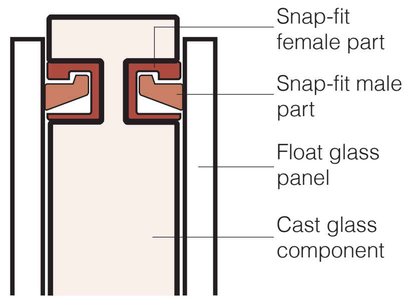
According to the alternative comparison, snap-fit connectors are the best for the cast glass to float glass connection. They are simple to construct and disassemble and allow considerably greater flexibility when replacing. The most significant consideration is the airtightness necessary to form a cavity between two glass components.

A cast glass component that can be molded into the required shape is a cantilevered sort of snap fit. While the connecting mechanism is feasible, the undercut feature complicates casting the glass block in the necessary form. The mold should be cut at the undercut junction or require a flexible sliding mechanism. These sorts of molds should be avoided for casting since the goal is to have an efficient and rapid manufacturing process.

Option B is an easy answer to this problem. A cantilever snap-fit can be designed with the male portion adhesively bonded to the float glass panel and the female part made as a profile that can be fitted in the niche designated for the cat glass components. The profile can be bonded or lugs in the shape of an annular snap-fit, with equal joints that can be put into the niche. The latter design approach is suggested because it eliminates adhesive or glue contamination of the cast glass component and adheres to the principle of reversibility. The design rules and procedures determine the size of the snap-fit connectors.



OPTION A



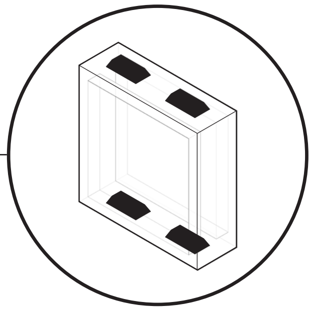
OPTION B

Figure 07.10: Snap-fit details Option

07.9.1

ALIGNMENT: ALTERNATIVES

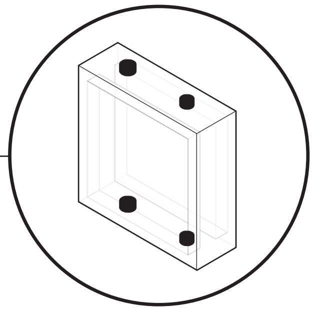
LEGO



- Good in terms of self alignment
- Average load transfer & manufacturing ease
- Disassembly possible ony from top

These alignments are very commonly seen in the lego blocks. The larger surface area enhances the load transfer. There is a top extrusion and bottom opening to hold pieces in one place. Replacement can be only done through either breaking or top direction

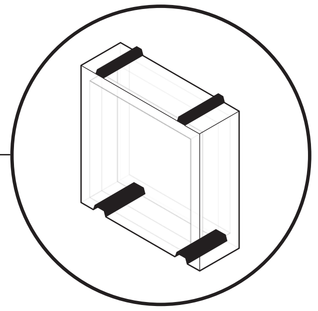
HEMISPHERICAL



- Good level of transparency & self-alignment
- Issue with manufacturing ease
- Issue with load transfer and disassembly

These alignments are very common and can be seen in most modular building blocks. The spherical notch has an extrusion on the top and a similarly shaped opening at the bottom to hold two pieces in one place. Due to its geometry, the load transfer is good, however, the size of the geometry required structural validation.

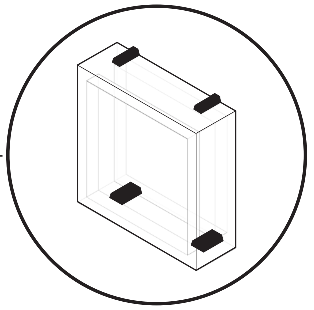
RUNNER



- Good for disassembly
- Average manufacturing & transparency
- Poor load transfer, issue of sliding

These are similar to the lego shape, however, the orientation is changed to allow replaceability in both directions. The key issue is with the load transfer as the blocks might slide due to lateral loads due to the absence of an interlocking element.

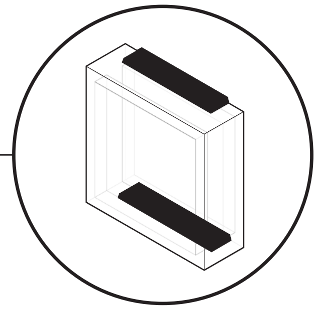
HALF RUNNER 1



- Good in terms of disassembly & self-alignment
- Average load transfer
- Average transparency

The design is slightly evolved from the runner alignment. These allow replaceability in one direction and provide an interlock that is a bit away from the center. The load transfer may vary, however, these work well in terms of the lateral loading.

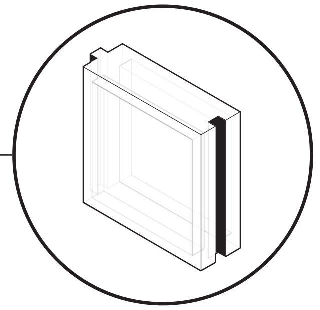
HALF RUNNER 2



- Efficient load transfer, manufacturing
- Good in terms of disassembly & self-alignment
- Compromised transparency

This design evolved from the previous designs that tries to resolve all the issues. The surface area is increased to allow stable load transfer. The orientation is changed to the lego type. This design works well in terms of self-alignment however the transparency might be affected due to the presence of a longer component.

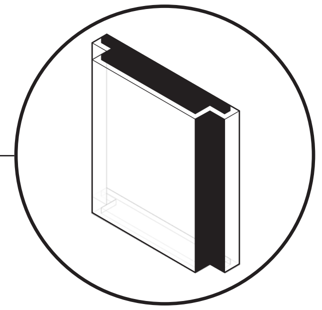
VERTICAL PROFILE



- Good transparency
- Average manufacturing ease
- Poor load transfer and disassembly

The vertical alignment provides ease in assembly and a good level of transparency. The issue is with the load trad transfer in a downward direction due to the absence of interlock between the top and bottom surfaces of the glass blocks. The blocks can be only replaced from above.

VERTICAL +OFFSET



- Good for load transfer & self alignment
- Average in manufacturing easy & disassembly
- Compromised transprency

This design uses the concept of vertical and offsets alignment. The verticals make it easy to guide the blocks during assembly and take lateral loads. The offset works like an interlock to efficiently transfer loads. The issue is with the replaceability that is alternatively oriented inside and outside.

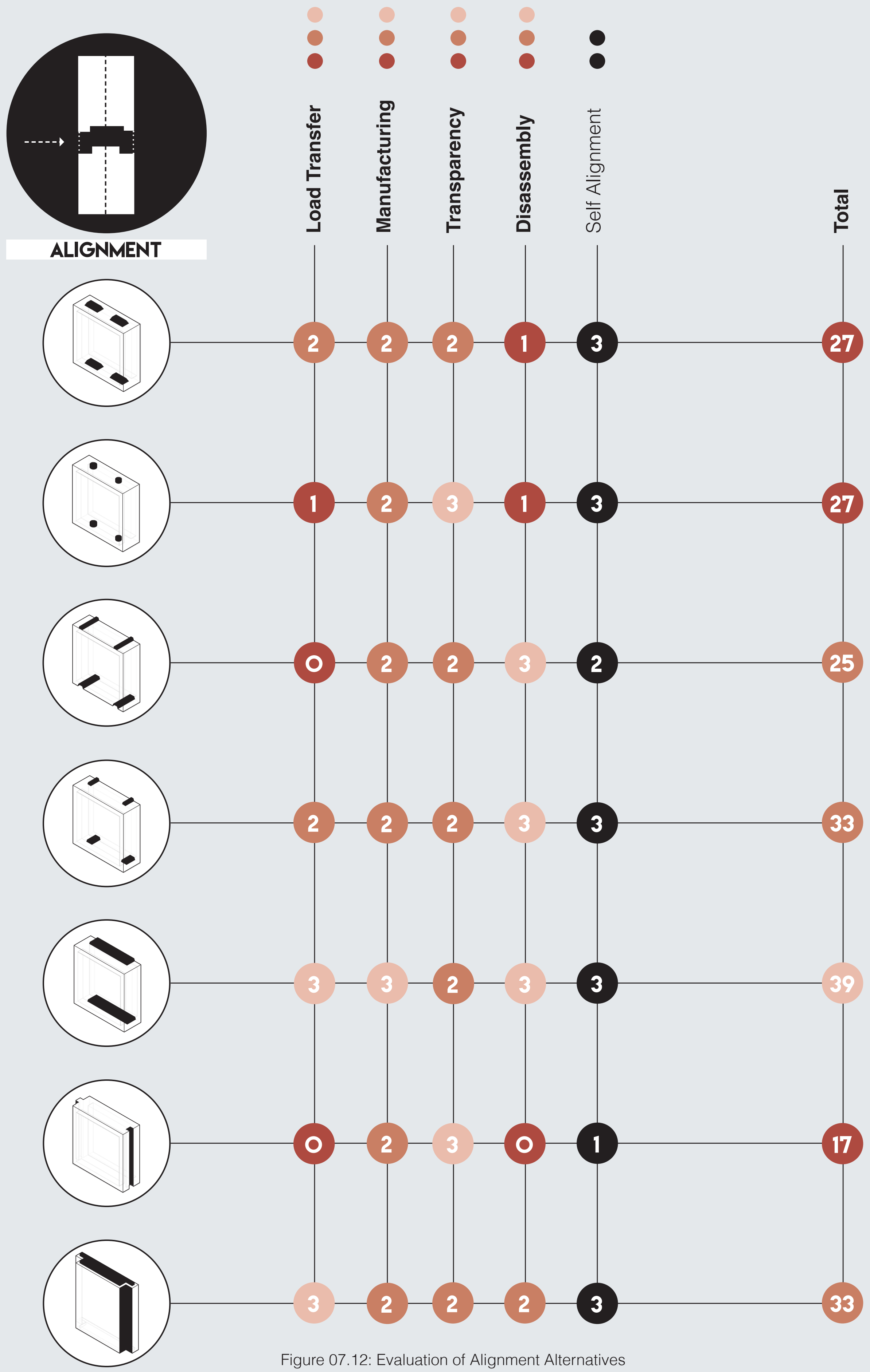


Figure 07.12: Evaluation of Alignment Alternatives

07.9.2

ALIGNMENT: CONCLUSIONS

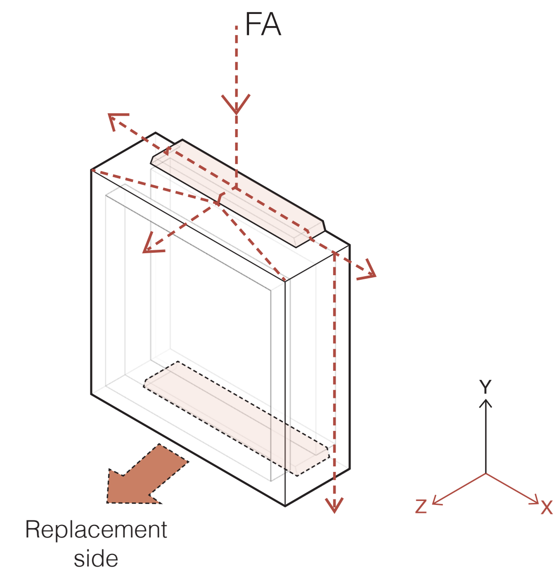
The alignment's fundamental goal is to interlock two glass blocks and efficiently transmit the load. The alignment's design is heavily influenced by the interlocking mechanism and load transmission, but it should also be simple to assemble. The ability of the block to slide over another and align itself is critical for accelerating the assembly process.

However, the design for disassembly and the ability to replace the block from the system are key boundary conditions. The interlocks are meant to stabilize the top and bottom blocks in one central axis for efficient load transmission, but also to prevent the blocks from moving in the X and Z directions when subjected to lateral loads such as wind or perhaps even leaning over the system.

Based on a comparison of the alternatives, the half-runner 2 design meets all of the boundary conditions and design criteria. For effective load transmission, the alignment has a higher surface area. To eliminate stress concentration at the junction, the edges are filleted and tapered in the direction of load transmission. Half of the top block is held in the X direction and the other half is in the Z direction. This indicates that the block requires a connection mechanism that will securely link the top as well as surrounding blocks in the Z direction.

The determination to use this design was determined by the ability to slide the block outward in the instance of replacement and position the new block in the same area without breaking the block in two, thus retaining the structural integrity of the system. The challenge here is redundancy; because the top and side blocks are not entirely supported by the bottom block, the connecting system must be built for redundancy.

One challenge here is that the alignment is eccentric to the axis of the structural glass cross-section which may lead to bending of the system. The strategies to reduce eccentricity are discussed in Design Evaluation (Chapter 11)



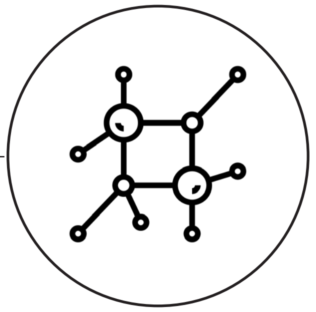
HALF-RUNNER 2

Figure 07.13: Load transmission & replacement direction

07.10.1

INTERLAYER: ALTERNATIVES

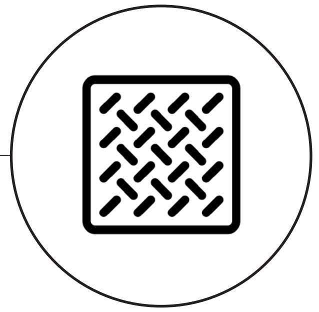
POLYMERS



- Good in load transfer & shaping
- Good level of transparency & durability
- Average resistance to creep

These are visco-elastic materials with both solid and liquid characteristics. They are easily adaptable to changes in form, however, they are prone to creep. Polymers such as PU, PVC, and Vivak are being studied for interlayer. They are durable and function well under static compression.

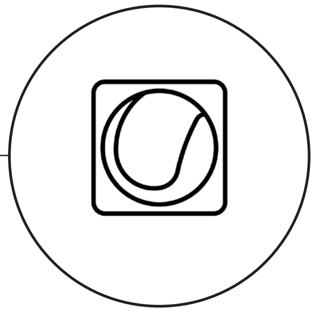
METALS



- Efficient load transfer and shaping
- Resistant to creep
- Poor thermal expansion & transparency level

The glass should not be kept in close contact with the metal surface to minimize stress development; however, this is not true for all metals. Materials such as copper, aluminum, and lead may be produced in thinner sheets, which may help to prevent stress development. Metals never creep at room temperature.

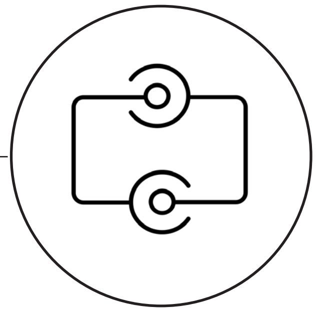
ELASTOMERS



- Good in compression & durability
- Average resistance to creep
- Compromised transparency

Elastomers are widely employed as sealants or between layers in glass-to-glass and glass-to-metal connections. Silicone is the most often used sealant, followed by neoprene. Teflon has high potential because of its durability and stiffness. Elastomers withstand well to long-term compression.

HYBRIDS



- Efficient load transfer & durability
- Issue with manufacturing
- Unknown thermal expansion coefficients

In terms of compression performance, a combination of two or more materials can produce outstanding results. The mixing of polymers with metal to create a creep-resistant and robust interlayer might be a promising combination. Metal foams, layered PU, and softcore aluminum are among the hybrids under consideration.

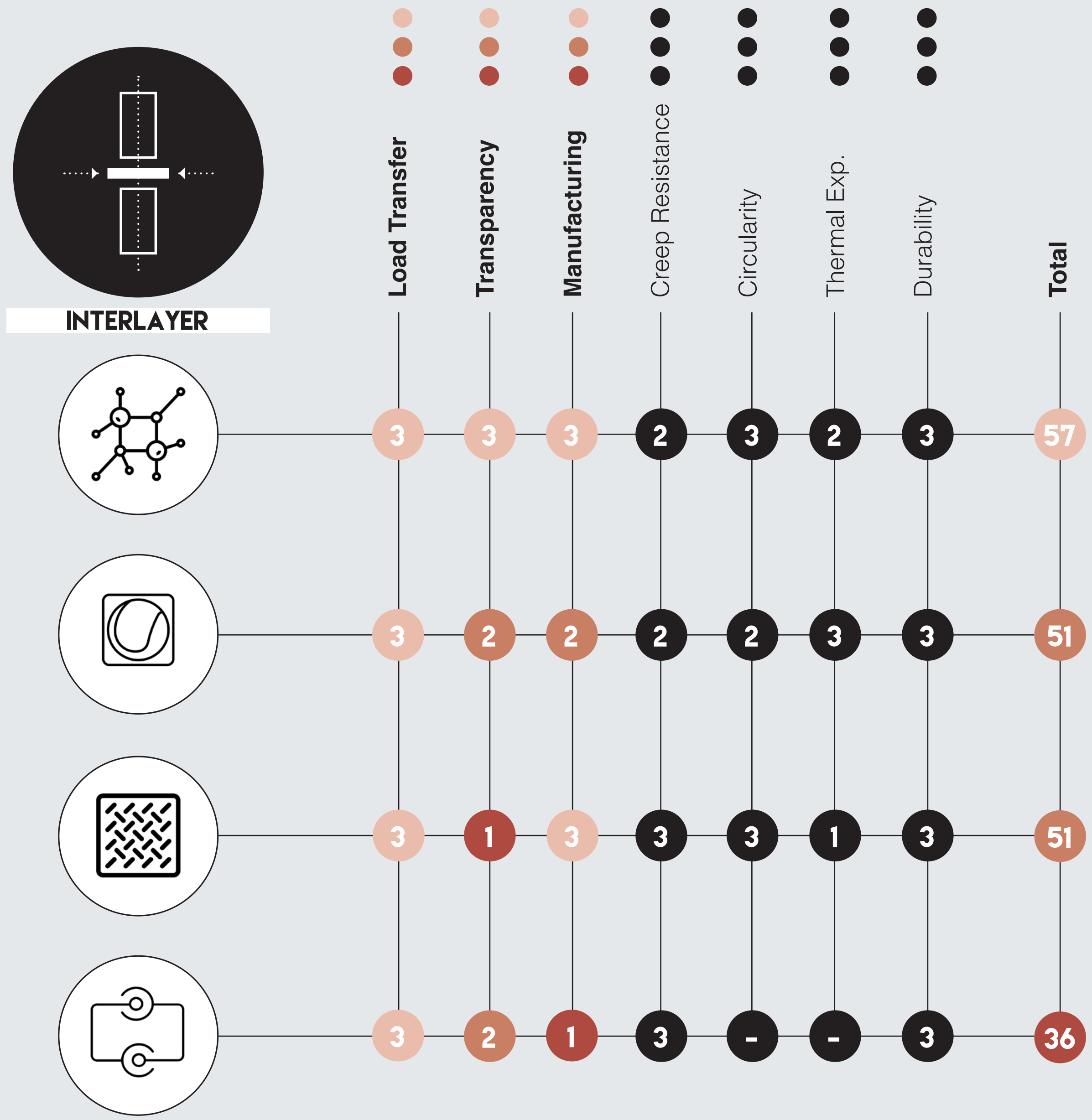


Figure 07.14: Evaluation of Interlayer Alternatives

07.10.2

INTERLAYER: CONCLUSION

The interlayer material alternatives comparison shows two viable options: polymers or metals. However, it is critical to evaluate the specific materials from the possibilities. Deeper research of a specific material is conducted to gain a distinct viewpoint. Polyurethane and Vivak were chosen from the polymer family, aluminum from the metal family, neoprene from the elastomers, and laminated PU from the hybrid family.

The comparison of these shortlisted materials indicates that there are two viable options to explore. These are chosen based on the aforementioned boundary requirements and criteria.

The first choice is Vivak, which is either transparent or translucent and can be vacuum-formed into the desired shape. This option is suitable for assembly systems when precompression is required. Aluminum can be used in assembly systems where pre-compression is not possible owing to site constraints.

The thickness of the interlayer can be found by using the Auriks formula and is discussed in depth in the next discussion.

		POLYMERS		ELASTOMER	METAL	HYBRID
		PU	Vivak	Neoprene	Aluminum	Laminated PU
BOUNDARY CONDITIONS	Compressive Strength >20MPa	YES	YES	YES	YES	YES
	Creep Resistance	UNKNOWN	UNKNOWN	UNKNOWN	YES	MAYBE
	Tear Strength	-HARDNESS	SATISFACTORY	SATISFACTORY	HIGH	HIGH
	Shaping Ability	YES	YES	NO	YES	MAYBE
	Manufacturing	INJECTION MOULDING	VACCUM FORMING	NA	PRESS FORMING	NA
CRITERIA	Circularity	YES	YES	YES	YES	MAYBE/NO
	Optical Quality	TRANSPARENT/ TRANSLUCENT	TRANSPARENT/ TRANSLUCENT	OPAQUE WHITE	REFLECTIVE SILVER	TRANSLUCENT/ OPAQUE
	Thermal expansion Coefficient	90-92	120-130	110-240	18-26	UNKNOWN
	Durability	YES	YES	YES	YES	YES

Table 07.1: Interlayer Material comparision adapted from (Dimas, 2020)

07.10.3

INTERLAYER: CALCULATIONS

For the development of hybrid glass blocks the material chosen is borosilicate glass with a maximal tensile strength of 15MPa. Therefore, the stress at the surface of the glass should not exceed more than the maximal tensile strength of the glass that is 15MPa.

$$\delta_{contact} \leq 15 \ [\mathrm{MPa}] \qquad ..1$$

The $E_{interlayer}$ might be determined by the thickness of the interlayer and the overall stiffness of the structure. (Aurik, 2017)

The amount of stress it can withstand is comparable to the material's maximum tensile stress. (Oikonomopoulou et al., 2014)

$$\delta_{contact} = E_{int.} * \frac{2\Delta}{t_{int.}} \qquad ..2$$

Δ Deviation in the components [0.25mm]

E_{int} Young's modulus of Interlayer

$t_{int.}$ Thickness of the interlayer

Combining equation [1] & [2] we get,

$$E_{int.} \leq [15 * t_{int.}]/2\Delta \qquad ..3$$

For an interlayer thickness of 1mm to 2mm the suggested range of E_{int} is,

$$30 \ [\mathrm{MPa}] \leq E_{int.} \leq 60 \ [\mathrm{MPa}]$$

The selected interlayer is vivak with a tensile strength of 15 [MPa]

To calculate the thickness of interlayer we use following equation,

$$t_{int.} \geq \frac{2.\Delta}{1 - \frac{\delta_{avg}}{E_{int.}}} \qquad ..4$$

Δ Deviation in the components [0.25mm]

E_{int} Young's modulus of Interlayer [15 MPa]

δ_{avg} Force on the Block / Area of the Block [3.9 MPa]

Substituting above values in equation [4] we get,

$$t_{int.} \geq \frac{2*0.25}{1 - \frac{3.9}{15}}$$

$$t_{int.} \geq 0.50 \ [\mathrm{mm}]$$

This is too thin, therefore for the selected design the 2 [mm] is sufficient.

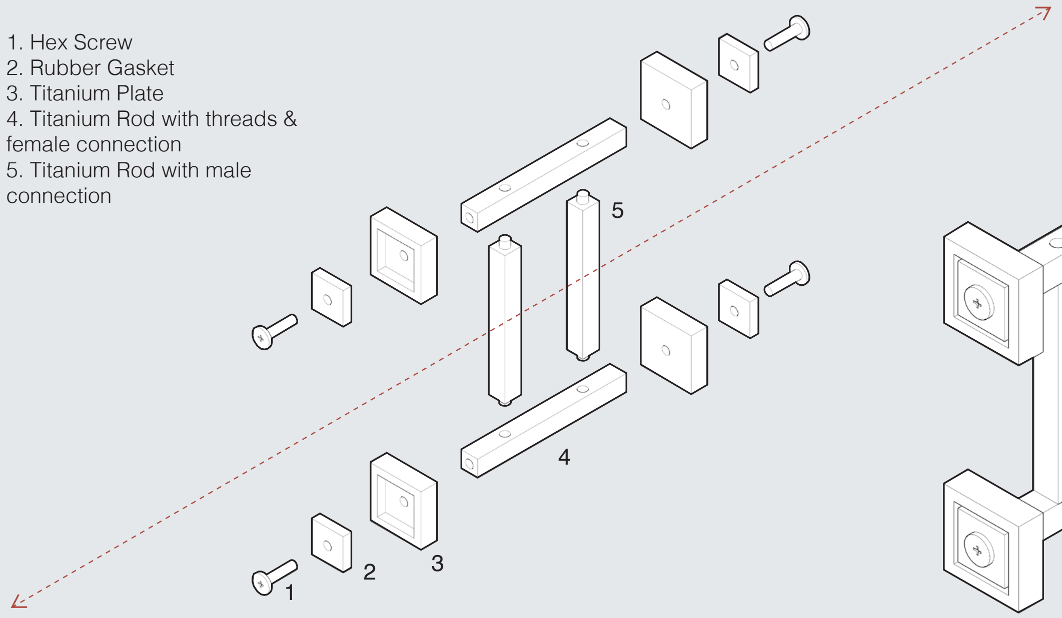
$$2.00 \geq t_{int.} \geq 0.50 \ [\mathrm{mm}]$$

07.11

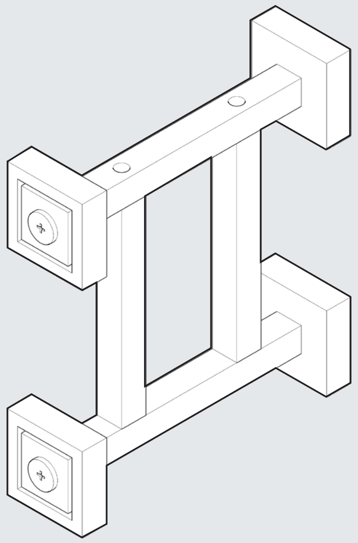
SYSTEM CONNECTION: EXPLORATION

LADDER: EXPLODED

1. Hex Screw
2. Rubber Gasket
3. Titanium Plate
4. Titanium Rod with threads & female connection
5. Titanium Rod with male connection



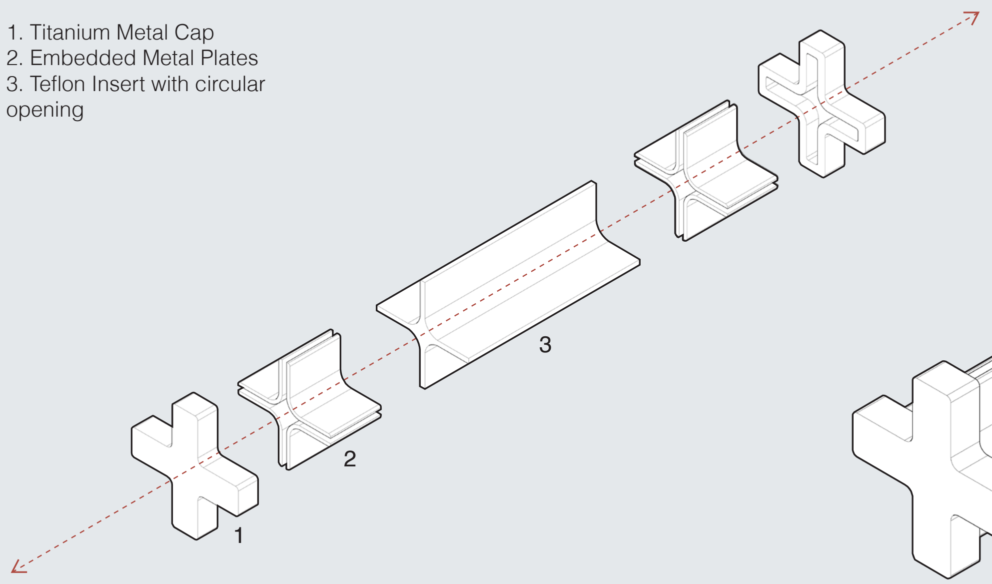
Ladder: Exploded



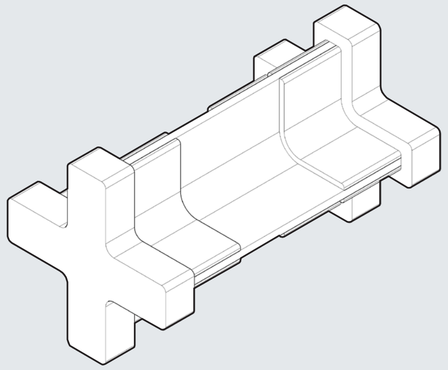
Isometric

PLUS 1

1. Titanium Metal Cap
2. Embedded Metal Plates
3. Teflon Insert with circular opening



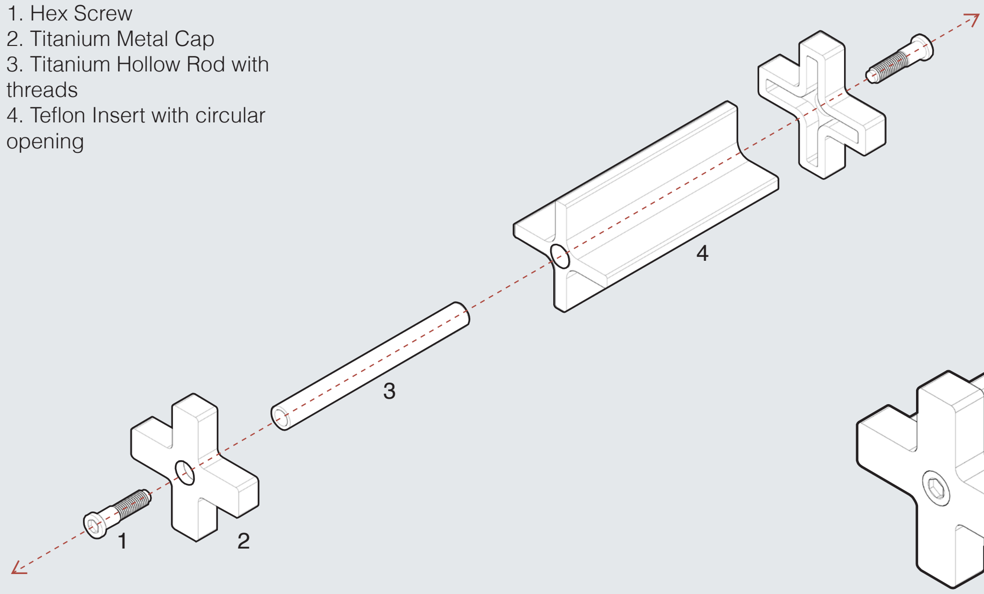
Plus 1: Exploded



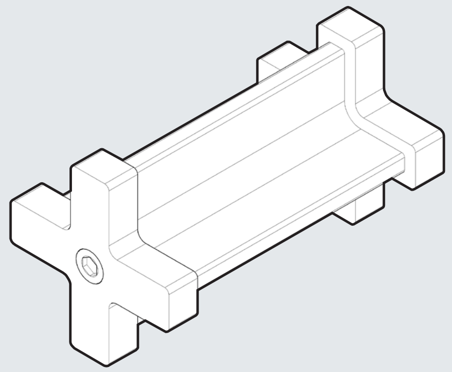
Isometric

PLUS 2

1. Hex Screw
2. Titanium Metal Cap
3. Titanium Hollow Rod with threads
4. Teflon Insert with circular opening



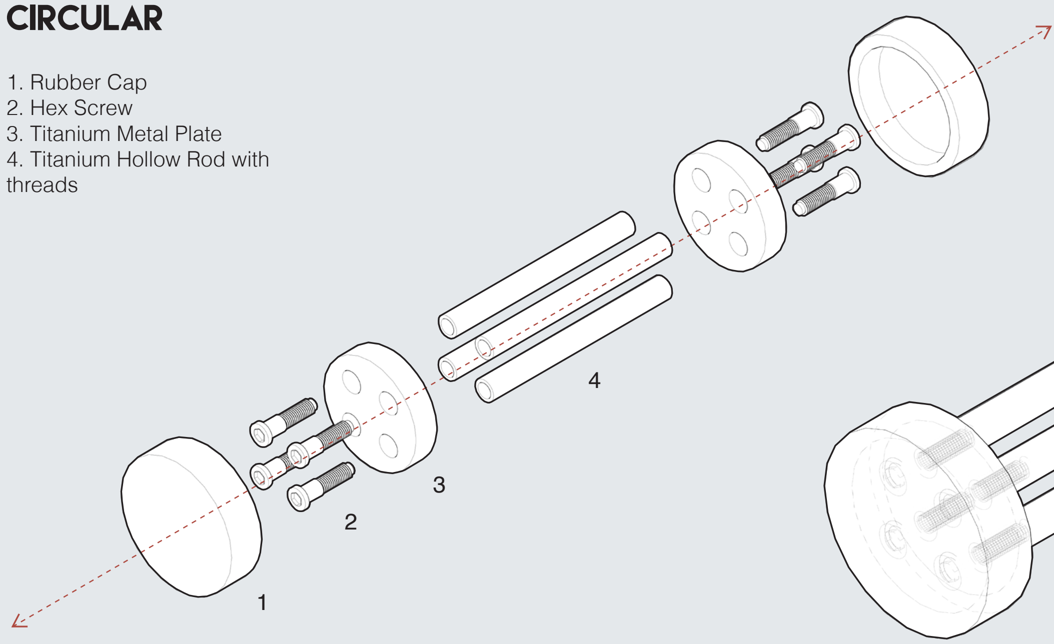
Plus 2: Exploded



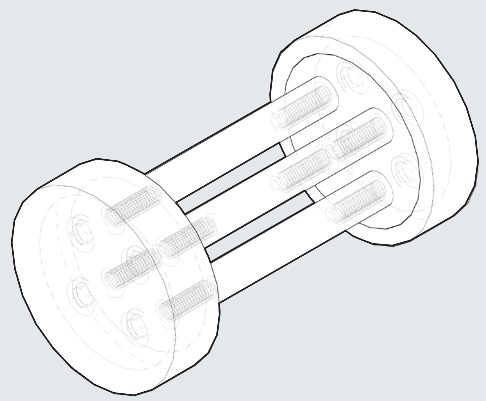
Isometric

CIRCULAR

1. Rubber Cap
2. Hex Screw
3. Titanium Metal Plate
4. Titanium Hollow Rod with threads



Circular: Exploded

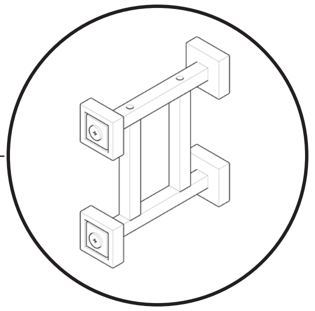


Isometric

07.11.2

SYSTEM CONNECTION: ALTERNATIVES

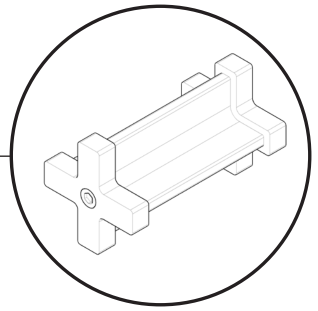
LADDER



- Efficient load transfer
- Issue with assembly & disassembly
- Issue with redundancy

The ladder system connects the glass blocks in the Y & Z directions. The vertical connection acts as a guide to place blocks and hold them together in a vertical manner. The assembly is however a bit complex as it involves additional connection components. The vertical connection does not allow for blocks to be replaced in the X or Z direction.

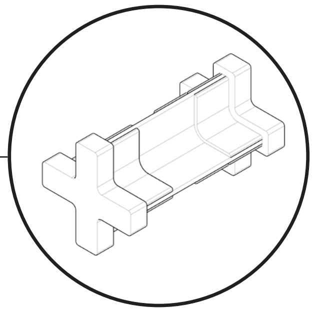
PLUS 2



- Good level of transparency & aesthetics
- Good redundancy and durability
- Average load transfer

This is a more advanced connection mechanism that fixes problems with the Plus-1 connection. It offers adequate support for the glass blocks; nevertheless, the problem may be with load transmission. Because of its simplicity of assembly and disassembly, as well as its aesthetically basic design, this system has a lot of promise. The system also functions effectively in the event of a breakdown and offers redundancy.

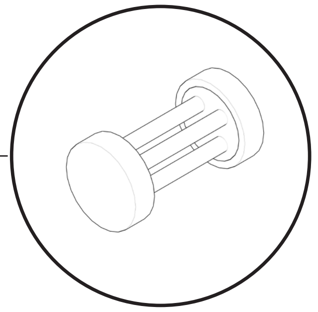
PLUS 1



- Good level of transparency & aesthetics
- Issue with load transfer
- Issue with redundancy

This connection system consists of metal angles embedded with the glass block, which adds to another process during manufacturing. The issue is with the metal embeds contaminating the cast glass surface. The system fails when one block is either removed or there is a structural failure. The connection system is also a bit complex as it requires a locking mechanism to hold blocks.

CIRCULAR



- Good in disassembly & redundancy
- Average aethetics & ease in assembly
- Issue with load transfer & transparency

Four screws made of either glass or metal pass through the cast glass blocks at the edges and are held together using a metal cap. The issue is with load transfer and transparency. In case of breakdown, the redundancy is offered by the screw, however, the connection is too big and impacts the level of transparency.

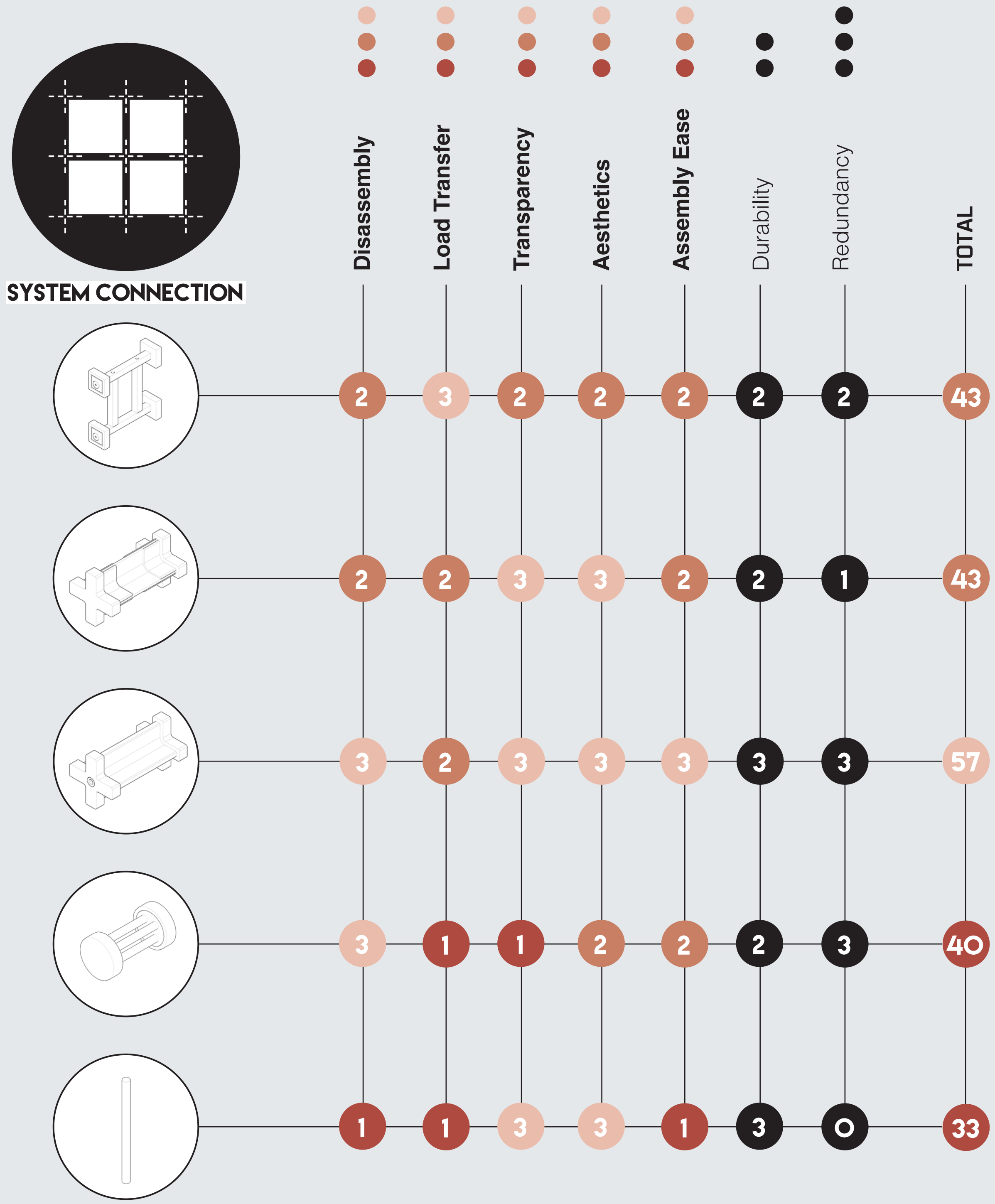


Figure 07.15: Evaluation of System Connections Alternatives

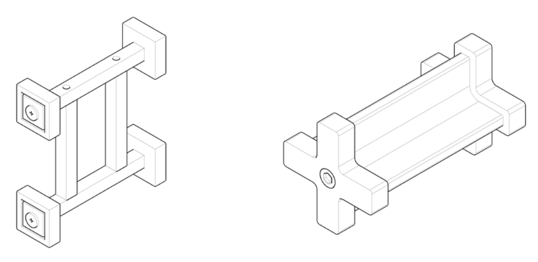
07.11.3

CONNECTIONS: CONCLUSIONS

Two promising designs are selected based on the alternative comparison for the connections at the system level. Even though the ladder connection received a lower grade than the plus-2 connection (figure 07.16), it remains a viable option for holding the glass pieces in all three axes. The ladder system provides great load transmission, maintains the glass pieces aligned, and accounts for vertical and horizontal tolerances. However, the system includes an extra set of components that renders the entire concept of manufacturing structurally stable glass blocks obsolete.

The primary objective is to provide maximum load transmission through the cross-section design of the cast glass components, and the connecting mechanism is simply to link the surrounding blocks. Another critical consideration is redundancy. In the event of a system failure, the adjoining blocks should be able to withstand loads comparable to the brick wall. However, because we have opted to create our design for vertical stacking, the connecting system must be able to withstand the stresses in the event of a system failure.

The Plus-2 connection design is promising since they are simple to assemble. In the event of a failure, the interior plus-shaped component should be rigid enough to withstand the strain of the upper blocks. The reversibility of the entire connection is feasible and may be reused effectively.



Ladder Connection Plus-2 Connection

Figure 07.16: System connections comparision

Initially, titanium was chosen as the material for the whole connection. However, the goal from the start has been to decrease the utilization of metal connections since they cause stress concentration along the surface well within metal contact. Metal parts require additional layering to eliminate thermal bridges, which have a significant impact on the thermal performance of the system. In the case of metal, an extensive study was performed to discover a material substitute, and a solution was found in Teflon.

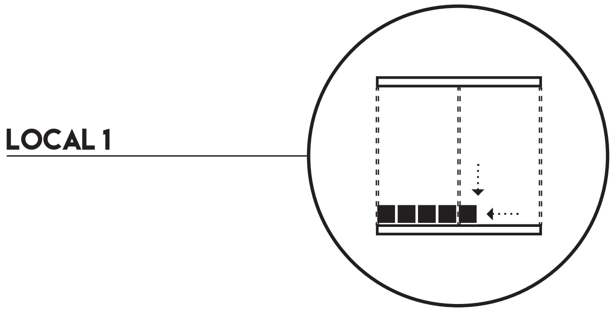
Teflon bushes and gaskets are commonly utilized within metal connections to provide insulation and prevent thermal bridging. Teflon is an extremely strong material that can endure enormous compressive stresses for an extended period. Because it is an elastomer, it is extremely durable in adverse weather conditions. Teflon, interestingly, is also regarded as an interlayer for glass-to-glass connections, but it is yet not widely employed. Although the material is not recyclable, the connections may be reversed and reused at the end of the system's life.

The final connecting system consists of four components that can all be manufactured by Teflon. The material's resistance to thermal shocks and chemicals is exceptional. Because it is a synthetic material, the color does not fade.

