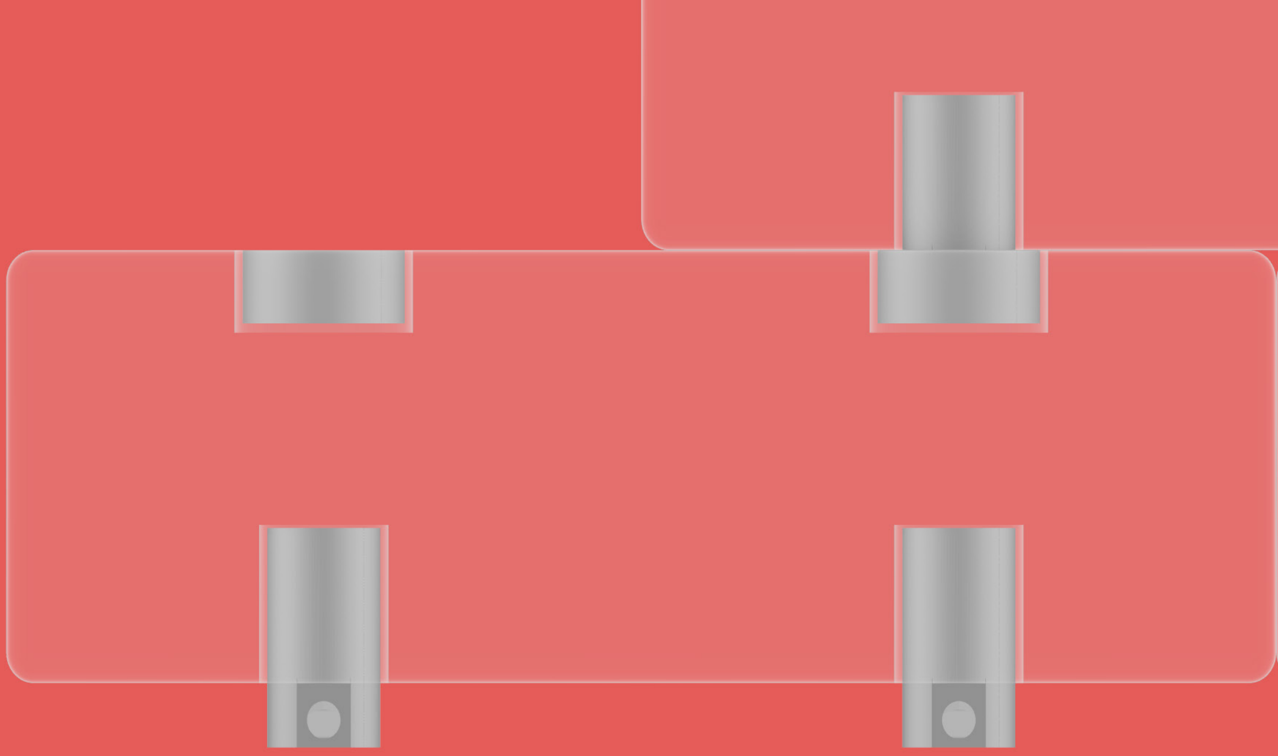
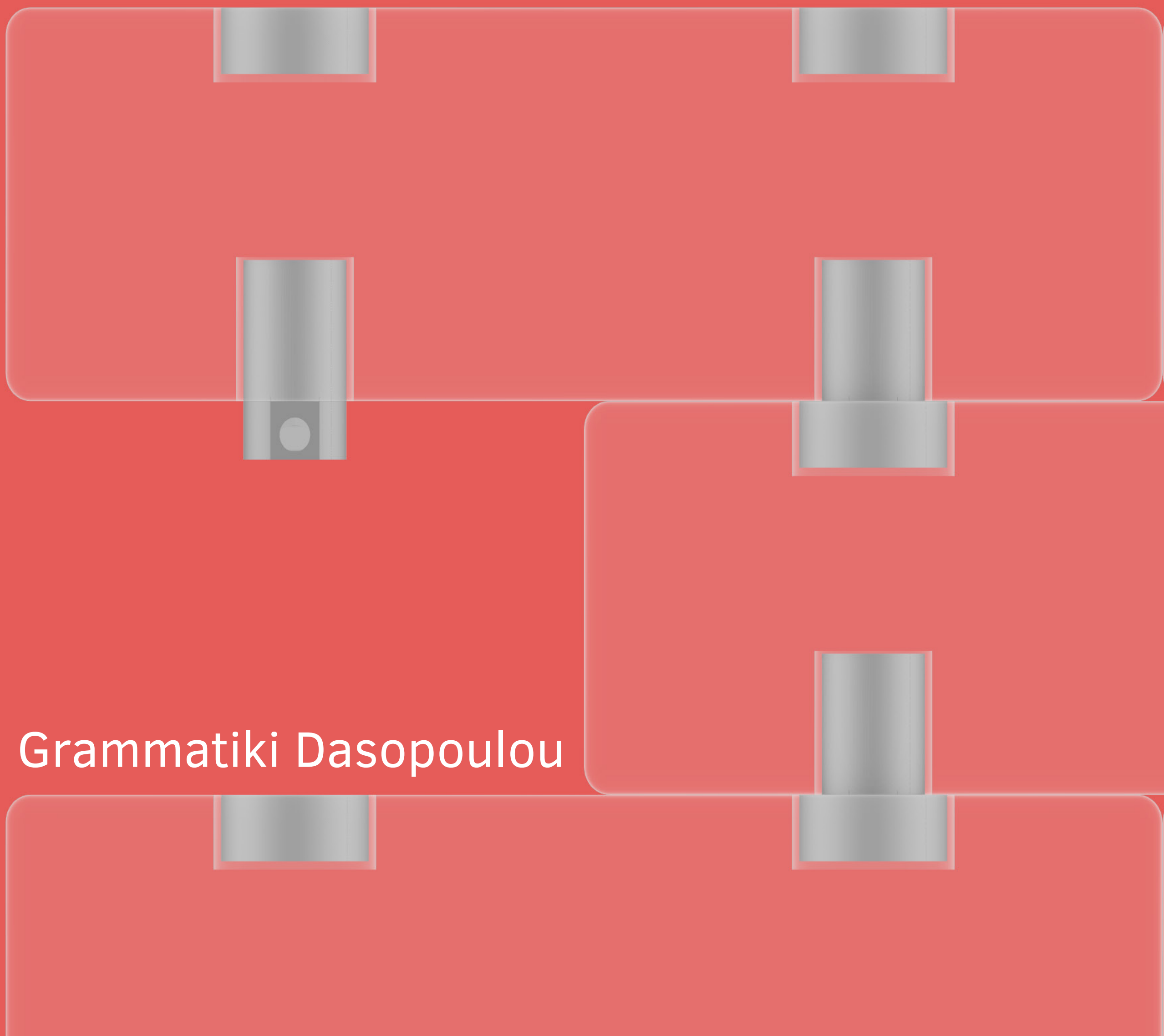


# Rolling in Transparency

## Exploring the potential of embedding connections in cast glass components



Grammatiki Dasopoulou

# Master Thesis

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Working on this research project for the last eight months has been in many levels, the most challenging and exciting period during my studies in Building Technology. From the very beginning of this master thesis, I betted with myself:

-Grammatiki, this is your last academic project, so…enjoy it and learn as much as you can!

Eventually, I won this bet, but this would not have been possible without the help of many people, who had great contribution in intellectual, mental and practical level, accordingly.

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This master's thesis is dedicated to my family. I would like to thank my parents, Konstantinos and Olympia, for their unconditional love and support all these years and for believing in me, even in moments I did not. Special thanks to my brother Dionisis and my sister Eleni, for supporting me and making me laugh especially during quarantine!

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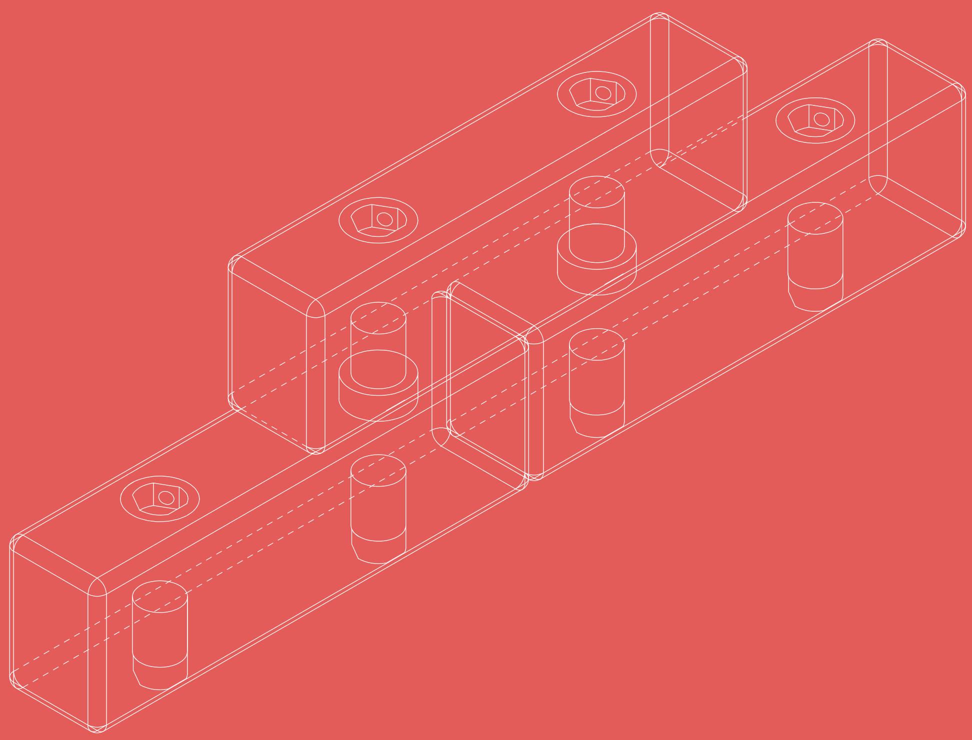
Thank you all,

Grammatiki

# Contents



# Summary


It has been only a few decades since glass has started revealing its full potential and emerged in the engineering world in three-dimensional repetitive cast glass units with the shape and size of typical masonry bricks. Cast glass stands as the most competitive and novel answer to the relentless eagerness for transparency in the built environment, expanding in this way the shape and size barriers imposed by float glass. At present, cast glass has already proved its dynamism in few realized projects since it is the foundation of three structural systems which employ cast glass units. The additional supportive substructure, the adhesively bonded units and the third which is still on research stage, the interlocking cast glass elements. The aforementioned systems present great potentiality for more transparent structures, yet some of the technical aspects could be further developed.

The present master thesis explores the potential of embedding connections in cast glass units as a fourth structural system, supplementary to the existent ones. This system stands as an attempt to address the intensive assembly, the compromised transparency or the irreversibility, some of the key difficulties that are introduced by the precedent systems.

Accordingly, this research started with an extended literature review related to cast glass technology and current types of connections both in glass and in various materials, respectively. The information derived from this literature research led to the establishment of the design criteria. The criteria divided into two categories, the first addresses the principles about the cast glass unit while the second focuses on the embedded connection.

Ensuing this, a material exploration on embedded connection considered as appropriate. The selection of the final material based not only on literature review but also on experiments and realised projects that use metal inserts in laminated glass. Moreover, an exploration on interlayer between the connection and the glass carried out to circumvent the metal – to – glass connection, a criterion founded since literature review.

Subsequent to this research and since all the parameters are set, Chapter 7 presents the design development of the embedded connection. This chapter introduces the system’s fundamental principle which derived from a meticulous analysis of multiple concepts. These concepts filtered based on the design criteria and by the end of this chapter, the most prevailing one is selected. Chapter 8 provides the final design of the embedded connection. The selected design is based on a locking mechanism which is magnet driven from outside. This ensures the ease of assembly and disassembly of the structure since there is no need for access through the glass brick. The connection has been designed with dimensions and shape that respect the design criteria entirely.

The following chapter focuses on the fabrication of the component, which will take place in two phases. Based on the findings from the literature review, a casting process along with a metal mould have been selected for the first phase, for manufacturing the cast glass unit. The second phase starts with the lamination of the embedded connection on the cast glass unit and ends up with the assembly of the whole component.

The proposed structural system will be applied as a glass wall in a selected case study to give a more realistic scenario. Chapter 10 provides an insight to the construction details and the assembly sequence of the glass façade.