Figure 07.17: Teflon gaskets and bushes [(Paul Van Nuenen)]

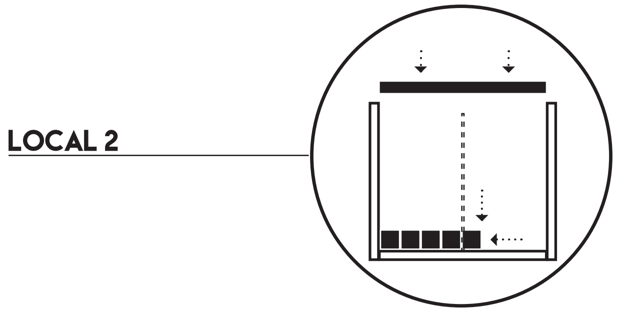
07.12.1

ASSEMBLY SYSTEM: ALTERNATIVES



- Good aesthetics - Seamless
- Complex replaceability
- Complex assembly, labor intensive

The local assembly system is similar to the brick wall construction. It requires an already constructed structural system over which the hybrid glass block wall can be constructed. In practice, the facade system requires additional structure elements like a ledge or cantilever beam over which the glass panels are assembled. In such cases, this assembly system will require additional clearance for manual handling of the hybrid glass blocks. The existing site conditions may or may not be properly constructed and may involve large or unavoidable tolerances. The standardized block size will remain the same in size, however, an additional frame or finishing is required to cater to the tolerances. The assembly process will be time-consuming due to the manual handling and precision required to build the blocks. This system will only work with interlayers that are creep resistant since the dry stacking assembly system will require a considerable amount of pre-compression for interlayers without creep resistance. Pre-compression is not alaways available due to limitations on site. During the exploration of the different interlayers, softcore aluminum was the only available material with the resistance to creep. The applicability of softcore aluminum will compromise the transparency as it is reflective and may also impact the thermal performance of the system. The result of such an assembly system is limited to a single floor as the stacking is done in between the structural members. In this system, the hybrid glass blocks will merely act as a building envelope without its load-bearing potential utilised.

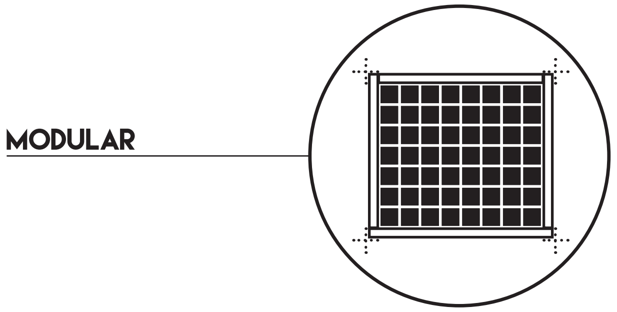


- Efficient assembly and disassembly
- Compromised aethetics due to frames.
- Issue with modularity

This system is similar to the local-1 assembly system, however, the major difference is a more transparent facade. This is because there are additional base and top frames that are connected to the structure. The assembly system is not limited to only a single floor but has a great potential to be built until the last floor. This is possible since an extended base is created for the assembly system. The base frame is constructed initially and then the substructure is raised. The corner supports to stay in position as they provide lateral support and alignment for the assembly process. Interlayers with resistance to creep are only used as precompression is not required to obtain a more seamless facade from top to bottom. The challenge in this system will be buckling since there is no limit for stacking the blocks. It will act as a continuous wall without any substructure that is constructed inside a large frame. To tackle buckling, a row of hybrid glass blocks can be tied to the structure with metal plates after equal intervals on the floor. Another issue is with the replicability of the glass block on the unit level, due to very small and precise tolerances. The overall system will have enhanced transparency on a system level, however, the unit level transparency is compromised due to the softcore aluminum interlayer. The assembly process will be time-consuming due to the manual handling and precision required to build the blocks.

07.12.1

ASSEMBLY SYSTEM: ALTERNATIVES



- Efficient assembly & disassembly
- Good in terms of modularity & replaceability
- Transparency is compromised

The modular assembly system is the one that is quick to assemble and disassemble on site and primarily focuses on the reduction of manual handling on site. This system is possible for any kind of interlayer. The system is assembled in an industrial unit under proper supervision and skilled labor. The frames of specific dimensions are pre-assembled and pre-compressed depending on the interlayer type. The result is a high-precision assembly of the hybrid glass blocks. The challenges like buckling or managing tolerances due to site condition does not affect the modular system. The tolerances are adjusted on a system-level on-site, which is much easier and more effective. The glass blocks can be easily replaced and the system can be deployed in any kind of building. The modular frames are transported to the site and mounted over the structure. Ease and quick in on-site assembly and disassembly. The whole frame can be reused. The major constraint of this system is the limitation of the size of the frames, due to truck dimensions and also the additional set of frames required for precompression.

07.12.2

ASSEMBLY SYSTEM: CONCLUSIONS

The assembly method has a significant impact on the effective utilization of heavy equipment, manpower, and material on the job site. Various scenarios using a modular approach might be built and evaluated to build a safe, rapid, and easy assembly system. On a system level, the conditions of circularity and reusability might be met.

The local-1 assembly system does not operate well in terms of ease of assembly and disassembly, which is the assembly system's key driving reason. As a result, it is not pursued further.

In a real-world context, the remaining two assembly systems are promising and relevant. Although the local -2 assembly is not modular, it is a viable solution when pre-assembled modular frames cannot be employed. The boundary conditions of new or renovated projects may differ significantly, and existing structural systems may or may not be built to accommodate the weight of modular frames. A local assembly system is preferred in such instances.

Both options work for the selected case study since the current facade system is likewise constructed of precast concrete frames that are built as unitized frames.

When developing these facade systems, the modular approach allows for a great deal of flexibility. They may be well incorporated into the circularity aims to develop reversible assembly systems that can be reused or recycled at the end of life.

As a result, both of these systems will be thoroughly developed and presented for the final design.

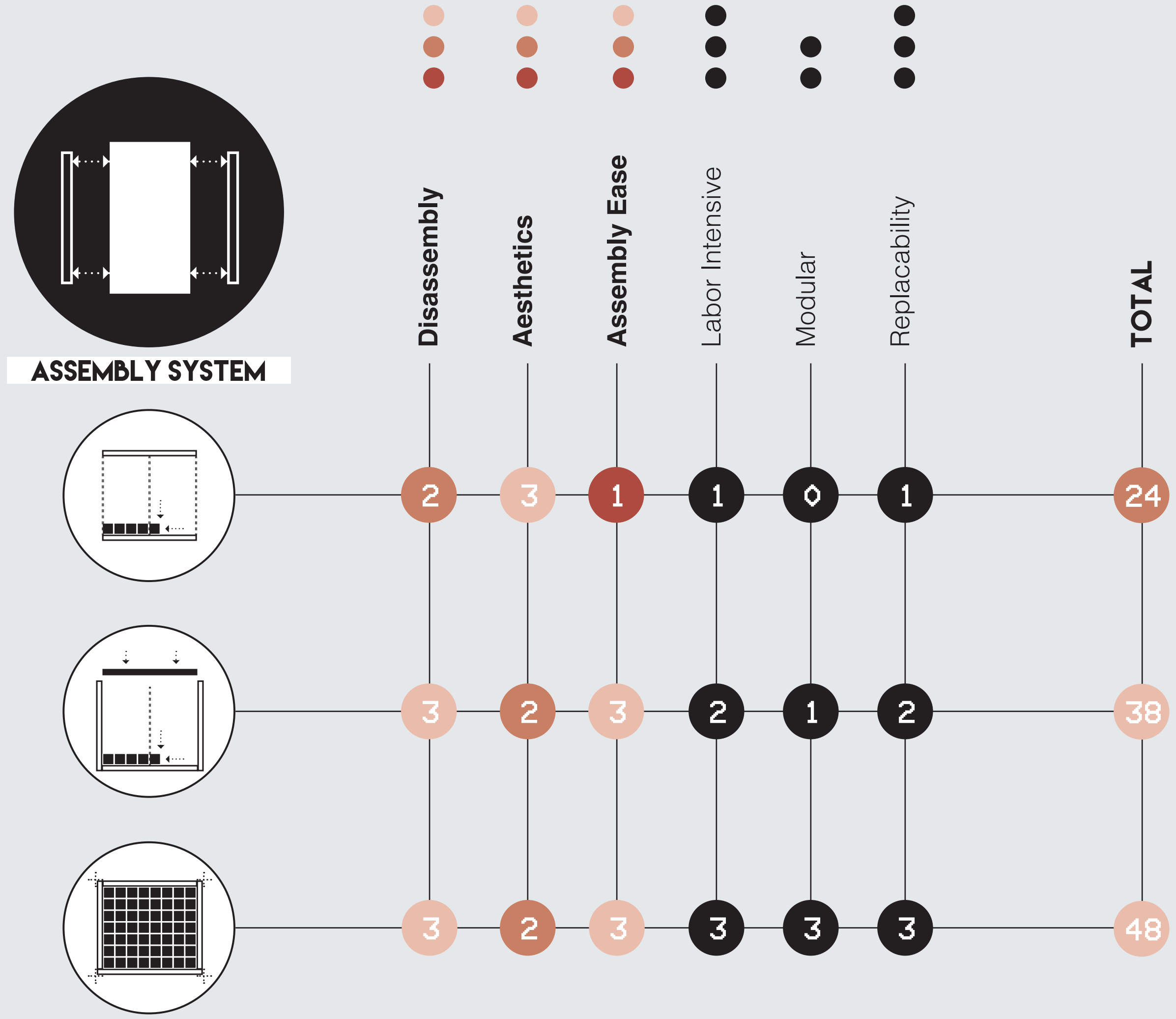
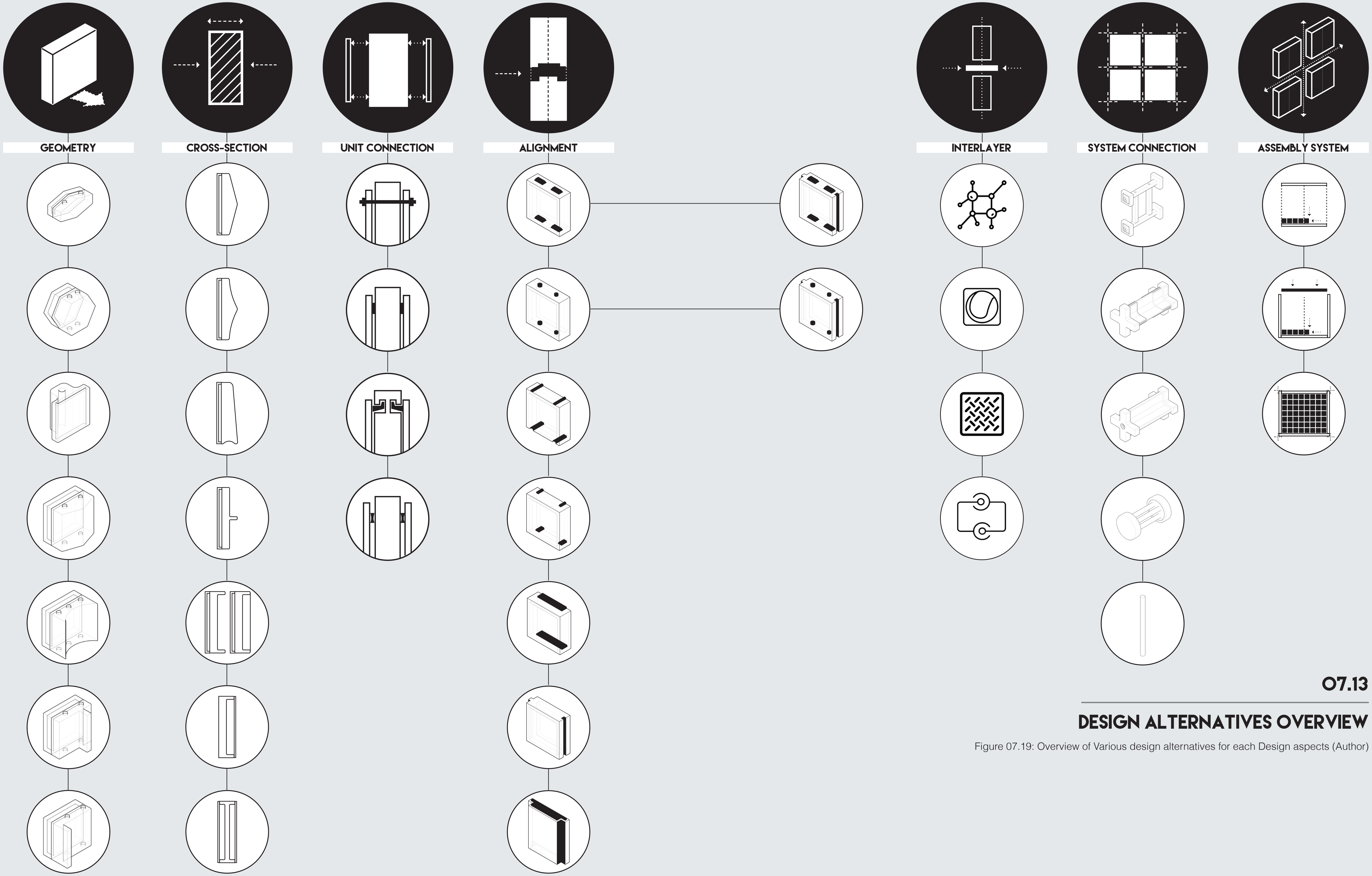


Figure 07.18: Evaluation of Assembly System Alternatives



07.13

DESIGN ALTERNATIVES OVERVIEW

Figure 07.19: Overview of Various design alternatives for each Design aspects (Author)

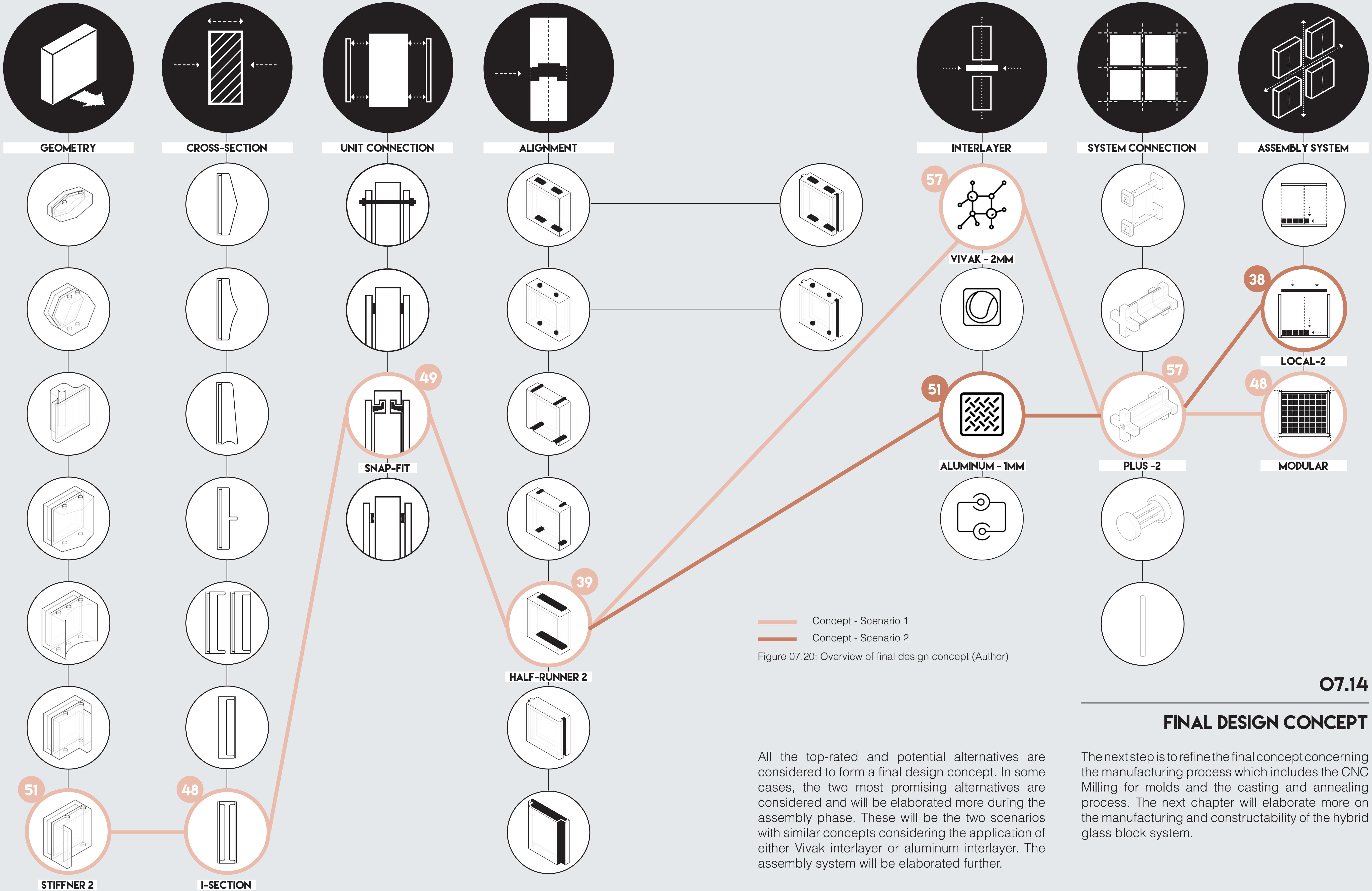


Figure 07.20: Overview of final design concept (Author)

07.14

FINAL DESIGN CONCEPT

All the top-rated and potential alternatives are considered to form a final design concept. In some cases, the two most promising alternatives are considered and will be elaborated more during the assembly phase. These will be the two scenarios with similar concepts considering the application of either Vivak interlayer or aluminum interlayer. The assembly system will be elaborated further.

The next step is to refine the final concept concerning the manufacturing process which includes the CNC Milling for molds and the casting and annealing process. The next chapter will elaborate more on the manufacturing and constructability of the hybrid glass block system.

Glass Casting for Crystal house (Oikonomopoulou. F, 2019)

08.

DESIGN REFINEMENT

The final design concept is refined with the influence of manufacturing processes like CNC milling, Casting & Annealing. Further, the design is refined with the consideration of constructibility criteria like movement, tolerances, and air & water seals for the facade system. A set of risk scenarios are discussed for consideration in the final design.

08.1.1

CNC MILLING FOR MOLDS

CNC Milling is a subtractive method of manufacture that is used to remove material from a standard component in order to achieve the desired design. It is a computer-controlled process wherein computer directs the machining tools. CNC machining techniques are useful for a wide range of materials, including plastic, metals, glass, acrylic, and wood. This procedure is used to create components and prototypes for a variety of purposes in a variety of manufacturing sectors. Because of the mechanized structure of this machining technique, high accuracy and cost-effective components and prototypes are produced. The level of complexity and intricacy possible with CNC machining is difficult to accomplish with traditional machining. (Rally, 2020) The suggested and theoretically possible values for the most frequent characteristics observed in CNC machined components are as follows.

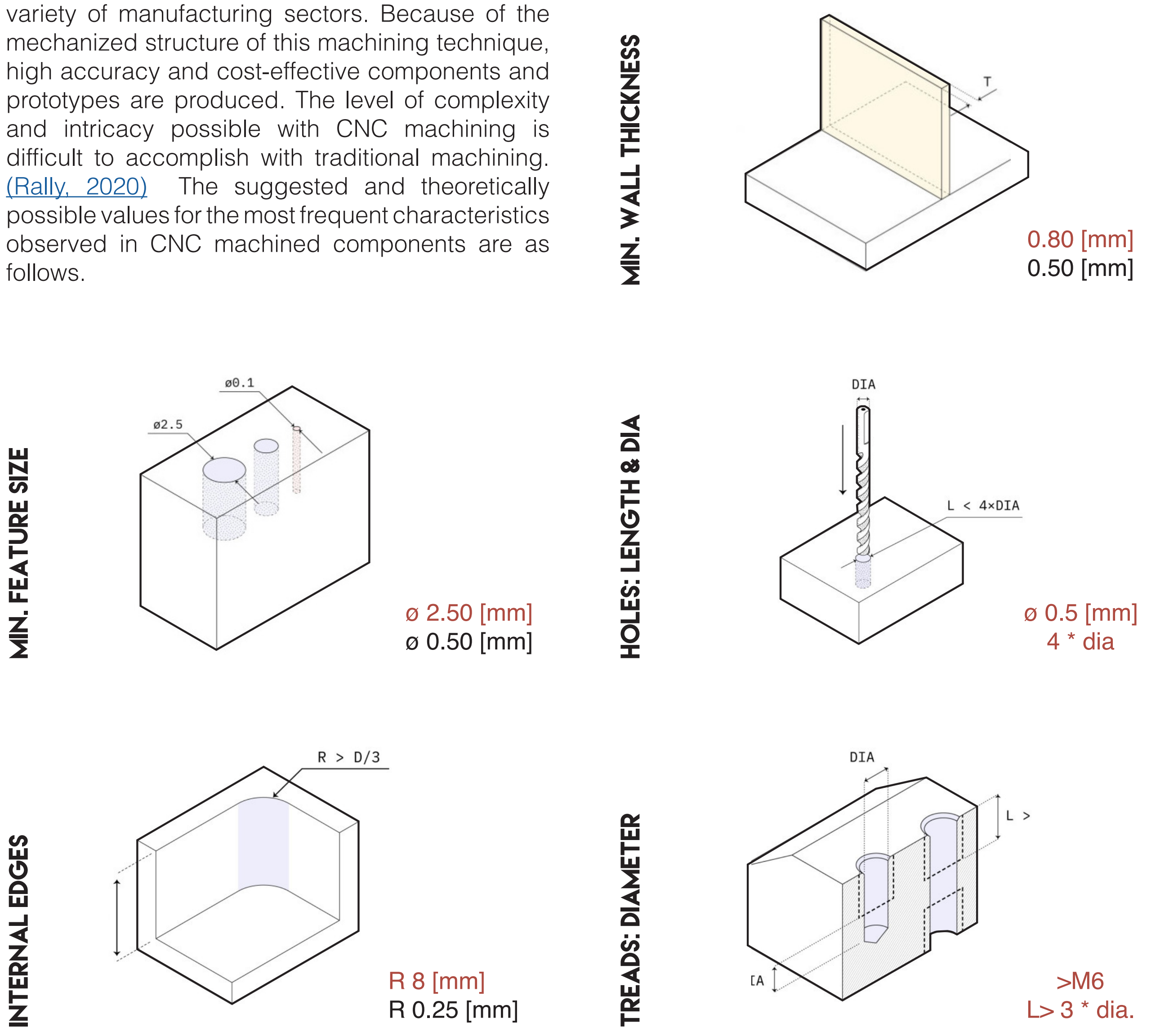


Figure 08.1: Standard recommendations for CNC milling (Hubs, 2020)

08.1.2

GLASS CASTING: STANDARDS

1. Limited volume
The meticulous and time-consuming annealing process of cast glass can jeopardise the components' marketability and render them financially unaffordable. (Oikonomopoulou et al. 2015) The mass of the glass component is the most important factor. The annealing time grows exponentially with the size of the component. As a result, for this study, solid cast glass elements with a mass limit of 10 kg are designed, roughly corresponding to the size range of standard masonry units. (Oikonomopoulou. F, 2019)

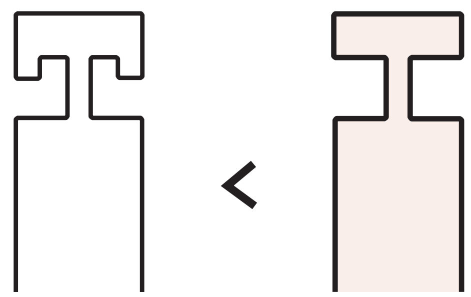


Figure 08.2: Revised detail based on undercut

2. Rounded shape and equal mass distribution
A rounded shape and an even mass distribution are critical for avoiding concentrated residual stresses during annealing. Curved, convex geometries are preferred over sharp, pointy edges, which can cause internal residual stresses due to inhomogeneous shrinkage. To that end, an equal cross-sectional area throughout the unit allows it to gradually cool down uniformly, preventing residual stresses from forming. As a result, projections like small connectors or notches should be avoided. (Oikonomopoulou. F, 2019)

3. Limited number of different units
A repetitive component geometry is preferred to facilitate structure production and assembly while limiting associated manufacturing costs. In particular, assembly is simplified because each unit can be placed anywhere in the structure, as opposed to predefined locations as is the case with systems with multiple geometries, such as the Incan walls. Furthermore, a single geometry results in fewer moulds and a more standardised production process. Given the foregoing, a single geometry is preferred, but configurations with a small number of different components may also be cost-effective. (Oikonomopoulou. F, 2019)

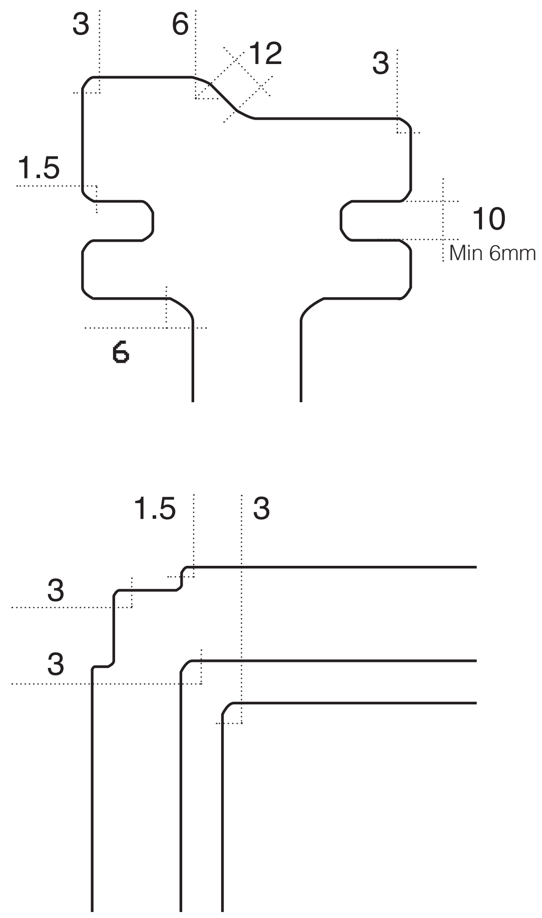


Figure 08.3: Edges rounded off as per casting standards
(All dimensions in mm)

08.1.3

GLASS CASTING: QUALITY CONTROL & ANNEALING TIME

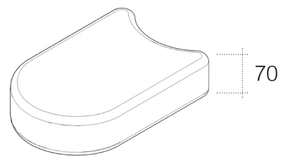
Casting may be a difficult process of producing glass blocks of particular sizes. The casted block's dimension is heavily controlled by the material recipe, mold type, and natural shrinkage during the cooling process. Because borosilicate glass has a lower thermal expansion coefficient than soda-lime glass, it is less prone to natural shrinkage and so allows for high precision cast blocks. For the manufacturing of borosilicate glass, the use of high precision steel molds allows for dimensional tolerances of ±1.0 mm. In our situation, because the assembly technique is dry stacked and the interlayer thickness is already set to 2.0 mm, we chose to employ a high precision steel mold with borosilicate glass.

Since dimensional tolerances of less than 1.0 mm are not attainable with the casting process, interlayers of less than 1.0 mm should never be employed. However, as demonstrated by the building of the Crystal House, post-processing procedures may be used to attain dimensional tolerances of ± 0.25 mm. The adhesive assembly system, which demands a high level of precision and wastes a lot of time and energy, necessitated these high-precision measurements. However, if post-processing is necessary, soda-lime glass is a better option than borosilicate glass since it is less expensive to produce. However, considering that soda-lime glass requires a longer annealing time, these dimensional tolerances can impact the design, performance, and manufacturing process.

A 400*400*80mm glass block is used in this research. The cross-section, on the other hand, is designed in an I-shape, thus the web thickness is 25 mm and the maximum thickness is 45 mm. The weight of the block is approximately 16.4 kg. The Atocha Memorial and Crystal House glass blocks can be used to investigate the impact of material composition on the annealing process. The borosilicate glass used in the Atocha Memorial had a thickness of 70 mm and a unit weight of 8.4 kg, which required an annealing period of around 20 hours, whereas a 65 mm thickness soda-lime glass unit with a unit weight of 7.2 kg took annealing time of 32 - 36 hours.

The annealing period for casting the hybrid glass block of 80 mm thickness, 16.4 kg weight, and borosilicate type are expected to be in between 10 and 12 hours. This is simply an assumption based on the actual data. To clarify, the tolerances generated by the interlayer are about 2mm in the vertical direction as a result of the interlayer's application on the top surface of the hybrid glass block. These tolerances may vary according to the level of the assembly system, but they are usually sealed off using silicone. In the event of a replacement, the silicone layer may be peeled off and replaced.

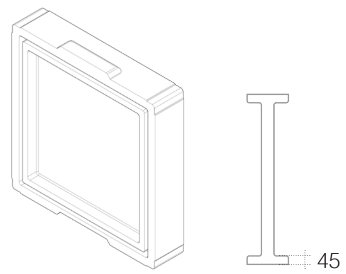
ATOCHA MEMORIAL



Glass Type	Borosilicate
Size of Block	300*200*70 [mm]
Max.thickness	70 [mm]
Weight	8.4 [Kg]
Annealing Time	20 [Hrs]

Table 08.1: Annealing Time for Atocha Memorial

HYBRID GLASS BLOCK



Glass Type	Borosilicate
Size of Block	400*400*80 [mm]
Max.thickness	45 [mm]
Weight	13.38 [Kg]
Annealing Time	10-12 [Hrs]

Table 08.2: Anticipated Annealing Time for hybrid glass block

08.2

RISK SCENARIO ANALYSIS

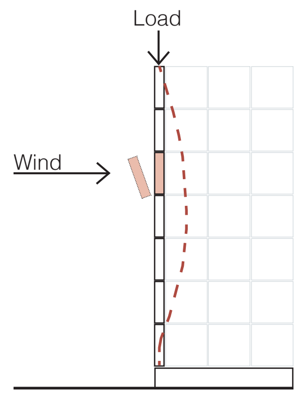
The risk analysis takes into account all possible scenarios that might occur in the façade and cause significant damage in the near future. There are six types of scenarios: structural damage, accidental damage, vehicle impact, vandalism, lack of maintenance, and natural disaster. More information is provided below.

Structural Damage
Excessive weight, uneven load distribution, and improper installation procedures can cause structural failure or damage to the facade. Under such loading circumstances, the damage can be evident as fractures propagating at the surfaces. In an unusual scenario, structural failure may occur, for which the structure should be designed with a safety factor of 4 for numerical validation. Because the wall is only stacked vertically, the possibility of complete failure is minimal; nonetheless, the connections are necessary to transmit the load of the blocks across the damaged block. The structural load of the floor is passed through the columns, although the intended system is load-bearing. Due to dry stacking, the system requires precompression during assembly to reduce the possibility of buckling and a block sliding outside.

Accidential Impact
Unintentional mishaps, such as a neighbouring tree or street lamp falling on the façade, may cause considerable damage to both the outer and inner surfaces of the facade. The proposed system is deployed in an educational campus that is easily accessible from the street level, increasing the possibility of such unforeseen consequences. Given the weather conditions in the Netherlands, such scenarios are fairly prevalent; consequently, the design of the blocks should be such that these blocks may be readily replaced without compromising the structural distribution. To lessen these effects, sacrificial layers might be applied to the surfaces.

Vandalism
The facade might be subjected to intentional destruction in the form of forceful body impact or spray paint all over the surface. Although the

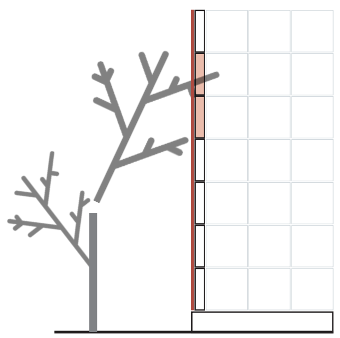
STRUCTURAL DAMAGE



Probability - 0.5
Exposure - 0.5
Consequence - 40
Safety factor - 4

Risk - 10

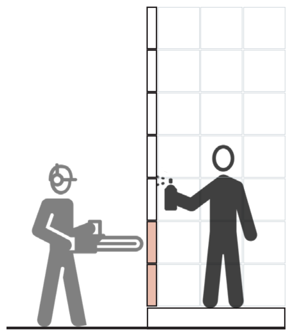
ACCIDENTIAL IMPACT



Probability - 3
Exposure - 1
Consequence - 7

Risk - 21

VANDALISM



Probability - 0.5
Exposure - 0.5
Consequence - 7

Risk - 1.75

O8.2

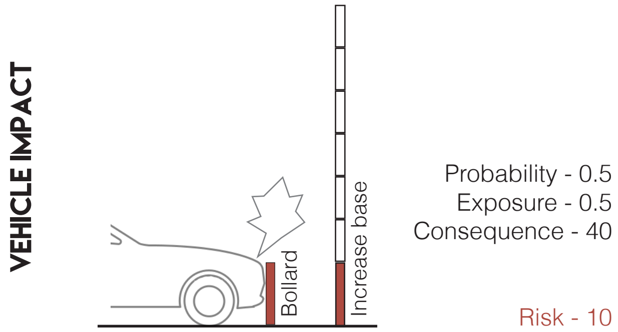
RISK SCENARIO ANALYSIS

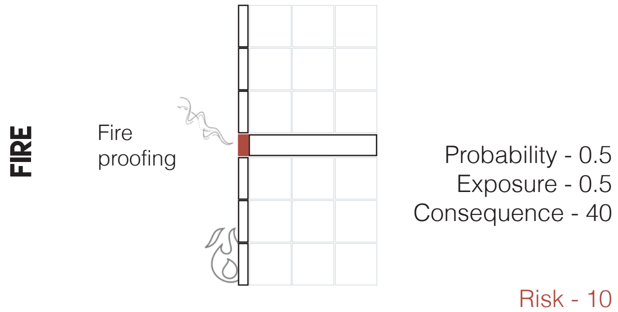
chances of this happening are remote, we cannot rule out the possibility. Depending on the location, the exterior surface of the hybrid glass block can be either heat strengthened or tempered. Because the ground to first-floor facade surface is easily accessible, an extra layer or coating may be applied to easily replace it rather than replacing the entire panel. To protect the surface from such unusual conditions, Gorilla Glass can be used for exterior panels instead of traditional float glass panels.

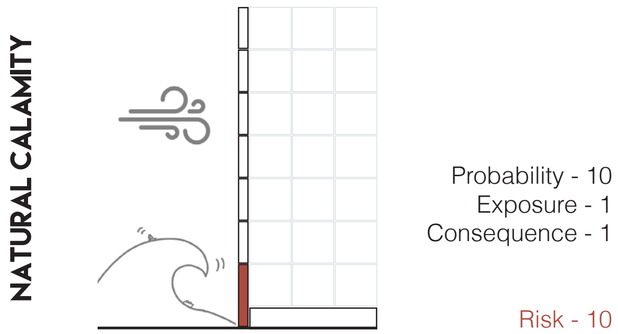
Vehicle Impact
The most likely scenario is for a vehicle, such as a car, bike, or even a crane (during maintenance work), to collide with the outer surface of the facade. In our situation the glass facade is designed from the ground floor, thus the risk scenario is very common and requires a design solution either over the facade or the space before it. Because the vehicle can collide with the base at a height of 0.6m to 1m, a concrete base can be considered to avoid the impact on the glass surface. Another option is to place bollards in front of the glass facade as a protective barrier.

Fire
In the event of a fire, the glass block should meet the fire rating criteria established by building codes. Because glass melts at higher temperatures, the entire facade is less likely to collapse. Even though the proposed system is load-bearing, the floor slabs are not directly reliant on the façade, which implies that the structure will stay in place even if the facade falls during the fire. One approach would be to utilize connections that are fire-resistant for up to 1 - 2 hours so that the gravity of the fire is not increased. To minimize direct fire propagation, another alternative would be to integrate fireproofing materials between the floor slab and the facade system.

Natural Calamity
Natural calamities such as earthquakes, floods, storms, and so forth are likely to generate unexpected movements in the facade, resulting in higher structural damage and catastrophe. The







facade system should be able to survive these occurrences up to a particular gravity intensity, preventing the entire structure from collapsing. A well-planned and well-executed connection and assembly system is critical for permitting the needed tolerances and movements in the facade to transmit loads in such situations. A simple solution is to not link all of the facade frames such that in the event of a natural disaster, the frame subjected to such extreme motions falls. High wind pressure and hailstorms are expected in the Netherlands, necessitating precompression of such a dry-stacked assembly technique to minimize block sliding and facade collapse.

Lack of Maintenance
Surface damage to the connectors and glass blocks is to be expected if maintenance is neglected. Because the facade is exposed to the sun or rain throughout the day, the outer surface is particularly vulnerable to these damages. Temperature variations between the exterior and inside can cause thermal shocks in the material. These flaws, while not causing catastrophic damage or injuries, can have a significant impact on the facade's effectiveness. Transparency can also be harmed by a lack of maintenance.

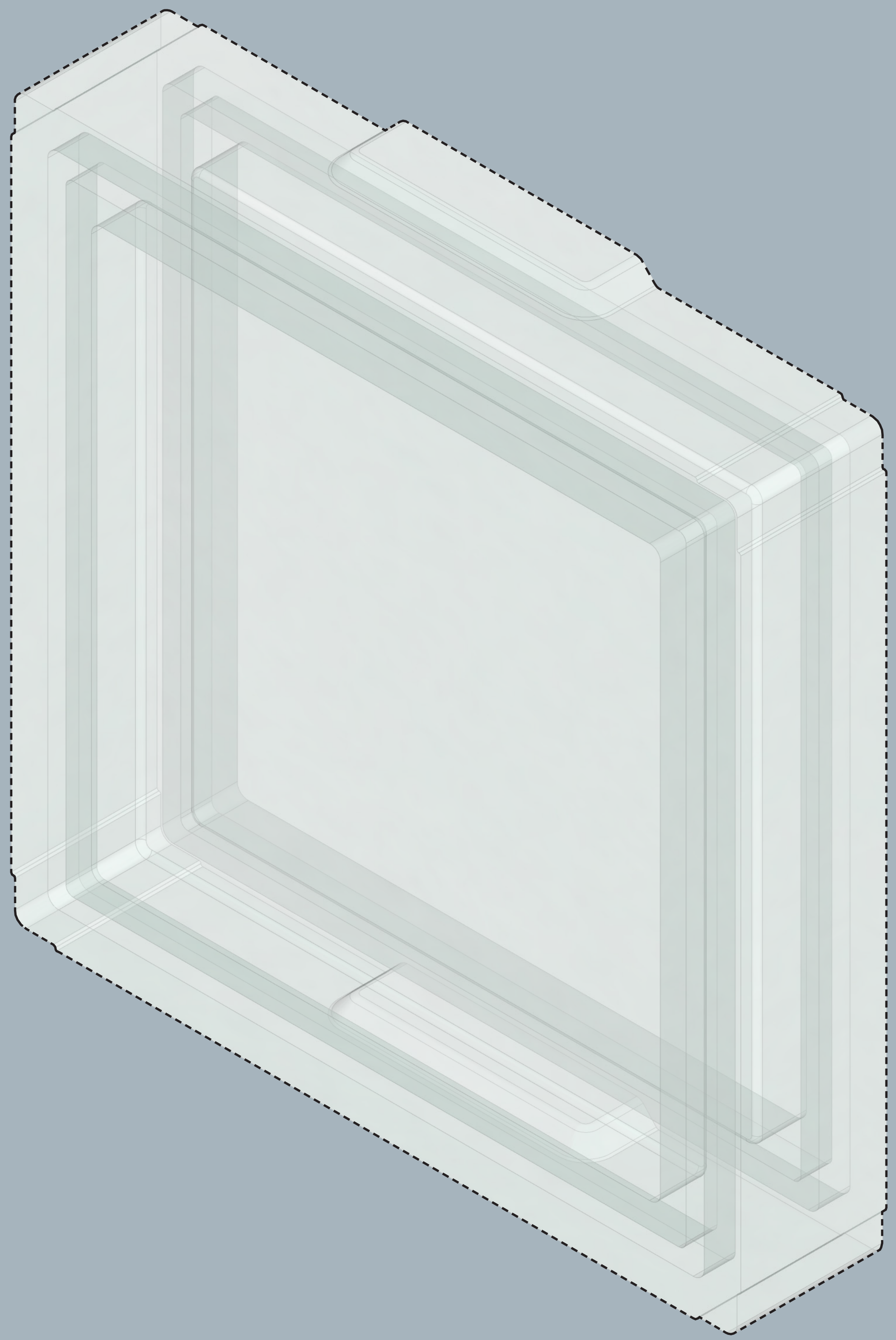
O8.3

CONCLUSION

Due to the existence of the interlayer, the predicted glass block through the casting process should be of high accuracy and allow for tolerances of +1mm. To attain such tight tolerances, the glass block will be cast in a high-precision steel mold. These molds are made using CNC milling, which has strict design criteria attached to them. The undercut in the design was modified and simplified based on these criteria. The edges were rounded to a minimum of 0.25 mm, but based on the casting and annealing requirements, a minimum of 1.5 mm rounded edge was considered throughout the design. These edges are critical for avoiding concentrated residual stresses during annealing. Curved, convex geometries are preferred over sharp, pointy edges, which can cause internal residual stresses due to inhomogeneous shrinkage.

The unit's homogeneous mass distribution and cross-sectional area are predicted to gradually cool down uniformly, avoiding residual stresses from developing. Small projections or notches have been advised to be avoided; nevertheless, because a notch is necessary for the design to accommodate the snap-fit feature, a minimum threshold of 6mm notch is contemplated. A single variation of glass block is decided to decrease the cost and time necessary for manufacturing since it results in a more standardized process, mold design, and annealing duration. The annealing time is proportional to the cross-section volume and thickness. Because the cross-section is already optimized to a maximum thickness of 45 mm, the expected annealing time for borosilicate glass is 10-12 hours. This is particularly promising since the improved cross-section enables a significantly larger glass block to be manufactured in a shorter amount of time.

The risk scenarios mentioned have a significant impact on the assembly system and necessitate a detailed structural calculation with a safety factor of four. The most significant factor to take into account is the amount of precompression necessary to retain the facade entirely as a single panel. This is outside the scope of this study since it necessitates an experimental setup with actual loading conditions.



Rendered View of the Hybrid Glass Block

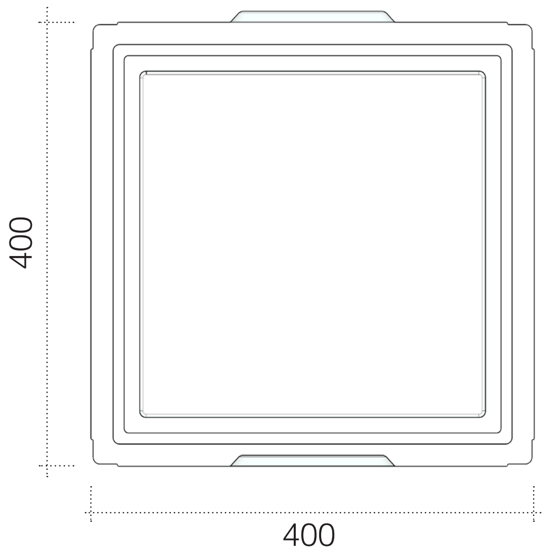
09.

FINAL DESIGN

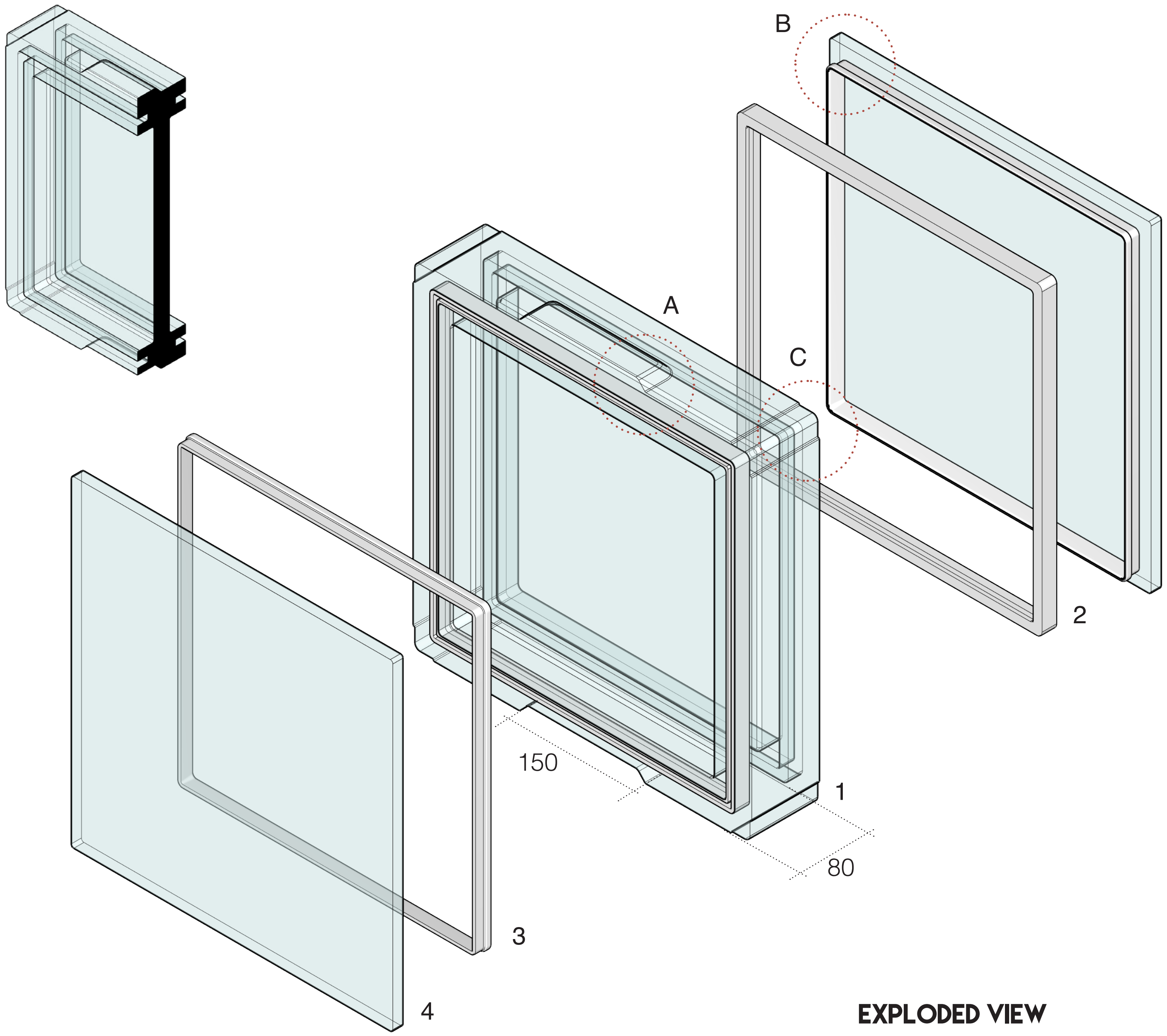
This chapter focuses on the final design of the hybrid glass and a step-by-step guide on how the glass blocks are manufactured and assembled on the site. All the necessary drawings, diagrams, and details are shown for the Academy of Arts building.

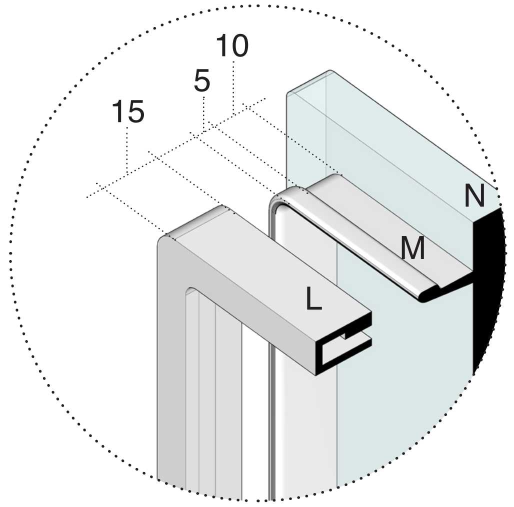
09.1

HYBRID GLASS BLOCK DESIGN



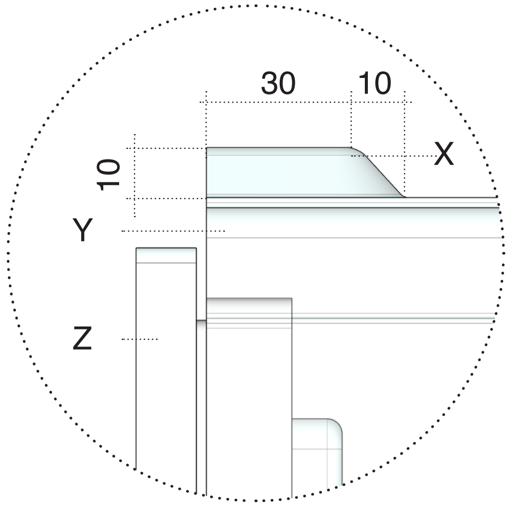
FRONT ELEVATION





SNAP-FIT DETAIL: B

L - Snap-fit Female component
M - Snap-fit Male component
N - Float Glass Panel



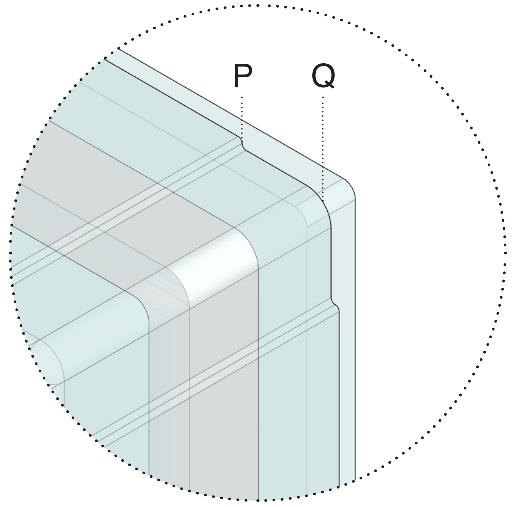
ALIGNMENT DETAIL: A

X - 3 mm Filleted edge
Y - Cast Glass Component
Z - Float Glass Panel

*All dimensions in mm

EXPLODED VIEW

1 - Cast glass component (400*400*80)
2 - Snap-fit Female plastic profile (15*10)
3 - Snap-fit Male plastic profile (10*6)
4 - Float glass panel (6-12mm thk)

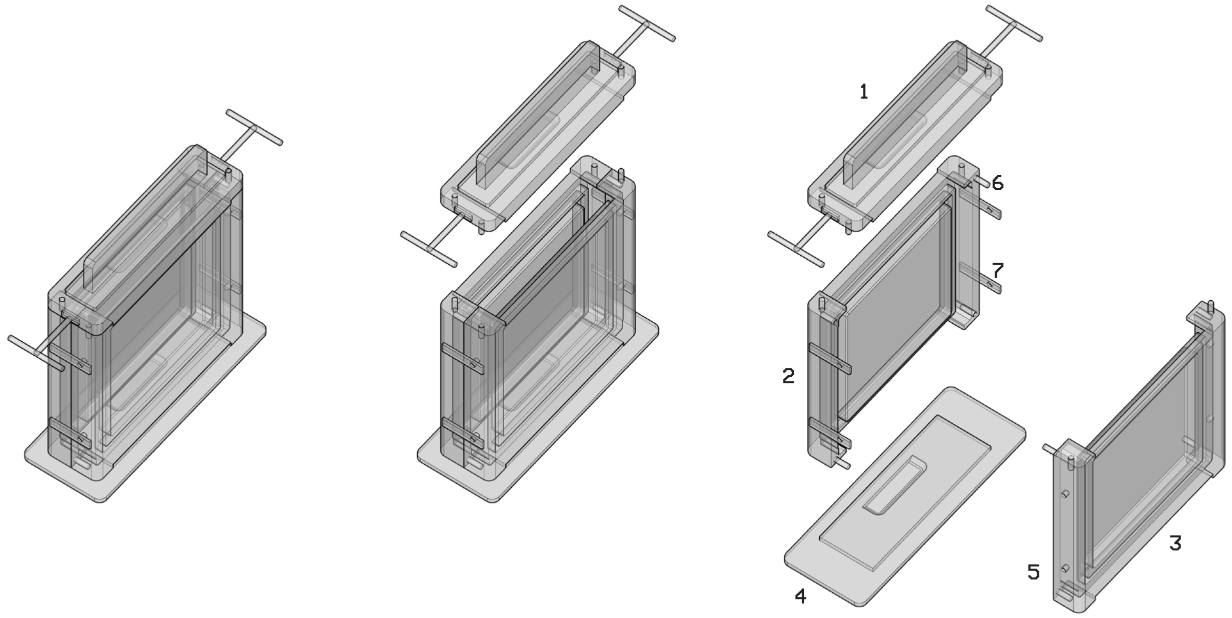


CORNER DETAIL: C

P - 2 mm Filleted edge
Q - 6 mm Fileted edge

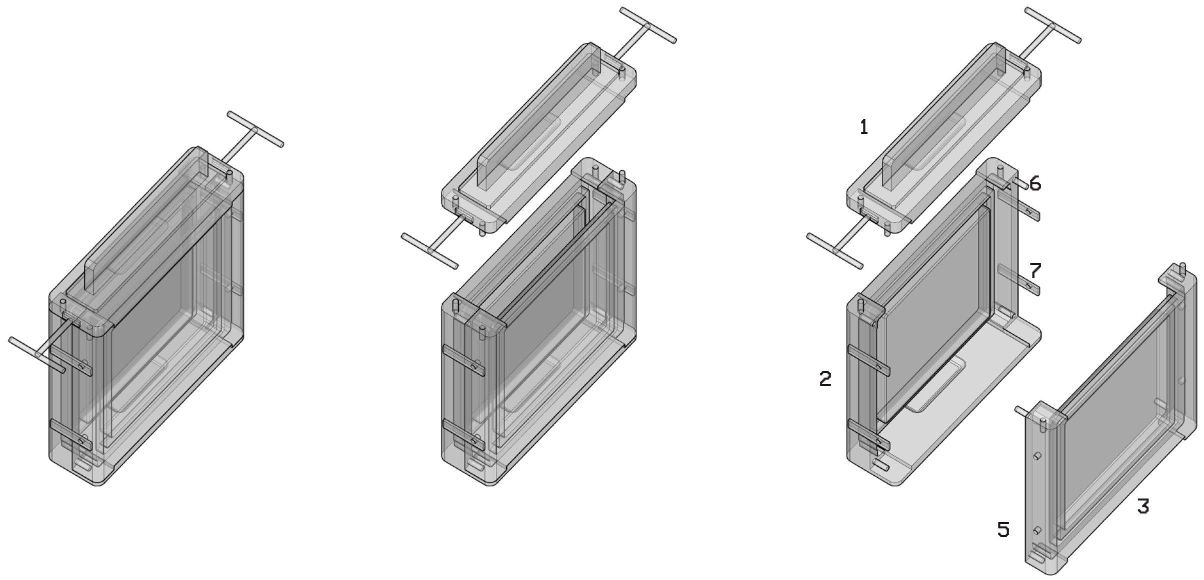
09.2

MOULD DESIGN



1. Hydraulic Press
2. Steel Mould part 1
3. Steel Mould part 2
4. Base Plate with alignment dip
5. Air Vent
6. Alignment pin
7. Mould Locking system

MOULD: OPTION 1

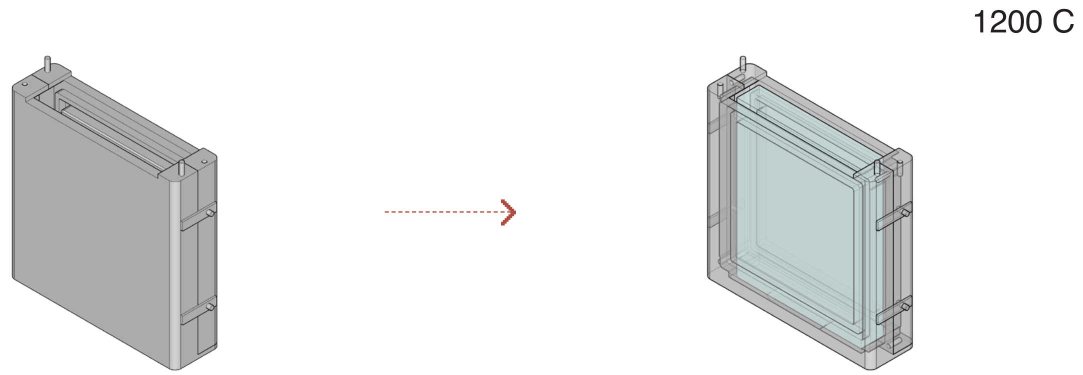


1. Hydraulic Press
2. Steel Mould part 1
3. Steel Mould part 2
5. Air Vent
6. Alignment pin
7. Mould Locking system

MOULD: OPTION 2

09.3

MANUFACTURING SEQUENCE

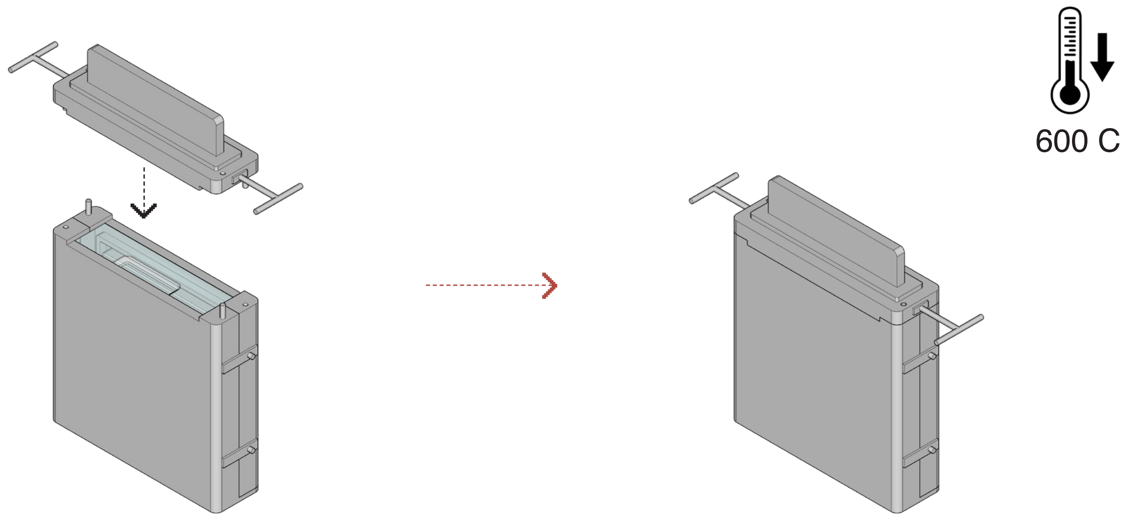


Step 1:

The high precision steel mould is set-up and preheated to a temperature just more than the room temperature.

Step 2:

The molten glass is poured inside the mould. The glass block is casted in the downward fashion so as to get a proper alignment dip. The molten glass is poured till brim level.

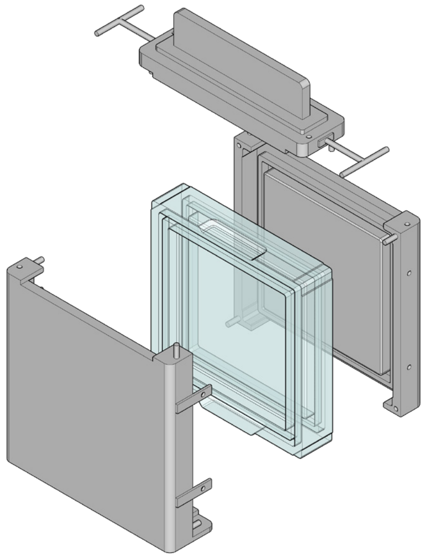


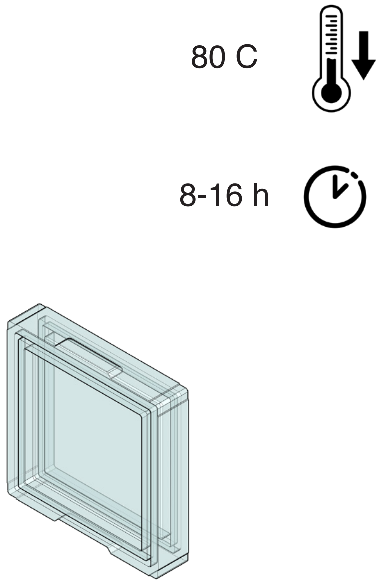
Step 3:

With the help of a hydraulic press, the top lid of the mould is placed to cover and create the dip alignment geometry.

Step 4:

The molten glass slowly takes the desired shape in the moulds with the help of gravity. The glass is now allowed to cool down until the softening point



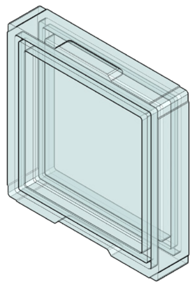


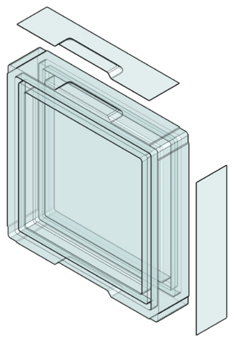
Step 5:

The molten glass is now allowed to cool down until the softening point. Once the glass block has reached the temperature the moulds are removed and the casted element is transferred for annealing.

Step 6:

The conveyor belt takes the casted element for the annealing process. The annealing is done under a controlled environment where the temperature of the glass is quickly lowered and increased until it reaches room temperature.



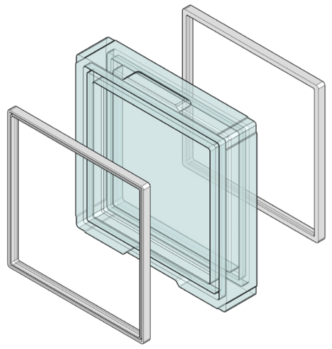


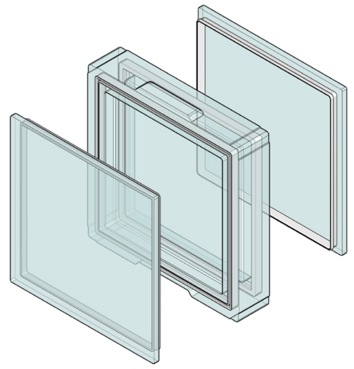
Step 7:

The casting process is now complete and the glass blocks undergo a quality check which ensures proper production output. The glass blocks are taken for the interlayer vaccum forming process and further assembly with the flat glass panels.

Step 8:

The casted glass component is taken to the vaccum forming process where the selected interlayer *vivak is applied on the top surface and/or side surface



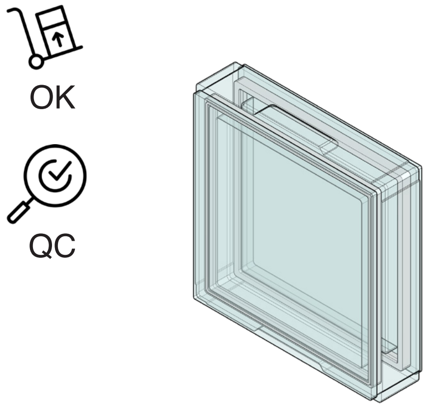


Step 9:

The snap-fit profiles are inserted inside the cutout created on both surfaces of the casted glass element. This is either done by using an adhesive or the profiles are compressed to create a suction vacuum bond.

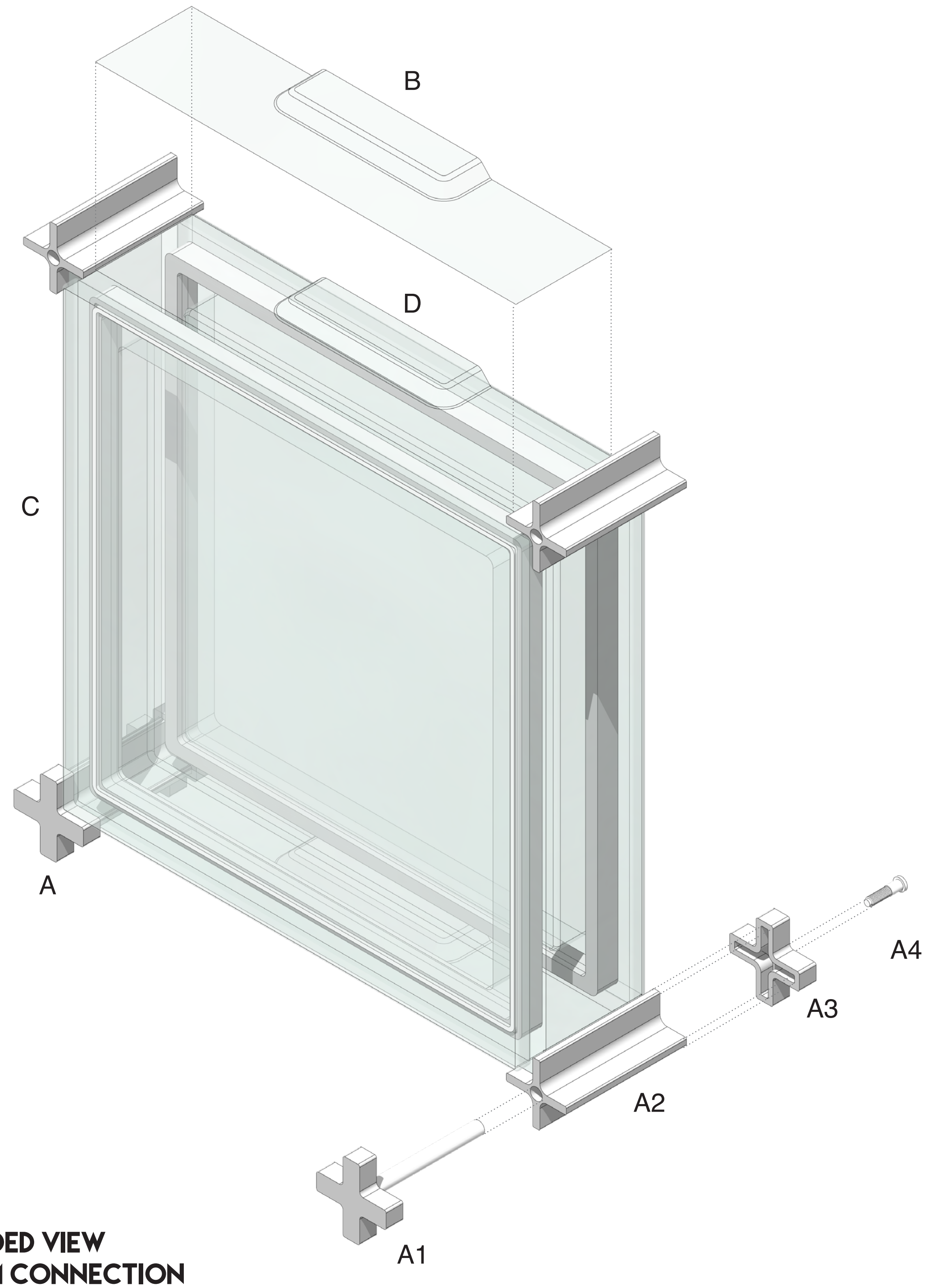
Step 10:

The float glass panels are now lifted and aligned over the snap-fit profile in the casted glass element. The process is repeated for the bottom part as well.



Step 11:

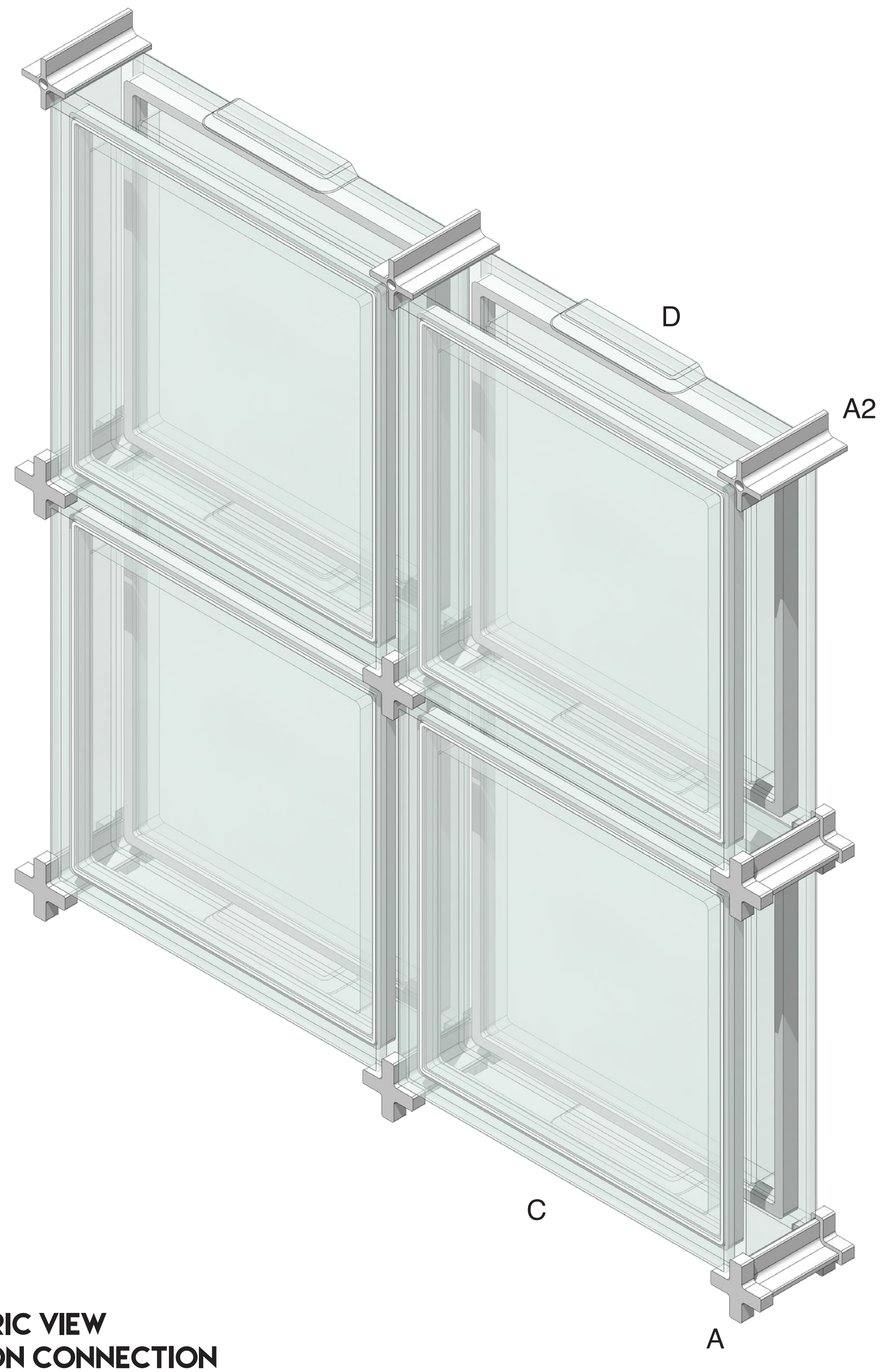
The hybrid glass blocks are now ready. Now, these blocks are checked for the proper panel connections and then packed and sent for shipping.



**EXPLODED VIEW
SYSTEM CONNECTION**

A - Teflon connection
B - Interlayer - 2mm thk Vivak
1mm thk softcore aluminium
C - Hybrid Glass Block (400.400)
D - Alignment interlock

A1 - Teflon connector with threaded screw cap
A2 - Plus shaped connector for alignment
A3 - Cover cap
A4 - Screw for securing connection

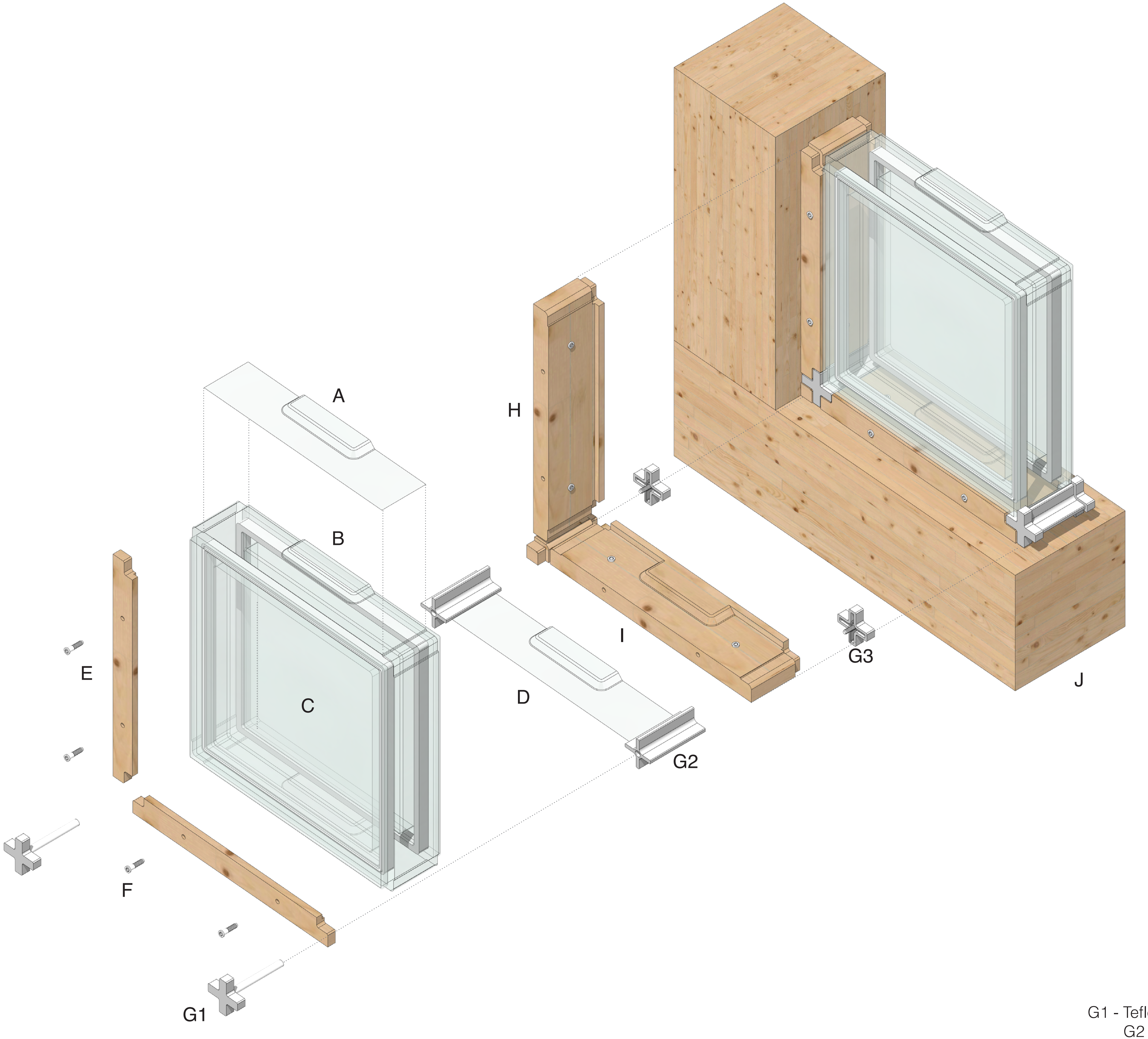


**ISOMETRIC VIEW
JUNCTION CONNECTION**

A - Teflon connection
A2 - Plus shaped connector for alignment
C - Hybrid Glass Block (400.400)
D - Alignment interlock

EXPLODED VIEW
ASSEMBLY SYSTEM

A - Interlayer - 2mm thk Vivak
1mm thk softcore aluminium
B - Alignment Interlock
C - Hybrid Glass Block (400.400)
D - Soft Padding or Interlayer with 4mm thk
E - Reversible Cover Plate
F - Screw for securing cover plate with base plate
J - CLT frame

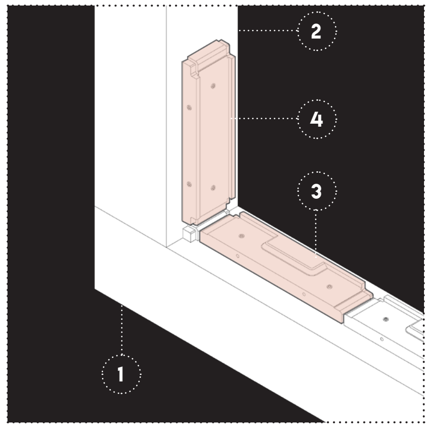


ISOMETRIC VIEW
ASSEMBLY SYSTEM

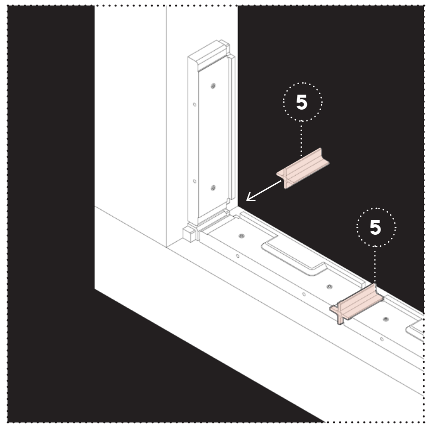
H - Vertical plate
I - Base plate with alignment interlock
G1 - Teflon connector with threaded screw cap
G2 - Plus shaped connector for alignment
G3 - Cover cap

09.4.1

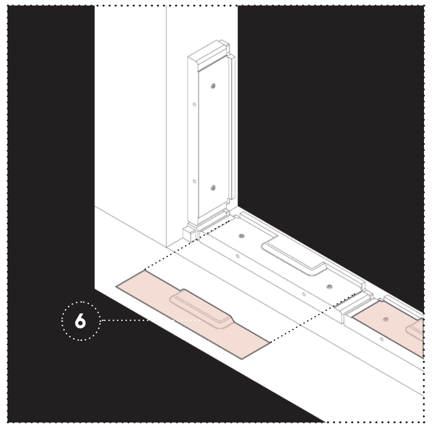
ASSEMBLY SEQUENCE: LOCAL



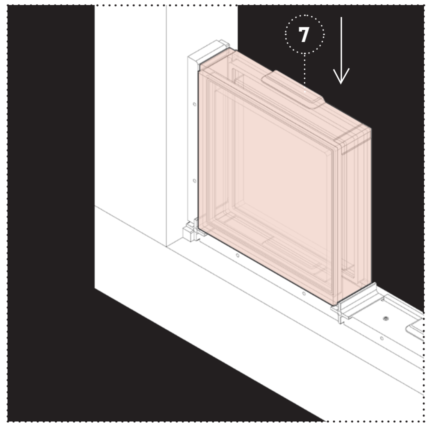
Step 1: Screw side & base plate



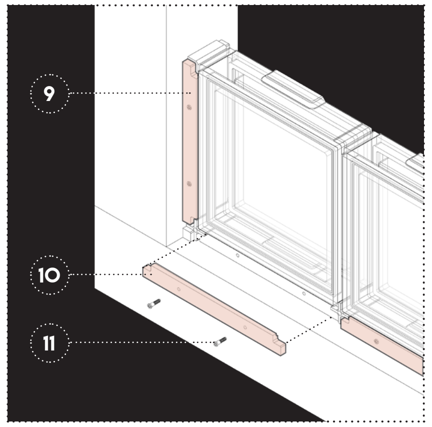
Step 2: Place connectors in between plates



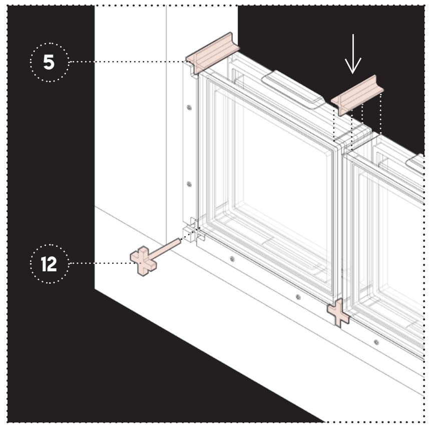
Step 3: Slide in the soft padding over the base plate



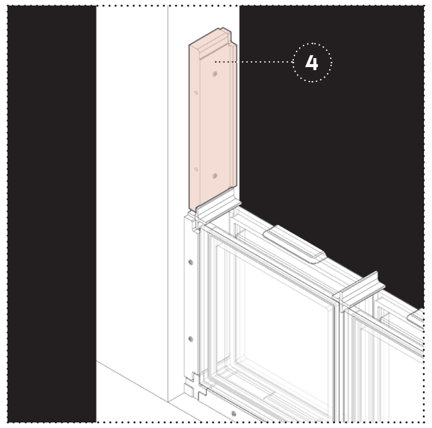
Step 4: Place the hybrid glass block on the corner



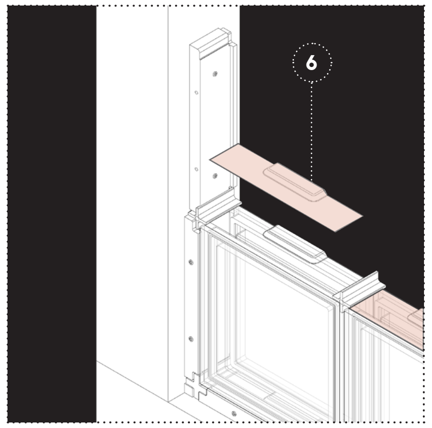
Step 5: Screw cover plate over side & base plate



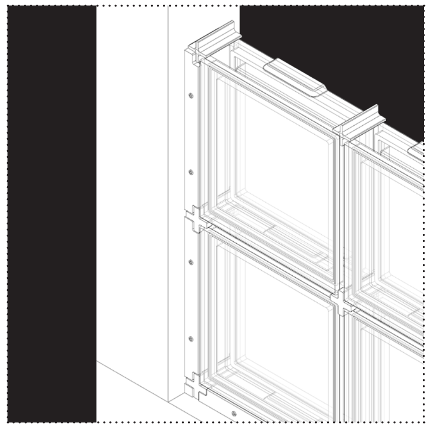
Step 6: Secure the connection & place connectors over block

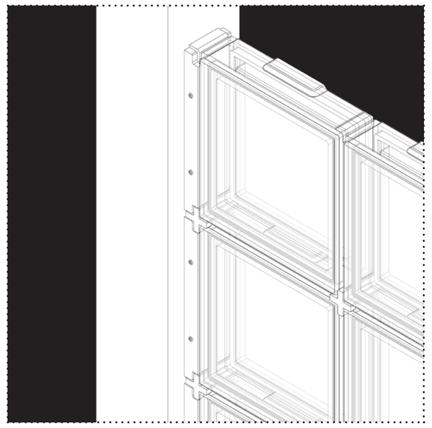


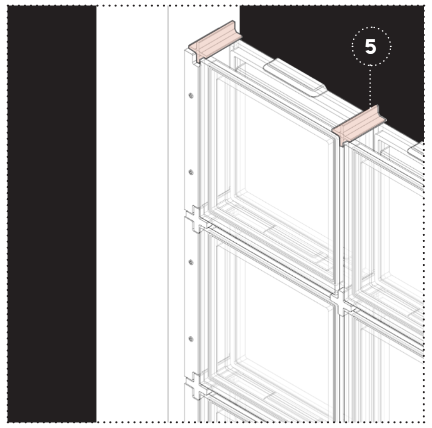
Step 7: Screw side plate for the next row



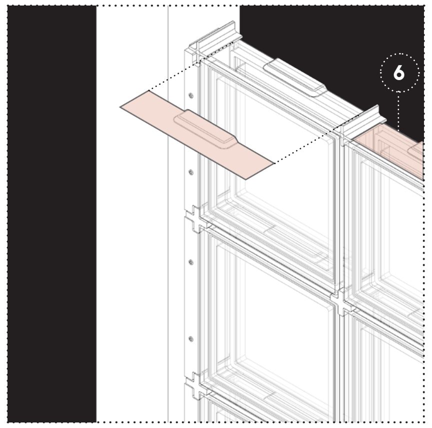
Step 8: Place the interlayer over the hybrid glass block


Step 9: Repeat step 4 - 8 for next course of blocks

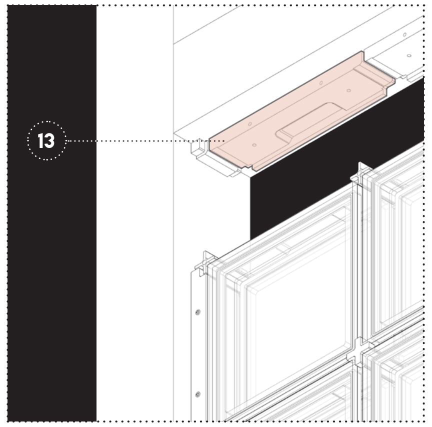

Step 10: Repeat step 4 - 9 till last course of hybrid glass block



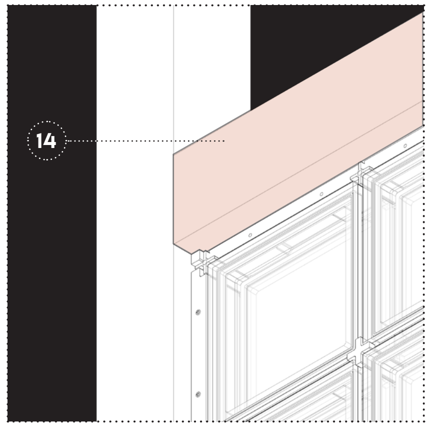
Step 11: Slide in the connectors in between hybrid glass block



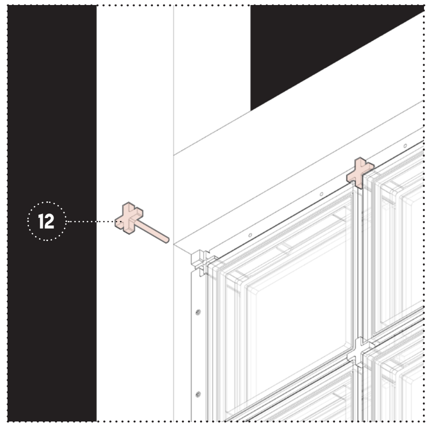
Step 12: Place soft padding over the hybrid glass block



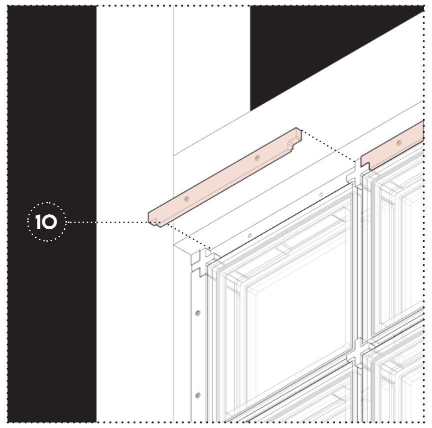
Step 13: Screw top plate to the top beam



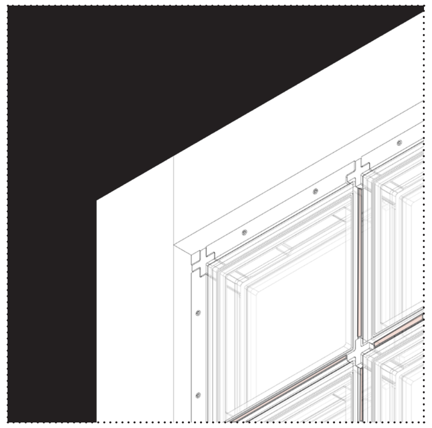
Step 14: Lower top beam



Step 15: Secure the connection



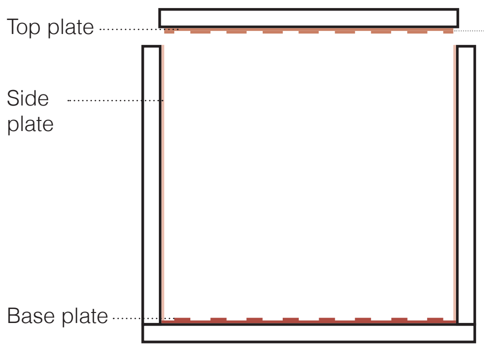
Step 16: Screw cover plate of ver the top plate

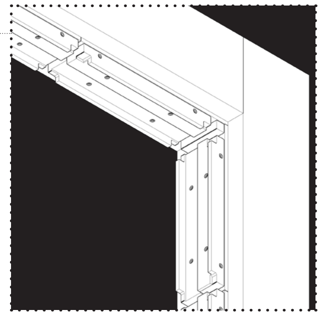

Step 17: Seal the gaps with silicone

Base beam	01
Vertical frame	02
Base plate	03
Side plate	04
Plus shaped connector	05
Interlayer/Soft padding	06
Hybrid Glass Block	07
Silicone	08
Side cover plate	09
Base cover plate	10
Screw	11
Teflon Connector with threaded screw cap	12
Top plate with alignment dip	13
Top beam	14

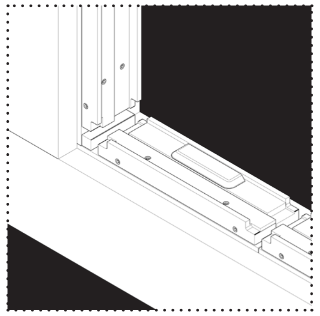
09.4.2

ASSEMBLY SEQUENCE: MODULAR





Top plate



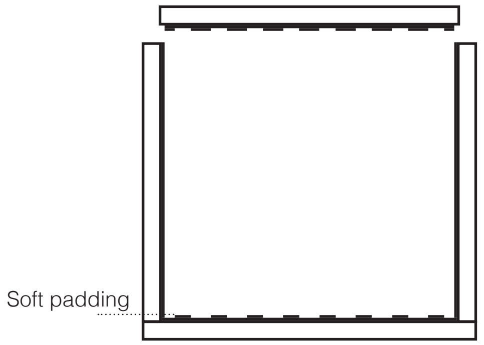
Base plate

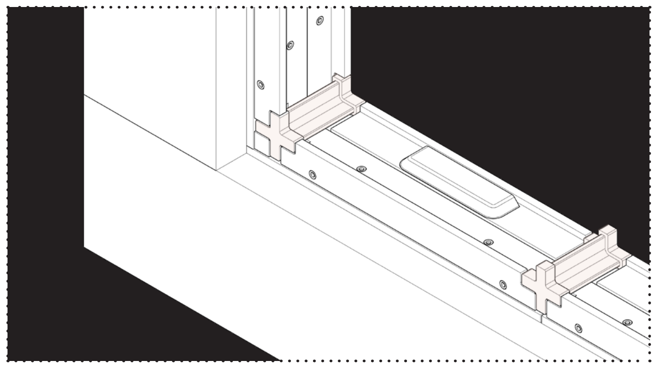
Step 1:

The horizontal base wooden/steel beam is placed on the ground. The vertical wooden/steel frames are erected and connected with the base frame.