The findings of this master thesis along with some recommendations for further development are presented in the last chapter. The development of this structural system promises an easy to assembly and reversible system in cast glass structures, targeting simultaneously to less compromised transparency.

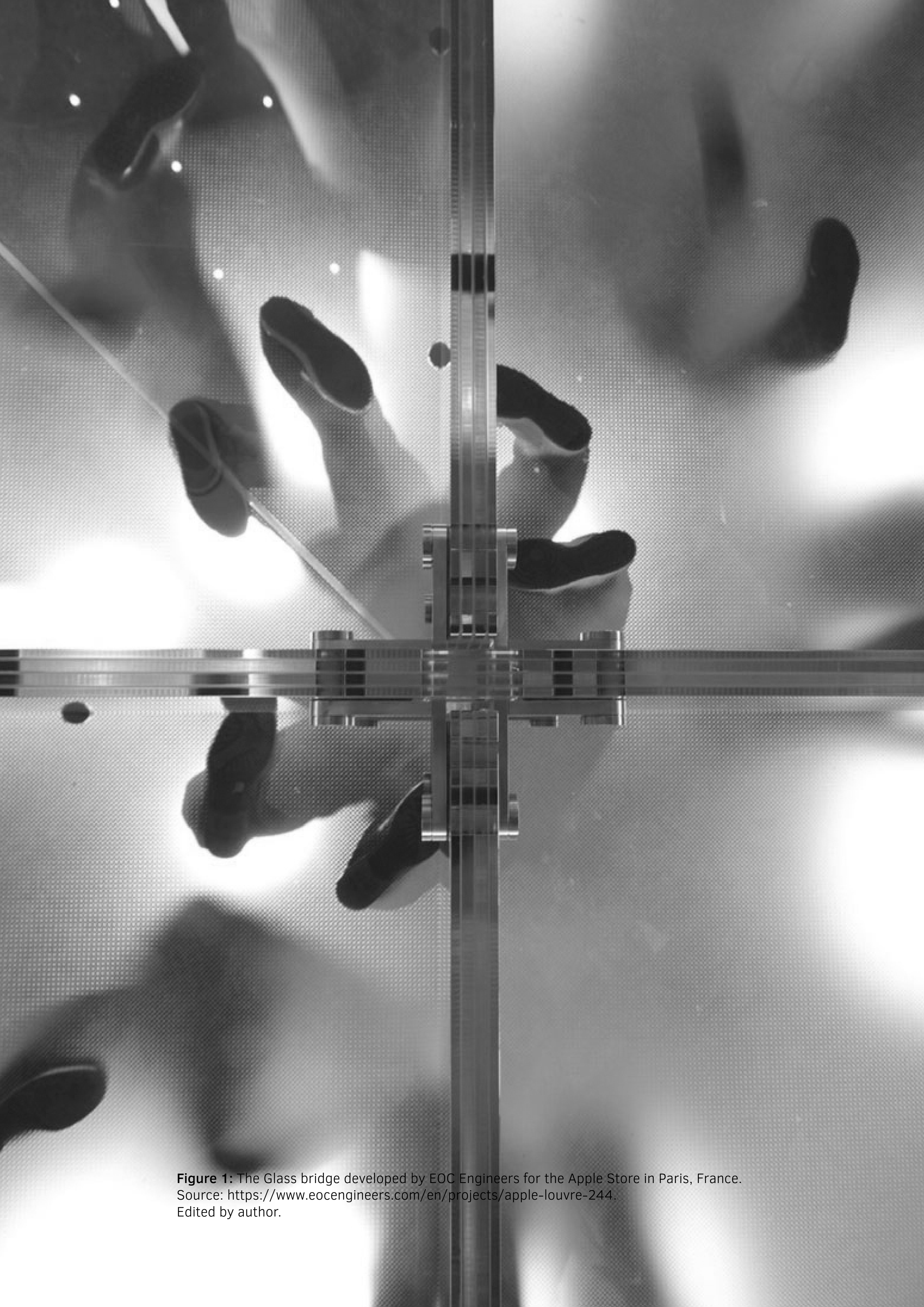


**Figure 1:** The Glass bridge developed by EOC Engineers for the Apple Store in Paris, France.
Source: https://www.eocengineers.com/en/projects/apple-louvre-244.
Edited by author.

# 1 Introduction

During the last decades, the unceasing eagerness for transparency in constructions have rendered the use of structural glass, irresistible. At the time being structural glass can be employed in different states, such as, columns, beams or fins, produced by float glass. Glass is a durable material, since its mechanical properties are not changed when it is exposed either in light or humid environment, while is not affected by corrosion.

Combining transparency, a comparatively long-life span and a great compressive strength, structural glass is undoubtedly a very competitive material. However, the constant desire for transparency in building industry, and the shape limitations imposed by the float glass, forced the researchers and the engineers to search for more innovative solutions.

This led to the emergence of cast glass as a structural material, in the construction world.

Nowadays, cast glass structures, consist of small cast glass units with the approximate dimensions of a “masonry brick” and are already employed in few realized projects with great success. As established by (Oikonomopoulou,2019) in her PhD thesis, some of the fundamental principles in structures which employ cast glass components are transparency, load-carrying capacity, reversibility, ease of assembly. Since, cast glass structures are at early stage in architecture, some of the aforementioned aspects in the existing structural systems are compromised.

Scope of this master thesis is to investigate the potentials of cast glass structures and to expand the boundaries related to the challenges they provoke such as the compromised transparency or the easy assembly.

Based on the findings from this research, a novel, reversible structural system for cast glass components is proposed as a supplementary to the current ones, targeting to more diaphanous, easy assembled glass structures by using embedded connections in cast glass units.

# 2 Research framework

## 2.1 Problem Statement

Over the last decades, there is a consistent desire for great transparency in building industry, which establishes the structural use of glass inevitable. Taking into consideration,durability, transparency and a compressive strength greater than that of or steel or concrete, glass manages to decline its fragile and brittle nature. Hence, glass emerges in the engineering world as a structural element of high compressive load-bearing efficiency of 1000 MPa (Ashby, Jones, 2006; Saint Gobain, 2016; Weller et al., 2008), substituting completely the way we conceive it (Oikonomopoulou, et al., 2018).

There is a dominant presence of float glass in the building industry, since it is specifically produced and used in two-dimensional shapes, for facades purposes and load-bearing structures. However, float glass is formed in two-dimensional, planar components: either with a cylindrical or orthogonal shape, contributing to glass elements with limited forms, dimensions and shapes.

Cast glass and cast glass components have managed to break away from float glass design limitations, by introducing new properties which establish it as a very competitive material. Solid three-dimensional glass segments are produced by pouring molten glass into moulds, expanding the boundaries in cross-sections and shapes that float glass has imposed. Their monolithic nature contributes to form repeated units that expand to the fullest the potential in constructing self-supporting glass-structures in three dimensions, diminishing the need for additional supporting elements (Oikonomopoulou, et al., 2018).

Despite the meticulous annealing time, cast glass is introduced in construction industry in a size variety of typical masonry bricks that take full asset of glass's great efficiency in compression. Unfortunately, the absence of fundamental research regarding their build-ability and structural efficiency, simultaneously to the challenging manufacturing process, have steered to limited cast glass applications in architecture with a few executed projects (Oikonomopoulou, et al., 2018).

At present, these few characteristic projects, which will be analysed excessively in the following chapters, represent the existing structural systems which employ cast glass components. There are currently three structural systems for creating self-carrying cast glass structures: with an additional supportive substructure, adhesively bonded and interlocking cast glass elements. The first two systems have been realized in the built environment whereas the third one has only been explored within a research context. The first system applies a supportive substructure to withstand the lateral forces while it carries glass's own dead load, resulting in a mortar-free structure. Moreover, the vertical metal net obstructs the transparency.

Furthermore, the second structural system uses a rigid structural adhesive to bond the glass bricks resulting in an entirely transparent load-bearing structure. The envelope operates as a single rigid unit, achieving a uniform load distribution. However, this system leads to an irreversible structure, arduous to assembly. The third structural system, has only been explored within a research context, proposes the potential of interlocking cast glass components, creating a structure with a minimum use, if any of metal framing (Oikonomopoulou, et al., 2018).

To a great extent, these three existent structural systems in cast glass components are very promising. Nonetheless, these unfavourable aspects such as and intensive labour, irreversibility or the compromised transparency, make the researchers reluctant to apply them in the built environment.

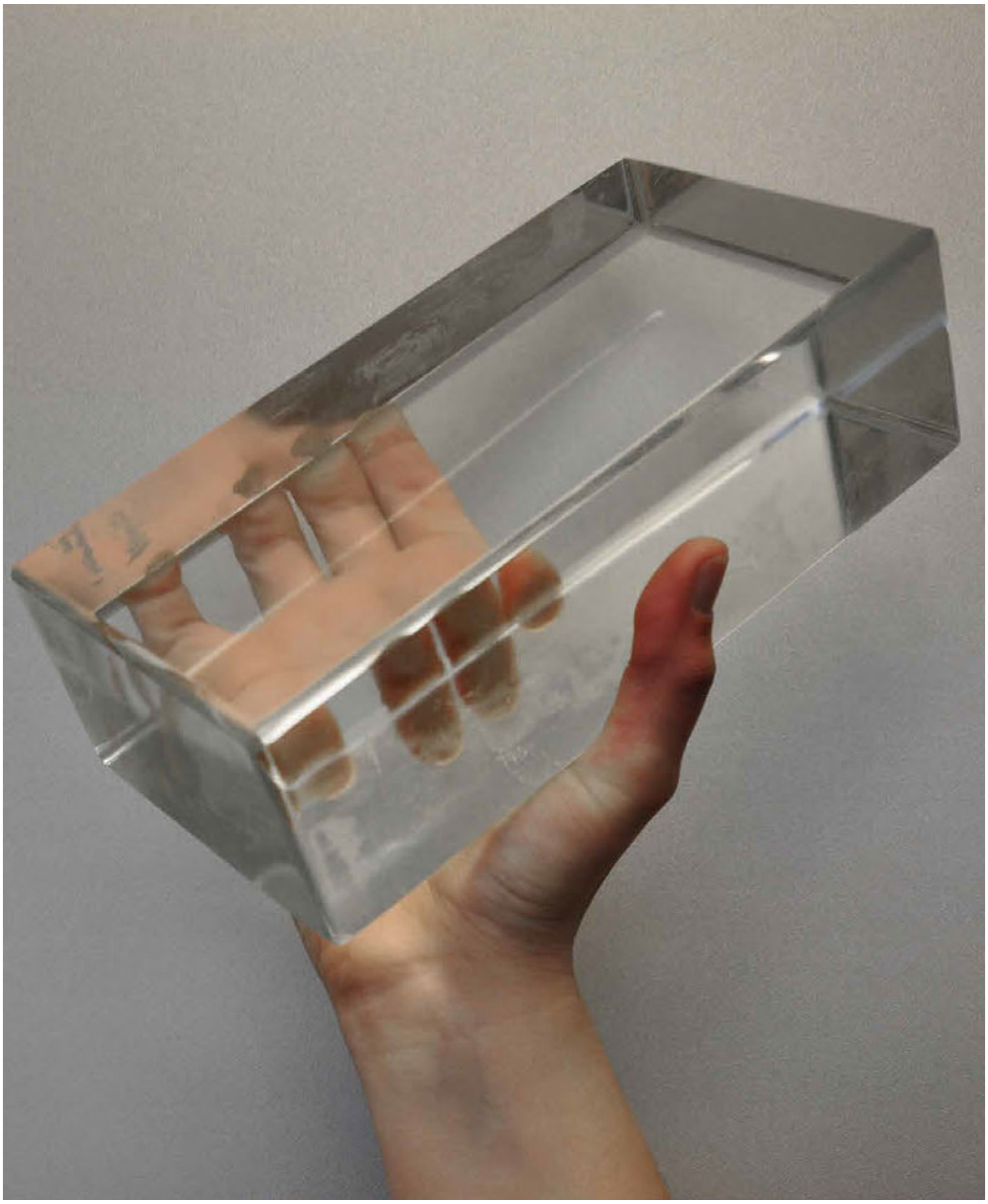


**Figure 2:** The cast glass unit manufactured by soda- lime glass employed in the *Crystal Houses.* Retrieved from (Oikonomopoulou, 2019).

## 2.2 Research Question

In consequence of the technical obstacles stated in the chapter above, this research explores the potential of generating a fourth structural system in cast glass via connecting the glass bricks. In terms of stability, transparency and reversibility, this research targets to a novel system, which would be able to minimize the need of supportive substructure, improve the compromised transparency and will ease the concept of reversibility in glass structures.
On behalf of this, a fundamental research question has been formulated:

**-What is the potential of employing an embedded connection in cast glass components in order to accomplish an easily assembled and disassembled load bearing cast glass structure, which is structurally predictable, and it is not visually intrusive?**

From the main research question, several sub-questions have been derived:

**Sub-questions:**

**1.** Which are the advantages and disadvantages of existing connections types in cast glass structures? (Chapter 3.5.1 and Chapter 4.4)
**2.** What are the design principles for designing an embedded connection in cast glass components? What are the practical design limitations involved in this endeavour? (Chapter 5 and Chapter 7.1)
**3.** Which are the constraints of the material used for an embedded connection in a cast glass component? Which are the main principles and challenges involved in the material compatibility between a cast glass component and the desired connection? (Chapter 6 and Chapter 9)
**4.** Which are the main challenges affecting the structural behaviour of a system employing embedded connections in cast glass components? (Chapter 8.1)

## 2.3 Research Methodology

The research framework is organised in six steps as it is illustrated in the diagram below (Figure 3).The first three steps concern the literature research that has been conducted and it is divided into three scientific fields. The first, is about cast glass technology and contributes to a broad understanding regarding, for instance, the production methods, the shaping potentials or the current structural systems. The second, explores extensively the current connection types in glass while it investigates the existent embedded mechanisms in other materials. The third section, dives into the material exploration concerning the connection. The literature study based on different sources between books, scientific papers, journals and websites. Ensuing this, the fourth step depends on the design development based on the findings and the design criteria set in the literature study. In this stage, the design process will involve a wide exploration in miscellaneous mechanisms while some preliminary physical experiments will provide a primary comprehension of them. The results will be assessed and the concepts which meets the design criteria to the fullest will be selected. In phase 5 as it is illustrated in the diagram the most prevailing concept will be chosen.  This stage will include the completion of the design among with some primary structural validations. The case study of Optical House in Hiroshima has been selected to constitute a realistic scenario; hence the architectural details of the façade will be developed along with the assembly sequence. Physical experiments will lead to enhance the design process while they will assist to the construction of the final prototype.

Consequently, the final results reflecting on the settled component will be presented.

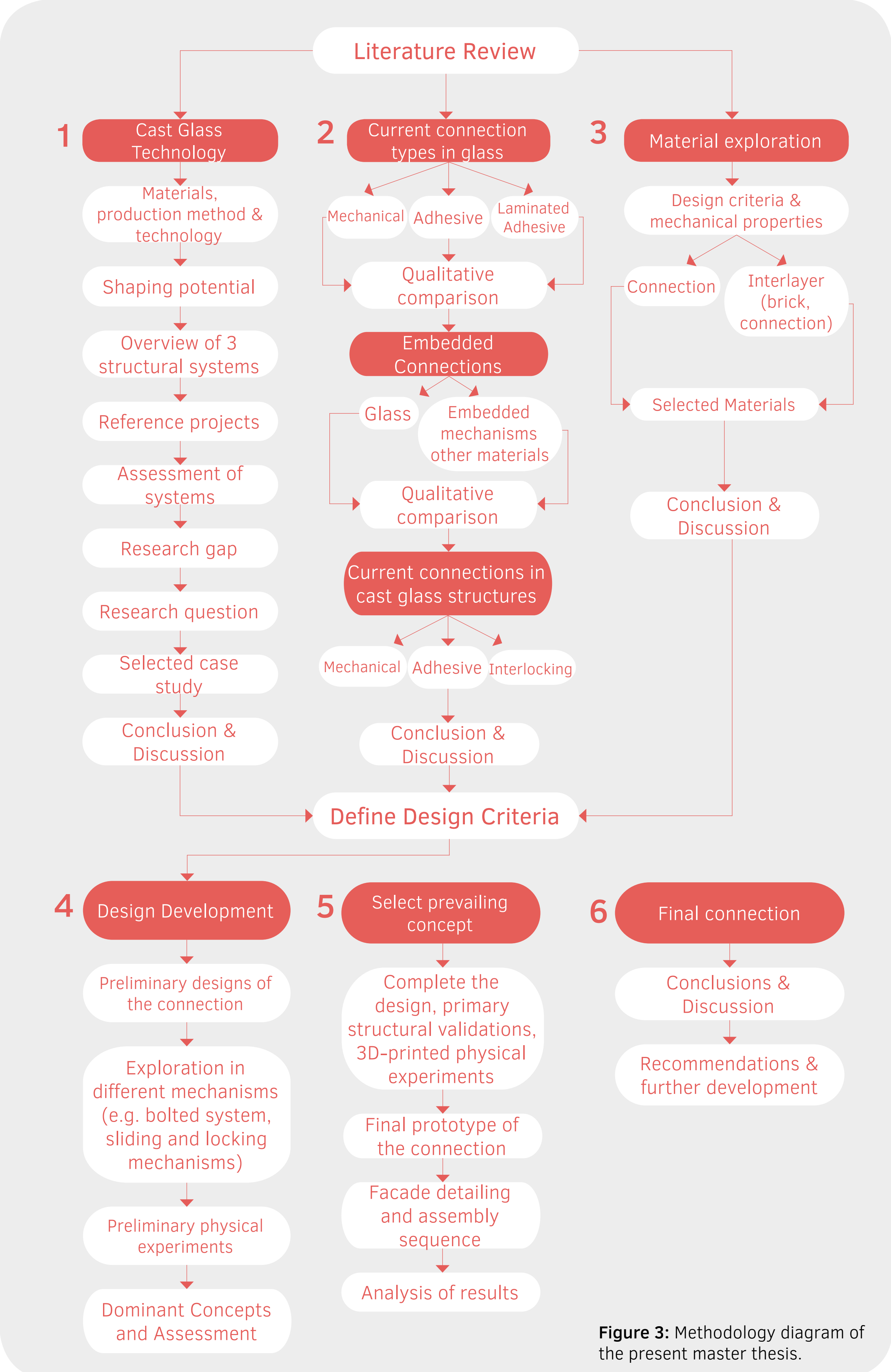



**Figure 3:** Methodology diagram of the present master thesis.

## 2.4 Relevance

This project presents an alternative solution in the cast glass structures supplementing the three existing ones. During a time-plan of seven months this project managed to meet the desired expectations to the maximum, which were an innovative solution, reversible and easy to assembly with minor visual impact. Although, there is a wide area of connection types, mechanisms or alterations of them that possibly have not been investigated due to the limited time-period and could be applied as well. Hence, the findings and the final product of this research could constitute a future reference for scientists, architects and civil engineers who are involved in this subject of interest and enhance their researches.

In a societal context, cast glass and cast glass components have managed to break away from float glass design limitations, by introducing new properties which render it a very competitive solution to the constant demand for high transparency in the building industry. This thesis proposes an alternative structural system in cast glass structures applied in an existed case study, which will ease the assembly and disassembly of the structure minimizing the labour time. Moreover, the lack of adhesives, render the system reversible and feasible to be reused in alternative projects or eventually get recycled. In total, this project renders an alternative, innovative solution for transparent load-bearing structures in the built environment.

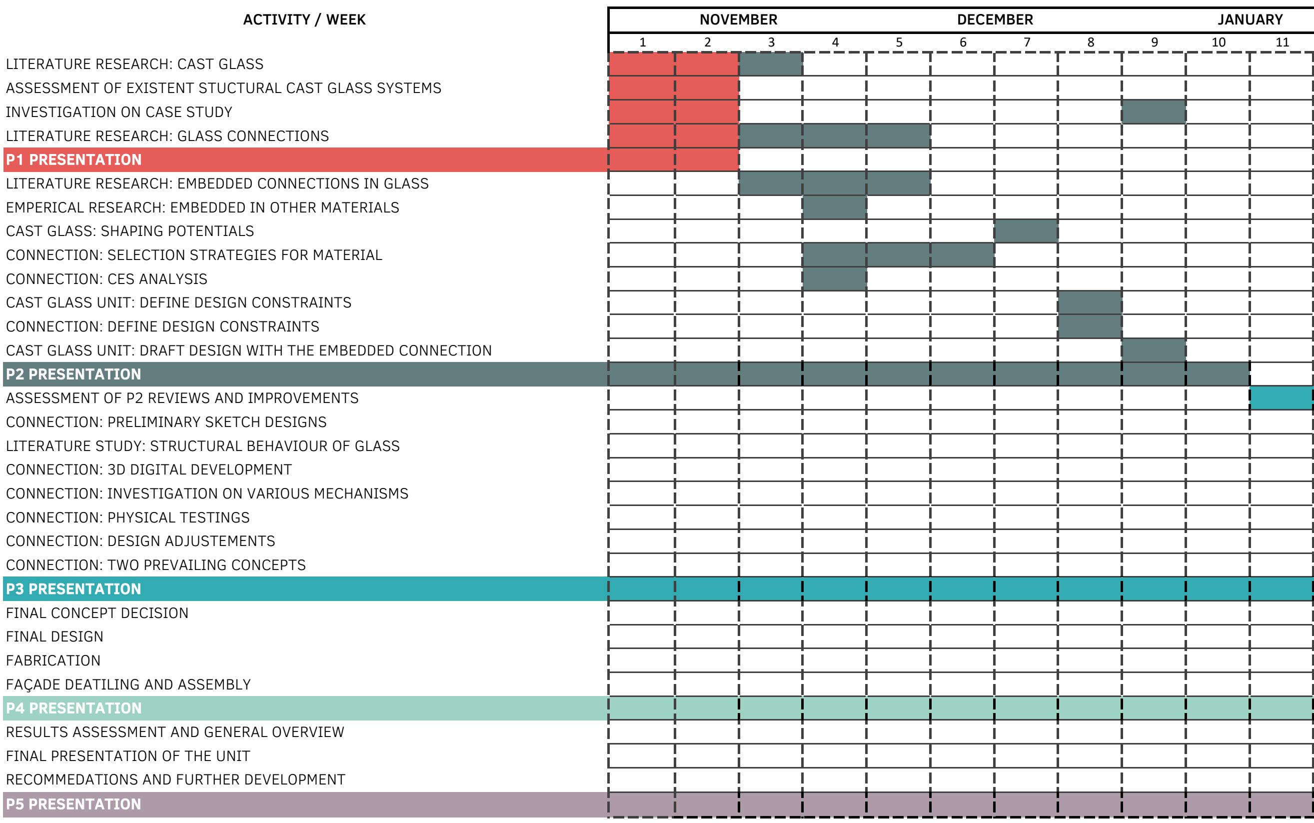



**Figure 4:** Time-plan

## 2.5 Time Planning

The structure of the time planning is based on the developed methodology in combination with the 5 presentations, during the scheduled time period of this thesis. The progress of this research is illustrated graphically in (Figure 4).

The period between P1 and P2 presentations, is dedicated to the literature research of this project. This research covers approximately the 80% of the literature and focuses mainly on the glass technology, the connections both in glass and in other materials, while a material exploration for the desired connection is carried out in the end. As a result, the design constraints are defined.

The next phase between P2 and P3, introduces the preliminary designs of the embedded connection based on the findings of the previous phase.

After P3 and since the prevailing concept is determined, the final design is determined. Following this, the fabrication process of the component is established along with the façade detailing and assembly of the selected case study.

The final component and an overview of this research will be demonstrated on the last presentation.