Step 2:

The wood/steel guide plates are screwed over the top surface of the base beam. The same process is repeated for both vertical frames & the top beam.





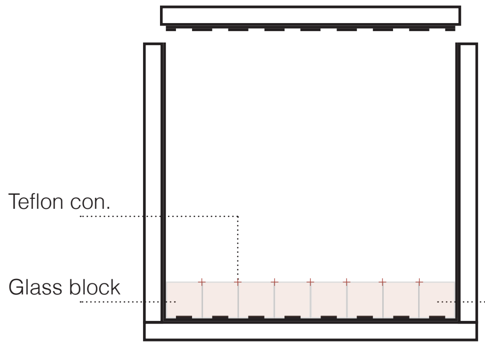
Teflon connections

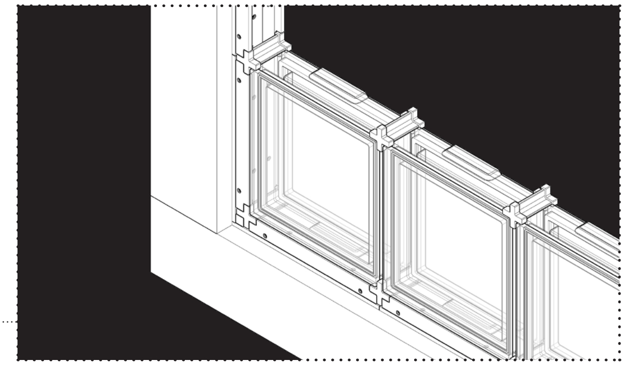
Step 3:

A soft rubber padding or interlayer is placed over these guide plates to avoid direct contact with the glass surface. They also provide resistance to thermal bridges and take care of tolerances.

Step 4:

The first Teflon connection is placed on the corner junction. This marks the starting position for placing the glass blocks.





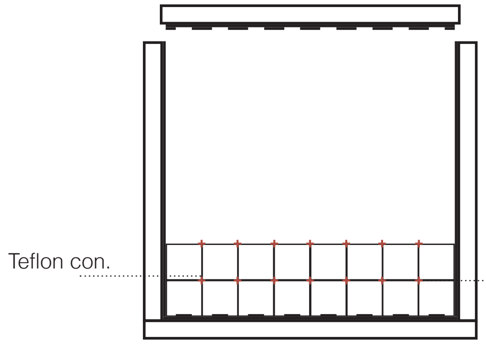
First row

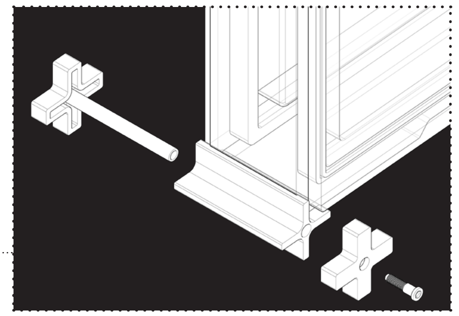
Step 5:

The blocks are assembled horizontally alternatively with a Teflon connection in between them. The last block is placed on the other corner.

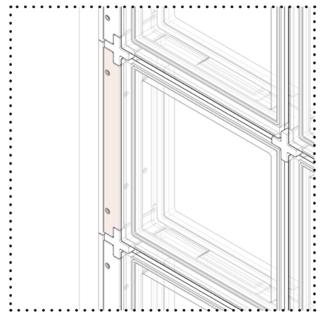
Step 6:

The Teflon connections are now placed over the first row of blocks followed by the assembly of the second row of glass blocks.





Securing teflon connection



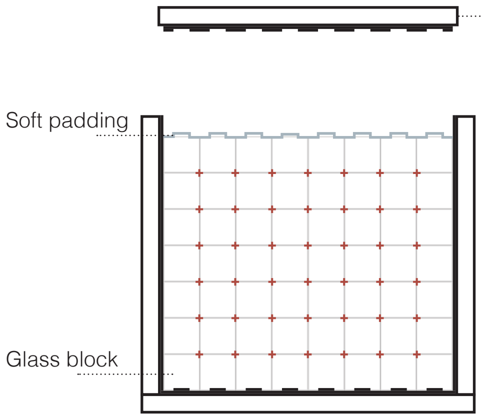
Cover Plate

Step 7:

The Teflon connections are secured from the inside with the help of the bolts passing through the hollow pin connection.

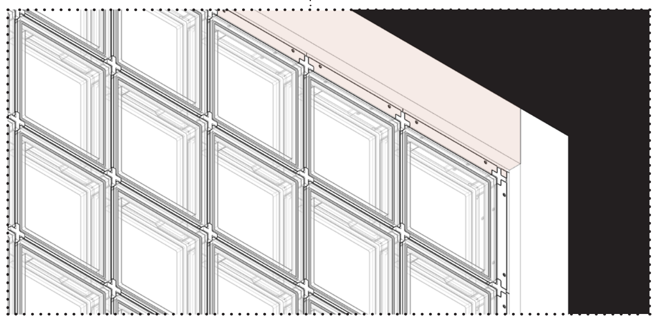
Step 8:

For each row, the corners are secured with the guide cover plate which is bolted to the main guide plate.



Step 9:

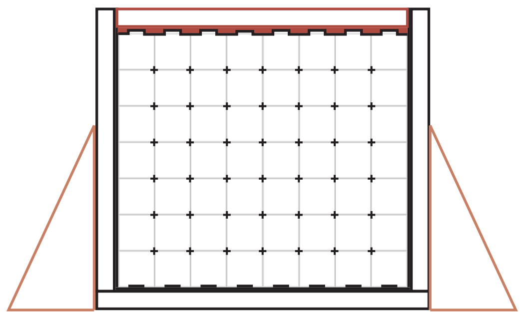
Steps 4-8 are followed in the mentioned sequence until the last row of the blocks is assembled. The soft rubber padding or the interlayer is placed over the top surface of the glass blocks.



Beam with guide plates lowered

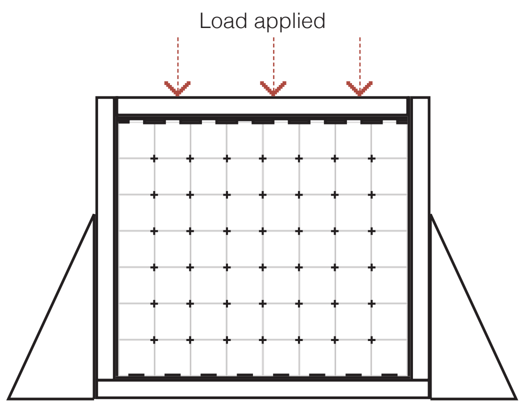
Step 10:

The top beam with the connected guide plates is placed over the last row of the glass blocks.



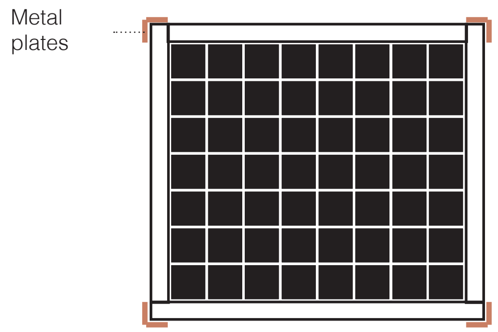
Step 11:

The vertical frames are secured with lateral support so that during the pre-compression process they don't slide on the outer edge.



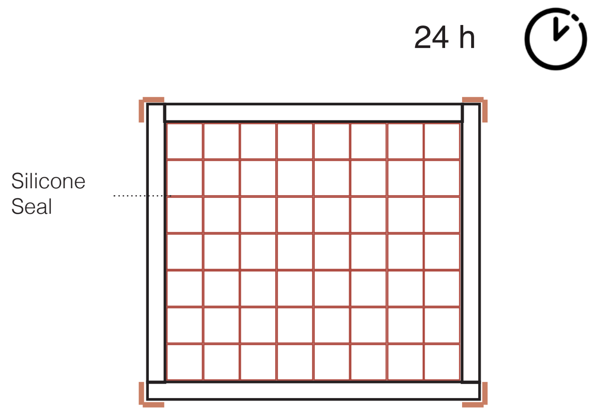
Step 12:

The top beam is now subjected to loading with the help of system-controlled force. This process results in the perfect bonding in-between the glass and interlayer surface.



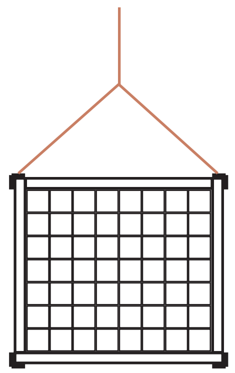
Step 13:

The top beam is now secured with the frame. Additionally, the corners of the frame are fixed with metal plates for quick assembly on the site.



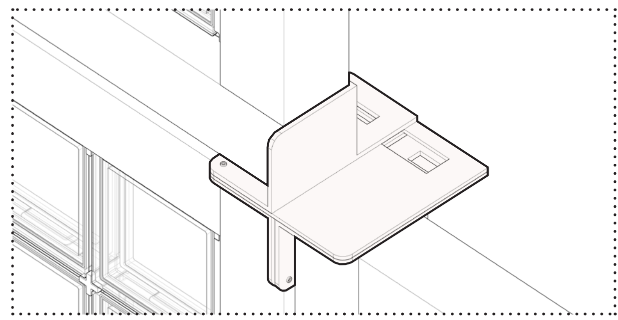
Step 14:

All the edges, corners, and junctions are examined. Now the gaps between the glass blocks are sealed using structural silicone. The silicone is allowed to dry.



Step 15:

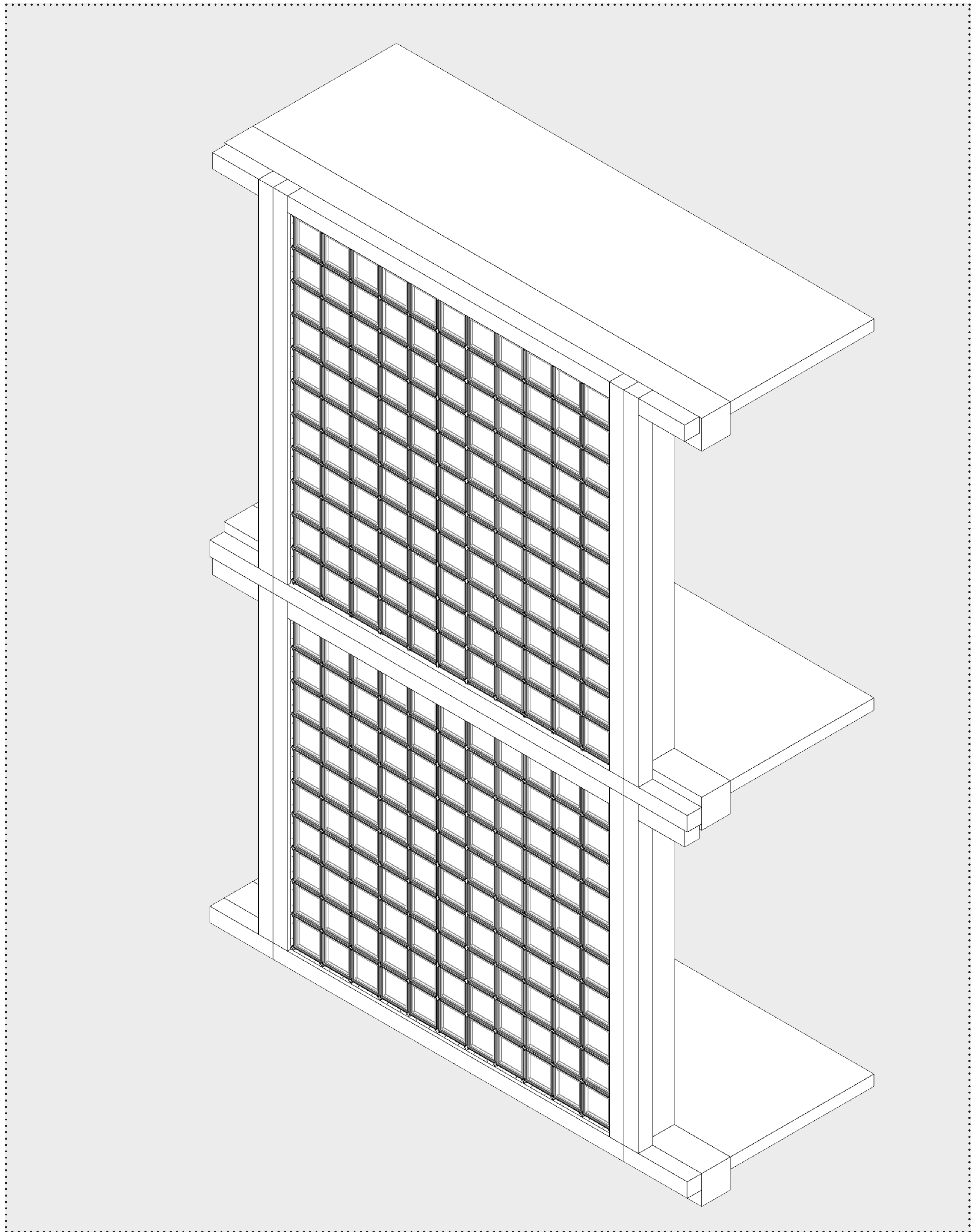
These pre-assembled frames of glass blocks are transported to the site. On-site the corners are fastened with the chains and lifted.



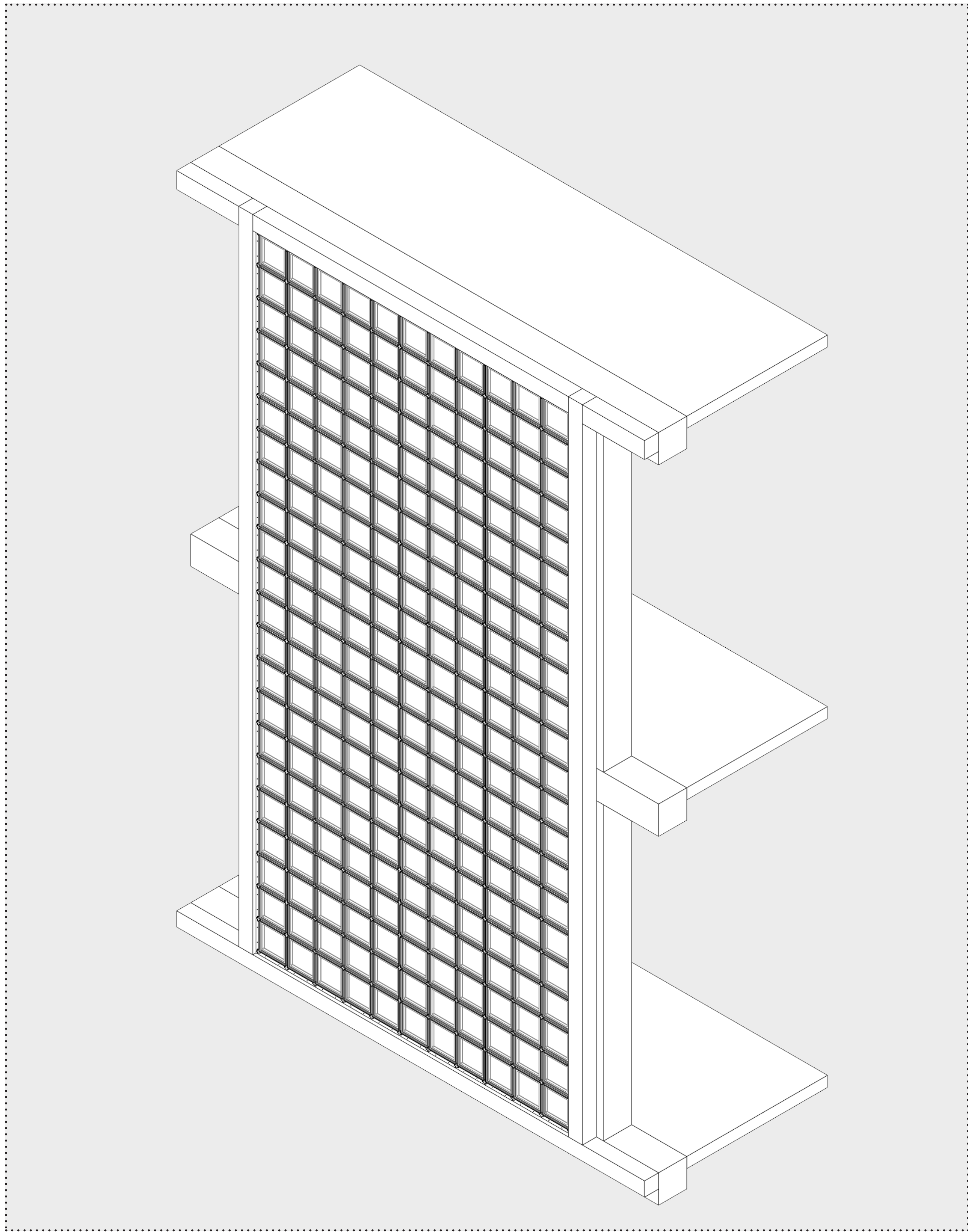
Corner Metal plates connection

Step 16:

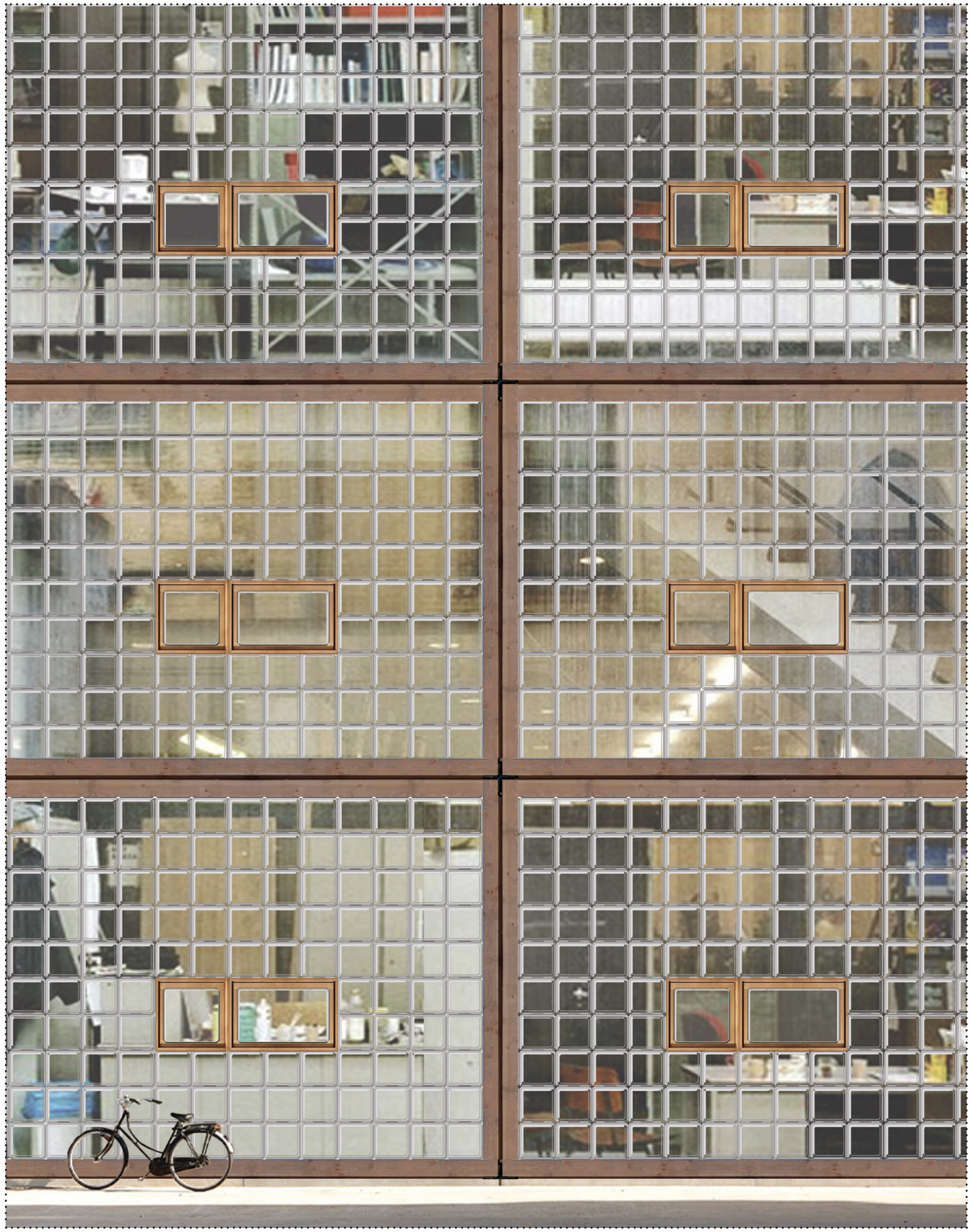
The corners are mounted over the embedded metal plate in the concrete ledge. The corner frames are first assembled on site followed by the middle frame. Later the connection between the embedded metal plate and the 4 frames is secured through bolting and adjusting their tolerances.



MODULAR ASSEMBLY

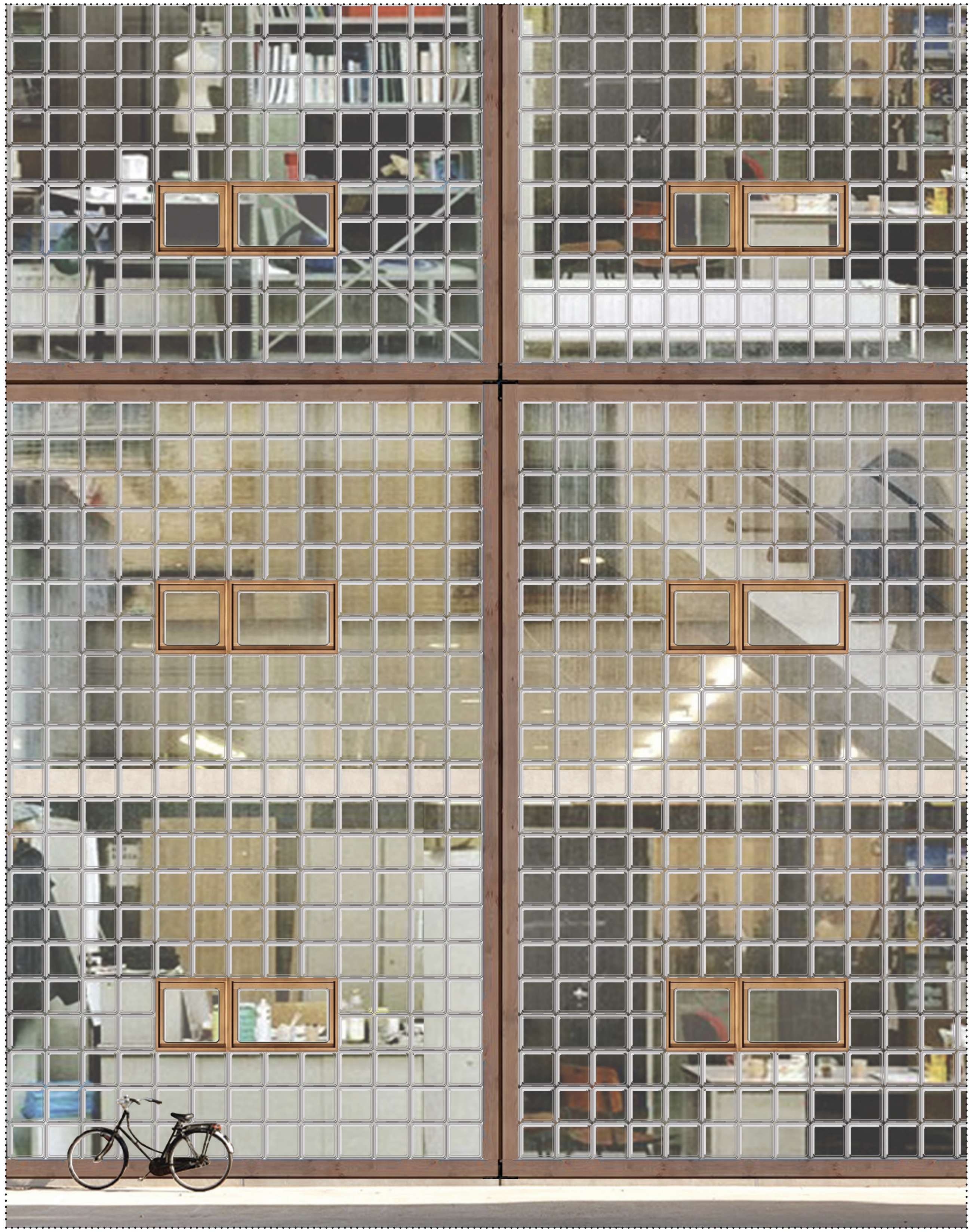


LOCAL ASSEMBLY



MODULAR ASSEMBLY

Envisioned for Academy of Arts, Maastricht

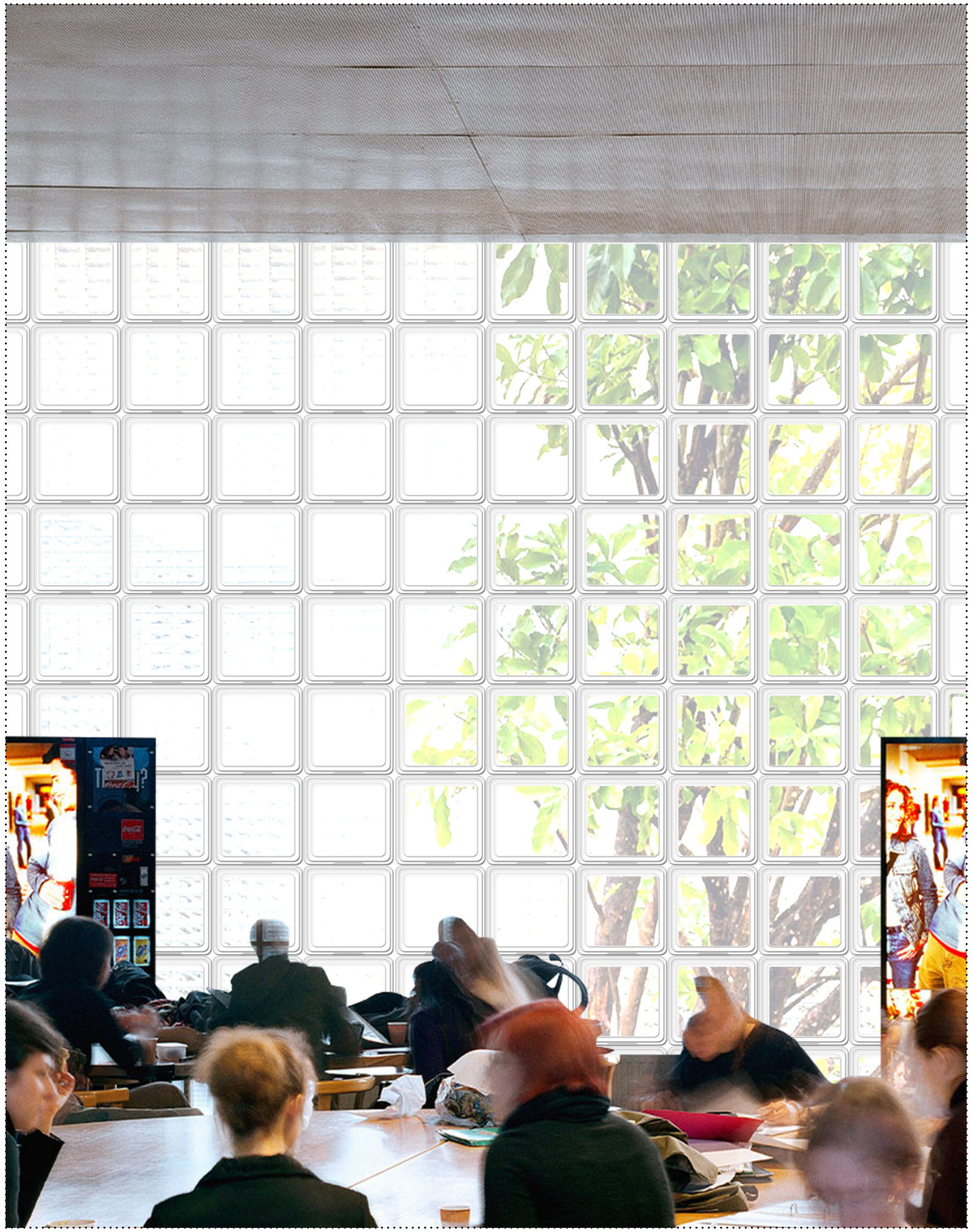


LOCAL ASSEMBLY

Envisioned for Academy of Arts, Maastricht

MODULAR ASSEMBLY

Envisioned for Academy of Arts, Maastricht

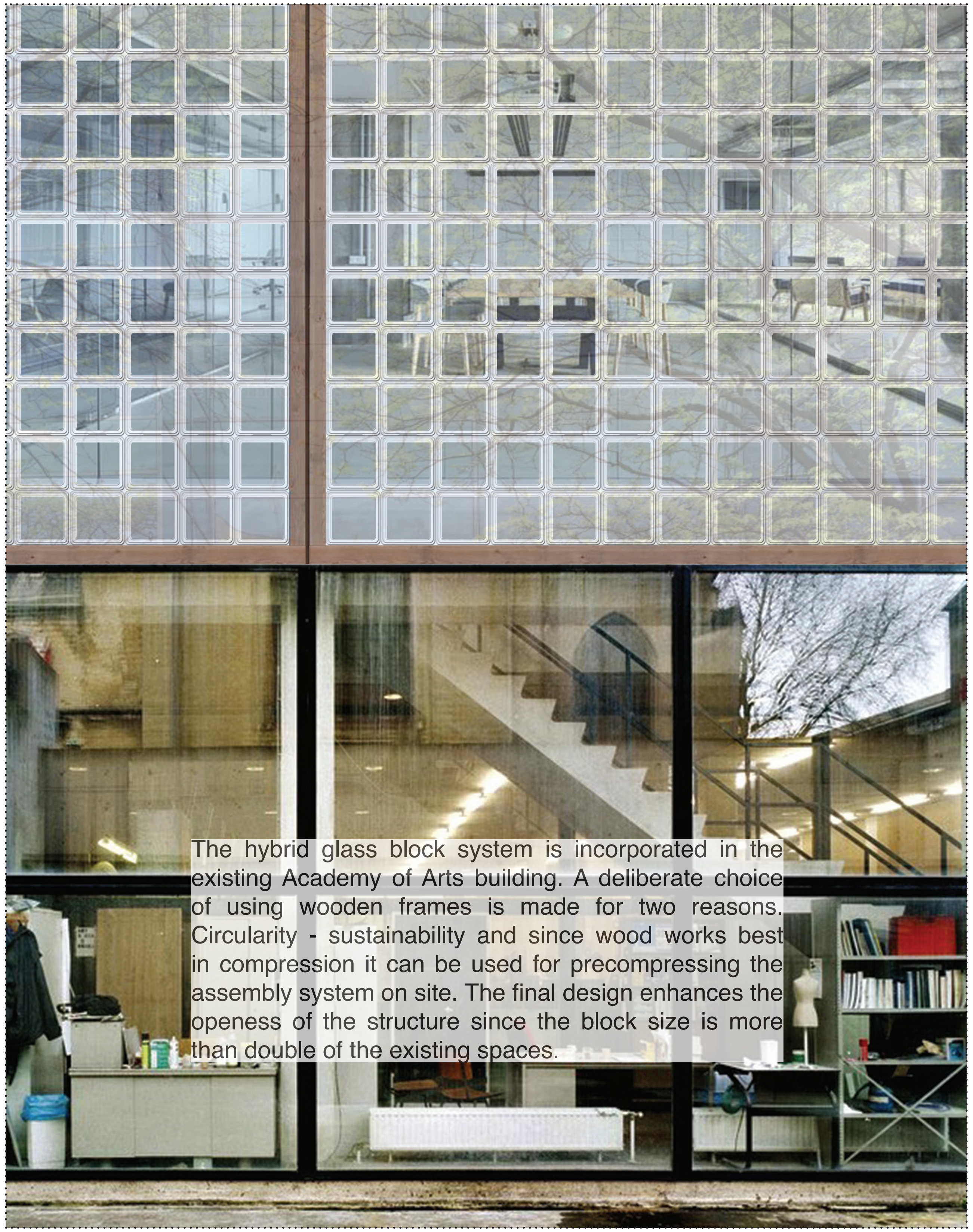


LOCAL ASSEMBLY

Envisioned for Academy of Arts, Maastricht

EXISTING SYSTEM

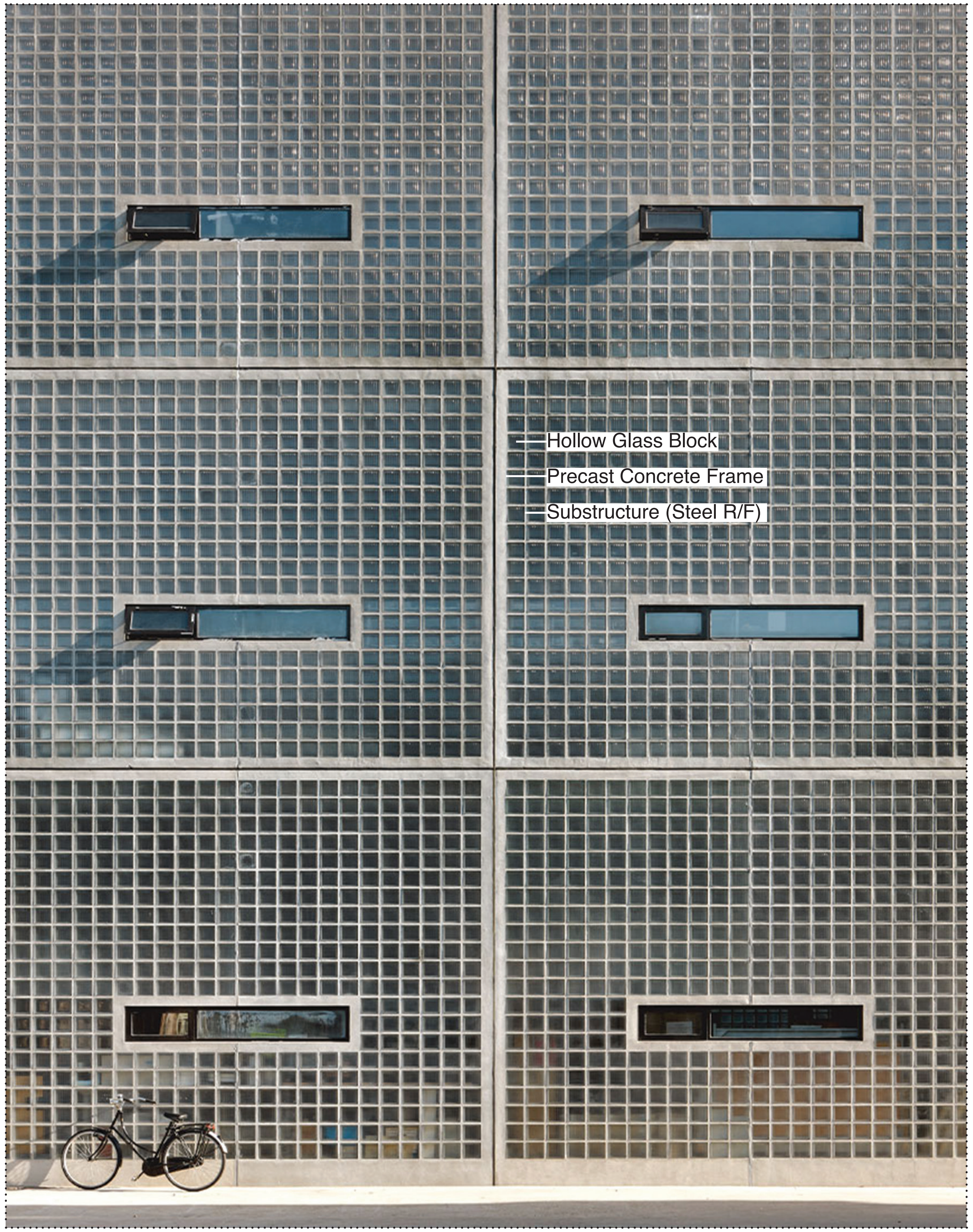
Existing facade Academy of Arts, Maastricht



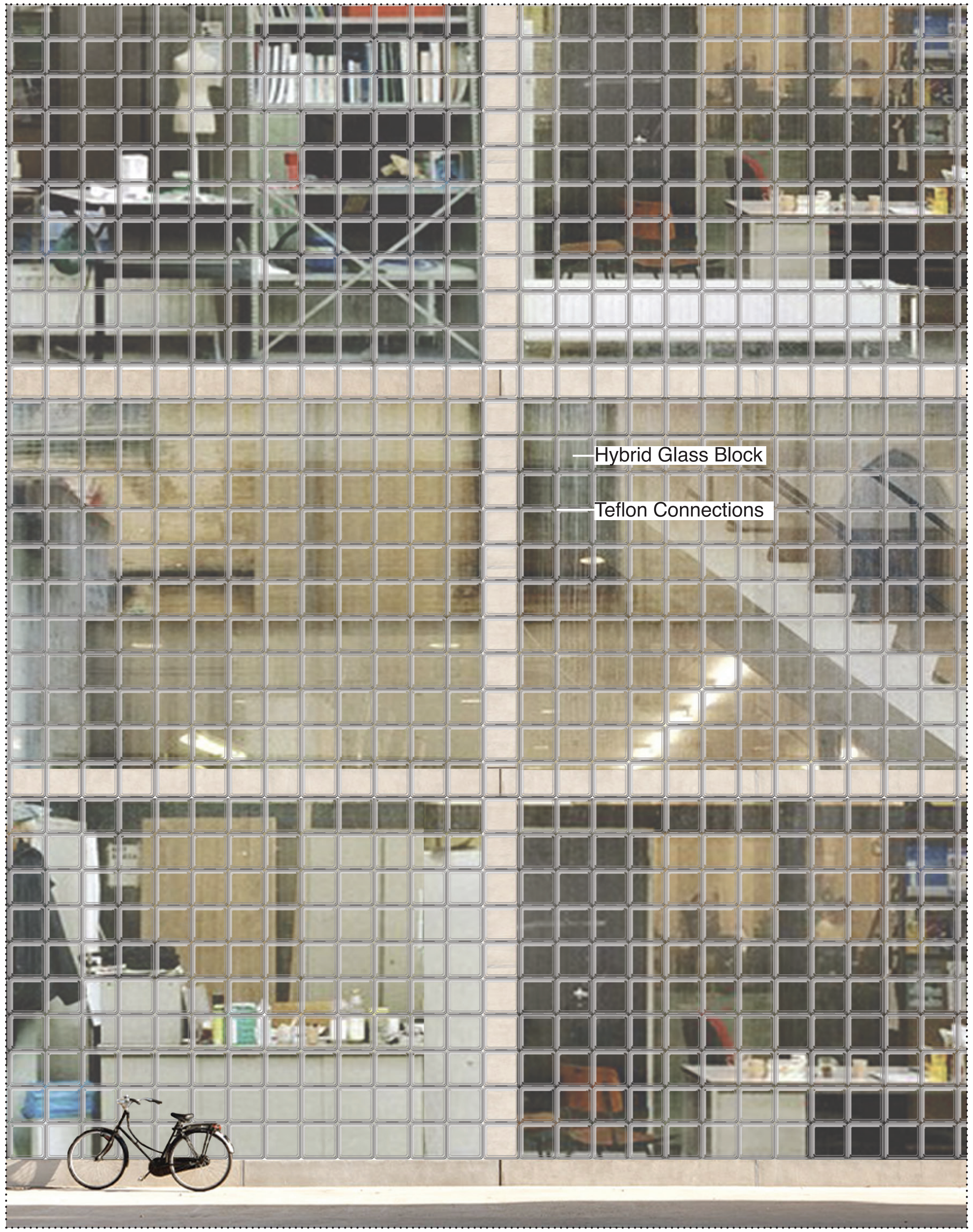
The hybrid glass block system is incorporated in the existing Academy of Arts building. A deliberate choice of using wooden frames is made for two reasons. Circularity - sustainability and since wood works best in compression it can be used for precompressing the assembly system on site. The final design enhances the openess of the structure since the block size is more than double of the existing spaces.

LOCAL ASSEMBLY

Envisioned for Academy of Arts, Maastricht



EXISTING SYSTEM
Existing facade Academy of Arts, Maastricht



SEAMLESS ASSEMBLY
Envisioned for Academy of Arts, Maastricht

Hybrid Glass block model made from plexiglass

10.

PROTOTYPING

The Hybrid glass blocks are prototyped at the Glass research lab in the Civil Engineering Department at TuDelft. The setup allows for the manual process of kiln casting and therefore is much more experimental and different from the prescribed automated industrial process. This exercise aims to identify the key issues and challenges involved in the casting of the final cross-section.

10.1

GLASS BLOCK CASTING

The actual prototype is one of the most significant components of verifying the design of the hybrid glass blocks in terms of its manufacturing process. Although an industrial technique is discussed for the actual manufacturing of the hybrid glass blocks, this thesis considers a more experimental method. This is mostly due to material and production resource limitations. The glass blocks were created in the Glass laboratory at TuDelft's Faculty of Civil Engineering under the supervision of Ir. Telesilla Bristogianni. For prototype manufacturing, a kiln casting process is explored, which comprises heating, cooling, and annealing within the kiln according to a predetermined firing schedule. The glass is cast inside a disposable mold made of high-temperature-resistant crystal cast investment powder. Because the weight of the 1:1 Component (16.6 kg) is too heavy for manual casting, the scale proposed for prototyping the hybrid glass block is 1:2. On a 1:2 scale, the weight of the casted block is approximately 2.8 kg. The complete mold-making and casting procedure takes around 21 days (this is highly subjective and the time frame is dependent on the size, geometry, and complexity of the design).

1 — 2 days

Geometry & Mold design

Sketchup 18 and Rhinoceros 7 are used to create the final geometry and mold. Once the final block design was finalized, the mold design, which was also the negative of the block design, was defined. Because the glass geometry features a protrusion on top and depression at the bottom which is critical for alignment, it was chosen to cast the geometry upside down, followed by a hydraulic press from the top to achieve the appropriate dip. The upside-down casting also helps the molten glass within the mold flow freely through gravity. The steel mold is divided into three components that can be opened to obtain the finished casted block. These various components are CNC milled and have interlocking mechanisms to ensure perfect alignment during mold setup. Air vents at the bottom of the mold are also required to eliminate the bubbles trapped during the molten glass pouring process.

2 — 2 days

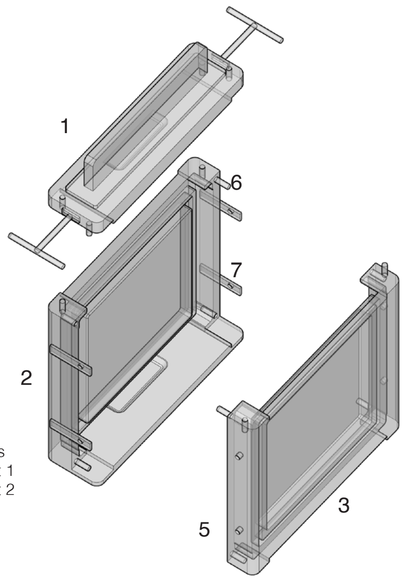
Foam Milling & treatment

For prototyping, a foam-based model was used as the base geometry. This was CNC Milled into two halves which were split vertically for ease in milling and later joined using a double-sided tape. The bonded pieces were then sanded to remove unwanted gaps. The choice of the material was dependent on the detail of the geometry and accuracy required. Even though MDF milling produces far smoother finishes than foam milling, it was impractical for the specified shape since it required extra treatment such as primer and varnish application.

3 — 4 hours

Silicone Mold preparation

It was decided to make a vertical mold with protrusion and recess surfaces on either horizontal side and a flat surface at the bottom and top for ease of casting. A 25 mm piece of foam was attached to the bottom of the foam block. This additional piece is necessary because the top layer sags during the glass casting process owing to shrinkage. Because a smooth surface is required, the casted block must be post-processed, in which extra glass is sawn off, grinded, and polished to obtain a smoother surface. The foam block is placed on a flat surface and the base is covered with clay to set the position. Wooden boards are arranged in the fashion of a bounding box around the foam block at a distance of around 25 mm from all sides and are secured with the help of clamps. The edges of the bounding box are sealed using clay to avoid any leakage. The top of the bounding box is left open for pouring silicone. Mould releasing spray ACMOS 82-2405 is sprayed throughout the surface of the foam block. This will facilitate the removal of the foam geometry easily from the silicone mold.