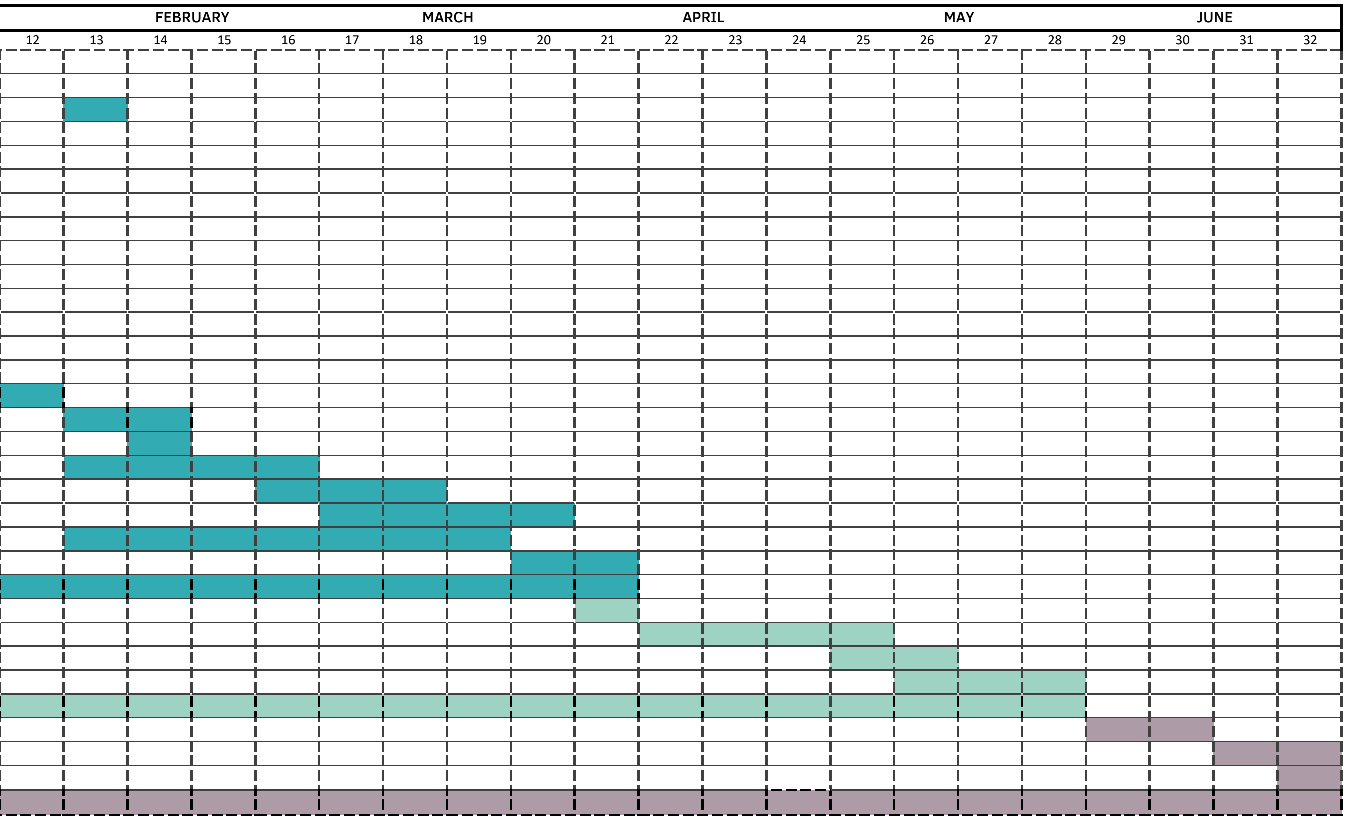


**Figure 5:** Casting process of soda-lime glass.
Retrieved from (Oikonomopoulou, 2019)

# 3 Cast Glass Technology

The first chapter of literature review starts with cast glass technology and the basic terminologies that characterize it.

**Cast glass. Why?**

Dating back to 2000 B.C. in Mesopotamia or in Roman times, cast glass constituted a renowned method for producing jewellery and small objects. Nowadays, the largest cast glass components are the monolithic pieces of the ground-based telescopic mirrors (Figure 7) whose size and shape optimized over the years achieving substantial stiffness by reducing their weight. Regardless of telescope mirrors, cast glass is an area of interest for art, too. There is a wide range of glass artists (Figure 7) who employ cast glass in their work. Among them, a well-developed example employing cast glass in art is the block for Denis Altar in France (Figure 8)(Oikonomopoulou, et al., 2018).

Far beyond our expectations and due to the constant need for transparency in structures, glass technologies have met a substantial breakthrough in engineering world, because of cast glass. When transparency is a necessary condition, cast glass could be considered as a very competitive structural material since it manages to overcome two major restrictions that glass confront in terms of material properties and glass applications: brittleness, shape and thickness limitations.

Float glass is a prevalent material in construction industry. Full-glass structures are reproduced by two-dimensional planar elements with an orthogonal or a cylindrical shape. At the present time, float glass panes can span in more than 20 meters length while they cannot be produced with a thickness exceeding the 25mm. These lopsided proportions render float glass as a structural material susceptible to buckling, restricting to take fully advantage of glass's impeccable compressive strength (Oikonomopoulou, 2019). These float glass elements are fully supported by glass fins or beams resisting to buckling using non-glass elements (Oikonomopoulou, et al., 2018).

**Figure 6:** Cast glass sculptures developed by artist Roni Horn. Retrieved from (Oikonomopoulou, 2019).

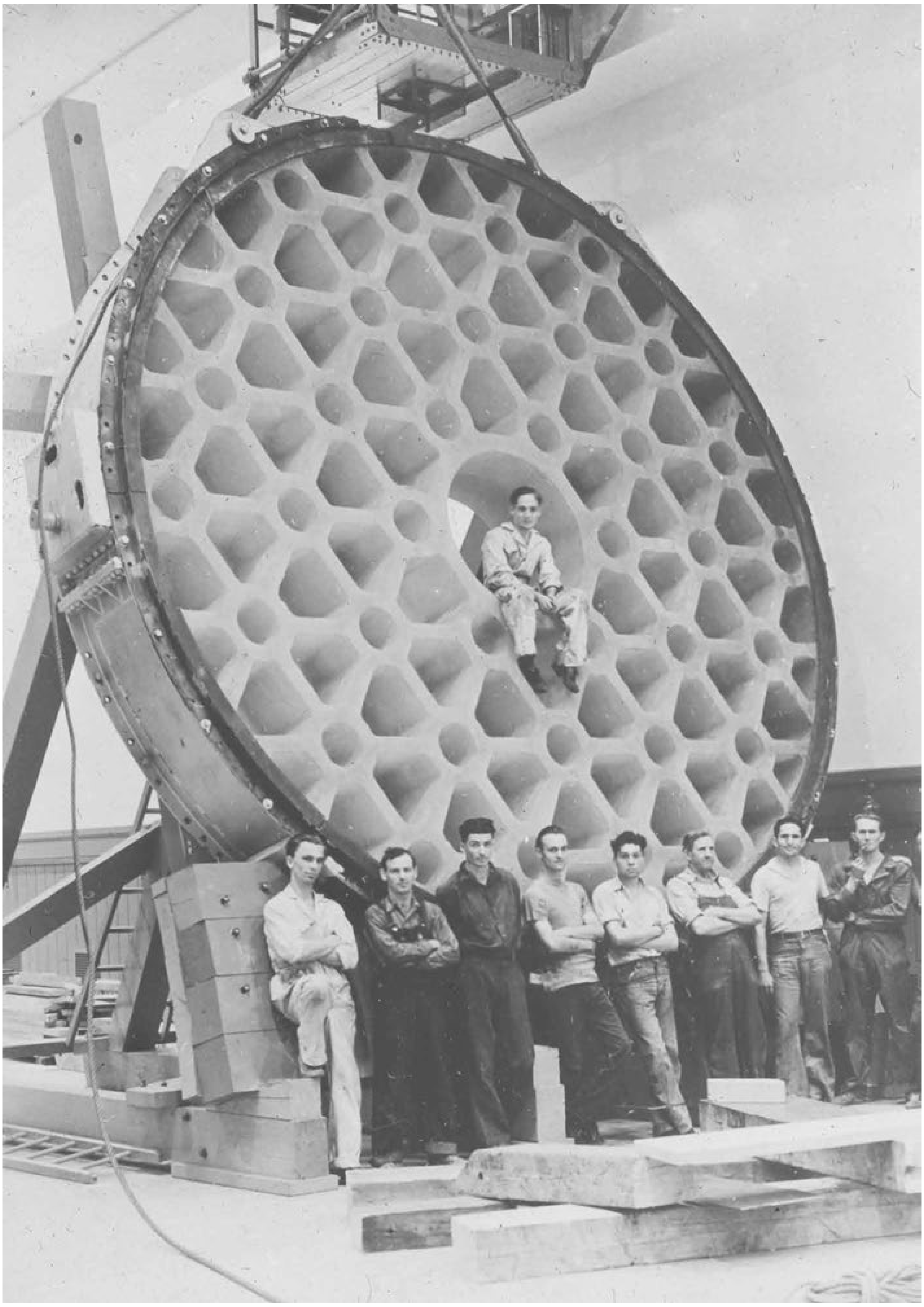


**Figure 7:** Mt. Palomar telescope with 5m glass mirror. Retrieved from (Oikonomopoulou, et al., 2018).

Cast glass evades from these design restrictions by pouring molten glass into moulds. Solid three-dimensional glass units are produced in any shape and cross section achieving in this way non-buckling self-supporting glass-structures. Furthermore, cast glass technology can tolerate many imperfections and fragmentations in the glass bricks. There is a crack prevention between the glass spacing contributing to an advanced fracture toughness (Oikonomopoulou, et al., 2018).

Nonetheless, cast glass is not a very common selected material for load-bearing reasons since there are several discouraging factors which prove it. Firstly, the immense manufacturing costs because of the conscientious and time-absorbing annealing, , have restricted cast glass to only few realised architectural projects. Moreover, scientists and artists manifested the fundamental knowledge in the fields of astronomy, nuclear power and art while in architecture and engineering there was a lack of expertise and many cast glass researches are on early stage (Oikonomopoulou, et al., 2018).

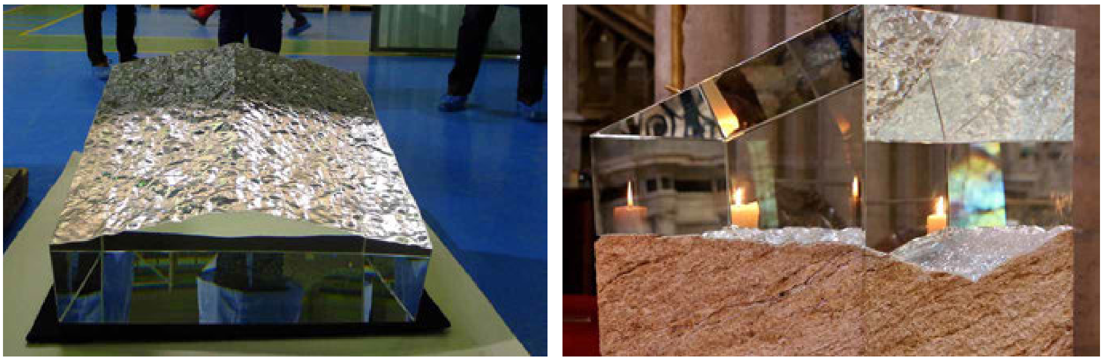


**Figure 8:** Cast glass component of the Denis Altar weighing 1.4 tn. Retrieved from (Oikonomopoulou, et al., 2018).

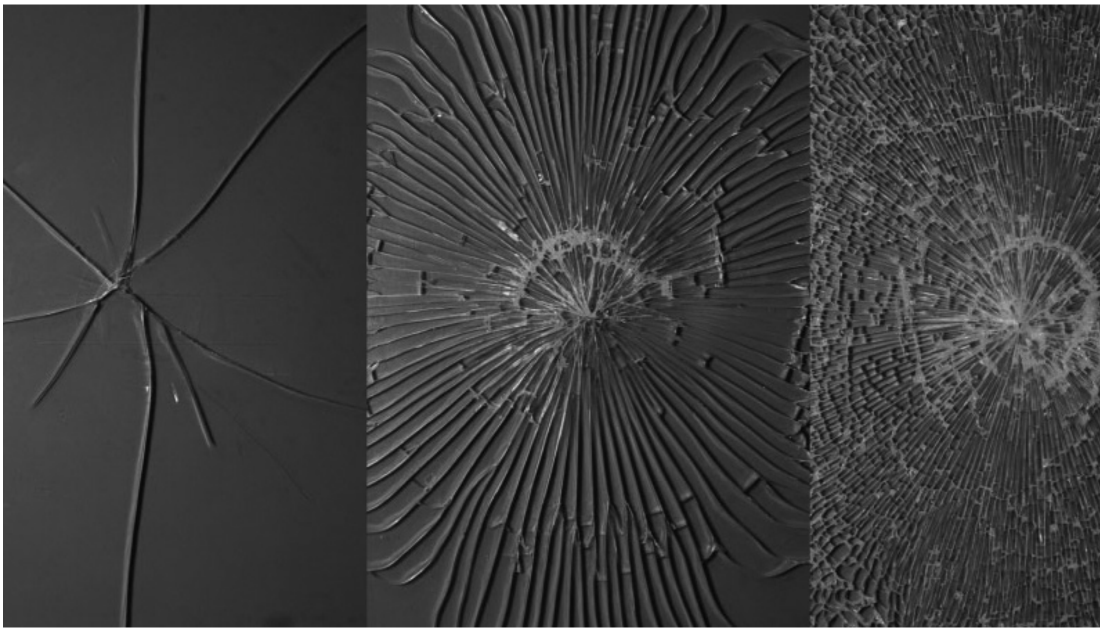


**Figure 9:** From left to right: Annealed glass cracking, heat-strengthened glass cracking (centre) and fully tempered glass cracking. Source: www.semanticscholar.org/paper/Diagnostic-Interpretation-of-Glass-Failure-Overend-Gaetano/6ce1f3696e4b68103a1f988bf08f3d5a8e955768

# 3.1 Glass Types

Glass can be produced following multiple recipes along with different manufacturing methods. Hence, glass can be provided with various properties. Depending on its composition, glass can be found in the market in six main types: : Soda-lime, borosilicate, aluminosilicate, 96% silicate,fused silica glass and lead (Oikonomopoulou, et al., 2018).

On behalf of their ability to be processed under lower melting temperatures and the comparable inexpensive manufacturing costs, borosilicate and soda-lime glass types are favoured in cast glass structures. For this reason, this research will be focused on cast glass components poured by soda-lime and borosilicate glass since these are the most prevalent types of glass in the built environment (Oikonomopoulou, 2019). Table 1 shows the typical chemical composition and the most distinctive applications in soda-lime and borosilicate glass as presented by (Oikonomopoulou, et al., 2018).

| Glass type | Approximate Composition | Observations | Typical applications |
|---|---|---|---|
| Soda-lime (window glass) | 73% $SiO_2$<br>17% $Na_2O$<br>5% CaO<br>4% MgO<br>1% $Al_2O_3$ | Durable. Least expensive type of glass. Poor thermal resistance. Poor resistance to strong alkalis (e.g. wet cement) | Window panes<br>Bottles<br>Façade glass |
| Borosilicate | 80% $SiO_2$<br>13% $B_2O_3$<br>4% $Na_2O$<br>2.3% $Al_2O_3$<br>0.1% $K_2O$ | Good thermal shock and chemical resistance. More expensive than soda-lime and lead glass. | Laboratory glassware<br>Household ovenware<br>Lightbulbs<br>Telescope mirrors |
| Lead silicate | 63% $SiO_2$<br>21% PbO<br>7.6% $Na_2O$<br>6% $K_2O$<br>0.3% CaO<br>0.2% MgO<br>0.2% $B_2O_3$<br>0.6% $Al_2O_3$ | Second least expensive type of glass. Softer glass compared to other types. Easy to cold-work. Poor thermal properties. Good electrical insulating properties. | Artistic ware<br>Neon-sign tubes<br>TV screens (CRT)<br>Absorption of X-rays (when PbO % is high) |
| Aluminosilicate | 57% $SiO_2$<br>20.5% $Al_2O_3$<br>12% MgO<br>1% $Na_2O$<br>5.5% CaO | Very good thermal shock and chemical resistance. High manufacturing cost. | Mobile phone screens<br>Fiber glass<br>High temperature thermometers<br>Combustion tubes |
| Fused-silica | 99.5% $SiO_2$ | Highest thermal shock and chemical resistance. Comparatively high melting point. Difficult to work with. High production cost. | Outer windows on space vehicles<br>Telescope mirrors |
| 96% silica | 96% $SiO_2$<br>3% $B_2O_3$ | Very good thermal shock and chemical resistance. Meticulous manufacturing process and high production cost. | Furnace sight glasses<br>Outer windows on space vehicles |

**Table 1:** Approximate chemical compositions and typical applications of soda-lime and borosilicate glass as retrieved from (Oikonomopoulou, 2019).

Soda-lime glass is the most usual and economical glass type. It presents insufficient resistance to high temperatures and rapid temperature variations. In comparison to soda-lime glass, borosilicate glass presents a lower thermal expansion coefficient which contributes to a comparably greater toughness to thermal shocks and reduced annealing time.

Table 2 provides significant information[1] about the mechanical properties of these two types. In the Atocha Memorial project (Oikonomopoulou, et al., 2017), borosilicate glass was preferred over soda-lime glass due to its thermal expansion coefficient. The final cast glass component produced with considerably less shrinkage during annealing and fewer deviations in size and shape.

In conjunction with the built environment, cast glass components have been widely applied in other fields such as astronomy or art. Lead glass is preferred for cast glass art components since it is softer to polish and grind comparing to soda-lime glass (Thwaites, 2011). A high proportion of lead oxide (min. 20% of the batch) is found in lead glass which is comparably soft while it presents great workability in lower temperatures than soda-lime glass.

Although it is the second least expensive type, lead glass presents low resistance to high operating temperatures and heat shocks rendering it vulnerable to scratching. Fused silica glass, aluminosilicate glass and 96% silica glass can withstand better thermal shocks and operations in high temperatures than borosilicate glass. Moreover, their fabrication requires high melting temperatures, leading to significantly increased manufacturing costs. For this reason, their applications are very specialized such as mobile screens (aluminosilicate) and spaceship windshields (fused silica) (Oikonomopoulou, et al., 2018).

| Glass type | Mean melting Point at 10 Pa.** [°C] | Soft. Point [°C] | Anneal. Point [°C] | Strain Point [°C] | Density kg/m³ | Coeff of Expan. 0°C - 300°C 10-6 / °C | Young's Modulus GPa |
|---|---|---|---|---|---|---|---|
| Soda-lime (window glass) | 1350 - 1400 | 730 | 548 | 505 | 2460 | 8.5 | 69 |
| Borosilicate | 1450-1550 | 780 | 525 | 480 | 2230 | 3.4 | 63 |

* 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 different recipes resulting into different properties.

**Table 2:** Approximate properties of soda-lime and borosilicate glass as retrieved from (Oikonomopoulou, et al., 2018).

[1] These values are given as basic guidelines of the differences between soda-lime and borosilicate glass. In practice, there is a wide range of recipes for each glass type resulting in different properties.

## 3.2 Casting Process

This section provides significant information about the casting process. The findings of this research will set the boundaries for the design criteria followed by the prototyping process, since annealing time and avoidance of thermal stresses are important factors in this procedure.

The casting process can be classified into primary and secondary casting depending on the initial state of the glass. In primary casting, glass is generated from its raw ingredients into a hot liquid substance, while in secondary casting, solid glass pieces are re-heated until it can flow smoothly and be produced in any shape (Cummings, 2002). Accordingly, lower operating temperatures are required in the secondary process compared to the primary casting process (Oikonomopoulou, et al., 2018).

In each of the aforementioned processes there is one main process. Hot-forming (melt-quenching) is the main process for primary casting, whereas kiln-casting for secondary. Besides the starting state of glass, the two processes have another fundamental difference, the specific infrastructure. In kiln-casting, a single kiln is used to melt the already shaped glass into the moulds for the later cooling process (Bristogianni, et al., 2017).  In contrast, hot-forming process employs two moulds, one for the pouring and the second one for annealing (Oikonomopoulou, et al., 2018).

**Figure 10:** Left: Hot-forming as primary casting process. Right: Kiln-casting as secondary casting process. Retrieved from (Oikonomopoulou, 2019).

The annealing procedure in both methods is similar. Since the glass is molten enough, the mould is filled, and then the glass is expeditiously cooled to a few degrees below its softening point (Oikonomopoulou, et al., 2018). This rapid annealing phase prevents the glass from any crystal molecular placement of the melt. At this point, the glass's low viscosity permits any caused thermal stress to be decreased into a negligible value directly (Shelby, 2005). During this phase, the cooling process of the component starts, targeting to remove any possible differential strain and restraining the propagation of internal residual stresses during further cooling. The cast glass element should be retained for sufficient time at the annealing point to eliminate any existing strains and then annealed at an adequately slow pace in order to exclude the creation of any residual stresses when the equilibrium is reached in the glass temperature (Shand, Armistead, 1958).

During the annealing time, the temperature fluctuations between the warmest and the coolest parts of the glass, its thermal expansion coefficient, and the thickness of the cross section, define significantly the magnitude of the resulting internal stresses (Shand, Armistead, 1958). For this reason, theoretically, round and ellipsoid edges are favoured over pointy and sharp edges, contributing in this way to less stress concentrations due to heterogeneous shrinkage (Oikonomopoulou, et al., 2018). Moreover, in practice, the desired temperature difference is also determined by miscellaneous factors. Such factors are, the exposed sides to cooling, the technical features of the furnace, the component's shape and mass distribution or the quantity of other thermal masses (Watson, 1999).

Table 3 outlines some of characteristics of the largest cast glass components ever made. This provides us with a deep comprehension concerning the potential and the technical restrictions of casting glass elements of such scale. The annealing time grows exponentially along with the dimensions if the object. Hence, the larger the object, the longer the annealing time and as a result the manufacturing costs.

Subsequently, according to the aforementioned information, the casting process will influence significantly the design criteria of the glass component, affecting the final shape of the cast glass component.

| Application | unit | Hale Telescope Mirror | Giant Magellan Telescope mirror | Nuclear Glass Blocks | Dennis Altar glass slab |
|---|---|---|---|---|---|
| **Dimensions** | mm | Ø 5080 | Ø 8417 | 1400x1600 | 1420x1420 |
| **Thickness** | mm | 660 (when cast) | Max:894<br>Min:437 | 400 | 280 |
| **Geometry** | | Honeycomb disc | Honeycomb disc | Rectangular massive block | Rectangular massive block |
| **Glass type** | | Pyrex® | E6 borosilicate glass | Corning® RSG52 (70 PbO%) | Corning® 7506 (alkali-borosilicate) |
| **Density** | g/cm³ | 2.23 | 2.18 | 5.22 | 2.29 |
| **Component weight** | t | 20<br>(14.5 after polishing) | 16 | 4.5 | 1.4 |
| $T_{batch\ melt}$ | C° | 1482 | 1180 | 1500 | 1495 |
| **Exp. Coeff.** | 1/°C | $32.5x10^{-7}$ | $28x10^{-7}$ | $82.8x10^{-7}$ | $51.5x10^{-7}$ |
| **Mould type** | | Steel mould with silica firebrick cores bolted with steel bolts | Base: SIC baselites lined with aluminosilicate refractory fiberboard<br>Cores: Carborundum Carbofrax SiC | Adjustable steel mould with refractory paper liner | Steel mould with refractory paper liner |
| **Casting method** | | Hot-pouring<br>Annealing within mould | Spin-(kiln) Casting<br>Annealing within mould | Hot-pouring within kiln<br>Annealing within mould | Hot-pouring<br>Reheating above softening point to imprint pattern |
| **Annealing time** | months | ~10 | ~3 | ~2 | ~1 (total production time 3 months) |
| **Post-processing** | | Grinding and polishing (10 years) | Grinding and polishing (3 years) | Slicing to size and polishing | Polishing |

**Table 3:** General features and characteristics of the largest cast glass elements made. Data retrieved from (Oikonomopoulou, 2019).

# 3.3 Moulds

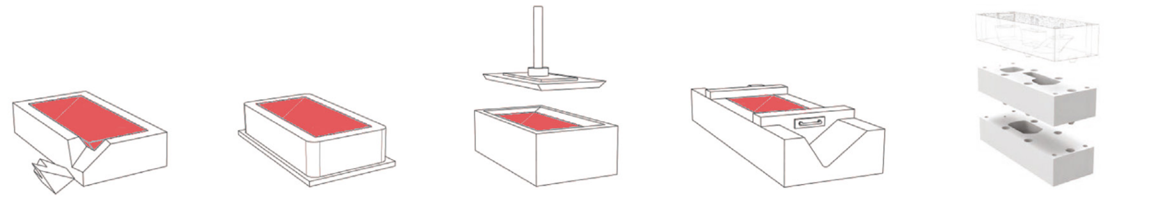



**Figure 11:** Illustration of the most common mould types (Oikonomopoulou, et al., 2018). The last type is a new type of mould proposed by (Bhatia, 2019).