1. Hydraulic Press
2. Steel Mold part 1
3. Steel Mold part 2
5. Air Vent
6. Alignment pin
7. Mold Locking system

Figure 10.1: CNC milled steel mold design

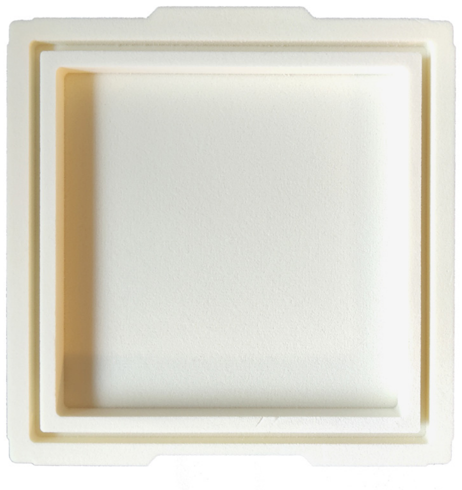


Figure 10.2: CNC Milled foam block

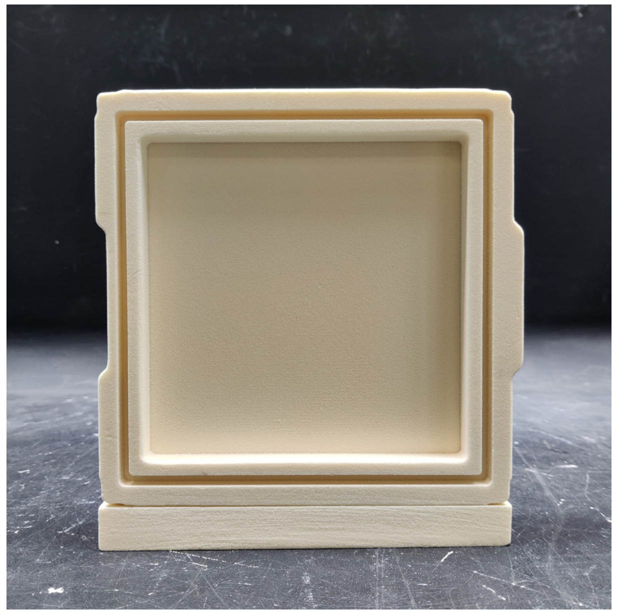


Figure 10.3: Foam block orientation for making mold

Figure 10.4: Bounding box set-up for the silicone pouring

4 1 day (20 hours for curing silicone)

5 6 hours (Wax poring and cooling)

Silicone Pouring

MOLD MAX 30 is a mold-making substance in which wax is cast to form the final geometry for the final crystal cast mold. The MOLD MAX 30 consists of 2 components, A and B, which must be combined in the ratio of 100A:10B. To accurately weigh both elements of the combination, a weighing scale is necessary. After pouring the components together, a constant stirring for around 2-3 minutes is necessary to obtain a homogeneous pour and eliminate any air bubbles. After carefully stirring the mixture, it is poured over the foam block and into the gap produced by clamping wooden boards. The mixture is poured at a single point, which is the lowest point, to produce the optimum results. Pouring is done up to 25mm above the foam block's top surface. The pour is allowed to cure overnight at room temperature for 16-20 hours.

After the silicone mold has been set, the corners are cut and the foam block is removed. After that, the silicone mold is completely cleaned with water to remove the clay from the inside surfaces. The silicone mold is allowed to dry and the water trapped inside it evaporates. Once fully dry, the mold is tightly taped to prevent leaking and is ready for wax casting. Wooden boards are wrapped around the silicone mold to make a bounding box, but no clay is used to seal the edges this time. The clamps are used to retain the silicone mold inside the box, and extra care must be taken not to clamp the bounding box too firmly, since this may distort the casted block.

Wax Casting

The silicone mold is used for casting wax in the shape of the hybrid glass block. The casted wax will be further used to make the final crystal cast mold that will be kept inside the kiln for actual glass casting. The reason behind using wax is that it can be removed from the crystal cast mold with the help of the steaming process. The hard wax is placed inside a metal container and heated at around 70°C on an induction plate for 1 hour. The melting process starts gradually and the important aspect is not to heat the wax until bubbles are created. A steady and constant melting will allow for a homogenous pour. When the wax has melted fully, it is poured into the silicone mold. Pouring should be done as soon as possible since wax hardens due to temperature changes, causing shrinkage.

On both the top layer and the internal side, there is apparent shrinkage and distortion of the geometry. Although the geometry is symmetrical, the casting is uneven due to the existence of protrusions and depression in the design. After allowing the wax to cool for around 4-5 hours, the silicone mold is removed. The design has a 5mm profile, the thinnest detail, and it is not accurately cast in wax. This might be owing to improper pouring or bubbles developing in the geometry's interior. These imperfections are seen as rough surfaces with little pores formed over smooth surfaces. The wax block is then handled further by removing extra wax saturated in the profile with a blade and wiping a dab of soft wax across the surfaces. The soft wax accumulates inside the perforations and smoothens the surface.

Figure 10.5: Silicone poured inside the bounding box

Figure 10.6: Silicone Mold & foam block seperated

Figure 10.7: Wax pouring inside the silicone mold

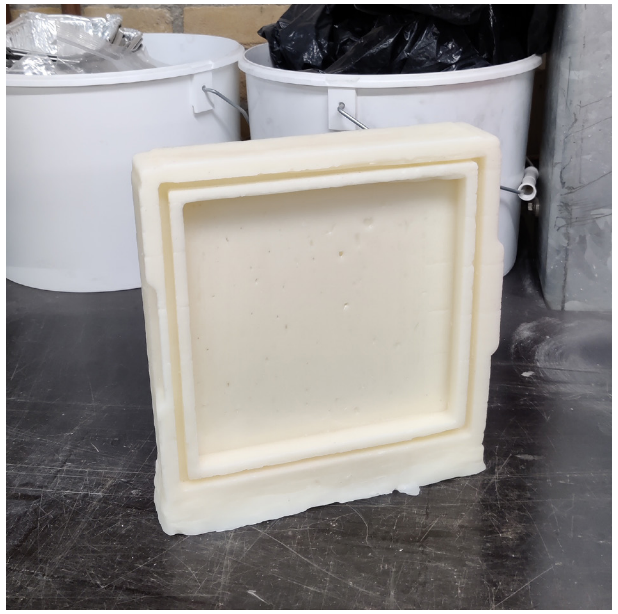


Figure 10.8: Wax block obtained after casting

6 1-2 hours

Crystal Cast Mold

Once the wax block is ready, it is placed on a level surface and its base is sealed with clay. A wooden bounding box is built around the wax block, with a minimum offset of 25mm on all sides. This offset is left to ensure that the final mold walls are not excessively thin, which might result in breaking and leaking during the casting process. Along with water, crystal cast M248 is employed as a foundation material. The recommended ratio is 1:2.75, which implies that for every 1000 mL of water, 2750 mL of crystal cast powder is necessary. Inaccuracies in measuring may cause the mold to become brittle and develop cracks. Once uniform, the liquid is poured into the bounding box and left to dry for 1-1.5 hours.

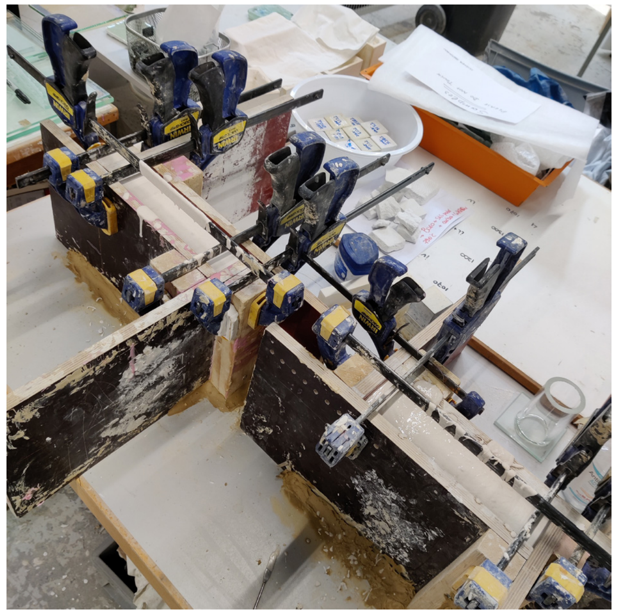


Figure 10.9: Crystal cast poured over the wax block

7 2-3 hours (depends on the depth of the geometry)
<<1 hour (for mold treatment)

Steaming

The crystal cast mold is removed from the bounding box and put into the tub upside-down, facing the lower side opening. The steaming nozzle is aimed at the wax aperture, and the mold is sealed with plastic bags to keep the steam within. The wax melts during the steaming process. The steaming process took a long time in our situation since the geometry featured thin profiles and considerable depth. To speed up the steaming process, wax was manually removed with a spoon in a few instances. To remove the wax that had collected in the delicate sections, hot water was poured inside the mold. At this point, a tiny break appeared in one of the molds. A sharp knife is used to scrape away any defects on the internal surface of the mold. The mold is now washed and cleaned with water to remove the clay and wax before drying.

Figure 10.10: Steaming process to extract the wax from mold

8 <<1 hour

Glass Volume Measurement

The rhinoceros model is used to calculate the volume of glass needed for the casting process, which is then compared to manual calculations. Another way is to fill the mold with water and then multiply the volume by the density of the glass. Because some glass is left attached to the clay pots throughout the casting process, a 10% surplus is assumed during the volume calculation. In our case, a volume of 0.01 m3 was required to cast a 0.2*0.22*0.04 m glass block with a glass density of 2520 kg/m3 (Bullseye Tekta glass). The required glass mass along with 10% excess was 2.8 kg. Before preparing the glass for casting, we scrape, clean, and dry the clay pots to eliminate any moisture. In an ideal scenario, the clay pots and crystal cast mold should be allowed to dry for 24 hours at normal room temperature; however, if this is not achievable, the clay pots and molds can be maintained inside the kiln overnight at 75°C.

Figure 10.11: Final mold cleaned and dried

9 <<1 hour

Glass Treatment

For casting the block, 2mm Bullseye Tekta glass sheets are used. The glass panels are weighed and then cleaned using propanol. We place the glass sheet on a clean cloth and cover it with another clean cloth to shatter and break it down into smaller pieces that can be placed into the clay pots. The glass pieces are put into the pot and weighed to ensure that the appropriate mass is reached.

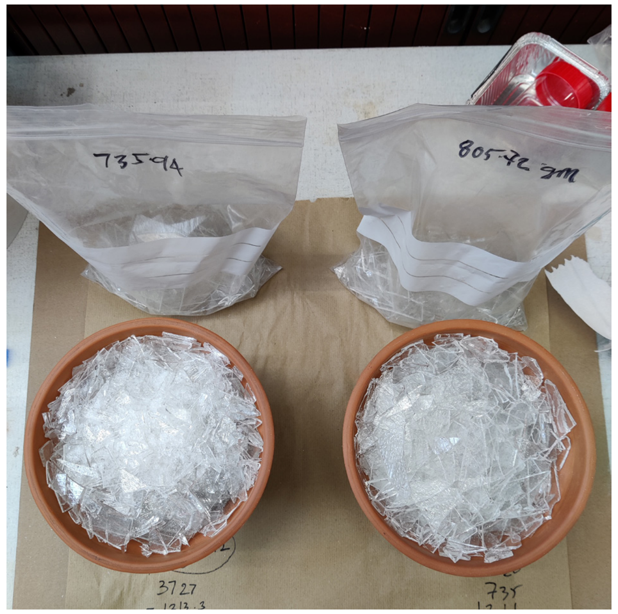


Figure 10.12: Glass pieces prepped for casting in clay pots

10 4-7 days (Depends on block thickness and Melting Point of glass

11 <<1 hour

12 2-3 hours

Firing

The molds are positioned within the kiln and are supported at various levels depending on the height of the mold and the weight of the glass inside the clay pots. In our case, we placed damaged mold pieces to form a support system on all sides of the mold. Because clay pots are put over the supports, the height was left somewhat over the mold. The opening at the base of the clay pots is aligned over the opening of the mold.

A firing schedule is created depending on the melting point of the selected glass and the thickness of the geometry that needs to be cast. The melting temperature of the glass in our case is 940°C, and the thickness is 22mm, requiring an annealing period of 4-6 hours. However, the dwelling time for each stage is carefully considered so that air bubbles do not form inside the casted block and cracking is prevented. As a result, a smooth cooling rate is assumed.

Description	Heating rate (°C/hr)	Temprature (°C)	Dwelling Time (hr)	TotaL Time (Hr)
Drying	50	160	3	6
Remove bubbles chemicals	50	677	2	12
Forming	50	940	10	16
Quenching	- 150	677	3 (Sucker hold)	5
Annealing point	- 25	482	6 (Anneal soak)	14
Annealing	- 10	427 (Strain pt.)	0	6
	- 20	371	0	2.5
	- 25	25	0	14
				75.5 hours

Table 10.1: Firing Schedule considered for the glass casting inside the kiln

Figure 10.13: Mold set-up inside the kiln for glass casting

Figure 10.14: Alignment of clay pot opening with the mold

Mold Release

When the casting process is finished and the kiln has reached room temperature, the molds are removed and immersed in water for 10-20 minutes. The crystal cast slowly dissolves in water, allowing the mold to be quickly removed from the glass surface. The glass block is then washed and rinsed to remove the crystal cast particles. The glass block has been verified for flaws and is now ready for post-processing treatment.

In our case, both crystal-cast molds broke within the kiln, allowing the glass to flow through the cracks. The final block was not cast, but the crucial observations were made throughout the prototyping phase, which is presented in the observations & conclusion section 10.3 of this chapter.

Post-processing glass

Since the glass block is cast inside a manually formed mold, defects appear on the glass surface. Imperfections like protrusions, depressions, roughness, or excess casted portions are fixed with dental tools, which allow for a safe treatment by avoiding the vibration impact of those other glass treatment instruments like grinders. The dental instruments also perform detailed glass treatment.

Figure 10.15: Mold Release process (Barou. L, 2016)

Figure 10.16: Post-processing glass block (Barou. L, 2016)

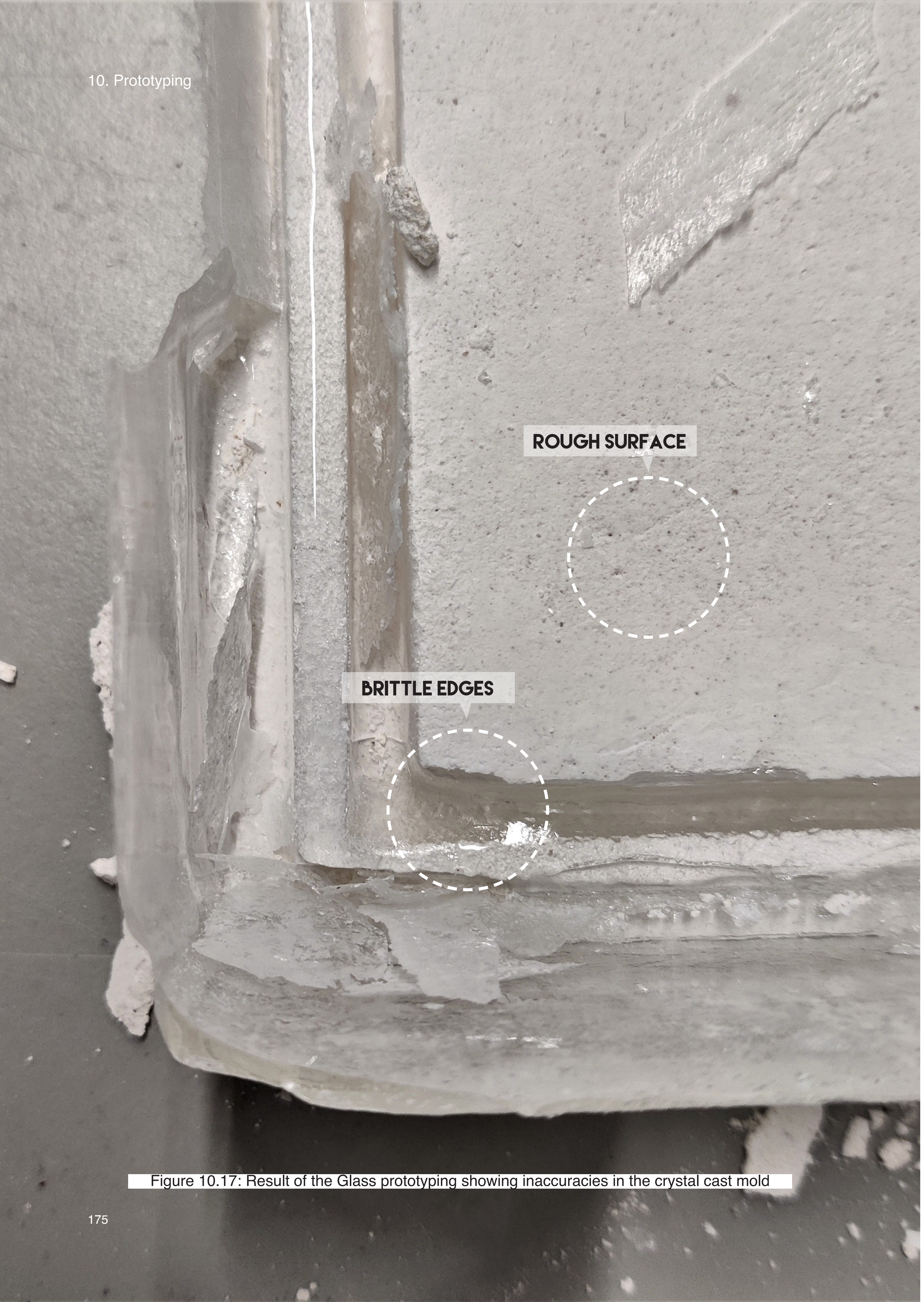


Figure 10.17: Result of the Glass prototyping showing inaccuracies in the crystal cast mold

10.2

INTERLAYER PROTOTYPING

Vivak PETG and soft-core aluminum are the interlayer materials under consideration for the final design. Both of these materials are investigated in the assembly process. Vivak creeps and requires precompression, whereas softcore aluminum is creep-resistant that allow ease in assembly process. The Vivak PETG has a calculated thickness of 2 mm (as calculated in Section 7.10.3). Vivak PETG of 1 mm thickness was chosen (as the glass block is prototyped on a 1:2 scale) for prototyping because it is readily accessible and can be prototyped using the thermoforming technique. The interlayer prototype method consists of two parts, the first of which is the preparation of a mold with identical geometry, which will subsequently be utilized as a base for the vacuum thermoforming process.

Mold Design Standards for Vivak PETG
Male molds are more suitable, however, material, size, and geometry should also be considered. Mold shrinkage of 0.2% to 0.3% should be considered and thus a minimum offset of 10 mm for the interlayer should be left around the mold. Draft angles of a minimum of 5°-7° or more should be designed for easy removal from the mold. A generous size of the radii of the fillet should be designed to achieve uniform wall thickness (Plaskolite). The surface of Vivak is smooth resulting into less friction in between the glass and the interlayer surface which is essential for holding the glass blocks in postion. This requires additional investigation in the form of shear tests.

1 — 1 Hour

Mold Preparation

The CNC Milled foam block is sliced horizontally to reduce its height and used as a base mold that will be placed inside the thermoforming machine.

2 — <<1 Hour

Thermoforming

The mold is placed in the vaccum thermoforming machine and heated at 80°C. The PETG layer is clamped above and the mold is lifted.

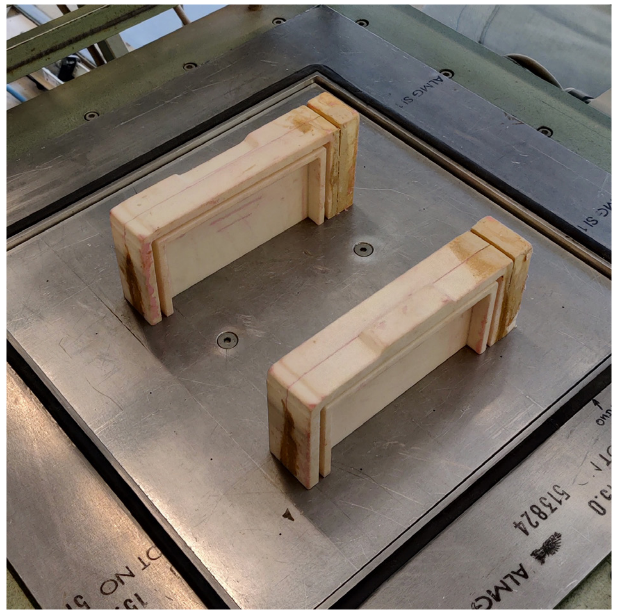


Figure 10.18: Mold used for the vaccum thermoforming

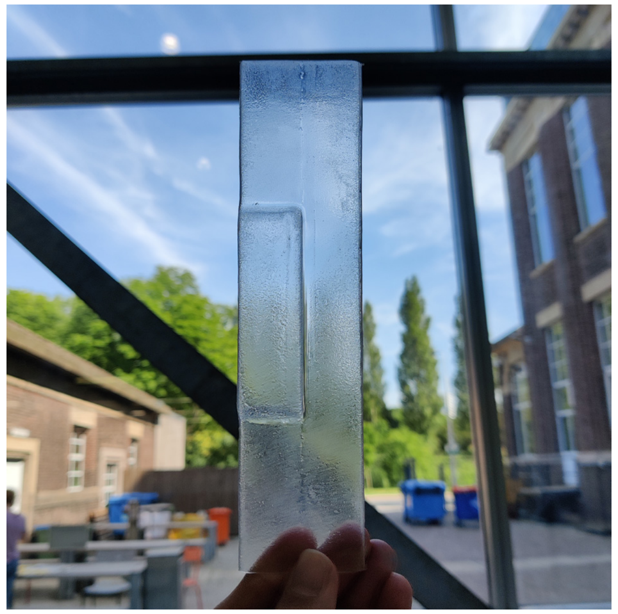


Figure 10.19: Interlayer post vaccum thermoforming

10.3

OBSERVATIONS & CONCLUSIONS

Kiln casting is a time-consuming procedure that requires several manual steps which have a significant influence on the quality and transparency of the casted block. The purpose of the prototyping phase was to determine the production viability of the designed hybrid glass block. During the casting process, both crystal cast molds fractured within the oven, resulting in molten glass leakage. Due to time constraints, the casting procedure was not repeated because it required us to return to the wax casting step. Even though the final hybrid glass block was not produced, the prototype process yielded several takeaways. The following are some of the significant observations, issues, and recommendations made during this process.

Simplification of geometry and scale for casting
The finished design has delicate notches in the shape of a profile with a width of 10mm and a depth of 15mm. For casting, the minimum width and depth are 6mm. Because the prototype was done on a 1:2 scale, the minimum width and depth became 5mm and 7.5mm, respectively. As silicone, wax, crystal cast, and glass have varying densities, the molding process was extremely difficult because of the decreased dimension. The movement of diverse materials inside such complex and intricate geometry becomes impossible to predict. Due to a very thin cross-section of 13mm, the wax-steaming process took longer than anticipated, as the steam was not able to penetrate inside the mold. At times, a manual procedure was utilized to remove the wax, followed by putting hot water within the mold. It will be essential to modify the design for future castings of identical geometry and cross-section to allow a simple and easy flow of the fluids by increasing the size of the notches or eliminating them.

Proportion of crystal cast and water
One of the key elements that may have contributed to the fracture of the mold within the kiln is inaccurate crystal cast and water proportions. According to standards, 2750 ml of crystal cast powder should be mixed for every 1000 ml of water. The excessive water content causes the mold to be brittle. At just 100°C, the crack formation was seen within the crystal mold during the wax steaming operation. Because the temperature at which glass melts is quite high (940°C in our case), crystal cast molds should be able to endure these high temperatures.

Mold wall thickness
During crystal cast mold assembly, a 25mm offset should be left around the wax geometry as a standard. The thicker wall will create a more stiff and more durable mold for glass casting. The thickness of the mold wall in our situation ranged from 10mm to 15mm, which is much less than the minimal standards. Thin walls may have assisted the cracking process within the kiln, resulting in the mold's ultimate collapse.

Horizontal casting
The design of the hybrid glass is similar to a large plate made from thin/float glass. The most common approach to casting such thin geometries is in horizontal directions, which allows for optimum glass flow. This is good since the molten glass's pressure is distributed across a wider surface area. However, due to the existence of minor notches, protrusions, and depressions in our case, the glass casting was done vertically. Because of the thin cross-section of the geometry, it is assumed that the base of the mold experienced significant pressure during glass casting, forcing the mold walls in the exterior direction and causing cracking. Even though horizontal casting has more advantages, the key issue associated with it is shrinkage over a large surface area. The tendency of the glass to shrink during the casting process might affect the desired geometry and create eccentricities during structural loading. In my opinion, the ratio of the height to the width of the block plays a vital role in considering the direction of casting.

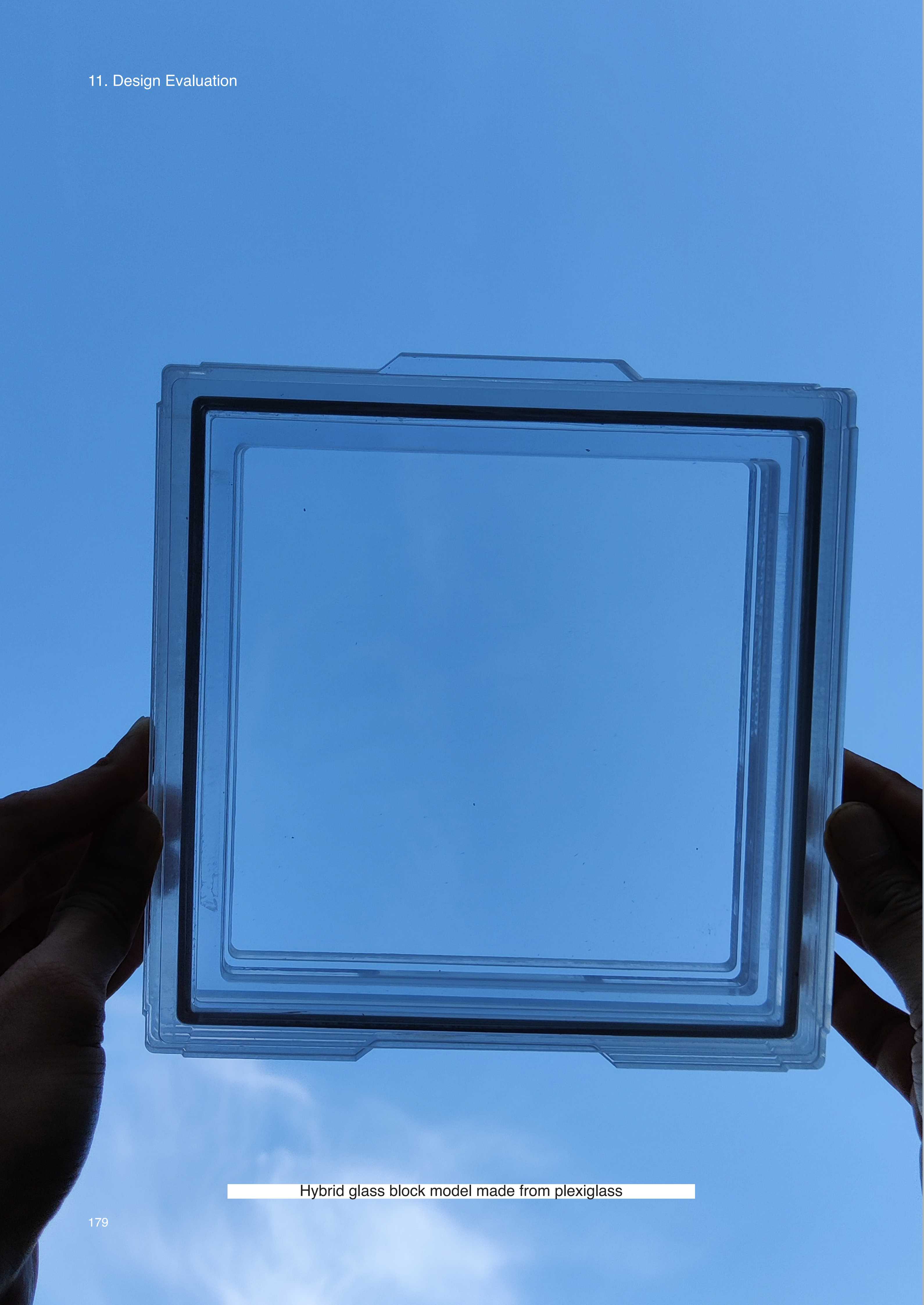
Shrinkage and deformation during wax casting
The wax pouring procedure encountered a few significant challenges due to the complex and intricate shape of the hybrid glass block. To begin with, the wax was not correctly cast in the complex notch sections at the bottom of the mold. This was associated with improper pouring at the bottom due to a thin cross-section. The wax continued to fall on the sides and rapidly hardened, blocking the passage for correct overflow at the bottom. Because there was enough area for pouring on the top, the notches on the top were correctly cast. Secondly, the retained moisture inside the silicone mold contaminated the wax, resulting in rough surfaces with tiny holes across them. Lastly, the silicone mold was manually taped to ensure that the wax did not leak, resulting in a distorted wax geometry. The top surface of the wax block begins to shrink as the wax hardens owing to temperature differences. All of these flaws necessitate an additional post-processing phase in which the collected wax in the notch is cut with a sharp tool and the rough surfaces are finished with soft wax. Because there is no moisture in the silicone mold after the first wax casting, the second wax casting is usually more promising.

Figure 10.20: Visible deformation and rough surface of the casted wax block.

Smooth draft angle for the alignment detail
A fracture forms at one of the alignment detail connectors. The true cause is unknown because the block was not correctly cast. It is hypothesized that fracture formation at the alignment junction is caused by an abrupt change in angle. Alignment details and draft angles should be smoother for a successful casting outcome. This will also help shape the interlayer during the vacuum thermoforming process.

All the above-mentioned observations and challenges during the prototype manufacturing process are most commonly associated with geometry and cross-section design. Since the prototyping is done on a 1:2 scale, they are more evident and noticeable. In reality, the manufacturing process explored in the final design chapter is more practical and suitable for the casting of glass using high-precision steel molds. For further study, it is better to cast the hybrid glass block into small parts on a 1:1 scale to develop a better understanding.

Figure 10.21: Visible cracks at the alignment detail



Hybrid glass block model made from plexiglass

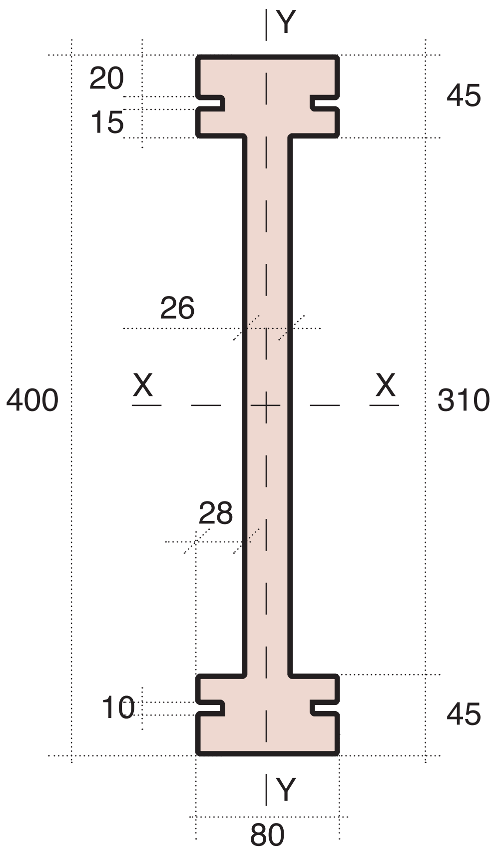
11.

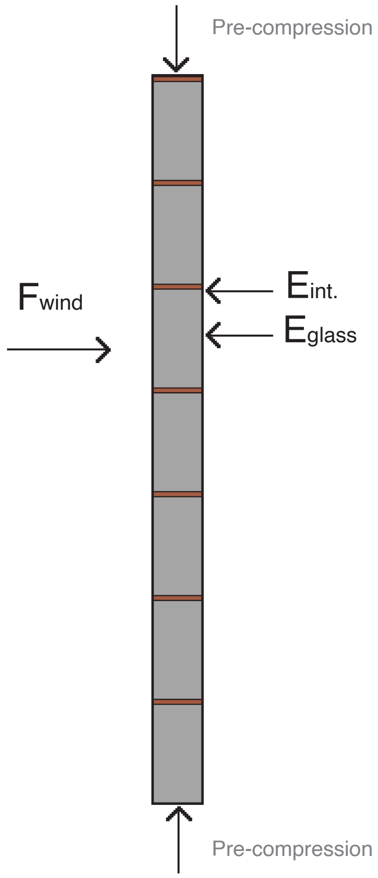
DESIGN EVALUATION

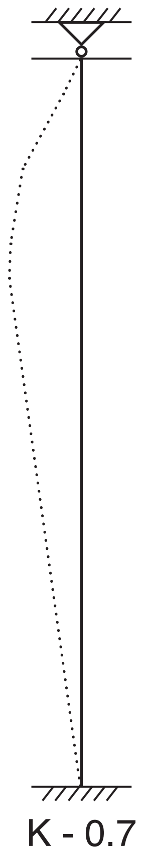
This chapter elaborates on the final design in terms of its safety and performance. The structural and thermal validation is conducted by a numerical approach. Further, the design goals are evaluated based on various design criteria.

11.1

STRUCTURAL EVALUATION: NUMERICAL APPROACH







1. Weight Calculation:

Size of the Block: 400* 400 * 80 [mm] : l*h*b
Surface Area = 400 * 80 [mm2]
= 32,000 [mm2] = 0.032 [m2]

Size of Cavity: 310 * 310 * 28 . [mm] . 2
Volume of Cavity = 5,381,600 [mm3]
Volume of Profile = 1,980,000 [mm3]
Volume of Block = 12,800,000 [mm3]

Total Volume = V.Block - V.cavity & V.profile
= 6,000,000 [mm3] = 0.006 [m3]

Density of Borosilicate glass = 2230 kg/m3
Mass = Volume . Density = 0.006 . 2230
= **13.38 [kg]**

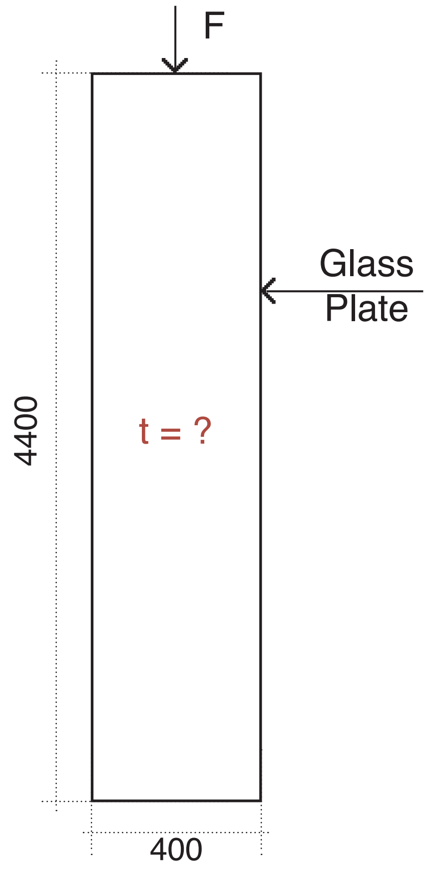
2. Compressive Load:

Force = Mass * Gravity [N] = 16.72 * 9.81 = 131.25 [N]

Compressive Load = Force/Area [MPa]
= 131.25/32,000
= 0.004 [MPa]

Height of the facade = 4400
Number of blocks = 11
Force [10] = 11 * 131.25 [N] = 1,443.75 [N]
Compressive Load over bottom block
= F[10] / Area
= **0.04 [MPa] < 0.5 [MPa]**

As a thumb rule the compressive strength of the lower layer of block < 0.5 [MPa]



3. Thickness check of the glass block:

Glass masonry may be thought of as a flat plate of constant thickness.

Compressive load over the last layer of the block,
Mass [blocks] = Density . Volume [kg]
= 2230 * 0.4 * 4.4 * t * 4 [sf]
= 15,700* t [kg]

Force = Mass * Gravity [N]
= 15,700 * t *9.81
Force = 154,017 * t [N] = 154.01 * t [KN]

critical = F/A
= 154.01 t / 0.4 t = 385 [KN/m2]

The glass plate is a combination of glass and interlayer. Both these materials have a different young's modulus. Therefore, for a composite structures the effective stiffness can be calculated using following formula,

$$E_{effective} = \frac{[L_{glass} + L_{interlayer}]}{[(L_{glass}/E_{glass}) + (L_{interlayer}/E_{interlayer})]}$$

Where,
L_{glass} = height of glass block = 0.4 [m]
$L_{interlayer}$ = height of interlyer = 0.002 [m]
E_{glass} = 64 [GPa]
$E_{interlayer}$ = 2 [GPa] ...assumption

$E_{effective}$ = 55.4 [Gpa] = 55,400,000 [KN/m2]

To find the thickness we use Bryan's formula for critical buckling elasticity,

σcritical = [k [π^2 E] / 12 [1-v^2]] * [b/t]^2

σcritical = 385 [KN/m2]
k = 4, v = 0.2, b = 4.4 m, t=?

σcritical = [k [π^2 E] / 12 [1-v^2]] * [b/t]^2

385 = (4[3.14^2*55400000]/12[1-0.2^2])*[4.4/t]^2

t = 0.02 m = 20 mm

As pe the calculations, for the height of 4.4 m and width of 0.4 m and glass thickness of 0.02 m is optimum.

For the design of hybrid glass block 0.026 m web thickness is considered. This suggests that there is still scope of further optimisation in the cross-section as the effective thickness is more than 0.026 m.

11.1

STRUCTURAL EVALUATION

Structural eccentricity
The final cross-section has the shape of an I-Section, which is symmetrical and always has the center of mass located at an equal distance from all sides. However, because of the interlocking alignment detail on one side, a slight asymmetry within the geometry is conceivable. This is due to the interlocking being eccentric to the cast glass's axis. The eccentricity might cause the system to bend. To avoid bending, the cross-section design must be simplified and refined further. These are some suggestions for reducing bending through eccentricity (figure 11.1)

1. Creating a large interlocking geometry: The interlocking in the current design is on one side of the center axis. This interlocking detail can be made larger by pushing on the opposite side of the axis. This will result in a more stable cross-section.
2. Introducing unequal cavity spaces: To produce a balanced cross-section, the cavity depth on the opposite side of the interlock might be raised.
3. Introducing a hard interlayer of varying thickness: To compensate for the increased stress caused by the interlock, a varying thickness and hardness interlayer can be provided to decrease eccentricity.

Structural redundancy
The dry-stacked assembly system is used for the hybrid glass blocks. Glass blocks with an interlocking system are stacked on top of each with an intermediate interlayer and are secured with dry connections. Because the glass blocks are vertically stacked, the structure functions as a stacked column rather than a wall. There is no load transfer to the adjacent glass block, and the force is always transported vertically downwards. However, the adjacent group of glass blocks provides the necessary horizontal stability. In the event of structural damage on a unit level, the cast glass block may break. In this case, the glass block at the bottom and the Teflon connections will offer the required support to the blocks above it. The entire system will not clash if the block fails or collapses since the connections give immediate support. During an accidental impact, the system will only fail at the junction where there is maximum impact, and that too in a particular row and not the whole facade.

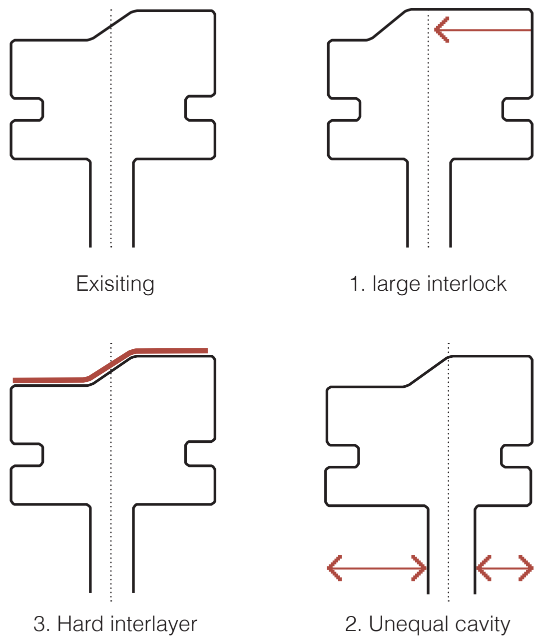


Figure 11.1: Recommendations to reduce eccentricity

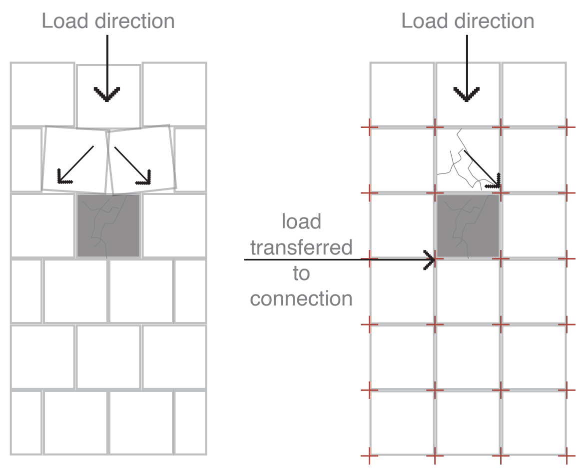
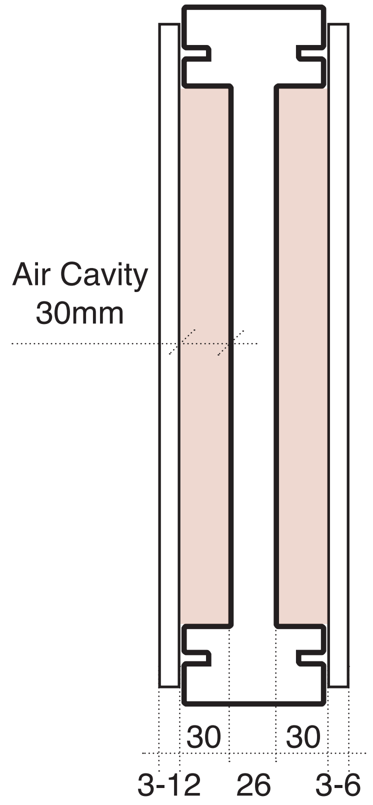


Figure 11.2: Structural Redundancy in alternate stacking(left) vs vertical stacking(right)

11.2

THERMAL EVALUATION: NUMERICAL APPROACH



Material	Cavity width	λ (W/mk)
Still Air	10-50 mm	0.025
Free Air	10 mm	0.066
Free Air	15 mm	0.088
Free Air	20 mm	0.11
Free Air	30 mm	0.14
Free Air (e)	30 mm	0.06
Wood	220 mm	0.08
Teflon	60 mm	0.3
Steel	220 mm	45
Soda lime	-	1
Borosilicate	-	1.15

Table 11.1: Standard Thermal conductivity values (W/mk)

U-Value (without e-coating)

Option 1: (Free air cavity of 30mm)
3-**30**-26-**30**-3 - U-Value = **2.18 W/m2k**....unit
U-Value = **1.89 W/m2k**....system

Option 2: (Free air cavity of 30mm)
6-**30**-26-**30**-6 - U-Value = **2.15 W/m2k**....unit
U-Value = **1.87 W/m2k**....system

Option 3: (Free air cavity of 30mm)
12-**30**-26-**30**-12 - U-Value = **2.10 W/m2k**....unit
U-Value = **1.83 W/m2k**....system
All the above mentioned options consider wood frame at a system level

Option 4: (Free air cavity of 30mm)
12-**30**-26-**30**-12 - U-Value = **2.10 W/m2k**....unit
(for steel) U-Value = **17.3 W/m2k**....system
Not feasible for steel frame.

U-Value (with e-coating for exterior glass panel)

Option 1: (Free air cavity of 30mm)
3-**30**-26-**30**-3 - U-Value = **1.34 W/m2k**....unit
U-Value = **1.22 W/m2k**....system

Option 2: (Free air cavity of 30mm)
6-**30**-26-**30**-6 - U-Value = **1.33 W/m2k**....unit
U-Value = **1.21 W/m2k**....system

Option 3: (Free air cavity of 30mm)
12-**30**-26-**30**-12 - U-Value = **1.31 W/m2k**....unit
U-Value = **1.19 W/m2k**....system
All the above mentioned options consider wood frame at a system level

Option 4: (Free air cavity of 30mm)
12-**30**-26-**30**-12 - U-Value = **1.31 W/m2k**....unit
(for steel) U-Value = **16.7 W/m2k**....system
Not feasible for steel frame.

11.2

THERMAL EVALUATION

Thermal Redundancy
The initial impact of glass block-breaking will be on the thermal performance of the glass block. Thermal bridging will occur as a result of the cracks, reducing thermal performance. To make the design thermally redundant following strategies can be implemented

1. Application of gorilla glass or laminated glass on the exterior side. This will reduce the possibility of cracks developing due to thermal shocks or vandalism.
2. In case of cracks developed on a cast glass replaceability of the structural component should be considered.
3. The current system works well since it has 2 cavities and even if the exterior panel cracks and thermal bridges are developed, the interior cavity will take care of the insulation.

Combination of Soda-lime and Borosilicate glass
The hybrid glass block is a combination of a borosilicate glass cast glass block with soda-lime glass float glass panels. Because of their varied thermal expansion coefficients, these glasses have distinct thermal characteristics. Due to fluctuations in outside and internal temperatures, the hybrid glass system may be susceptible to huge temperature variations. In such instances, the glasses would respond differently, potentially affecting thermal performance. The design allows for a 2mm gap between these two separate glass surfaces. This is accomplished by extending the snap-fit male detail, which is composed of an insulating material (such as Teflon or plastic). This feature stops the glass surfaces from coming into contact with one another and improves thermal insulation.

Cavity Width
Various cavity widths were examined throughout the design development process to attain a standard U-Value. (Nathani. T, 2021) (Velden. M, 2020) study was used as a baseline to assess the different design possibilities. According to the conclusions of the research (Binarti et al., 2014) a maximum air cavity width upto 20mm provides excellent heat resistance, which was taken into account while designing the hybrid glass block. However, the thickness of the immediate outer surface and the width of the first cavity has a significant impact on heat resistance. For the final design, 20-30mm cavity width is considered on both sides, however, there is a scope of optimization for the width of the second cavity, as its influence is not that significant. The U-Value calculations also indicate that the thickness of the cast glass has less of an impact on thermal resistance. This indicates that additional optimization of a structural cross-section is possible, although a minimum thickness of 15-20mm should be considered

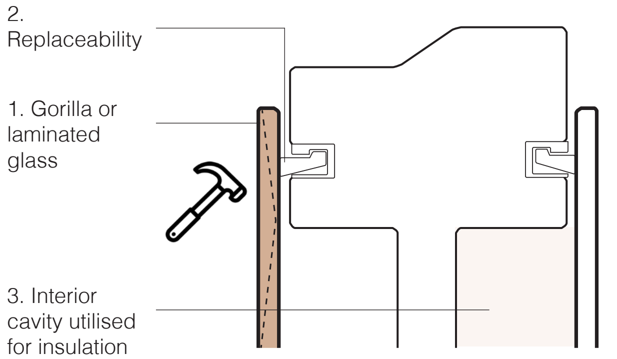


Figure 11.3: Thermal redundancy strategy

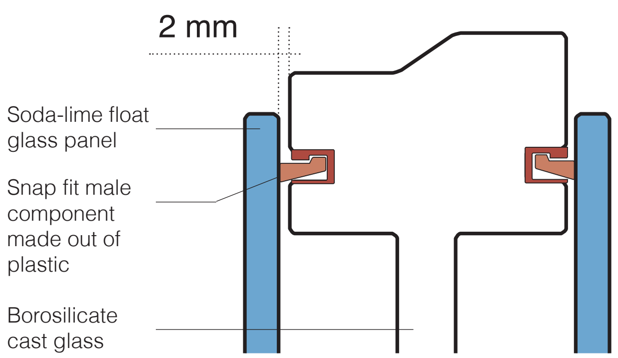


Figure 11.4: Gap between Borosilicate glass and soda lime glass

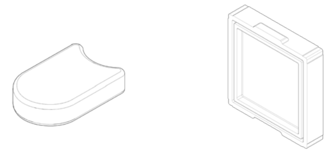
11.3

MANUFACTURING PROCESS EVALUATION

Faster annealing as a result of improved cross-section thickness
The investigations for various cross-section alternatives resulted in an optimized cross-section thickness. According to research findings from the literature and practical cases, the annealing time is heavily determined by the thickness of the cross-section rather than the weight of the block. In Atocha Memorial, the annealing period for a 300*200 mm solid glass block with a thickness of 70mm and a weight of 8.4kg was 20 hours. The predicted annealing time for a hybrid glass block with a cross-section thickness of 45mm, a dimension of 400*400mm, and a weight of 13.38kg is 10-12 hours. This assumption implies that bigger glass blocks may be annealed with less annealing time due to improved cross-section thickness.

Standardization
One of the primary goals of this thesis was to create a standardized manufacturing process while also considering the influence of design standardization on overall manufacturing. During the geometrical explorations, the design alternatives were assessed based on the number of variations in design and corner details. The design alternatives that involved more than 2 variations were given low scores as they required additional mold design, followed by different firing schedules due to varying thicknesses. The current design is made up of a single glass block that may be stacked into a column shape. A single block may be used to create a variety of compositions in terms of heights and apertures. The intended connection mechanism also makes it easier to use existing standardized systems, allowing for more practical and cost-effective implementation. The existing approach, however, has a drawback when it comes to curved surfaces. Nonetheless, the hybrid glass block allows for a great deal of flexibility in stacking arrangements.

Ease in manufacturing
The hybrid glass block system is an assembly of numerous components. The design refinement phase considered all the manufacturing standards and design guidelines to achieve a refined final design. A step-by-step industrial manufacturing method is also investigated. Although the design comprises a variety of components, they all adhere to the same manufacturing standards and techniques that have previously been defined and implemented. The table 11.2 provides an overview of the components and their comparable production method. To maintain the quality of the glass, a careful evaluation of soda-lime and borosilicate glass is done. Since the final design involves tolerances of +1 mm borosilicate glass was chosen as it accounts for smaller tolerances. Another reason for choosing borosilicate glass was to speed up the annealing process. The casted glass block is much more transparent and clear as compared with soda-lime glass.



Glass Type	Borosilicate	Borosilicate
Size of Block	300*200*70	400*400*80
Max.thickness	70 [mm]	45 [mm]
Weight	8.4 [Kg]	13.38 [Kg]
Annealing Time	20 [Hrs]	10-12 [Hrs]

Figure 11.5: Anticipated Annealing Time for hybrid glass block

Product	Production Method
Cast Glass	Hot-pour mold casting
Float glass	Float Method
Interlayer	Injection Molding
Steel Mold	CNC Milling
PTFE Connection	Extrusion
Snap Fit	Extrusion

Table 11.2: Standard Thermal conductivity values (W/mk)

11.4

ASSEMBLY & DISASSEMBLY EVALUATION

Ease in Assembly
The design explores 2 assembly systems depending on the choice of interlayer and its resistance to creep or not. To expedite the speed of construction on site, a modular pre-assembly approach is also considered. The choice of assembly depends on the visual preference which can be either a modular system or a continuous facade of hybrid glass blocks that are self-supported. In both cases, careful attention is given to ease the complexities in the assembly process. The designed hybrid glass blocks allow for tolerances on a system level of 2mm due to the presence of the interlayer. To facilitate a precise stacking of the blocks an interlocking system and the connection system are designed that allow for ease in alignment. The on-site assembly system is very straightforward, however, it involves a complex process of precompression. For sites that do not allow any room for pre-compression, a modular approach can be considered. In both cases, there is an increased risk of buckling, however, the modular assembly system is more secure and safe.

Ease in Disassembly
The Academy of Arts building consists of a wet connection facade made out of hollow glass blocks and precast concrete frames. The main issue is with its disassembly and replaceability on a unit level. The current design follows dry connections that are easy to assemble, disassemble and replace. The modular approach also allows for quick assembly and disassembly on site which can be reused on a system as well on a unit level. Replaceability is always an issue in wet connections, therefore, the design of hybrid glass blocks consists of cover plates and connections that can be easily unsecured. The one-side oriented interlocking alignment allows for the whole block to be slid in/out from the external side.

11.5

SUSTAINABILITY EVALUATION

Circularity
The recyclability goals for the cast glass component necessitated the design of a dry-stacked assembly system, although the focus was not directly oriented toward circularity. As previously noted, the present design is simple to assemble and disassemble. As a result, the hybrid glass block system or individual components can be reused when their building function is completed.

Recyclability
The recyclability of the cast glass component is important to the design of the hybrid glass. From the very beginning, the focus was oriented toward achieving the maximum recyclable component without any contaminations. To embrace this idea, a dry-stacked interlocking assembly system is being considered, which allows the cast glass blocks to be reused as well as recycled. The design was primarily focused on improving thermal performance, for which cavities were inserted inside the cast glass, necessitating air-tight connections at the unit level to cover the cavity with another glass panel. The only possible solution is to connect the float glass panel to the cast glass using adhesives, however, to maintain the purity of the cast glass component a rather unique dry connection system was envisioned that allowed for the cast glass component contaminated free. Apart from the recyclability of cast glass, the connections and the interlayer cannot be recycled, however, they are considered because of their lower thermal conductivity, high durability, and load transfer ability. The connections made out of Teflon can be reused since they have good resistance to heat and chemicals.

11.6

VISUAL AESTHETICS AND TRANSPARENCY EVALUATION

The hybrid glass block system is a façade system that prioritizes transparency, and thermal and structural performance. To maximize transparency, the extra substructure necessary to support the facade should be minimized or eliminated, and the glass blocks should be self-supported and load-bearing. The initial method was to create several design geometries with varying visual effects on the user. Various forms were investigated, with preference given to designs that allowed for more transparency.

The final hybrid glass block design is simple and elegant as it maintains the basic geometrical character and enhances transparency due to its enhanced size. The system's simplicity is what makes it appealing and allows it to mix in seamlessly with the existing urban fabric. The material selection for the connection and frames is distinctive since it combines the novel applications of glass and wood. The glass blocks can be stacked inside a wooden frame or in a continuous seamless opening without any support frameworks. As a result, the design may be created at any scale.

The hybrid glass blocks feature three glass surfaces, which may create optical distortion but are critical for improving thermal performance. If the criteria are adjusted and, more significantly, transparency is taken into account, the present architecture has the potential to provide such a customized solution.

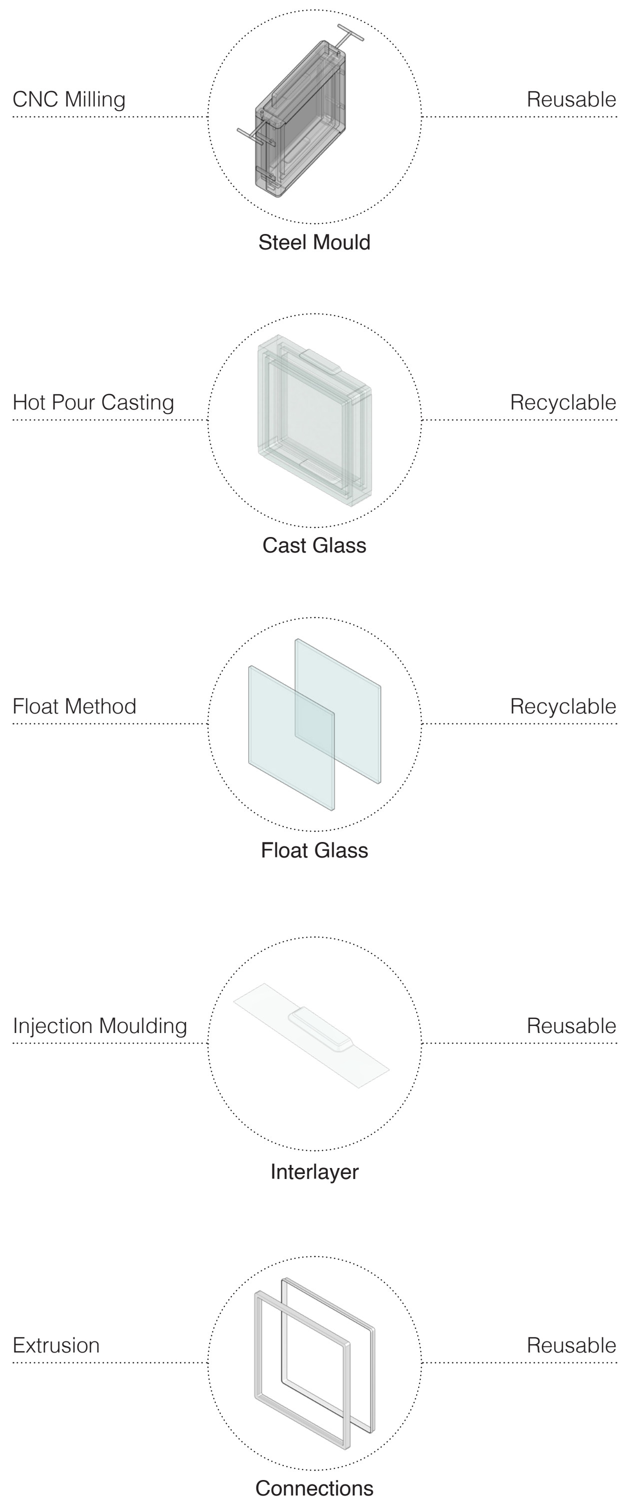


Figure 11.6: Manufacturing & Sustainability of Components

COMPARITIVE ANALYSIS OF THE HYBRID GLASS BLOCK

	GLASS BLOCK TYPE	HOLLOW GLASS BLOCK Seves (HTI WAVE) & Pittsburgh Corning (Thickset 90 VUE)	SOLID GLASS BLOCK Seves (VISTABRICK) & Pittsburgh Corning (VISTABRICK)	HYBRID GLASS BLOCK Developed by Natahani. T	STRUCTURAL CAST GLASS Developed by Velden. M	HYBRID GLASS BLOCK Developed by (Author)
PROPERTIES	(A) U- VALUE	1.8 - 2.5 [W/m2K]	4.1 - 4.9 [W/m2K]	1.65 - 2.20 [W/m2K]	1.61 - 2.66 [W/m2K]	**1.8 - 2.2** [W/m2K]
	(B) COMPRESSIVE STRENGTH	3 - 6 [MPa]	82 - 400 [MPa]	15 - 20 [MPa]	-	15 - 25 [MPa]
	(C) LIGHT TRANSMISSION	70 - 76 [%]	60 - 90 [%]	-	-	-
	(D) SHGC	0.32 - 0.68	0.52 - 0.78	-	-	-
	(E) SOUND INSULATION	43 - 50 [STC]	43 - 50 [STC]	-	-	-
		ACADEMY OF ARTS, MAASTRICHT	ATOCHA MEMORIAL	FUSION BLOCK Natahani. T	LATTICE BLOCK Natahani. T	I-SECTION BLOCK Author
PRODUCTION METHOD	(E) PROCESS	Casting, Fusing and Annealing	Casting	Casting	Casting	Casting
	(F) GLASS TYPE	Soda Lime	Borosilicate	Borosilicate	Borosislicate	Borosilicate
	(G) MOULD USED	Pressed Steel Mould	Pressed Steel	Open high precision	Open high precision	Pressed Steel
	(H) ANNEALING TIME	Unknown	20 [hr]	more than 20 [hr]	more than 20 [hr]	**10-12 [hr]**
	(I) BLOCK WEIGHT	2.7 - 3.7 [Kgs]	8.4 [Kgs]	16 [Kgs]	16 [Kgs]	**13.38 [Kgs]**
	(I) BLOCK SIZE	190*190*100 (mm)	300*200*70 (mm)	300*300*105 (mm)	300*300*150 (mm)	**400*400*45** (mm)
CONSTRUCTIBILITY	(J) SYSTEM	Metal substructure with mortar	Adhesive bonded	Embedded + Bolted	Interlocking	Interlocking + clamped
	(K) LOAD DISTRIBUTION	Not-load bearing. Forces are carried by a metal substructure	Homogeneous load transfer via rigid adhesive	Load bearing. In-plane forces are carried by the glass block & lateral forces (e.g. wind load) is transferred with the help of metal embed.	Load bearing. Homogenous load transfer with interlayer.	Load-bearing. In plane forces are carried by the glass block and interlayer & lateral forces are transferred with the help of teflon connections
	(L) CONNECTION SYSTEM	Blocks are connected through mortar/adhesives	Interlayer	Metal Embeds	Interlayer	Interlayer
	(M) ASSEMBLY SYSTEM	Adhesively bonded (mortar)	Dry Assembly	Embedded + Bolted	Dry Assembly	Dry Assembly
	(N) TRANSPARENCY	Compromised transparency	High Transparency	High Transparency	High Transparency	High Transparency
	(O) REVERSIBILITY	Non-reversible	Reversible	Reversible	Reversible	Reversible

Table 11.3 Comparitive Study of all the blocks adapted from (Oikonomopoulou. F, 2019) (Nathani. T, 2021) (Velden. M, 2020)

Developed Hybrid glass block prototype along with the hollow glass block in the background

12.

CONCLUSIONS

The thesis seeks to investigate a unique concept of a thermally performing and load-bearing cast glass system. This chapter highlights the findings obtained by responding to the subquestions and main research question. It also addresses the technological development constraints and makes recommendations for future research.

12.1

ANSWERING SUB-QUESTIONS

1. What design characteristics influence the load-bearing capacity and thermal performance of glass blocks? What strategies can improve the load-bearing capacity and thermal performance? What are the advantages and limitations of these strategies?

Cross-section design: The design of the cross-section of the glass blocks has a lot of influence on the structural as well as thermal performance. Individually glass blocks have impeccable compressive strength and can withstand heavy loads. The issue with structural failure begins when the glass is kept in contact with glass or other stiffer materials. Glass is brittle, which means it requires special attention while designing it structurally.

For designing a cross-section, references can be drawn from the standard steel profiles such as H & I- beams. The steel sections are efficiently designed to cater to stress concentration at specific junctions. Glass can be molded in any desired shape, however, the design of the cross-section is largely influenced by the casting process. During the cross-section refinement process, the edges are rounded to avoid the development of premature stress concentration during the casting process. In practice, organic shapes of glass blocks perform well under heavy loads due to the absence of pointed edges. The thickness of the cross-section has the most significant impact on the annealing process and as a thumb rule thickness of more than 100mm should be avoided.

For this design, an extensive exploration of various designs and thicknesses of the cross-section was investigated. The key parameters considered were the weight of the block, the center of mass, and if the design is symmetrical or not. Essentially a symmetrical cross-section has a better load transmission and keeps the whole system stable. The thickness also influences thermal performance as it can obstruct heat transmission through the thicker cross-section.

Cavity width: Cavities are effective in design to enhance the thermal performance of the system in absence of insulation. The cavity width influences the effective thermal conductivity of air, however, from the research it is observed that larger cavity widths (from 35mm and above) can actuate the flow of air current causing heat transfer through convection. In practical applications, multiple cavities perform better, however, in the case of glass blocks there may be an issue with thermal bridging due to the absence of any insulative material. Another alternative is to apply low e-coatings on the external surfaces which is a straightforward solution that involves challenges to tackle the recycling goals of the glass. A costly solution to increase thermal performance is to consider gas-filled cavities, the inert gases work extremely well to reduce heat transmission. The key to designing a cavity depends on the type of cross-section (which influences the structural performance) and the level of expected transparency.

Intermediate material: The intermediate bonding material used for connecting the glass blocks influences the load-bearing capacity. The research was aimed at developing a dry-stacked system with an effective interlayer that transmits load efficiently. Polymers and elastomers have stiffness less than glass, which are good alternatives for conventional wet connections. However, these materials are not resistant to creep and require a certain amount of pre-compression to form a bonding between glass surfaces. In theory the larger the surface area of the interlayer, the better the ability to bond, however, the thickness of these interlayers are not always the same, therefore compromising the overall system.

Connections: The primary aim is to design a self-supported hybrid block system through a dry-stacked assembly system. Connections can be combined with the shape of the hybrid glass blocks in the form of interlocks that allow for homogenous load transfer. The interlocks also facilitate the self-alignment of the blocks for easy and quick assembly. The design of these interlocks plays vital role to enhance the load-bearing capacity by restraining the block movements along the center axis. It is not easy to anticipate the failure of the interlocked glass blocks, however, a theoretical understanding of load transfer and symmetrical cross-section designs should be implemented.

In our case, the design system focused on the replaceability of the hybrid glass blocks due to which the interlocking feature was merely used for alignment purposes, and an additional connection system was implemented to support the blocks in the horizontal direction. The material choice of such connections greatly influences the load-bearing as well as the thermal performance of the system. Metal connections have high thermal conductivity, due to which there is a possibility of thermal bridging in the design. In practice metal connections are more durable, however, they require additional insulation to avoid direct contact with the glass. Since most metals have relatively higher young's modulus than glass, they possess the possibility of large stress concentrations at the contact surface. Materials such as thermoplastics and Teflon can be considered for the connections as they have lower stiffness than glass, good thermal resistance, and are durable.

2. What are the structural and thermal properties associated with the performance of hybrid glass blocks?

The concept development of the hybrid glass block is the foundation behind merging the two important aspects of any building material, i.e. its structural and thermal performance. For the development of this newly emerged concept, it is important to lay some ground rules and criteria on which the glass blocks will be evaluated.

Structural properties: Glass is a brittle material that inherits the structural properties of solids and liquids combined due to its manufacturing process. However, the compressive strength is impeccable, more than 200 MPa which makes it suitable for structural applications. Even though the material offers great potential, it is important to validate and assess its structural performance under loading considering various risk scenarios. For the development of hybrid blocks, it is essential to consider the basic benchmarks that will allow the system to be implemented in the building industry. The structural performance of the hybrid glass can be considered good if the glass block,

- Can withstand compressive loads for a longer period without failure.
- Can uniformly transfer the loads with effectively no or limited stress concentrations.
- Can withstand lateral loads on a system level and has deflection within the specified standards.
- Has Effective stiffness within the specified standards

For a dry-stacked assembly system, interlocking hybrid glass blocks are designed. The eccentricity possessed by these interlocks and the introduction of softer interlayers in between the glass blocks will essentially give rise to buckling. To reciprocate the challenges of buckling, a symmetrical cross-section can be ideated along with the strategy of pre-compression of the system, so that the developed system is not eccentric and will create the necessary bond between the glass surface and the interlayers.

12.1

ANSWERING SUB-QUESTIONS

As discussed in the chapter (6) for design guidelines, the compressive strength of 15-25 MPa is sufficient to cross the minimum load-bearing threshold. These numbers are set from the reference of the traditional brick masonry which has a compressive strength of 6-20 MPa and has been in practice for a long time. In reality, the specified compressive strength for the hybrid glass block is more than enough. The data extracted from the realized projects with the use of solid cast glass elements (Oikonomopoulou et al. 2022) suggest that the nominal anticipated compressive stress due to the own weight of the structure does not exceed 1 MPa. This means that such cast glass blocks are over-dimensioned and there is the scope for further optimization. The numerical validation conducted in chapter (11) gives an overview of all the structural properties associated with the performance of the system.

Thermal properties: The aim to develop hybrid glass blocks is to enhance the thermal performance of the buildings. This means that to bring this product to the building industry, it first has to be deployed at a local level. The thermal performance of any system depends on its U-Value and heat transmission. According to the literature, the U-Value of hollow glass blocks is in the range of 1.5-1.8 W/m2K (Seves n.d.), whereas the U-Value of solid glass blocks is near 4.0 W/m2K (Pittsburgh Corning Corporation, 2007). Since the design product will be implemented in a case study located in the Netherlands, Bouwbesluit (Dutch Building Code) and Eurocodes are used as standards to set the range. As per the Dutch Building code, the maximum U-Value for a glazed facade is 1.65 W/m2K and as per Eurocodes, it is 2.2 W/m2K. Therefore, for the design of a hybrid glass block, the U-Value of a maximum of 2.2 W/m2K is set as a benchmark.

For assessing thermal performance, this thesis considers a numerical way of validation. The U-Value for the designed unit ranges from 1.8-2.2 W/m2k and has a further scope of improvement by the introduction of an airtight cavity connection.

3. What is the relationship between the shape of glass blocks and their structural performance? What is the optimum cross-section thickness to improve structural performance?

To improve the structural performance, most often optimization concerning the size is done. However, a change in the shape or geometry could also be a solution instead of size optimization. The first design problem that this research focuses on is developing a relationship between different geometries and their influence on structural performance on a system level.

For developing a load-bearing glass block, the square or rectangular geometry is often considered as it is easy to manufacture and assemble. When glass surfaces come in contact with each other large stress concentrations observed. In such cases, the load transfer does not happen through the perimeter but it propagates through the shortest distance. Considering this as the basic logic behind load transfer for glass blocks, tapered shaped or geometries made from triangles should be ideal for enhancing structural performance. The cast glass blank of the Hale Telescope is a perfect example that suggests that geometrical shapes like circles, trapezoids, and hexagons can be efficiently used to manufacture cast glass and aid to increase the stiffness of the design. In the exploration of geometries, the evaluating factor was the influence of geometry on the assembly system. If the geometry creates issues for the manufacturing and the assembly system, then it may create issues for load transfer as well.

To understand the scientific relationship between geometry and structural performance actual validation experiments could be done. The aim would be to see how the load transfers and which geometries are least affected. The results will help us design the glass blocks more suitable for the compressive loads and therefore enhance the structural performance.

The cross-section thickness depends on the design as well as manufacturing factors. The first consideration can be based on the expected height of the system. As we have already established that the compressive stress due to the own weight of the block is nominal and less than 1 MPa Oikonomopoulou et al. 2022), the thickness of the cross-section can be subsequently optimized. The next consideration is based on the type of assembly system. For a dry-stacked assembly system, the anticipated cross-section will be based on the mechanical properties of the interlayer and the effective stiffness of the whole system. For an adhesively bonded assembly system, the surface area of the block is accountable for load transfer whereas in a dry-stacked system the interlocking design, interlayer, and cross-section design are considered. In reality for a dry-stacked system, thick cross-sections will provide a large surface area for load transfer, however, it will end up increasing the manufacturing time, material usage, and dead load of the system.

The optimum cross-section thickness is highly subjective as there is no correct number and it depends on the loading conditions and the assembly system. If we consider a super rigid assembly system then the optimum cross-section would be equivalent to the float glass used for the particular span. To find the optimum cross-section thickness basic rules of slenderness ratios can be considered. Even though they are not precise for short blocks, we can consider a column made of stacked glass blocks and try to find the optimum cross-section thickness. Even though the optimum cross-section thickness is highly subjective, the thesis explores the optimum cross-section designs that impact and influence the casting process, integration of the connection system, and the structural stability of the assembly.

4. What are the main design standards that affect the production and assembly process?

The production and assembly process is greatly affected by the Geometry, Size, and weight of the cast glass, the necessary connection system, and their relevant manufacturing process and standardization and quality production.

Geometry, Size & thickness: The complex geometry may create a great level of challenge to cast it using manual techniques. Some geometries require constant mold-making processes which are tedious and time-consuming. Even though the casting provides freedom in terms of shape and volume, it is important to understand its limitations based on manual handling and the time required for its annealing process. Usually, the thickness of the geometry dictates the annealing time required. The geometry and thickness are also relevant for attaining structural stability on a system level. A curved form aids in the distribution of stresses across the component. Round edges are also ideal for a smoother annealing process. Interestingly, the geometry size and weight are all interconnected and dictate the connections required for stable assembly. The weight of the glass block is an important consideration for manual handling on site. To reduce the intensive heavy lifting, it was set in design guidelines that the hybrid glass block would be limited to a range of 5-12 kg.

Connection: The type of connection influences the assembly system. The connections should elevate and pace up the assembly system. It is crucial to design connections based on ease in assembly and manufacturing. The material used for connections also influences the overall stability of the system.

Standardisation: Due to the absence of an automated industrial process of manufacturing a standardized methodology is required. The question that could be followed should be how much can we automate. The standardization in the manufacturing process will provide a specific set of guidelines for the designer to follow while developing their geometries.

12.1

ANSWERING SUB-QUESTIONS

5. What are the engineering standards and challenges involved in fabricating the Hybrid glass blocks?

The hybrid glass block is designed with the integration of various materials and connecting systems that require a lot of customization due to absence of the standard manufacturing processes. For example, the cast glass component is manufactured by casting them into a CNC milled steel mold. The annealing process requires a controlled environment for proper cooling down of the glass. Further the design also involves sourcing from external manufacturers for float glass, snap-fit profile, Teflon connections, and most importantly the vacuum-forming or thermo-forming process required to shape the interlayer which is sourced from a different manufacturer. The immediate response to these varied manufacturing processes and materials would be to develop design and engineering standards that adhere to the various industrial processes involved.

The first challenge is to establish the number of processes required, and conceptualize a system that standardizes each process individually. Based on this standard guidelines and interrelations between various processes can be identified. For example, casting is done using a CNC mold that does not support undercuts and has specific engineering standards. These sets of standards and limitations need to be conveyed to the designers so that the glass block geometries follow them. The next step is to define the interdependency of the manufacturing processes. For example, the interlayer has to be vacuum-formed over the casted geometry, thus the manufacturing process should be located within the facility.

Until now, cast glass constructions have employed custom-designed blocks; there are no standards for size, mold, or glass type. Each design is tailored with diverse factors and hence varies greatly. One of the most significant limitations is the lengthy annealing time required for these blocks. This is because of the thick cross-sections, which are necessary for load-bearing strength.

6. What are the design strategies to develop a sustainable (recyclable) hybrid glass block?

Many interesting interlocking geometries can be developed using the circular use of glass components and their recyclability. Although it may not be possible to make glass 100 percent recyclable (due to contamination from connections and coatings), sensible predetermined design guidelines and a circular approach can lead to maximum glass sustainability. The key aspect can be a dry assembly system with interlocking glass components designed in a way that does not require additional substructure for support and can be easily assembled and maintained. Although the use of adhesive connections for solid cast glass blocks can improve transparency, they are not recyclable. As a result, a middle ground must be found where all important aspects meet the sustainability guidelines.

To incorporate sustainable goals while developing hybrid glass blocks, it is of utmost importance to consider recyclability and reusability as the key boundary conditions. The design for disassembly was one of the guiding factors during the alternatives comparison and evaluation process. The main focus was on the cast glass block component as it was supposed to be left as much recyclable as possible. For this, the unit-level connections required reversible and dry connections that can be easily disassembled. Since the design also focused on enhancing thermal performance, it was decided not to use e-coatings on the glass surfaces to avoid contamination.

If transparency is not one of the important criteria in the design, then cast glass produced out of waste glass can also be considered. However, it is important to address the change in the material properties by use of such waste glass as a lot of exploration and validation are still required for the practicality of structural and thermal performance.

12.2

ANSWERING MAIN RESEARCH QUESTION

What are the main design considerations and challenges in designing and manufacturing a hybrid glass block system that exhibits good thermal and structural performance?

The focus of this research is to contribute to the development of novel glass systems. The findings of the study include the design and development of a hybrid glass block system with good load-bearing and thermal qualities. Understanding the requirement and applicability of a novel product in the building environment is critical for its design development. For this, existing product and system research act as a starting point for establishing product attributes. The research follows the product development methodology with the approach of the material-manufacturing-design process.

1. Material Composition:
The main components used to produce glass are sand, ash, and soda, but their diverse compositions result in glass with varying qualities. The properties of several glasses are investigated, and borosilicate glass is selected because it has a low thermal coefficient and conductivity, performs well with thermal shocks and chemicals, and is much more clear or transparent than other glasses owing to the absence of iron. Because of its greater melting point than soda-lime glass, borosilicate glass is not widely used because it needs more energy to manufacture. However, because of its reduced thermal expansion coefficient, it speeds up the annealing process, making it more suited for fast casting. It is critical to choose the type of material used for casting early in the design process since it has a considerable influence on total expenses and has a significantly bigger impact on the designed shape. Because of its strong heat resistance, compressive strength (264-348MPa), and almost similar to young's modulus, borosilicate glass is the obvious choice for the fabrication of hybrid blocks if cost is not a problem. Borosilicate glass can be manufactured as tubes, panels, or even cast to create more intriguing geometries.

2. Standardisation of design and Manufacturing Process:

The manufacturing process is determined by the batch size, design variations, volume, and weight of the product. Casting is indeed the preferred technique for objects with complicated geometries and greater quantities. However, there are some restrictions to the casting process in terms of thickness. It has been noted that components with a thickness more than 100mm take longer to anneal, requiring more energy. The block thickness was limited to 100mm to save time and boost energy efficiency.

The challenges in casting occur due to the molten glass taking the desired shape inside the mold. The design of the mold is important to get the desired output. The hybrid glass block design is influenced by the design standard involved in mold making. The edges are rounded off to avoid any stress concentration occurring due to pointed edges that obstruct the flow of molten glass. CNC milling does not support the undercuts in the design, thus a limitation to consider during the designing of the cast glass block. The structural performance is also dependent on the direction in which the casting is done. Ideally, the glass block should be cast in a way such that the molten glass takes the internal spaces through gravity. This leads to sagging at the top and thus should be considered while designing. Small portions in the design of less than 6mm should be avoided to maintain the homogeneity of the output. Currently, the process of casting is vastly customized to meet the different requirements, however, it should opt for a much more standardized product manufacturing process. The number of processes involved in the manufacturing process largely varies on the type of connections and processes required to shape them. The interlocking alignment design depends on the interlayer material and its ability to be shaped as desired. These two aspects also have an impact on the load transfer, and thus interdependence of these methods is key for design considerations.

The number of blocks needed, the volume and shape of the block and the type of mold utilized are all critical elements influencing the manufacturing procedure. To have an efficient and easy

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manufacturing process, the impact of variations in the design of the components should be considered. A change in shape necessitates a change in mold and annealing time, which impacts the overall efficiency of the production process. The size and volume of the components also have an impact on the final block's quality. It is also critical to adopt pre-established standardized procedures since they give technical standards upfront and identify challenges and constraints.

3. Optical Properties:
Both the hollow and solid glass blocks have similar light transmission properties; however, the hollow glass block has more optical distortion due to the presence of the cavity. Before designing the hybrid glass blocks, it is critical to establish a design vision. It provides a better middle ground for designs where transparency or thermal performance is the most desired evaluation criterion.

The transparency depends on the thickness, the number of cavities and width, and the number of glass surfaces. The key relation between these aspects is the thermal performance of the glass block. The cavity width and thickness of the glass blocks have a lot to do with achieving the desired U-Value. Through research it was observed that cavity widths (up to 35mm) show great resistance to heat transmission, however, the increase in the number of cavities can also reduce the U-Value. The increase in cavities may be beneficial, however, there may be an issue of thermal bridging due to a continuous cross-section. The hybrid glass should be designed to first cater for the thermal performance and then to the desired transparency. There is also a possibility to apply low e-coatings on the glass surface to achieve a lower U-Value, however, it impacts the color of the glass and is also not a very sustainable solution. Borosilicate glass is considered in this research as it is much more clear and transparent, which was one of the key criteria for the geometry assessment.

4. Assembly system:
In most situations, the design of the glass blocks is dictated by the assembly system. The selection of an assembly system is influenced by the current boundary conditions, and the design goals and vision serve as guiding factors for further design development. The assembly system's primary goal is to provide ease and precision when constructing the facade. A complicated connection system should be avoided in all situations since they are highly specialized and need careful attention during construction. However, there must be a sense of design and aesthetics involved. The envisioned assembly method for the development of hybrid glass should enable a rapid and easy assembly with reversible connections that allow for ease of replacement, disassembly, reusability, and/or recyclability at the end of their material cycle.

A dry-stacked assembly approach was chosen to combine the circularity and sustainability goals. This proved to be a driving aspect of design development since it has a significant impact on structural performance on a system level. Since glass is brittle we cannot simply place the glass blocks on top of each other. As a result, an interlayer or intermediate material is necessary for the loads to be transferred uniformly. To eliminate any extra supports that may impair the transparency and attractiveness of the façade, the hybrid glass blocks must be load-bearing. As a result, the interlayer should be transparent and have an effective stiffness no more than that of glass. The hybrid glass blocks must be designed differently for dry-stacked systems, both in terms of cross-section and shape. To facilitate construction, self-aligning interlocks are designed on the cast glass to resemble the design of Lego blocks. The interlocks are critical because they enable a rapid and precise assembling procedure. When the glass block needs to be replaced, such interlocks have a constraint. This is another factor to consider while planning the assembling system.

Adhesives can be used to stack glass blocks on top of each other if a permanent bonding assembly is required. Precision in such systems is difficult to attain in unprocessed glass blocks. Another issue is the reusability and recycling of such adhesives since they strive to contaminate the glass surfaces.

This thesis proposes two distinct assembly systems. The first one employs an onsite assembly technique similar to that of a brick wall. The modularity of the facade wall is the emphasis of the second system. Both approaches have equal potential and challenges; nevertheless, design goals and boundary conditions will aid in making smart judgments. The selection of connection materials is particularly critical since it has a significant impact on structural and thermal performance. Metal should be avoided because of its strong conductivity and the need for additional soft insulation when in contact with glass. For this thesis, Teflon connections are used as they also behave as an interlayer and avoid stress formation.

5. Tolerances:
The thickness of the interlayer or adhesive should be predetermined before the casting process. Different materials need varying degrees of accuracy during the production and assembly processes. The desired level of accuracy is also related to the glass material employed. During the casting process, dimensional tolerances of less than 1 mm are not possible. This is entirely dependent on the type of casting mold utilized. Because of the great accuracy of the glue used for glass bonding, tolerances of 0.25mm were necessary for a few practical applications, such as the crystal home project. These tolerances were achieved by meticulous post-processing of the glass blocks after casting. Because post-processing was necessary, soda-lime glass was chosen because it is less expensive than borosilicate glass. Tolerances have a significant influence on both design and production processes, as demonstrated by this example. Due to the identical thickness of the interlayer, tolerances of 2mm were acceptable in this design. The magnitude of the tolerance is also determined by the interlayer's capacity to shape.

6. Structural Safety:
The design of the assembly system is to provide structural safety in terms of performance under loading and in case of failure, the redundancy. A careful strategy planning with risk scenarios can be considered at this stage so that the designed block adheres to all the structural safety standards. For this, a numerical validation method can be implemented to understand the influence of various cross-sections under loading and aid to assess and select based on the scientific values. To design glass structurally, safety factors should be implemented during the design. Structural safety can also be implemented at the unit level. The hybrid glass block design proposed in this thesis ensures structural safety at both the system and unit levels. We must establish redundancy to safeguard the load-bearing component of the unit. One such method may be observed in the design, which includes structural cast glass components that are covered by float glass on both the exteriors and interiors.

7. Boundary Conditions:
One of the important guiding factors is the existing boundary conditions available on the site where the hybrid glass block system is to be deployed. In this research, a case study was selected which had a modular facade system, which allowed us to consider a modular and standardized approach for designing the assembly system. Careful consideration regarding the existing structural system is required, before designing. It may drastically change the assembly system depending on the additional requirement of the substructure.

8. Building standards:
Hybrid glass blocks are rather a recent concept that is still under development. Despite the design's immense potential, one of the most significant problems is the lack of building requirements for cast glass components. For the practical applicability of hybrid glass blocks in the building industry, the product should adhere to the building standards prescribed on a universal as well as local level. The design guidelines developed and elaborated in chapter (6) are the basic criteria that the product needs to meet. These guidelines are formulated by taking references from the building codes and existing product information. TuDelft's Glass Transparency research group is currently conducting promising research on assessing the mechanical properties of cast glass components.

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One such study, undertaken, focuses on determining the fracture resistance of cast glass (Bristogianni et. al 2021). To acquire realistic values, a series of tests can be performed on the developed prototype. In general, appropriate testing of the blocks should be performed before they are placed on the market so that they can compete with hollow glass blocks.

9. Safety & Maintenance:
The hybrid glass blocks are to be deployed as a facade component, thus, it is the building system that comes in immediate contact with the weather. The choice of materials is a guiding aspect of ensuring the safety of the structure. Even though the maintenance is not directly impacting the safety on a structural level, careful consideration is required for safety during the replacement of blocks. A method or system has to be devised for such scenarios where any component can be replaced with ease and safety.

10. Sustainability:
Many interesting interlocking geometries can be developed using the circular use of glass components and their recyclability. Although it may not be possible to make glass 100 percent recyclable (due to contamination from connections and coatings), sensible predetermined design guidelines and a circular approach can lead to maximum glass sustainability. The key aspect can be a dry assembly system with interlocking glass components designed in a way that does not require additional substructure for support and can be easily assembled and maintained. Although the use of adhesive connections for solid cast glass blocks can improve transparency, they are not recyclable. A middle ground must be found where the design meet sustainability guidelines.

11. Design Scale:
This thesis aims to develop a hybrid glass block system through design exploration. To arrive at the final design concept, several design alternatives for various design challenges are explored and assessed. A case study was implemented as a practical approach, to replace the existing hollow glass block system with a hybrid glass system. The case study created some constraints in terms of the existing structural system due to which the design of the assembly system focused more on the modular approach. The existing hollow glass blocks are 190*190*100 in size, resulting in a reduced level of transparency. To improve the transparency of the existing system, a block size of 400*400 (more than double the size) was considered for the design of a hybrid glass block. The weight of the block increases with its size, which poses a challenge. To facilitate hand lifting during the assembly phase, a weight barrier of 10-15 kg of glass block was proposed. To achieve such a lower weight of the block cross-section of the hybrid glass block was optimized. Although the design output is well optimized, these limits will alter if the hybrid glass block system is used in a completely new development. This means that there is potential to revise the size and proportions of the hybrid glass block system. If the assembly system's manual lifting is disregarded and a crane is used for building, the size of the cast glass components can vary from floor to floor, making them self-supporting. There are currently no restrictions for glass casting volume; however, the thickness of the geometry, which will impact the annealing process, should be taken into account. The hybrid glass can be potentially scaled from a unit level to a single system-level block to achieve much more transparent structures that do not require a sub-structure. Buckling and increased dead load will be the challenges of such massive self-supported cast glass components in comparison to the unitized facade system. The scale of the cast glass components is easily customizable; however, to have a much more standardized manufacturing and assembly procedure, one universal size comparable to clay brick can be explored so that the new product can be actively employed alongside the existing systems.

12.3

RECOMMENDATIONS

1. Cross-Section optimization:

This research has explored various cross-section designs through the numerical method. The values achieved were based on the hand calculations and as such, there is no conclusive result that could suggest that the selected cross-section design performs well under loading. It would be a great study of optimization firstly using a computing method, which assesses various designs based on simulated results. The next step would be the development of the cross-section design through prototyping and experimental validation.

2. Gorilla glass instead of float glass panel:

The design of the hybrid glass block consists of two float glasses on the exterior surfaces. To protect the structural cast glass component they were designed, however, the float glass is subjected to cracks and failure due to vandalism or any risk scenario affecting the thermal performance. Thus gorilla glass can be used instead of float glass panels to add much more needed strength and stability

3. Prototyping & Validation:

The initial aim of this thesis was to prototype and experimentally validate the final design and understand the challenges involved during its manufacturing. Due to time constraints, it was decided to develop the cast glass after P4. The prototyping conducted after P4 was not conclusive as the hybrid glass block was not completely casted due to improper mold preparation. The prototyping phase resulted in step-by-step methodology and key observations which can be adapted for further research and actual manufacturing. However, it would be beneficial to begin the exploration through prototyping. Simple tests like keeping the block in a polarisation scan can help us assess the stress concentration in the glass block.