The level of accuracy in the final component is essentially dependent on the choice of the mould. (Figure 11) presents the most common types for moulding cast glass components while a new type with 3d printed sand mould presented resently by (Bhatia, 2019). The production volume, the desired level of efficiency, the cost and the time determine significantly the selection of the mould (Oikonomopoulou, et al., 2018).

More specifically, there are two types of moulds, disposable and permanent and their selection depends on, whether it will be a series production or not. Therefore, disposable moulds are favoured over permanent for a single component, because they render a more economical alternative than the permanent. Generally, the types of the moulds vary from low-cost silica-plaster moulds for casting below 1000 ° C to milled alumina-silica fiber ceramics. For this reason, the choice between these specific types affect the degree of achieved accuracy and the maximum melting temperature. Moulding with the both types though, will result to a translucent, rough skin that requires post-processing for achieving transparency. Due to brittleness of these moulds, kiln-casting is preferred over quenching. In contrary, for a production series, permanent moulds from steel or graphite combining with melt-quenching process are chosen over disposable since this solution is more time-efficient. A high level of accuracy can be accomplished in case of pressed-moulds while graphite moulds offer a great degree of surface detailing (Oikonomopoulou, et al., 2018).

To prevent additional imperfections, the mould should not be extracted during the annealing time, a potential when the mould is from steel. Hence, for the easy release of the glass unit, the presence of a coating attached to the steel mould is indispensable. The permanent moulds provide a wide shape adjustability, yet the degree of efficiency might be compromised. In general, the final surface is glossy and transparent while, the least post-processing is necessary considering that the moulds have been adequately heated before casting (Oikonomopoulou, et al., 2018).

Finally, as far as concerned the cost-influencing aspect, the complex geometries and the customised production could increase the price of graphite and steel moulds. When a complex project with numerous different glass units occurs, the need of a novel solution appears to be necessary. Therefore, 3D-printed sand moulds render an innovative affordable solution forcustomized glass elements of high precision. Arup and 3Dealise have already produced 3D-printed sand moulds for the casting of individually developed and complex steel nodes (Niehe, 2017). Furthermore, 3D-printers of sand, for instance the ones employed by 3Dealise and ExOne, are already used for the development of sand-casting moulds for metal elements (steel, aluminium, magnesium and iron) of excellent precision and complex shapes (ExOne, 2019). On research development, excessive explorations have been conducted by (Bhatia, 2019; Damen, 2019) promise a high accuracy for casting customised glass units and/or solid glass elements of complex forms (e.g. topologically optimized) in an affordable cost.

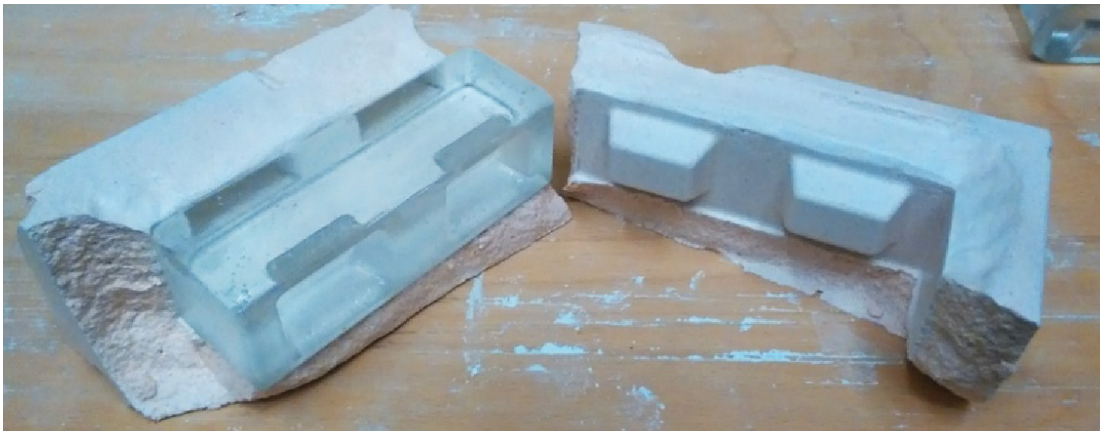


**Figure 12:** Disposable mould. Retrieved from (Oikonomopoulou F. et al., 2018).

**Figure 13:** Permanent open steel moulds of high precision designed for the manufacturing of the glass bricks for the Crystal Houses. Retrieved from (Oikonomoulou F. et al., 2018).

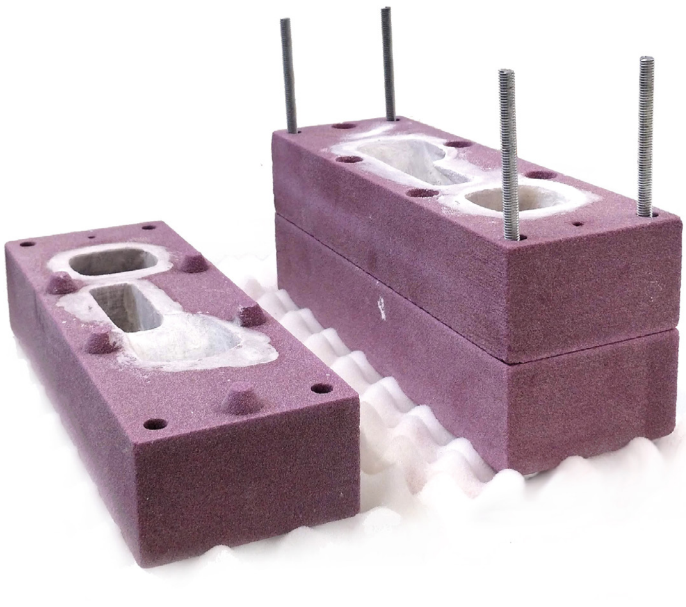


**Figure 14:** Crystal cast coated sand mould. Retrieved from (Bhatia, 2019).

# 3.4 Shaping Potential

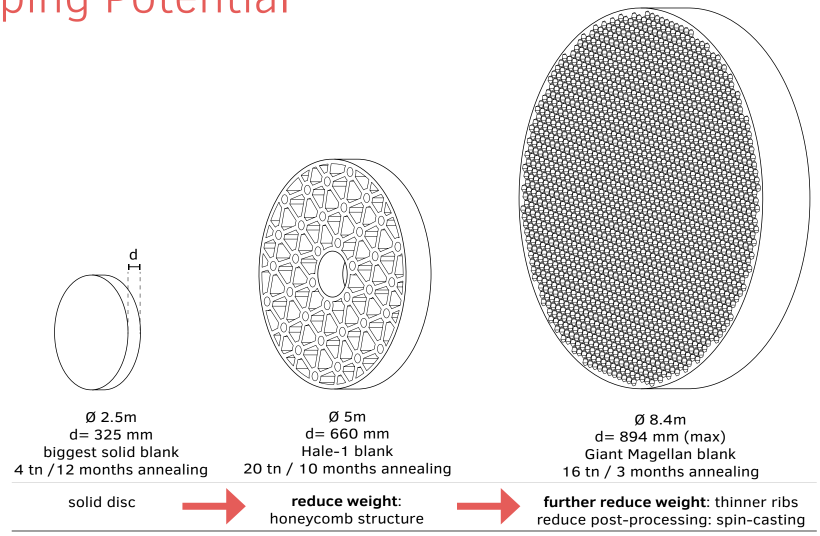



**Figure 15:** Evolution of the cast glass telescope mirrors in dimensions and annealing times due to smart geometry and enhanced manufacturing process. Retrieved from (Oikonomopoulou,2019).

Cast glass presents a great shaping potential. Figure 15 illustrates the shape and the size evolution occurred in cast glass telescope mirrors. In comparison with the solid disc, the improved shape with the honeycomb structure and the thin ribs in Hale-1 blank and Giant Magellan blank mirrors respectively, revolutionized both in the annealing time and in the shaping potential.

By pouring glass into moulds, solid three-dimensional units can escape from any design limitations, and be produced in any shape and cross section. Figure 16 illustrates graphically the shape dynamism and evolution of cast glass elements, meeting the highest expectations of any designer. Rectangular bricks have been employed in several projects such as the Crystal Houses in Amsterdam or in the Optical House, in Hiroshima. In the Atocha Memorial, customized cast glass units with curved edges were produced to create a cylindrical shape monument. Cast glass units prove their shaping potential in the interlocking mechanisms where different geometries and especially organic or osteomorphic shapes have been produced successfully (Oikonomopoulou, et al., 2018). (Damen, 2019) introduced a cast glass grid shell node topologically optimised to reduce annealing time while it is structurally efficient. Employing sand moulds (Bhatia, 2019), the final component presents an exceptional result proving the shaping potential of the cast glass to the fullest.

Nonetheless, to achieve a great degree of accuracy, special attention is required during casting process and annealing time, whereas the choice of the most appropriate mould is crucial.

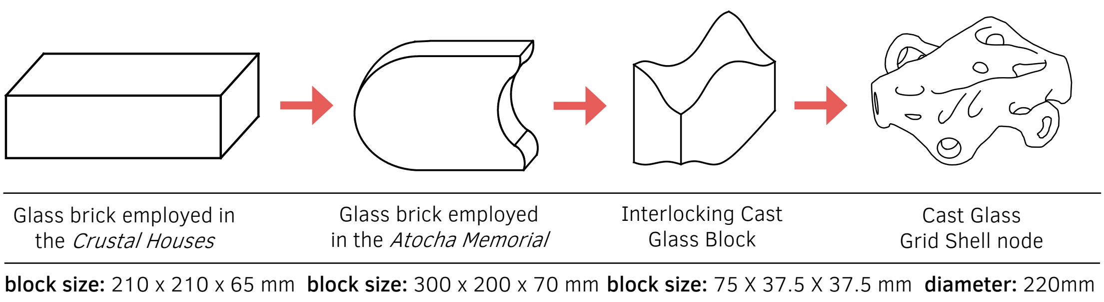



**Figure 16:** Shaping potential. Own illustration.

# 3.5 Cast Glass as a Structural Material

Glass has proven its potential to be a very reliable structural element in many applications which involve beams, columns, floor slabs, bridges. Moreover, due to tremendous time-consuming annealing time and the lack of fundamental knowledge, solid cast glass units have been applied as structural elements to only few realized projects. The current structural systems in cast glass technology employ cast glass units in the shape and size range of typical masonry bricks, assembled on site.

These envelopes have been accomplished either with a supportive substructure or a rigid structural adhesive. Nonetheless, a third structural system, which is on an early research stage, employ interlocking cast glass units and promises a structure with the least use if any of metal supporting structure. At this moment, it should be mentioned that hollow glass blocks or solid cast glass units that are non-load-bearing-elements and have been widely applied as facades elements are out of the scope in this review (Oikonomopoulou, et al., 2018).

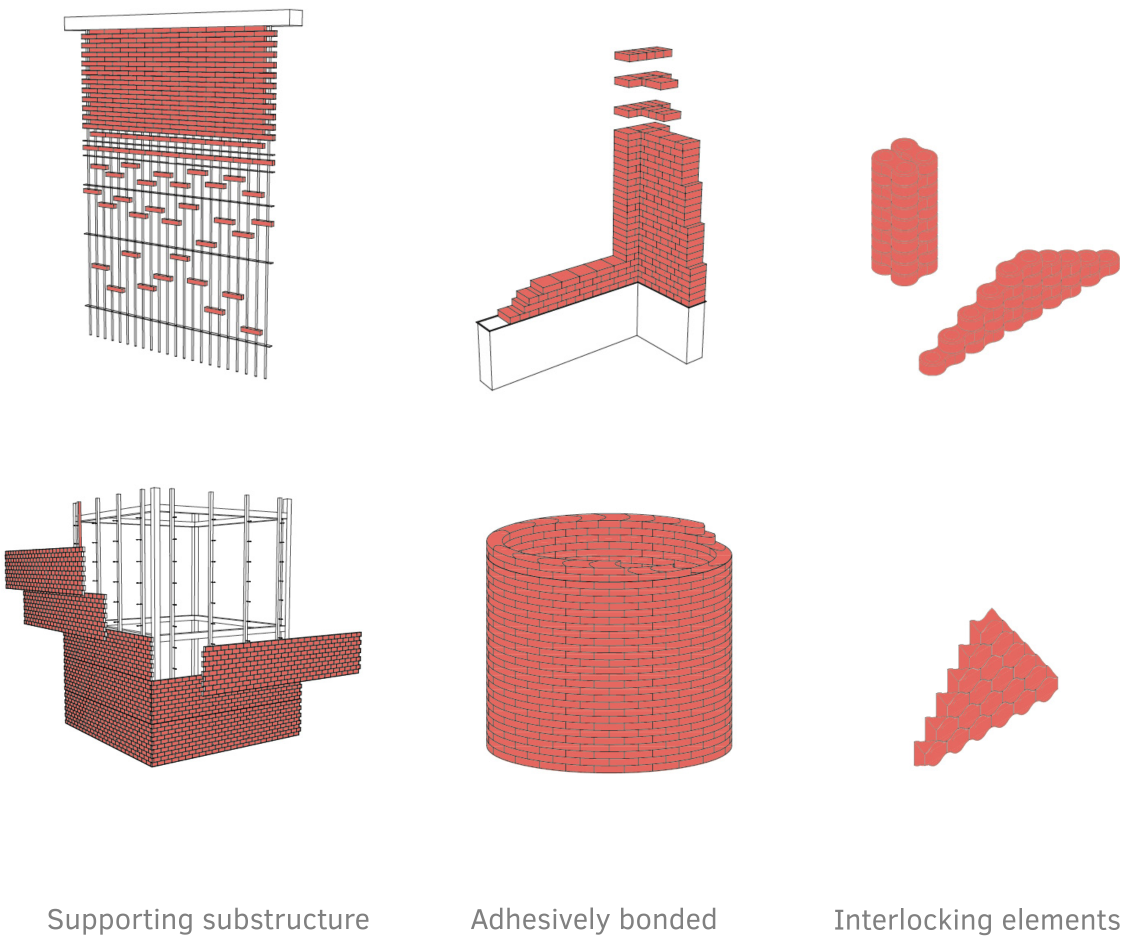



**Figure 17:** Overview of the existent structural systems employing cast glass units. Illustrations retrieved from (Oikonomopoulou,2019). Edited by author.

## 3.5.1 Application of cast glass elements in architectural examples: overview of current structural systems.

• Additional Supportive Substructure

In this structural concept, the tensile forces are carried by a supportive metal substructure which promises the required resistance to lateral forces and buckling, while the solid glass elements act mostly under compression. The most representative projects are the Crown Fountain and the Optical House. The façade of the Optical House project, dimensions 8.6x8.6 m and is consisted of 6000 solid cast glass bricks. Each cast glass unit sizes 50x50x235 mm and is manufactured from borosilicate glass because of its optical quality in comparison to soda-lime glass (Oikonomopoulou, et al., 2018). 75 stainless steel rods develop a pre-tensioned vertical net which is suspended from a steel beam cast in reinforced concrete (Hiroshi, 2013). The supportive substructure which is completed with two supplementary steel fins, is perfectly resistant to lateral forces and wind load, allowing the glass blocks to carry only their own weight. The cast glass elements were cast in a special way so stainless-steel flat bars (40x4mm) could be placed on the glass unit with100mm space between them. In specific, these steel flat bars connect the vertical steel cables and diminish the lateral stresses resulting on the glass bricks. The final result employs a façade of great slenderness accompanied by an adhesive free structure (Oikonomopoulou, et al., 2018).

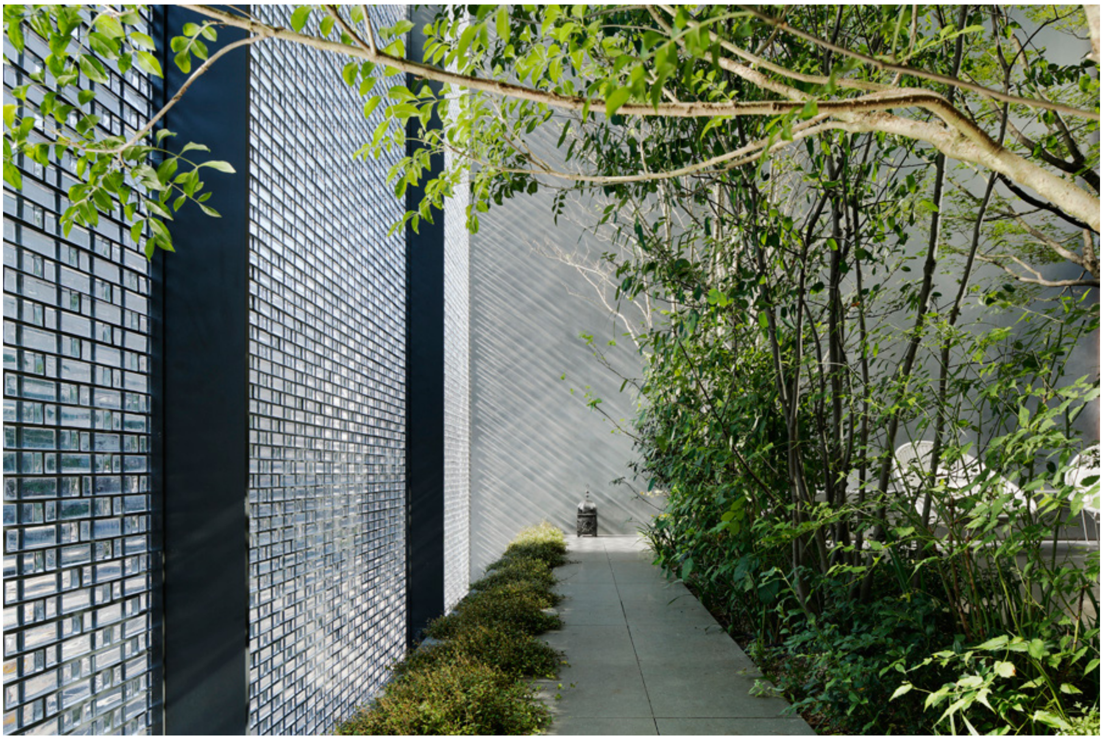


**Figure 18:** The glass façade in the Optical House. Source: NACASA & PARTNERS INC.

The Crown Fountain tower is the second project that relies on an additional supportive substructure. The difference in this system is subjected to the fact that the 11.250 glass units are first assembled on the substructure and then anchored to a stainless-steel internal mesh. The total envelope in each tower is 12.5x7x4.9m. Both the vertical and lateral forces are directed through this combined system. (Oikonomopoulou, et al., 2018). Every panel is consisted of 250 pre-assembled glass bricks with dimensions of 127x254x51mm, made by low-iron soda-lime glass (Yang, 2019). The glass bricks were manufactured with the melt-quenching casting process and an excellent precision steel mould, resulting with units that required to be polished only on the one face. A steel T-profile frame which is entrenched to the base transfers the forces through a zigzag pattern. The lateral reliability of the building is strengthened by Ø13mm cables attached to the structure and corner brackets in triangular shape (Oikonomopoulou, et al., 2018).

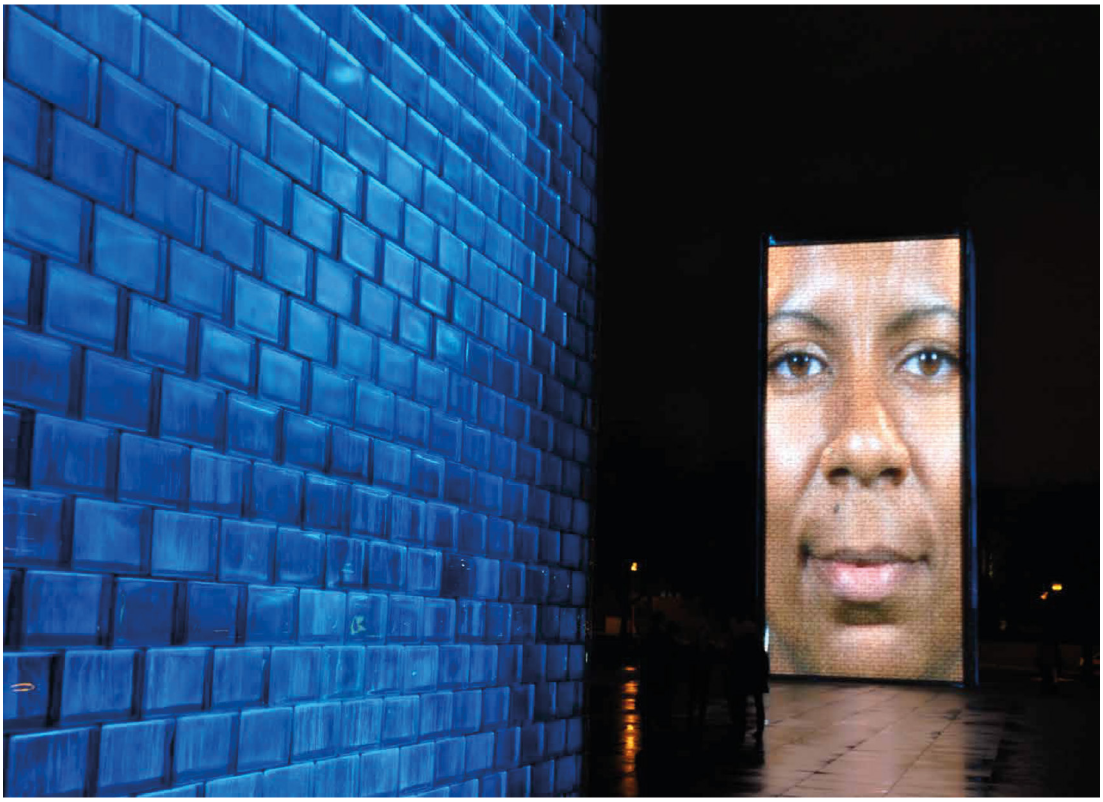


**Figure 19:** The two Crown Fountain towers at night. Retrieved from (Oikonomopoulou,2019)

## • Adhesively bonded blocks

Tremendous transparency in cast glass structures can emerge by bonding the glass bricks with an achromatic rigid structural adhesive. Hence, the connections in this system are permanently impervious, compatible with glass and present low-intensity stresses. Undoubtedly, the mechanical properties of the selected adhesive should be equivalent to glass's resulting to a single rigid structural element, where the loads are distributed homogeneously. For this reason, structural glues, such as acrylates or epoxies are crucial to guarantee the required bond firmness. Two representative examples which employ adhesively bonded cast glass components are the Crystal Houses and the Atocha Memorial (Oikonomopoulou, et al., 2018).

The Crystal Houses in Amsterdam, constitutes an emblematic example of adhesively bonded cast glass elements, contributing to a highly transparent glass façade, a reproduction of a typical 19th century masonry brick façade. The total envelope is 10x12 m and constitutes of 6500 solid glass units, manufactured in three different sizes, while enormous glass elements were cast to replicate the typical timber door and window frames.

Elevating to the top, terracotta bricks blend with the glass ones, converting the glass façade to a typical masonry one (Oikonomopoulou, et al., 2018).

The realisation of the Crystal Houses was a very challenging undertaking, since the architect's ambition for non-prevented transparency, resulted to the construction of an exclusively self-supporting adhesively glass block system (Oikonomopoulou, et al., 2018). For this reason, several structural tests were carried out proving that the ideal thickness for an optimal bond is between 0.2-0.3 mm. Delo Photobond 4468 was selected after meticulous testing experiments between a wide range of adhesives. It is a colorless, UV-curing acrylate which is optimized for creating high strength bonding between the glass/glass or glass/metal components (Oikonomopoulou, et al., 2017).  Additionally, it is designed with great mechanical properties as it demonstates decent coompressive behaviour, while it is highly resistant to shear stresses and humidity.


**Figure 20:** The Crystal Houses Facade in Amsterdam by MVRDV. Retrieved from (Oikonomopoulou, et al., 2018).

Moreover, tests in four architectural mock-ups proved that tolerances above ±0.25mm would lead to an unequal spread of the glue that could affect the structural efficiency of the facade. The low viscocity of the selected adhesive created a uniform bonding at the horizontal direction while the left open vertical joints granted for thermal expansion (Oikonomopoulou, et al., 2018).Undoubtely, the Crystal Houses façade is a project of tremendous accuracy and precision. The demanded ±0.25mm tolerance affected the final glass recipe and the type of mould as well. A combination of soda-lime glass and open high precision moulds were favoured to balance the production costs since the glass's surface would expect a demanding post-process during the bonding procedure. The required precision on the bonding surfaces attained after CNC polish leading to an uniform load distribution with a great optical result. A custom-made polypropylene template was designed to control the quantity, the flow and the spread of the glue (Oikonomopoulou, et al., 2018).However, in the Atocha Memorial, 15600 components from borosilicate glass gloued together in a 2mm bond from a transparent UV-curing adhesive.