4. Use of recycled cast glass:

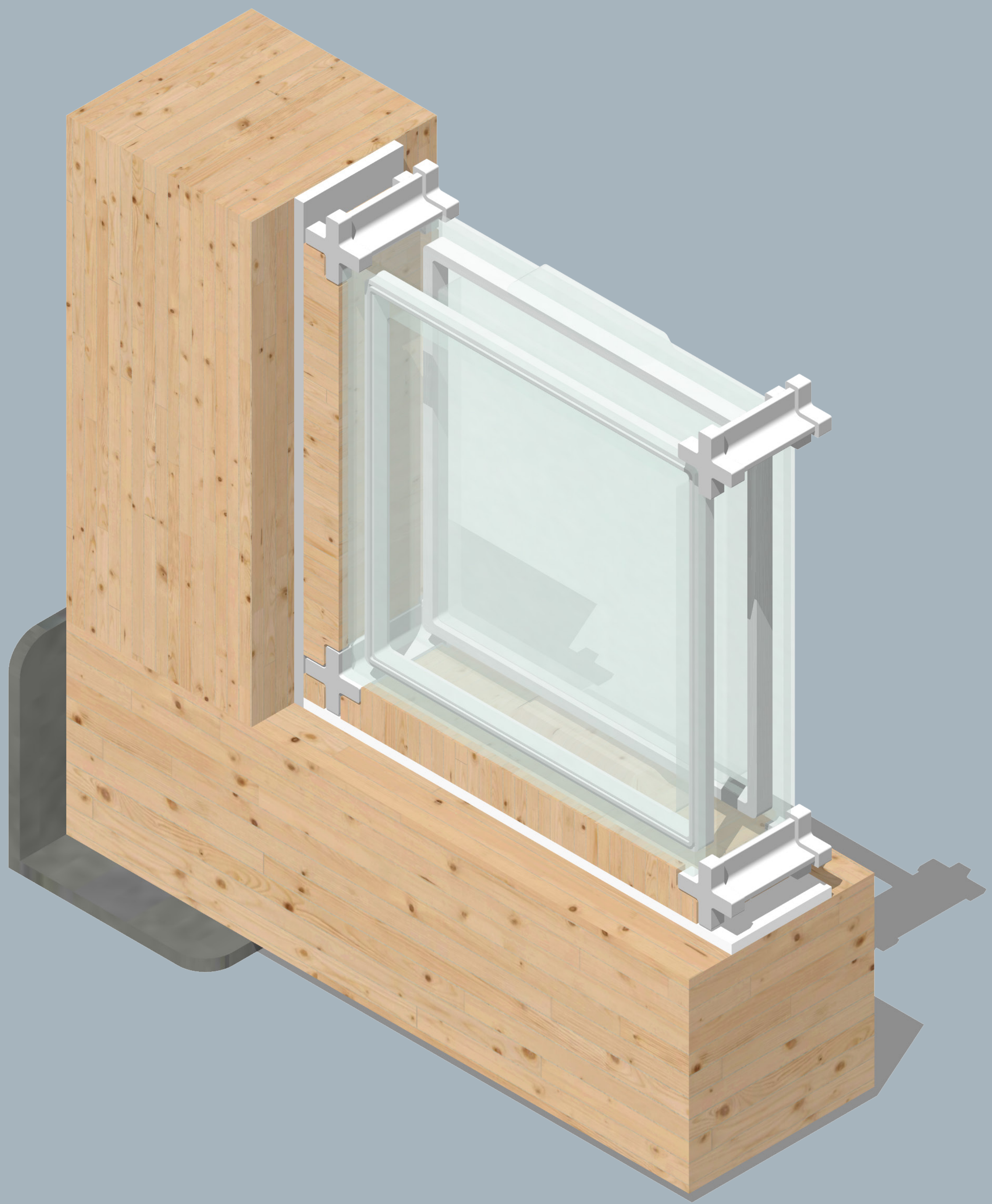
The relevant research in the field of recycling cast glass suggests that glass could be reused in the form of cullets for casting. similarly, a study on cross-sections developed by using recycled cast glass could be done to see the potential of recycled glass for structural application and different colors and textures.

5. Enhancement of the snap-fit detail:

A brief study of the material that is used to make snap-fit details can be done. The ultimate aim can be to understand the interrelation between material and the U Value. Further to the final design, extensive research can be carried out to understand if the designed detail is airtight. The calculated U-Value of the design makes consideration of free air inside the cavity since the air-tightness of the detail is not thoroughly demonstrated. Further research on such dry connections can also aid in the development of more reversible connection systems for the glass while providing the similar thermal performance.

6. Teflon connections are interlayers:

The design currently explores the use of Teflon connections for connecting glass geometries. Teflon possesses great thermal resistance and provides much-required durability to the connection system. Since the stiffness of Teflon is very less in comparison to the glass, but just above the explored interlayers (PU & Vivak), it has the potential to be used as an interlayer. If such a study is conducted, the key would be to combine the interlayer with the connection system, which would provide a quick and easy assembly system.



Rendered View of the developed hybrid glass block system

13.

REFLECTIONS

The overall thesis research and design phase are reflected in this chapter. The following points are considered and elaborated briefly

- Relationship between research & design
- Relationship between graduation topic, studio topic, master track and master programme
- Research Method & approach
- Relationship between graduation project & wider social, professional & scientific rframework
- Ethical dilemmas faced during research

13.1

RELATIONSHIP BETWEEN RESEARCH AND DESIGN

The current thesis aims at the product development of hybrid glass blocks by rethinking shape, manufacturing process, and assembly system. The design philosophy followed is based on the 'Materials as design tool' developed by Hanaa Dahy which suggests that the choice of the material can be used as the main driver for product development. The aspects of the study are Material selection, efficient production technology, design and validation. The initial two aspects need thorough research that generates guidelines for the design development.

The research first explores the potential of glass as a high-performance material in the building industry. This enables us to look at the glass on a microscopic level by researching its classifications, material compositions, applications, properties, and essentially limitations. Furthermore, the current 3D glass blocks (hollow, solid, and hybrid) were thoroughly examined in terms of manufacturing, assembly system, application, and performance. Various design solutions for improving structural and thermal performance were investigated, which assisted concept development. The conclusions derived from the existing research aid to formulate the design guidelines for the development of hybrid glass blocks. For practicality in the design process, a case study was selected on which the final design output was implemented. Based on current research material, various methodologies were investigated for numerical validation of structural and thermal performance. The product development approach, which was defined during the research phase, was used to evaluate the developed design concepts. Thus, the research and design were two interconnected parts of this thesis.

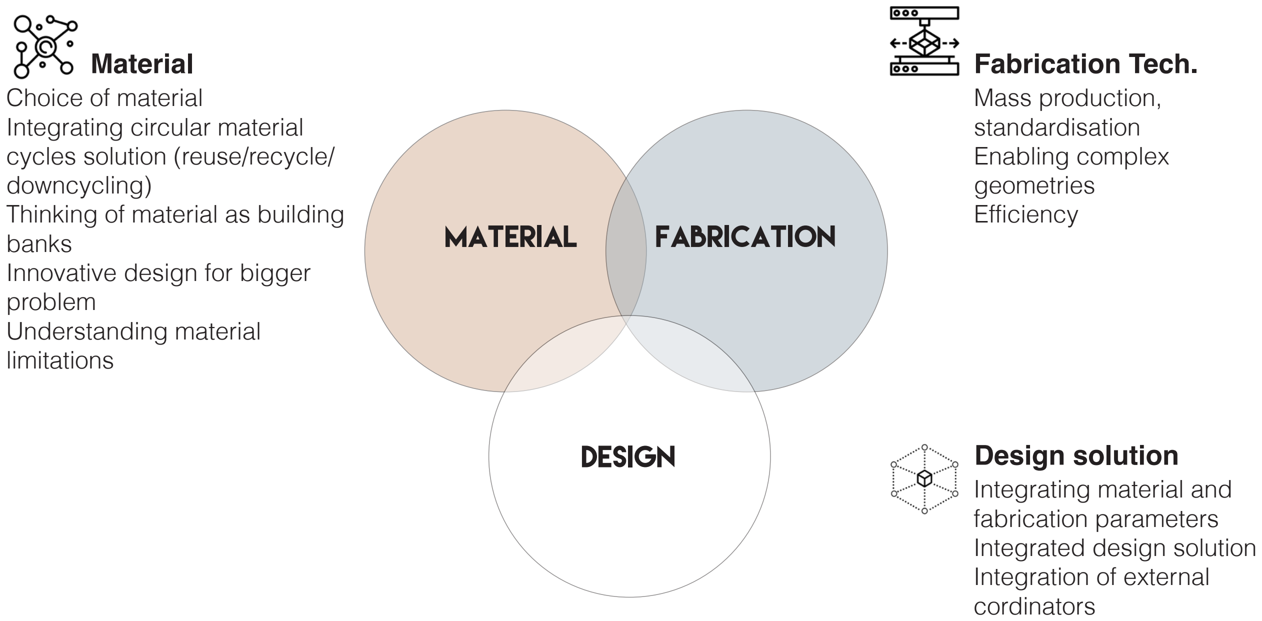


Figure 13.1: Materials as design tools adapted from (Dahy. H 2020)

13.2

RELATIONSHIP BETWEEN GRADUATION TOPIC, THE STUDIO TOPIC, MASTER TRACK, AND MASTER PROGRAMME

The Sustainable design graduation studio focuses on the development of innovative design technologies within the built environment. The material 'Glass' is widely used in the building industry due to its distinctive optical, thermal, and structural properties in various forms, for example, partitions, glazing panels, glass blocks, etc. The existing glass block systems offer either optimal thermal performance or structural stability but neither a combination of both. 'Hybrid glass block' is an innovative concept that endeavours to bridge the gap between the solid glass blocks' thermal performance and hollow glass blocks' load-bearing capacity.

Since this is a recently emerged concept, the research focuses on defining design guidelines, manufacturing methodology, assembly system, and numerical validation along with the freedom of exploration of various design concepts in a realistic case study. This research resulted in an energy-compliant sustainable glass product for application in the building industry. On a broader level, the focus is on structural design and climate design, which are two branches of the Building Technology track. The output of this thesis is the design of a hybrid glass block with its potential application and integration on a facade system with goals of sustainability and circularity. Overall it is a perfect integration of architecture and engineering streams that has an emphasis on the design of innovative and sustainable building components. The research topic is also related to the ongoing research on Sustainable structures in TU Delft.

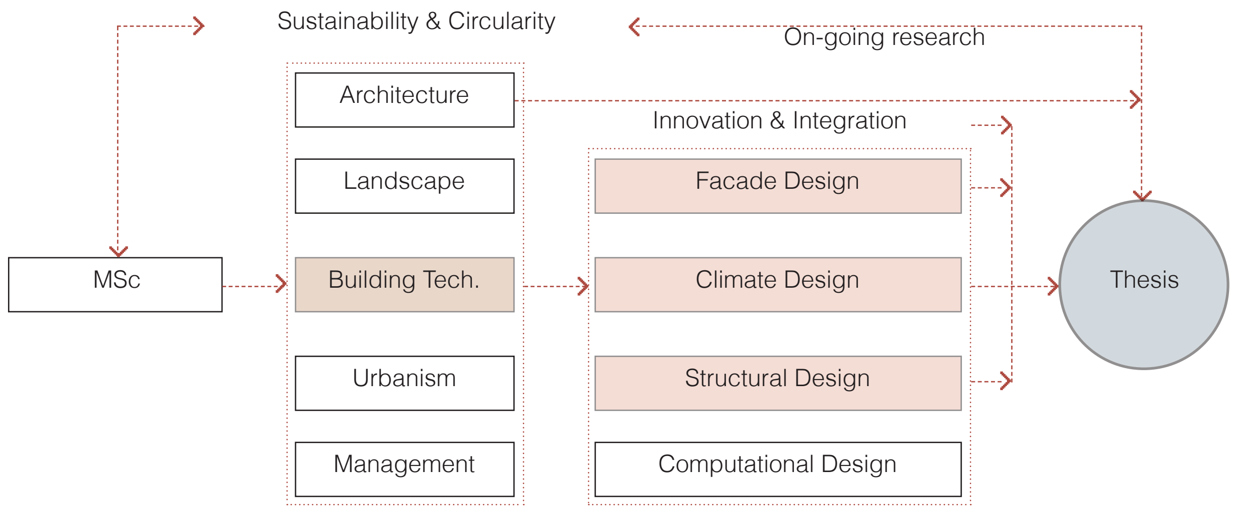


Figure 13.2: Interrelation between MSc course, track and graduation studio

13.3

RESEARCH METHOD AND APPROACH CHOSEN IN RELATION TO THE GRADUATION STUDIO METHODICAL LINE OF INQUIRY

The product development of Hybrid glass block is categorised into five phases;

Phase 1: Literature study and theoretical framework
The first section of the thesis relied on evaluating current literature, notably on glass and glass block technology. Material qualities, compositions, manufacturing procedures, geometries, assembly systems, configurations, and challenges were thoroughly investigated. Various design approaches were also investigated to improve the structural and thermal performance of the current glass blocks. A case study from the Maastricht Academy of Arts (1993) was identified and studied to offer a realistic scenario for developing structural, thermal, and assembly parameters. To develop the design guidelines, the European building codes were reviewed. This phase concluded with a clear set of design goals, guidelines, and concept development methodologies.

Phase 2: Design Development
During this phase, different design approaches based on form, assembly mechanism, and optical quality were investigated. To improve structural performance, a comprehensive investigation of alternative geometries and cross-section thicknesses was carried out and assessed using first-hand calculations. A product development methodology was implemented for the evaluation of these concepts. Every design component was reviewed based on its specified criteria, and the selected alternatives were further appraised based on the design goals and standards. This phase concluded with a final design concept.

(My ear and jaw difficulties were an interesting factor that helped me come up with the final design concept. I noticed that the disc between the jaw and the ear bone is becoming thinner as a result of poor teeth alignment owing to inappropriate jaw movement. This led me to create the dry-stacked interlocking assembly concept. The two glass blocks cannot be kept in direct contact as there is a considerable risk of stress development along the contact surface and when the load is applied they will slide due to friction. To transmit the stresses and decrease friction, an interlayer similar to the ear disc is necessary, as is an interlocking element to position the blocks together. The final cross-section is inspired by human anatomy and mimics the shape of a human bone.)

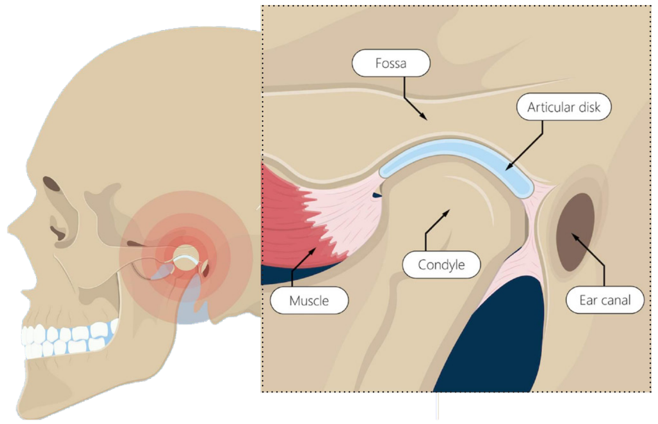
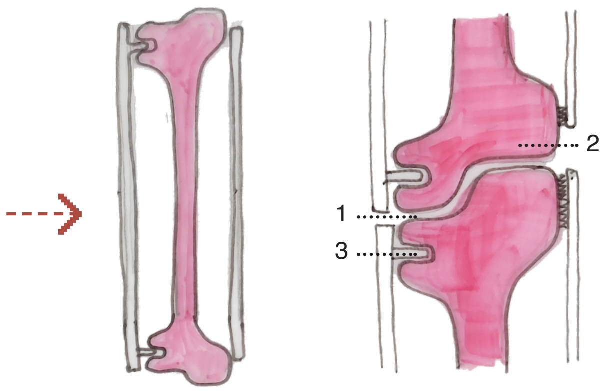


Figure 13.3: TMJ Dysfunction (Eric Davis Dental)



1. Interlayer similar to articular disc
2. Alignment detail
3. Condyle detail

Figure 13.4: First Concept Sketch

Phase 3: Design Refinement
The final design concept was refined in terms of manufacturing and constructability. Based on the results of the research phase, a step-by-step manufacturing methodology was investigated. The inter-relationship and impact of the manufacturing process on the design were addressed, resulting in design improvement. Furthermore, a dry-stacked interlocking assembly system was investigated in terms of its connection to the unit as well as system level, with the definite direction of reversibility and ease of assembly being evaluated. This phase is completed with the final design being refined depending on the manufacturing process and constructability. At this stage, many risk scenarios were explored to include them in the design. The initial plan was to prototype the chosen designs and further assess them, however, because of time and material constraints, it was decided to detail just one final design (and if time permits can prototype it in the glass lab)

Phase 4: Design Evaluation
This phase concentrated on a thorough examination of the final design using the numerical approach of validation. Hand calculations were used to assess the glass block's thermal and structural performance. Several strategies are proposed for validating the design through experimentation.

Phase 5: Design Application & Conclusion
In this phase, the final design is detailed, and the design output is delivered in the form of facade drawings, installation procedures, and risk scenarios.

A systematic approach for design development is followed throughout the whole thesis which was built on the conclusive research study. The research output is the design of a hybrid glass block, its design and engineering guidelines, and its manufacturing process and assembly system with numerical validation and improvement recommendations.

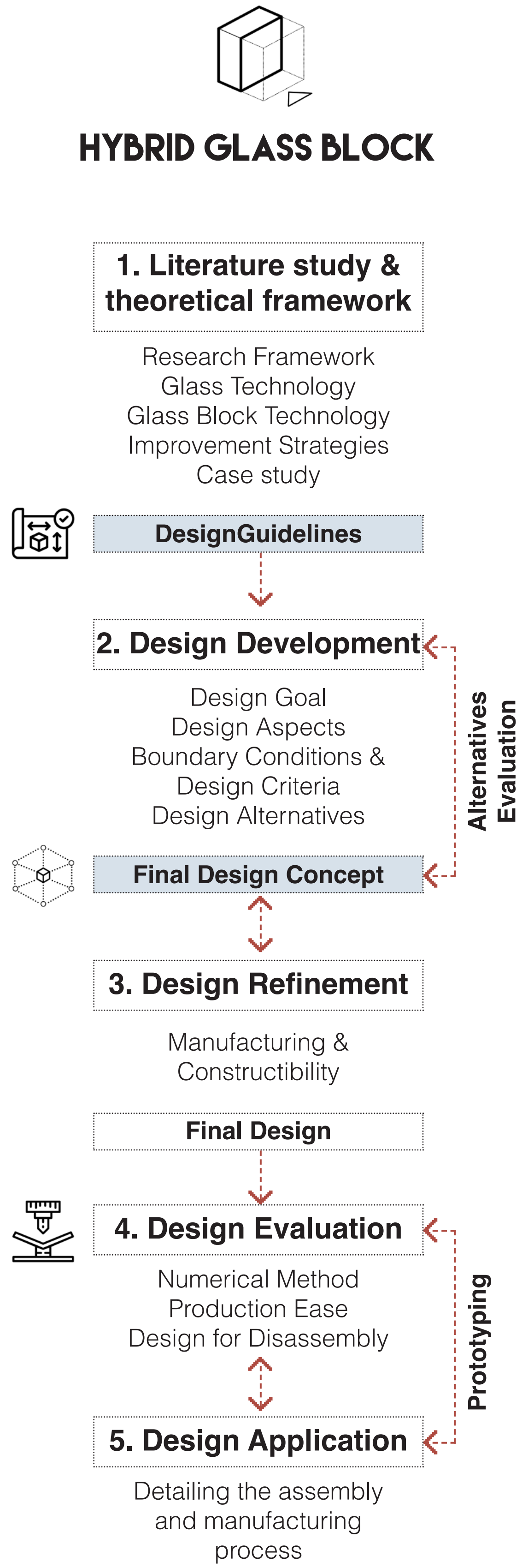


Figure 13.5: Reseacrh Method & Approach

13.4

RELATIONSHIP BETWEEN THE GRADUATION PROJECT AND THE WIDER SOCIAL, PROFESSIONAL AND SCIENTIFIC FRAMEWORK

In the last two decades, the building industry is slowly evolving and transitioning toward designing and creating sustainable environments to meet the global challenges of climate change and scarcity of natural resources. The focus is aligned toward adaptable building systems that are energy efficient and have a low carbon footprint. This simply means that every product that goes into the making of the building environment should be energy-efficient, sustainable, and have less carbon footprint. The focus is not only limited to a system level but also a unit level.

“The use of glass in architecture has never been more popular, but the global drive to increase the energy efficiency and sustainability of buildings is posing a challenge to architects, engineers, and manufacturers alike” (James O’ Callaghan, 2020) To ensure the future of architectural glass it is important to push the boundaries of products that provide innovative solutions to meet these global challenges. A lot of architectural projects are increasingly using glass in many innovative ways and this will significantly increase in the future since it is sustainable.

The current research aims at developing a glass block that adheres to energy efficiency and sustainability goals by unveiling its true potential.

The design focuses on two main aspects,
(i) increasing the thermal and structural potential of 3-dimensional glass components
(ii) a dry-stacked interlocking assembly system that is modular and circular. To increase the thermal performance of the glass additional e-coatings are applied on the surface which makes them undesirable for recycling at the end of the life cycle.

An attempt is made in this research to focus on designing a maximum recyclable glass component by eliminating the application of e-coatings and incorporating air cavities within the design. Furthermore, an interesting approach to the dry-stacked interlocking assembly system is explored by eliminating the use of adhesives and designing the system for disassembly. This allows the ease of replaceability and reusability of the glass components. This will completely change the way how glass is perceived in society. The methodology in which the potential of the glass has been explored relates to the scientific curiosity of developing innovative glass structures that are energy giants and sustainable.

13.5

ETHICAL ISSUES AND DILEMMAS WHILE DOING THE RESEARCH, ELABORATING THE DESIGN AND POTENTIAL APPLICATIONS OF THE RESULTS IN PRACTICE

The application of glass in architecture is presumably owing to its great optical characteristics; however, structural glass has lately become increasingly widespread, which may or may not have equivalent optical quality. It was established during the research phase that increasing cross-section thickness and cavity width improves structural and thermal performance. However, the application of these strategies has a significant impact on transparency. As an architect, I like the transparency that glass offers to the design; nevertheless, as a young building technologist, it is my moral obligation to prioritise the performance of the glass block. When developing the design assessment criteria, it was determined to prioritise performance above transparency. As a result, the developed product is significantly better suited to achieving high building performance while overlooking optical quality.

The design evaluation process is particular to the initial guidelines and criteria developed. Based on this, many potential concepts were designed, however, only one was selected based on its suitability to the selected case study and design goals. Other design approaches offer room for improvement if the design and assessment criteria are altered. As a result, the final design solution is specific to the case study and is applicable in practice when performance and sustainability criteria must be satisfied.

The purpose of this research is to validate the structural and thermal performance of the developed hybrid glass block. A numerical method of validation is being investigated for this. The design focuses on the dry-stacked assembly system for cast glass blocks, which is still under development and has yet to be thoroughly verified. Thus, structural calculations are performed only based on the current research and safety assumptions. The preceding thesis on enhancing the thermal performance of the cast glass block presents values for various cavity widths and glass thicknesses. These numbers, however, are specific on a unit level and are determined by software simulation. These thermal performance data serve as the foundation for the current design. For a dry-stacked glass assembly system, it is rather essential to generate values on a system level. The initial intent was to validate various design concepts through prototyping and experimentation. However, a novel system that is yet to be completely developed, requires a lot of time and resources for experimental validation.

Lastly, it would be beneficial to involve the production and assembly system specialists in the design process to get a more practical approach to design development.

14.

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14.1

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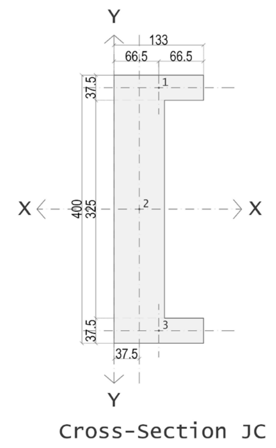
15.

APPENDICES

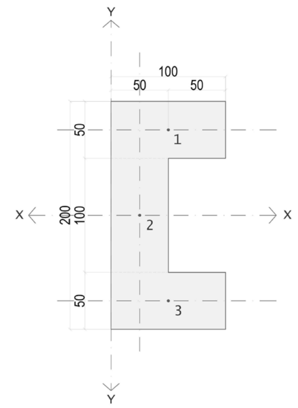
15.1

APPENDIX



	Rectangle	b	d	Area	X1	Y1		
Cross Section JC 1								
		[mm]	[mm]	[mm^2]	[mm]	[mm]		
	1	133	37.5	4987.5	66.5	NA		
	2	75	325	24375	37.5	NA		
	3	133	37.5	4987.5	66.5	NA		
			Total Area	34350	[mm^2]			
	X'	**45.921**	h	400	[mm]	H	4600	[mm]
			V	13740000	[mm^3]	T. Blocks	12	
	Y'	**NA**	ρ	2320	[kg/m3]	Blk ovr btm	11	
			Mass	**31.8768**	[kg]			
			Force	**312.711408**	[N]	**Force acting over bottom block**	**3439.825488**	**[N]**
	I (XX)	Ixx1+Ixx2+Ixx3				[mm]		
	Ixx1	4.68E+08	[mm^4]		hx1	306.25		
	Ixx2	2.15E+08	[mm^4]		hx2	0.00		
	Ixx3	4.68E+08	[mm^4]		hx3	306.25		
	I (XX)	**1.15E+09**	[mm^4]					
	I (YY)	Iyy1+Iyy2+Iyy3				[mm]		
	Iyy1	7.48E+06	[mm^4]		hy1	20.58		
	Iyy2	1.14E+07	[mm^4]		hy2	8.42		
	Iyy3	7.35E+06	[mm^4]		hy3	20.58		
Global axis is from center	**I (YY)**	**2.63E+07**	[mm^4]					
		1.18E+09	[mm^4]	1.18E-03	[m^4]			
	Compressive Load	**0.10014048**	MPa	?				

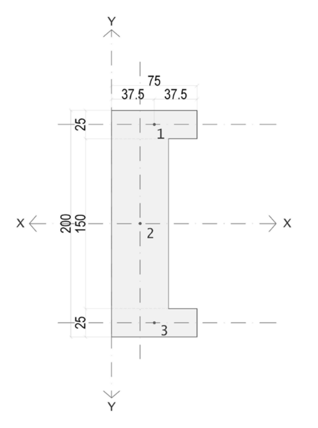
Appendix 1: Cross-section 1 optimisation



	Rectangle	b	d	Area	X1	Y1		
Cross Section D-3								
		[mm]	[mm]	[mm^2]	[mm]	[mm]		
	1	100	50	5000	50	NA		
	2	50	100	5000	25	NA		
	3	100	50	5000	50	NA		
			Total Area	15000	[mm^2]			
	X'	**41.667**	h	200	[mm]	H	4600	[mm]
			V	3000000	[mm^3]	T. Blocks	23	
	Y'	**NA**	ρ	2320	[kg/m3]	Blk ovr btm	22	
			Mass	**6.96**	[kg]			
			Force	**68.2776**	[N]	**Force acting over bottom block**	**1502.1072**	**[N]**
	I (XX)	Ixx1+Ixx2+Ixx3				[mm]		
	Ixx1	2.92E+07	[mm^4]		hx1	75.00		
	Ixx2	4.17E+06	[mm^4]		hx2	0.00		
	Ixx3	2.92E+07	[mm^4]		hx3	75.00		
	I (XX)	**6.25E+07**	[mm^4]					
	I (YY)	Iyy1+Iyy2+Iyy3				[mm]		
	Iyy1	4.17E+06	[mm^4]		hy1	8.33		
	Iyy2	1.04E+06	[mm^4]		hy2	16.67		
	Iyy3	4.17E+06	[mm^4]		hy3	8.33		
Global axis is from center	**I (YY)**	**9.38E+06**	[mm^4]					
		7.19E+07						
	Compressive Load	**0.10014048**	MPa	?				

Appendix 2: Cross-section 2 optimisation

Cross Section D-2

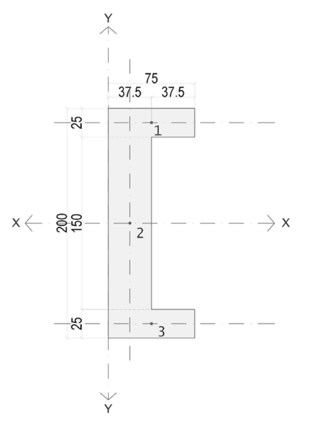


Global axis is from center

Rectangle	b	d	Area	X1	Y1		
	[mm]	[mm]	[mm^2]	[mm]	[mm]		
1	75	25	1875	37.5	NA		
2	50	150	7500	25	NA		
3	75	25	1875	37.5	NA		
		Total Area	11250	[mm^2]			
X'	**29.167**	h	200	[mm]	H	4600	[mm]
		V	2250000	[mm^3]	T. Blocks	23	
Y'	**NA**	ρ	2320	[kg/m3]	Blk ovr btm	22	
		Mass	**5.22**	[kg]			
		Force	**51.2082**	[N]	**Force acting over bottom block**	**1126.5804**	**[N]**
I(XX)	Ixx1+Ixx2+Ixx3				[mm]		
Ixx1	1.45E+07	[mm^4]		hx1	87.50		
Ixx2	1.41E+07	[mm^4]		hx2	0.00		
Ixx3	1.45E+07	[mm^4]		hx3	87.50		
I(XX)	**4.30E+07**	[mm^4]					
I(YY)	Iyy1+Iyy2+Iyy3				[mm]		
Iyy1	8.82E+05	[mm^4]		hy1	8.33		
Iyy2	1.56E+06	[mm^4]		hy2	4.17		
Iyy3	8.79E+05	[mm^4]		hy3	8.33		
I(YY)	**3.32E+06**	[mm^4]					
	4.63E+07						
Compressive Load	**0.10014048**	MPa	?				

Appendix 3: Cross-section 3 optimisation

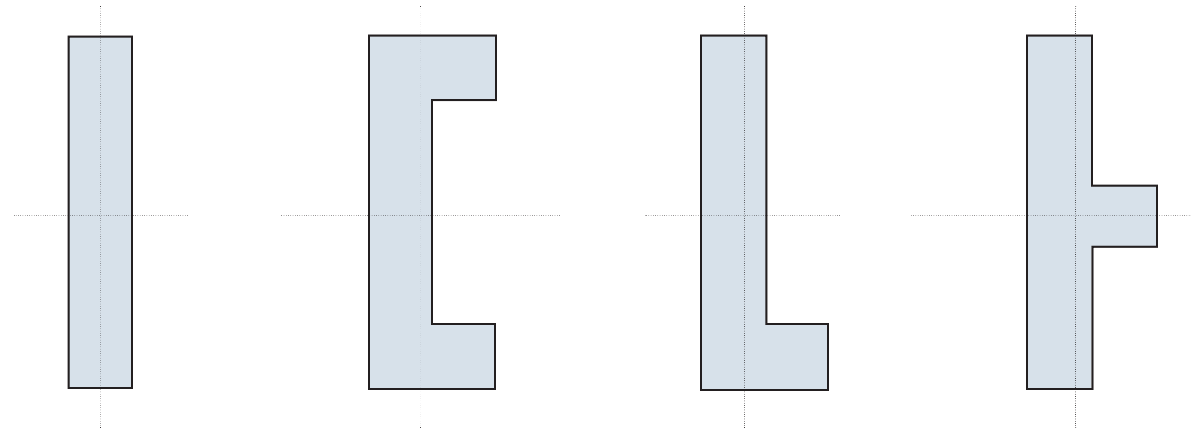
Cross Section D-1



Global axis is from center

Rectangle	b	d	Area	X1	Y1		
	[mm]	[mm]	[mm^2]	[mm]	[mm]		
1	75	25	1875	37.5	NA		
2	37.5	150	5625	18.75	NA		
3	75	25	1875	37.5	NA		
		Total Area	9375	[mm^2]			
X'	**26.250**	h	200	[mm]	H	4600	[mm]
		V	1875000	[mm^3]	T. Blocks	23	
Y'	**NA**	ρ	2320	[kg/m3]	Blk ovr btm	22	
		Mass	**4.35**	[kg]			
		Force	**42.6735**	[N]	**Force acting over bottom block**	**938.817**	**[N]**
I(XX)	Ixx1+Ixx2+Ixx3				[mm]		
Ixx1	1.45E+07	[mm^4]		hx1	87.50		
Ixx2	1.05E+07	[mm^4]		hx2	0.00		
Ixx3	1.45E+07	[mm^4]		hx3	87.50		
I(XX)	**3.95E+07**	[mm^4]					
I(YY)	Iyy1+Iyy2+Iyy3				[mm]		
Iyy1	8.84E+05	[mm^4]		hy1	11.25		
Iyy2	6.59E+05	[mm^4]		hy2	7.50		
Iyy3	8.79E+05	[mm^4]		hy3	11.25		
I(YY)	**2.42E+06**	[mm^4]					
	4.19E+07						
Compressive Load	**0.10014048**	MPa	?				

Appendix 4: Cross-section 4 optimisation



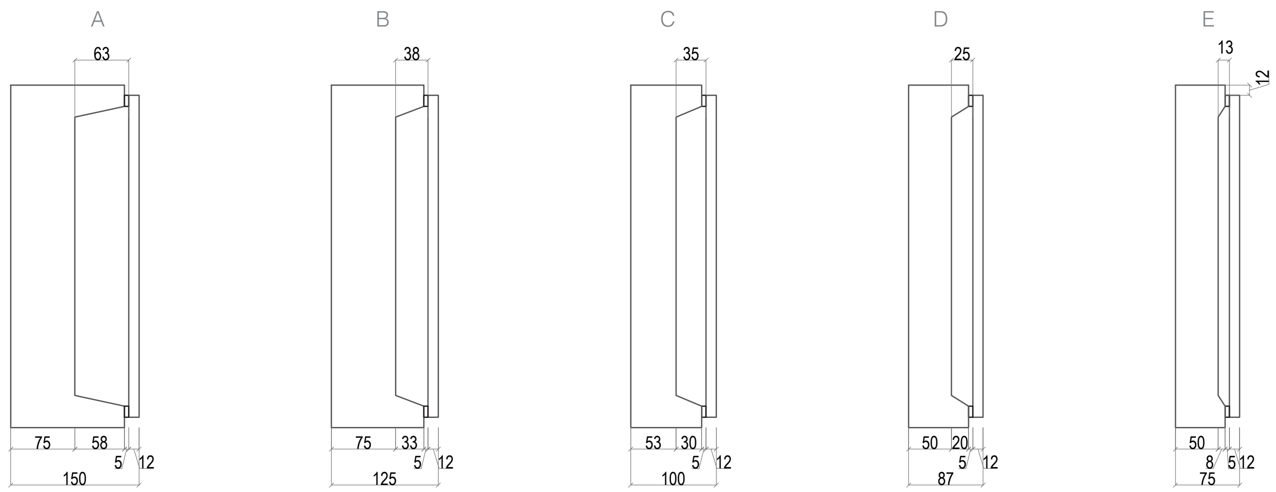
Block size: 200*200 [mm], Mass: 4.2 [Kg], Axial Load on the bottom block: 703[N], Compressive Load: 0.09 [MPa]
M.I: 1.675e 06 [m4]

Block size: 200*200 [mm], Mass: 6.8 [Kg], Axial Load on the bottom block: 703[N], Compressive Load: 0.1 [MPa]
M.I: 7.19e 07 [m4]

Block size: 200*200 [mm], Mass: 5.3 [Kg], Axial Load on the bottom block: 703[N], Compressive Load: 0.1[MPa]
M.I: 3.86e 05 [m4]

Block size: 200*200 [mm], Mass: 5.3 [Kg], Axial Load on the bottom block: 703[N], Compressive Load: 0.1[MPa]
M.I: 2.15e 06 [m4]

Appendix 5: Cross-section Exploration



Block Type	Total Block Dimension			Volume A	Cavity Dimension			Volume B	Final Volume	Density	Mass	Area	Area	Force	Compressive Load
	[l]	[b]	[h]	[m^3]	[l]	[b]	[h]	[m^3]	[m^3]	[kg/m^3]	[kg]	[m^2]	[mm^2]	[N]	[MPa]
A	0.400	0.150	0.400	0.024	0.325	0.063	0.325	0.007	0.017	2230	38.681	0.040	39525.00	379.46	0.00960
B	0.400	0.125	0.400	0.020	0.325	0.038	0.325	0.004	0.016	2230	35.649	0.038	37650.00	349.72	0.00929
C	0.400	0.100	0.400	0.016	0.325	0.035	0.325	0.004	0.012	2230	27.436	0.029	28625.00	269.15	0.00940
D	0.400	0.087	0.400	0.014	0.325	0.025	0.325	0.003	0.011	2230	25.153	0.027	26675.00	246.75	0.00925
E	0.400	0.075	0.400	0.012	0.325	0.013	0.325	0.001	0.011	2230	23.698	0.026	25775.00	232.48	0.00902

Appendix 6: Cross-section Optimisation

	Length	Breadth	Height	Area 1	Area 2	Total Area (m2)	Volume (m3)	Density (kg/m2)	Mass (kg)	Force (N)	Compressive Strength (MPa)	Compressive Strength 100KN (MPa)	Center of Mass	Cavity Width	Outer Pane	U-Value W/(m2K)
Cross-section 1	0.400	0.050	0.400	0.020	0.010	0.030	0.012	2230.000	26.760	262.516	0.009	3.333	Yes	0.018	0.012	2.6
Cross-section 2	0.400	0.030	0.400	0.012	0.014	0.026	0.010	2230.000	23.192	227.514	0.009	3.846	Yes	0.018	0.012	2.6
Cross-section 3	0.400	0.070	0.400	0.028	0.006	0.034	0.014	2230.000	30.328	297.518	0.009	2.941	No	0.018	0.012	2.6
Cross-section 4.1	0.400	0.050	0.400	0.020	0.002	0.022	0.009	2230.000	19.624	192.511	0.009	4.545	Yes	0.018	0.012	2.6
Cross-section 4.2	0.400	0.050	0.400	0.020	0.001	0.021	0.008	2230.000	18.732	183.761	0.009	4.762	Yes	0.018	0.012	2.6
Cross-section 5	0.400	0.100	0.400	0.040		0.040	0.013	2230.000	29.900	293.317	0.007	2.500	Yes	0.018	0.012	2.6
Cross-section 6	0.400	0.100	0.400	0.040		0.040	0.013	2230.000	29.900	293.317	0.007	2.500	Yes	0.03	0.012	2.63
Cross-section 7	0.400	0.100	0.400	0.040		0.040	0.011	2230.000	24.120	236.614	0.006	2.500	Yes	0.018-2	0.012	1.71

Appendix 7: Cross-section alternatives

	Outer glass	**cavity**	**core glas:**	**cavity**	**inner gla**	**Total (glass block)**	
Tickness (mm)	12.00	30.00	26.00	30.00	12.00		
Lamda	1.00	0.14	1.15	0.14	1.00		
R value	0.01	0.21	0.02	0.21	0.01	**0.48**	
					U value	**2.10**	
	glass	connection:	wooden frame 1		wooden frame 2		
Number	130.00	154.00	4.40	0.22	5.80	0.22	
Area per nos (mm2)	160000.00	3600.00	1.94		2.55		
							Total
Area in m2	20.80	0.55		1.94		2.55	**25.84**
U*A	43.77	1.66		0.77		1.02	**47.23**
						U value of system	**1.83**

Appendix 8: U-Value calculation for 12-30-26-30-12

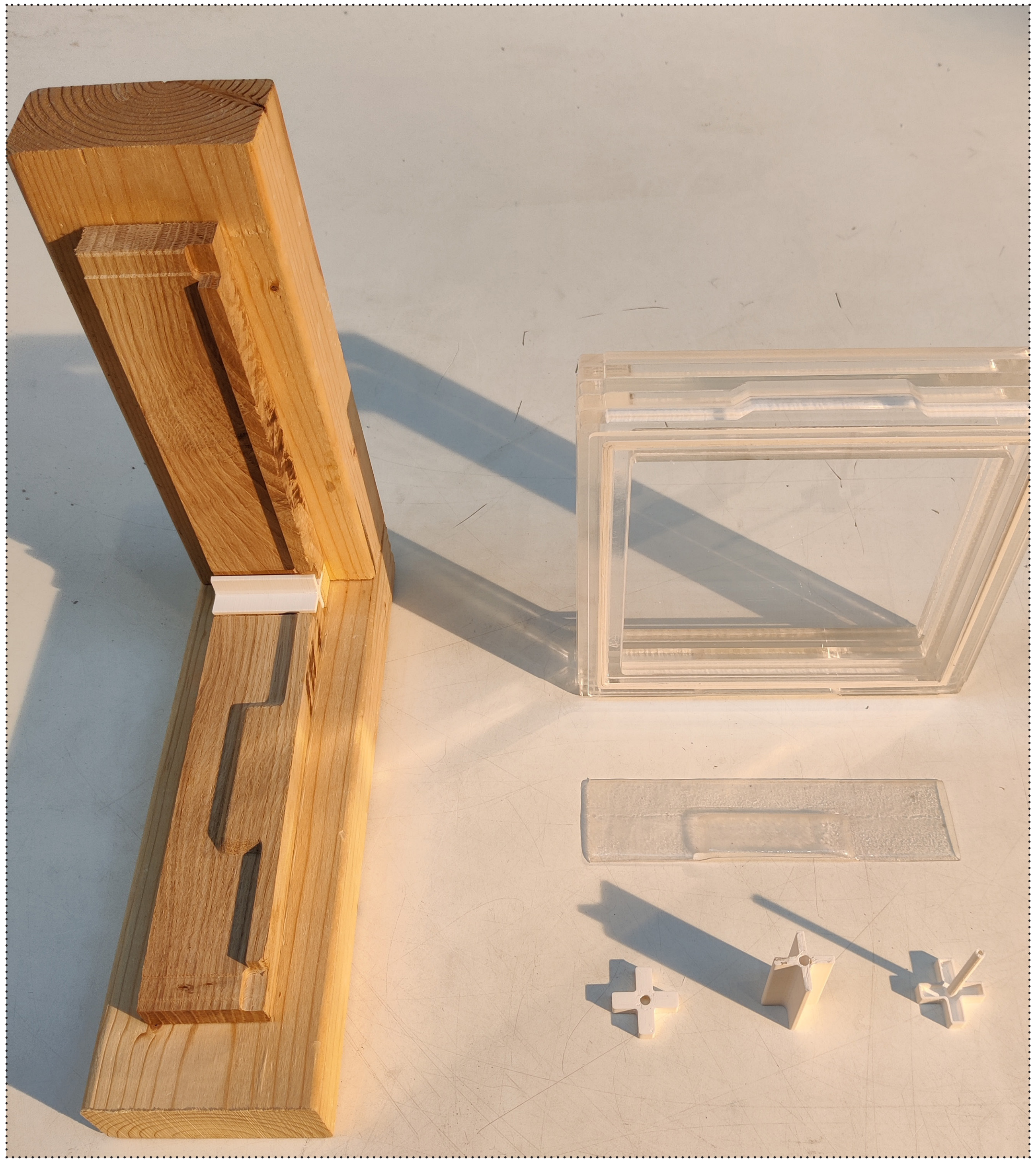
	Outer glass	**cavity**	**core glas:**	**cavity**	**inner gla**	**Total (glass block)**	
Tickness (mm)	6.00	30.00	26.00	30.00	6.00		
Lamda	1.00	0.14	1.15	0.14	1.00		
R value	0.01	0.21	0.02	0.21	0.01	**0.46**	
					U value	**2.16**	
	glass	connection:	wooden frame 1		wooden frame 2		
Number	130.00	154.00	4.40	0.22	5.80	0.22	
Area per nos (mm2)	160000.00	3600.00	1.94		2.55		
							Total
Area in m2	20.80	0.55		1.94		2.55	**25.84**
U*A	44.91	1.66		0.77		1.02	**48.37**
						U value of system	**1.87**

Appendix 9: U-Value calculation for 6-30-26-30-6

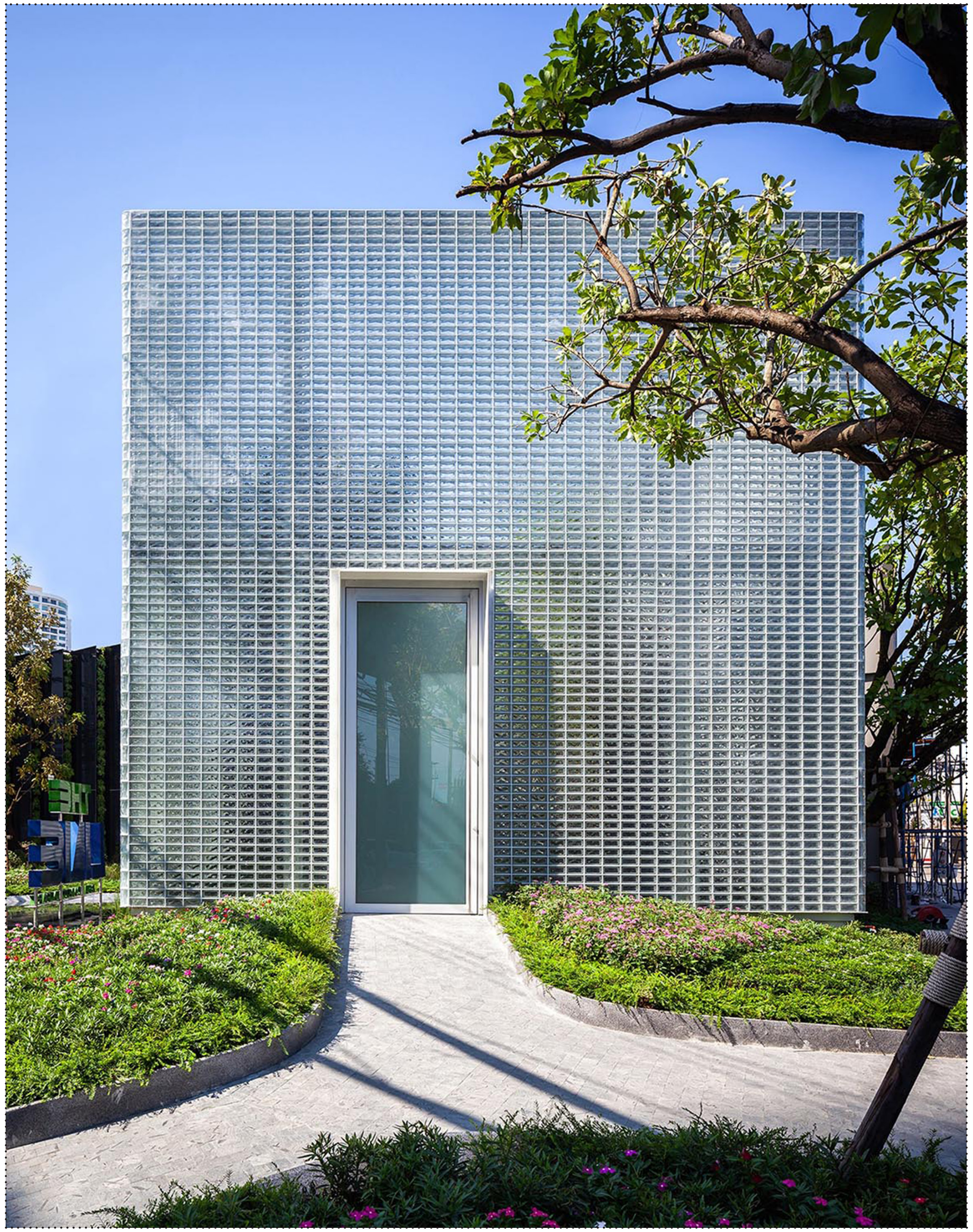
Tickness (mm)	3.00	30.00	26.00	30.00	3.00		
Lamda	1.00	0.14	1.15	0.14	1.00		
R value	0.00	0.21	0.02	0.21	0.00	**0.46**	
					U value	**2.19**	
	glass	connection:	wooden frame 1		wooden frame 2		
Number	130.00	154.00	4.40	0.22	5.80	0.22	
Area per nos (mm2)	160000.00	3600.00		1.94		2.55	
							Total
Area in m2	20.80	0.55		1.94		2.55	**25.84**
U*A	45.50	1.66		0.77		1.02	**48.95**
						U value of system	**1.89**

Appendix 10: U-Value calculation for 3-30-26-30-3

Appendix 11: Hybrid glass block model in plexiglass



Appendix 12: Hybrid glass block model in plexiglass



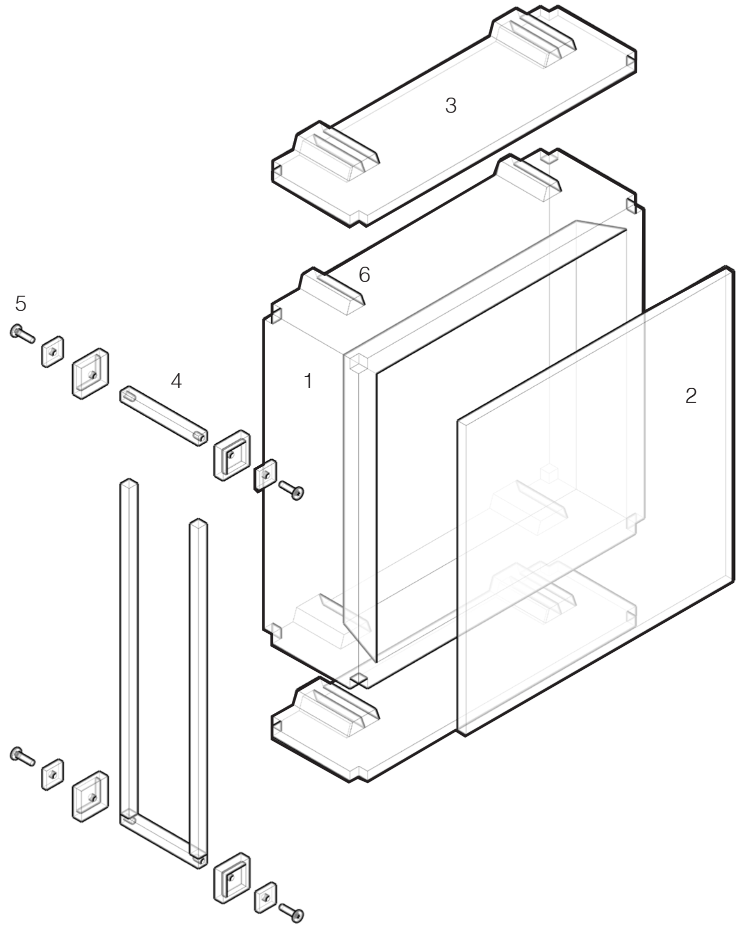
Appendix 13: The Glass Fortress, Archismith Architects (Archdaily)

CURRENT- HOLLOW GLASS BLOCK

Appendix 14: Envisioned for The Glass Fortress, Archismith Architects

FUTURE - HYBRID GLASS BLOCK

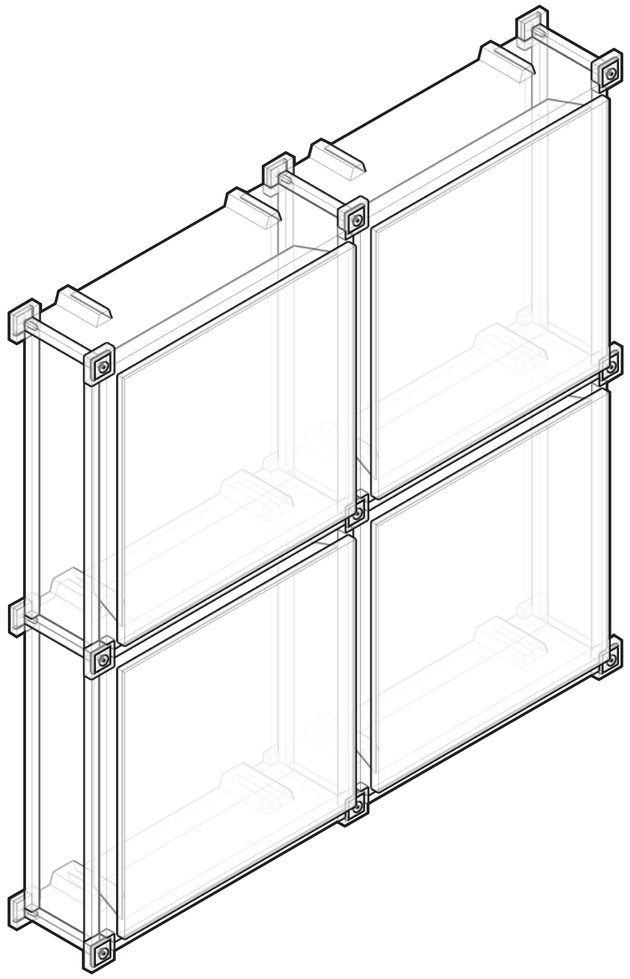
1. Cast glass - C Shaped
2. Float glass panel
3. Interlayer
4. Glass connection
5. Metal Connection
6. Interlocking Notch



Exploded View

Different Components coming together

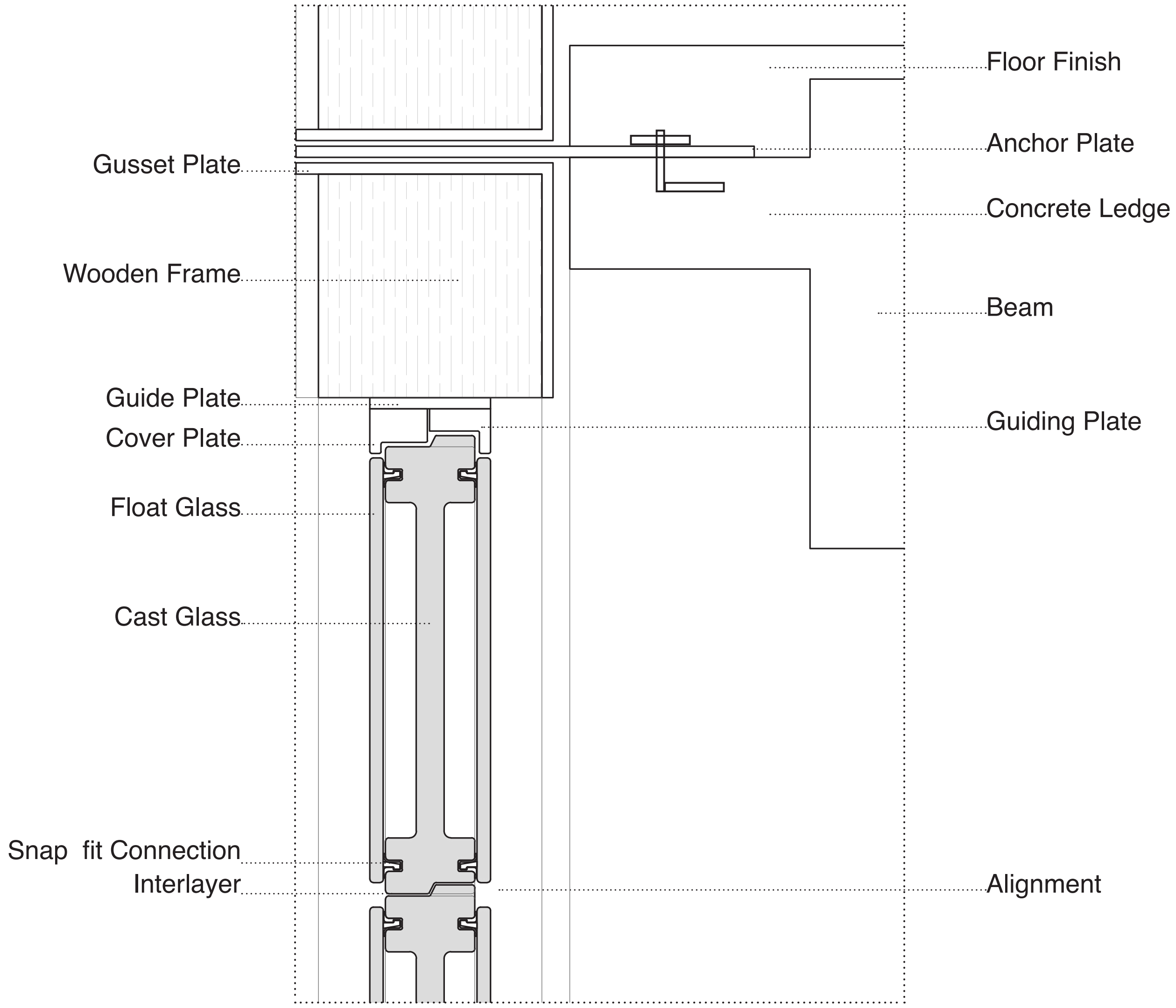
Appendix 15: Ladder Connection Concept



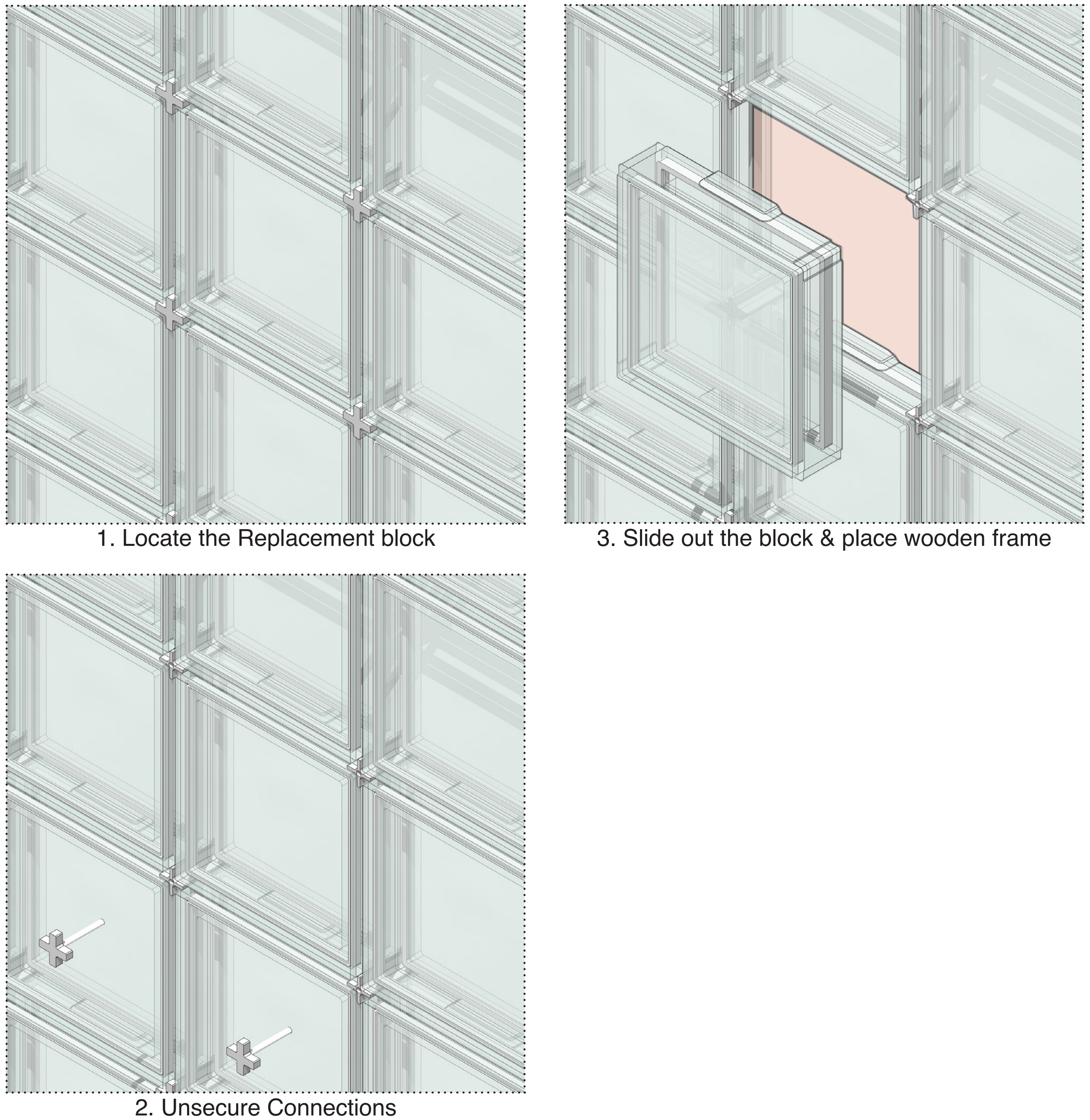
Assembly System

With an additional ladder or portal

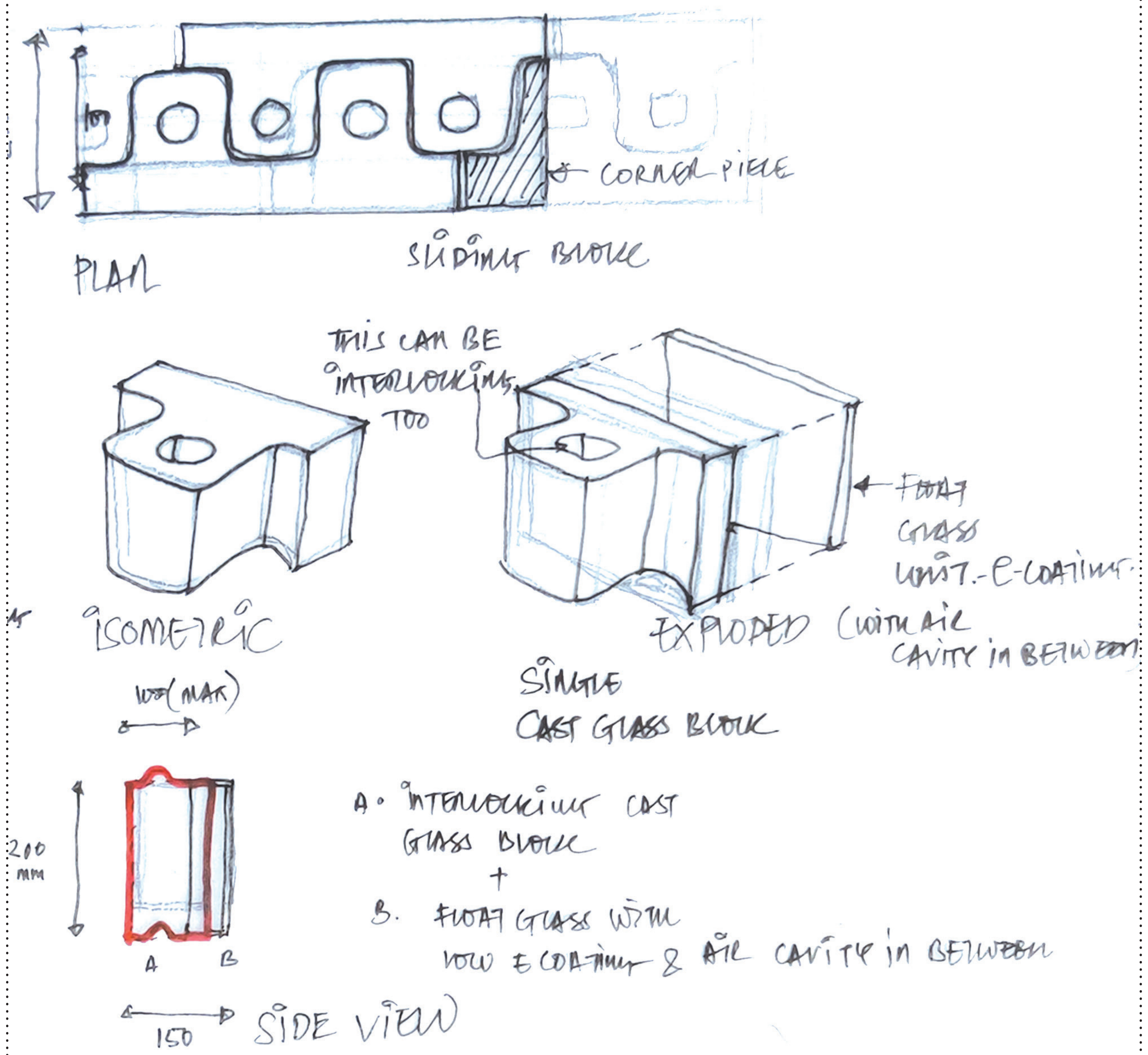
Appendix 16: Ladder Connection Assembly Concept



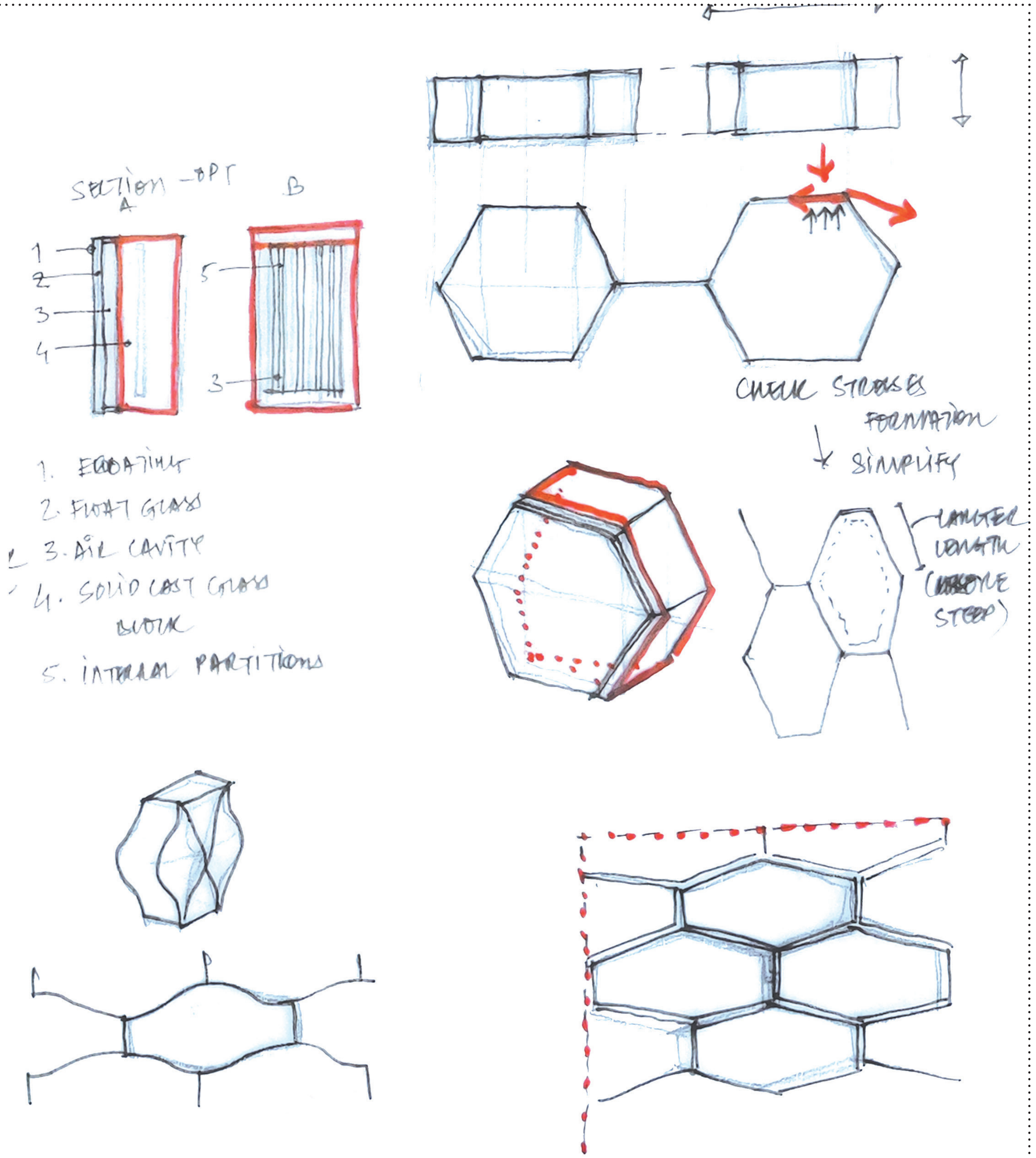
Appendix 17: Cross-Section of Hybrid glass block system



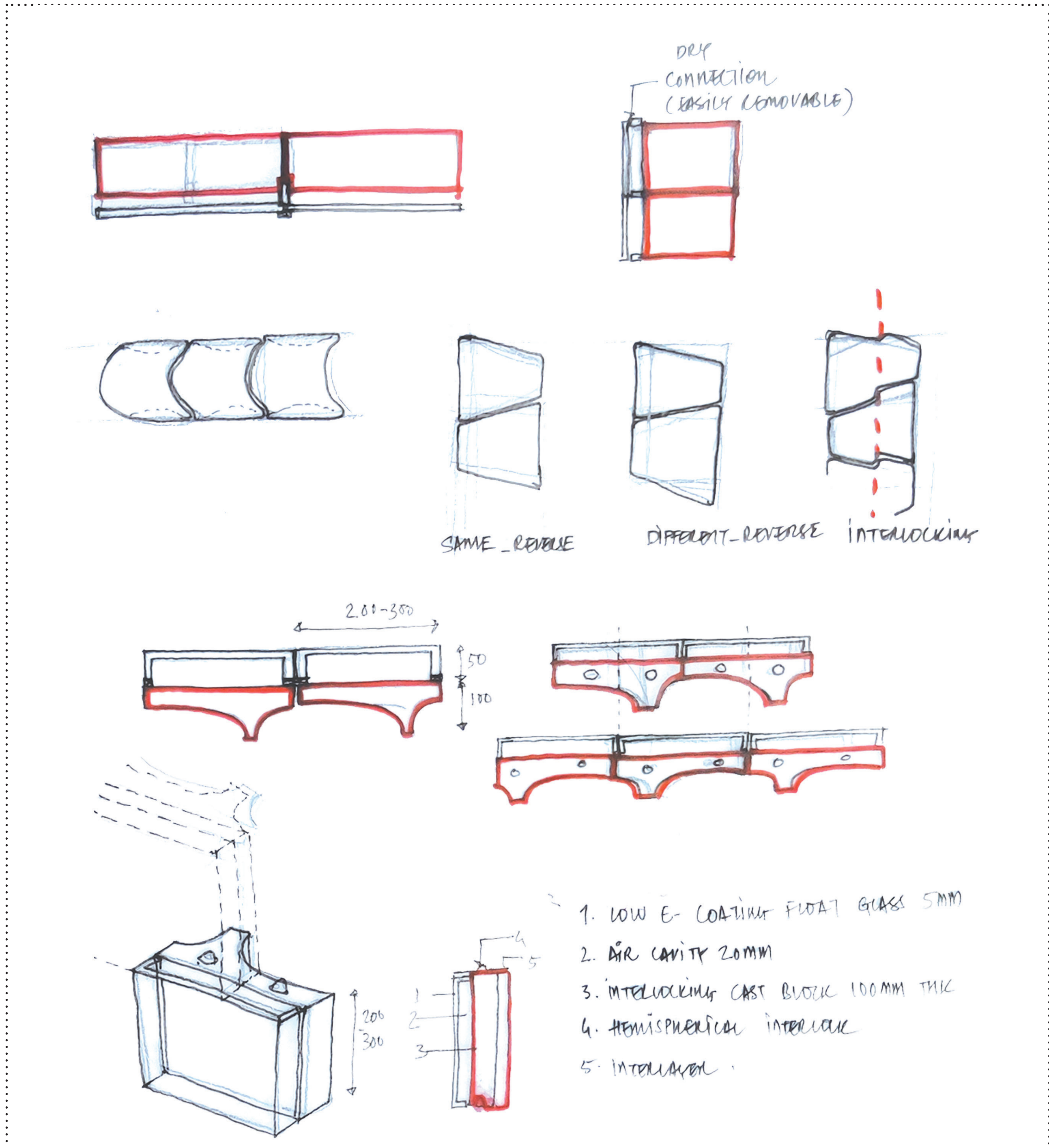
Appendix 18: Replacement of Hybrid Glass Block on Unit level



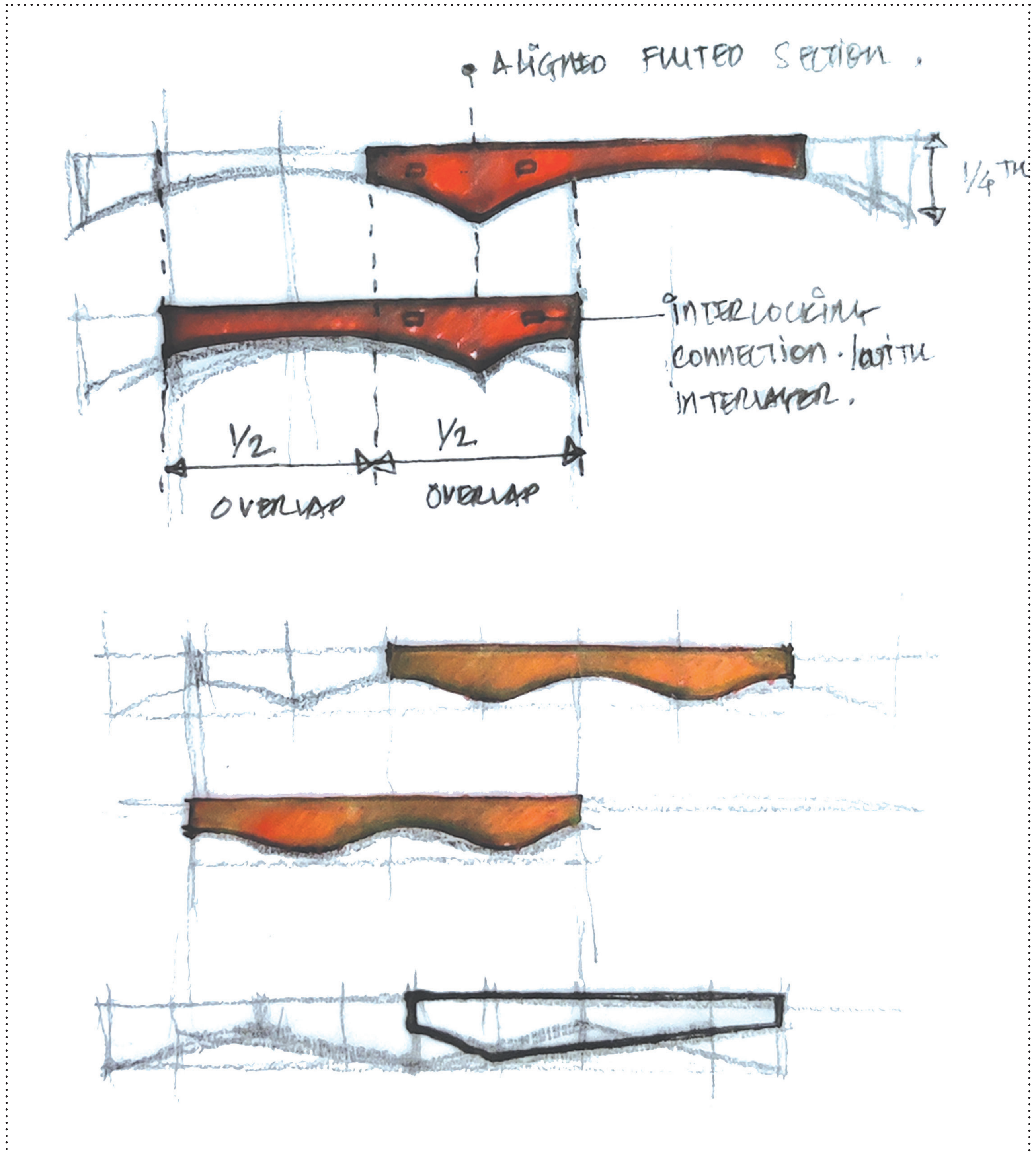
Appendix 19: Conceptual Sketch - 1



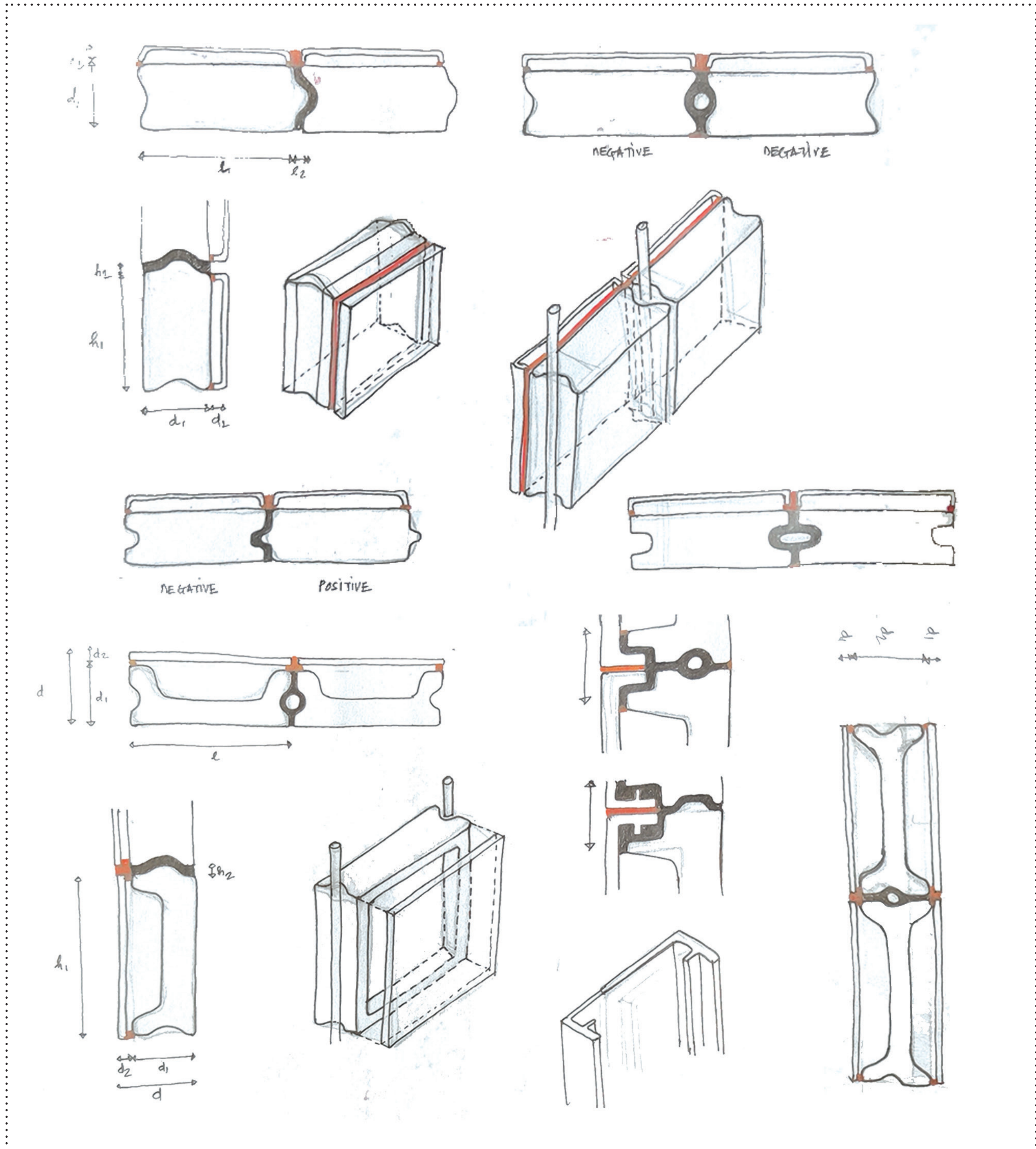
Appendix 20: Conceptual Sketch - 2



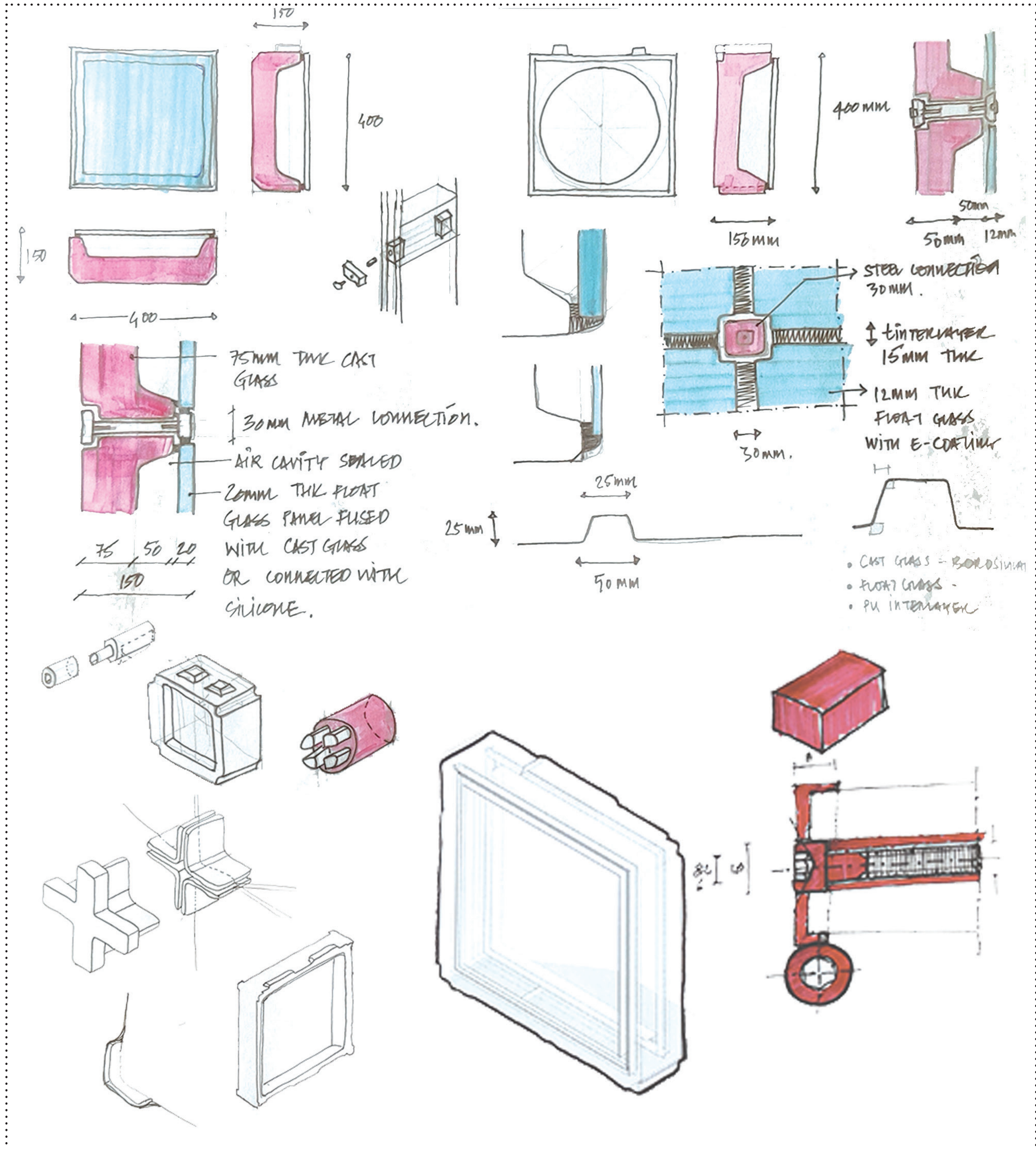
Appendix 21: Conceptual Sketch - 3



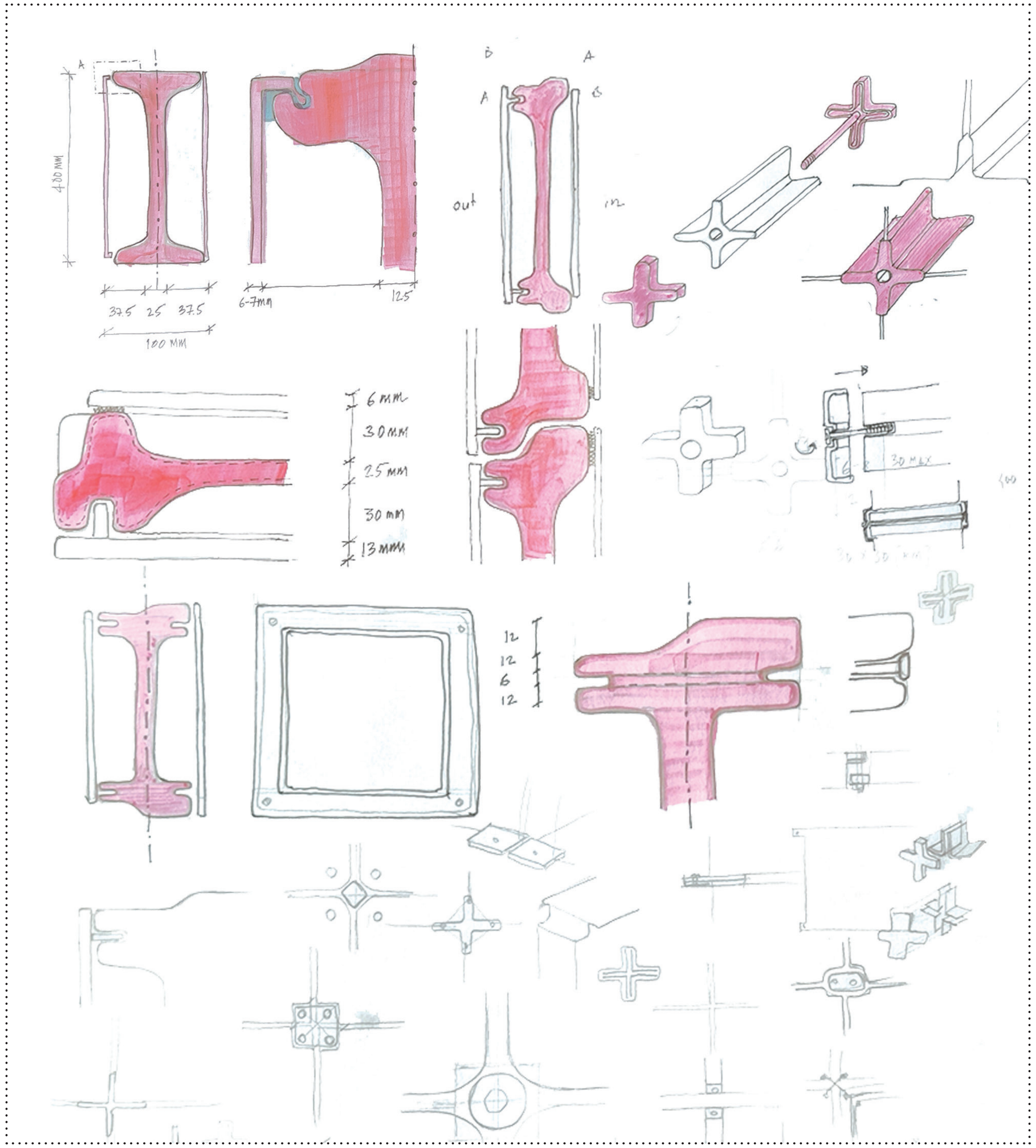
Appendix 22: Conceptual Sketch - 4



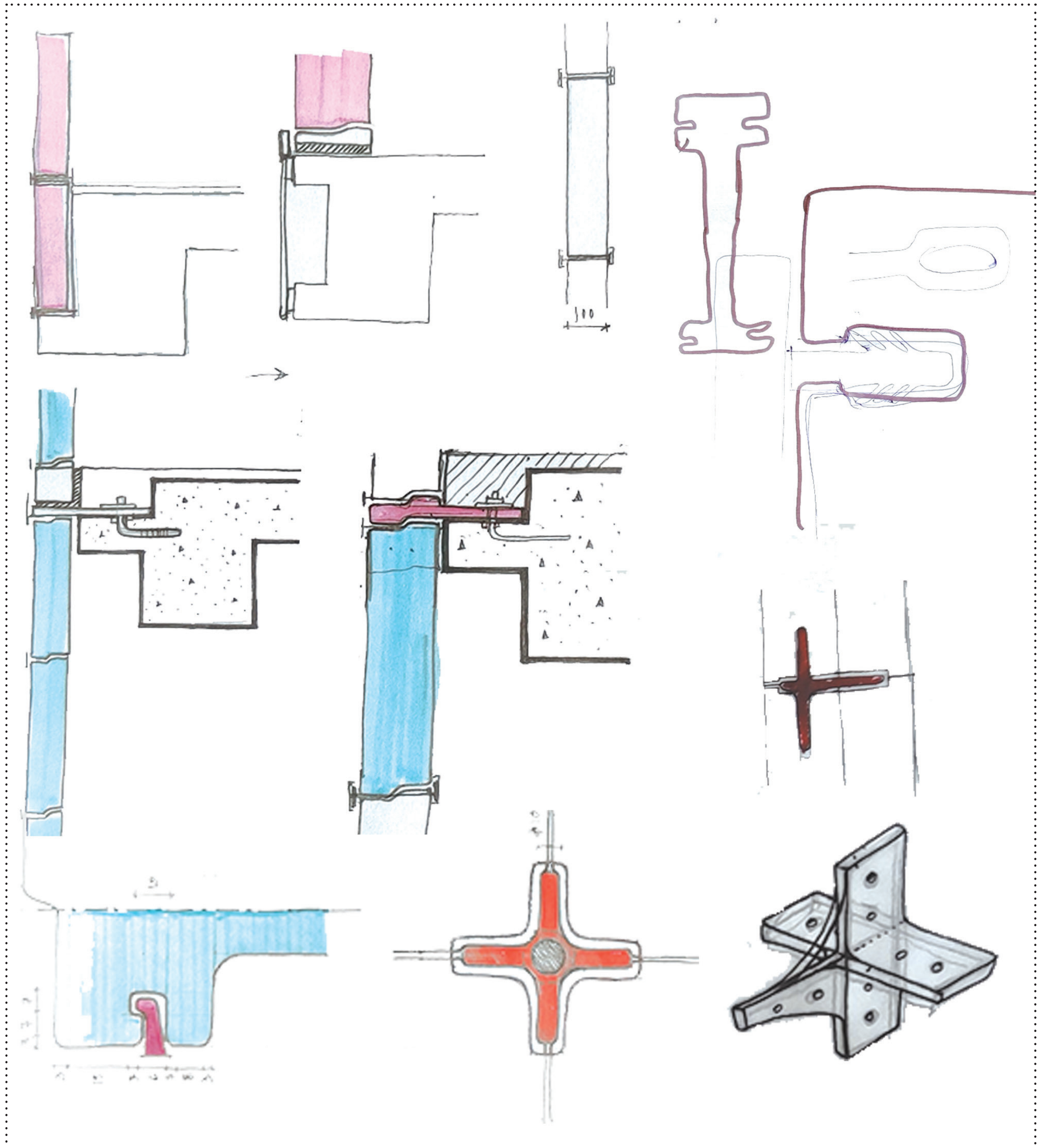
Appendix 23: Conceptual Sketch - 5



Appendix 24: Conceptual Sketch - 6



Appendix 25: Conceptual Sketch - 7



Appendix 26: Conceptual Sketch - 8

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