In contrary to the Crystal Houses, the glass blocks in the Atocha Memorial employed a curved shape, convex on one side and concave on the other resulting to a stiff shell structure without the adoption of an additional substructure (Oikonomopoulou, et al., 2018). Excessive temperature variations occurred on the glass blocks, leading to great surface tensions. Due to low thermal expansion coefficient borosilicate glass was favoured over soda-lime, while high precision press steel moulds promised the required homogeneity sparing the necessity of post-processing (Goppert, et al., 2008).

The selected adhesive, an acrylic from Delo Photobond family, was placed on each brick by employing an aluminum plate to achieve the most accurate result in terms of size and position (Yang, 2019). Similar to the Crystal Houses, several physical tests carried out to certify the structural efficiency of the adhesive-glass structure (Oikonomopoulou, et al., 2018).

Both in the Atocha Memorial and in the Crystal Houses, a special UV-filtering tent was set up in the construction site to protect against solar radiation, dust and severe weather conditions, while humidity and temperature rates were controlled as well (Oikonomopoulou, et al., 2018).

**Figure 21:** The Atocha Memorial. Retrieved from (Oikonomopoulou, 2019).

• Interlocking elements

Interlocking units is the third so far structural system which employs cast glass blocks. In many research projects the initial idea behind this system was inspired from “Lego” components (Barou, et al., 2016). This system, currently on research, examines the possibility of creating full-glass structures acting mainly under compression such as columns, walls and arches, from interlocking cast glass elements. The required stiffness is accomplished from compression produced by the structure’s dead-load in combination with the interlocking geometry. The interlocking elements, mitigate the lateral loads, resulting to a metal-substructure-free structure. Moreover, a dry, colourless interlayer between the glass blocks is suggested, such as polyurethane rubber (PU) or Polyvinyl Chloride (PVC). In this way, the interlayer avoids the stress concentrations because of the glass to glass contact, while it prevents from any impending dimensional tolerances in the blocks’ size. Up to now, many geometries, dry interlayers and various structural purposes have been extended tested and experimented. Among them, a dry-assembled arched glass masonry employing interlocking elements proposed by (Aurik, 2017; Aurik, et al., 2018; Snijder, et al., 2016; while (Akerboom, 2016) explored the creation of a glass column with an optimised cross section, manufactured from solid and hollow interlocking cast elements. Numerous studies (Barou, et al., 2016; Frigo, 2017; Jacobs, 2017; Oikonomopoulou et al. 2018) employ interlocking glass elements with curved shapes, such as osteomorphic units, and uniform mass distribution, considering the casting process of the interlocking elements and the desired shear capacity.

Lastly, the arduous calculation and simulation processes led to limited physical experiments and no sufficient statistical data can be derived yet. Hence, interlocking cast glass elements can be an auspicious solution for future cast glass structures and more specifically, elements in more organic shapes without pointy edges to avoid the residual stress concentrations (Oikonomopoulou, et al., 2018).

**Figure 22:** 3 mm thick, cast interlayer from PU70 prototype (Oikonomopoulou et al. 2018).

## 3.5.2 Assessment of the systems & Qualitative Comparison

(Yang, 2019) in his master thesis assessed the three structural systems on behalf of the references projects in terms of transparency, connection methods, tolerance and precision. Concluding from the literature review, Table 4 illustrates a qualitative comparison, adding to the aforementioned criteria, the ease of assembly, reversibility and predictability of structural performance.

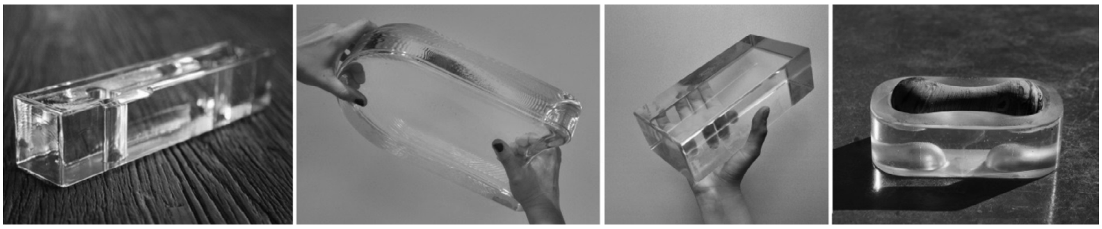


**Figure 23:** From left to right: Cast glass bricks employed in the Optical House, Atocha Memorial, Crystal Houses and Interlocking research. Retrieved from (Oikonomopoulou, et al., 2018). Edited by author.

At present, there are three structural systems employing cast glass components contributing to self-supporting system:

1. an additional supportive substructure
2. a rigid diaphanous adhesive
3. interlocking cast glass components

The first system constitutes a compromise to the overall transparency[2] while the second solution constitutes an irreversible and hardly assembled solution, while the third system promises to mitigate the constraints imposed by both previous methods. Moreover, the interlocking cast units is a solution that is hard to be simulated and get accurate structural results. Nonetheless two critical aspects that affect the structural performance is the size and the shape. Size plays an important role during the cooling time, since annealing procedure lasts longer in a bigger cast glass brick comparing to a smaller one (Oikonomopoulou, et al., 2018).

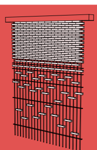
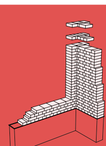
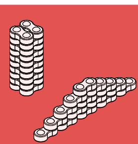
| Criteria / Systems |  Additional Supportive Substructure |  Adhesively Bonded Blocks |  Interlocking cast Glass untis |
|---|---|---|---|
| Buildability | + | - | ++ |
| Transparency | - | ++ | ++ |
| Reversibility | ++ | - | ++ |
| Predictability Of Structural Performance | ++ | + | -still on research stage- |

**Table 4:** Qualitative comparison of the existent structural systems. ++ Stands for very high.

[2] Transparency is a critical aspect. The Optical House project is a private dwelling and, in this case, translucency was preferred because of privacy.

## 3.6 Case Study - Optical House

Scope of this research is to investigate the potential of embedding a connection in cast glass components, targeting to a reversible and structural efficient structural system. This research will be conducted while the findings will simultaneously be applied on an existent project, with realistic load-case scenarios. The Optical House in Japan has been selected as a case study. The results of this proposal will reciprocate to the site and the material requirements of the case study.

| | |
|---|---|
| **Location:** | Hiroshima, Japan |
| **Envelope dimensions [m]:** | 8.6x8.6 |
| **Geometry:** | Flat envelope |
| **Structural System:** | Supportive substructure |
| **Number of blocks:** | 6000 |
| **Size of blocks [mm]:** | 235x50x50 |
| **Number of different blocks:** | 1 |
| **Weight of blocks [kg]:** | 2.2 |
| **Total Weight [t]:** | 13 |
| **Type of glass:** | Borosilicate |

**Figure 24:** Optical House, glass facade. Source: NACASA & PARTNERS INC.

**Figure 25:** "A garden enclosed in 6000 bricks". Scattering effect of the glass façade. Source: NACASA & PARTNERS INC.

In 2012, the Optical House residence presented in Hiroshima, Japan by Hiroshi Nakamura & NAP architects. It is a three-storey dwelling with its east side adjacent to the main road. The ground floor is used for services purposes and the upper storeys for a living. The glass brick façade is developed in the east side of the building where a two-level height patio exists. The garden is accessible from the first floor where the living room is but not from the second floor. In the garden, trees of two-levels height were planted as the original architectural plan determined (Yang, 2019).

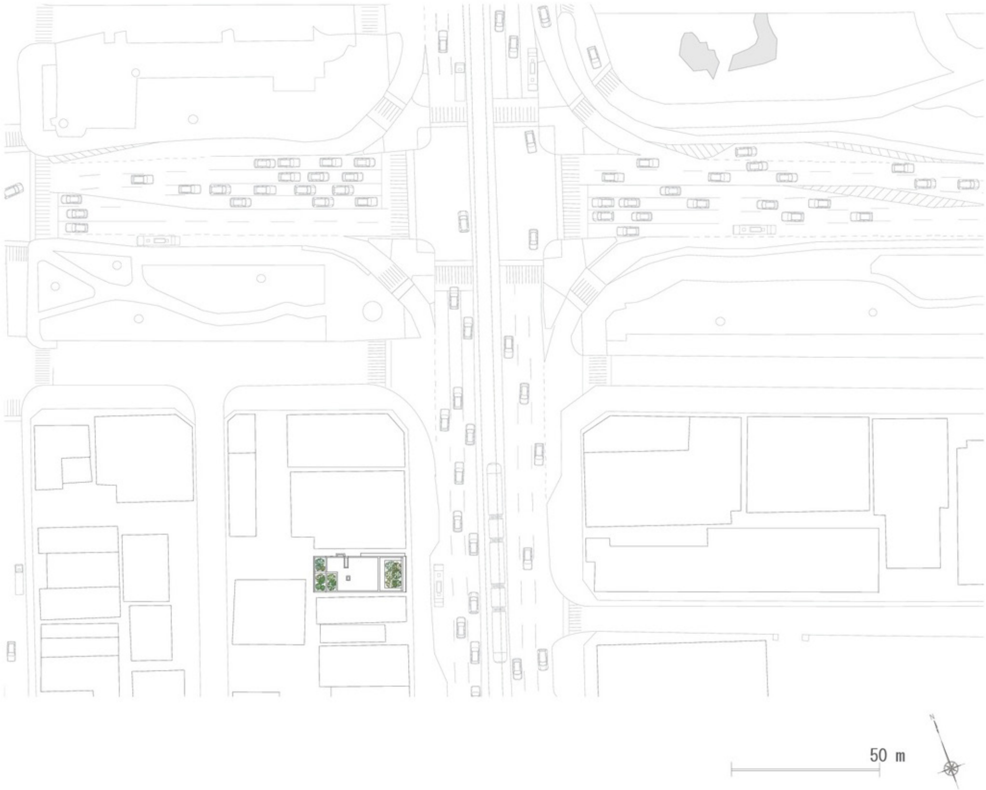



**Figure 26:** General overview of the site. Source: HIROSHI NAKAMURA & NAP.

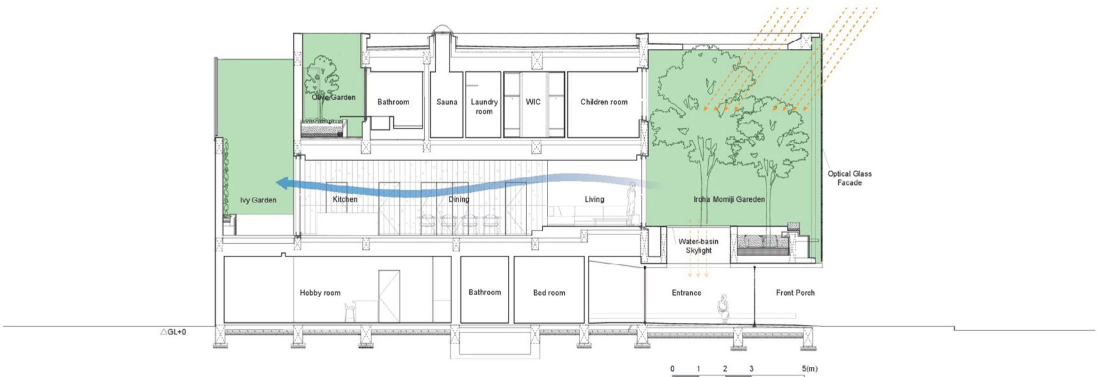



**Figure 27:** Section. Source: https://www.archdaily.com/885674/optical-glass-house-hiroshi-nakamura-and-nap?ad_medium=gallery

“A garden enclosed in 6000 bricks”.

There is a half meter distance between the façade and the garden which renders the façade unapproachable for everyday use. Moreover, for maintenance purposes, a special podium has been constructed slightly below the garden. The glass façade is completely exposed to the exterior since the garden is open on the top (Yang, 2019).

As it is already described in previous section, the Optical House is one of the projects where the tensile forces are carried by an additional substructure. The façade is divided into three segments by two robust mullions. The glass bricks are aligned in numerous horizontal steel plates which are connected to these mullions. Moreover, multiple steel rods are connected to the horizontal bars. The out-of-plane loads are distributed through the horizontal plates while the vertical rods carry the tensile forces (Yang, 2019).

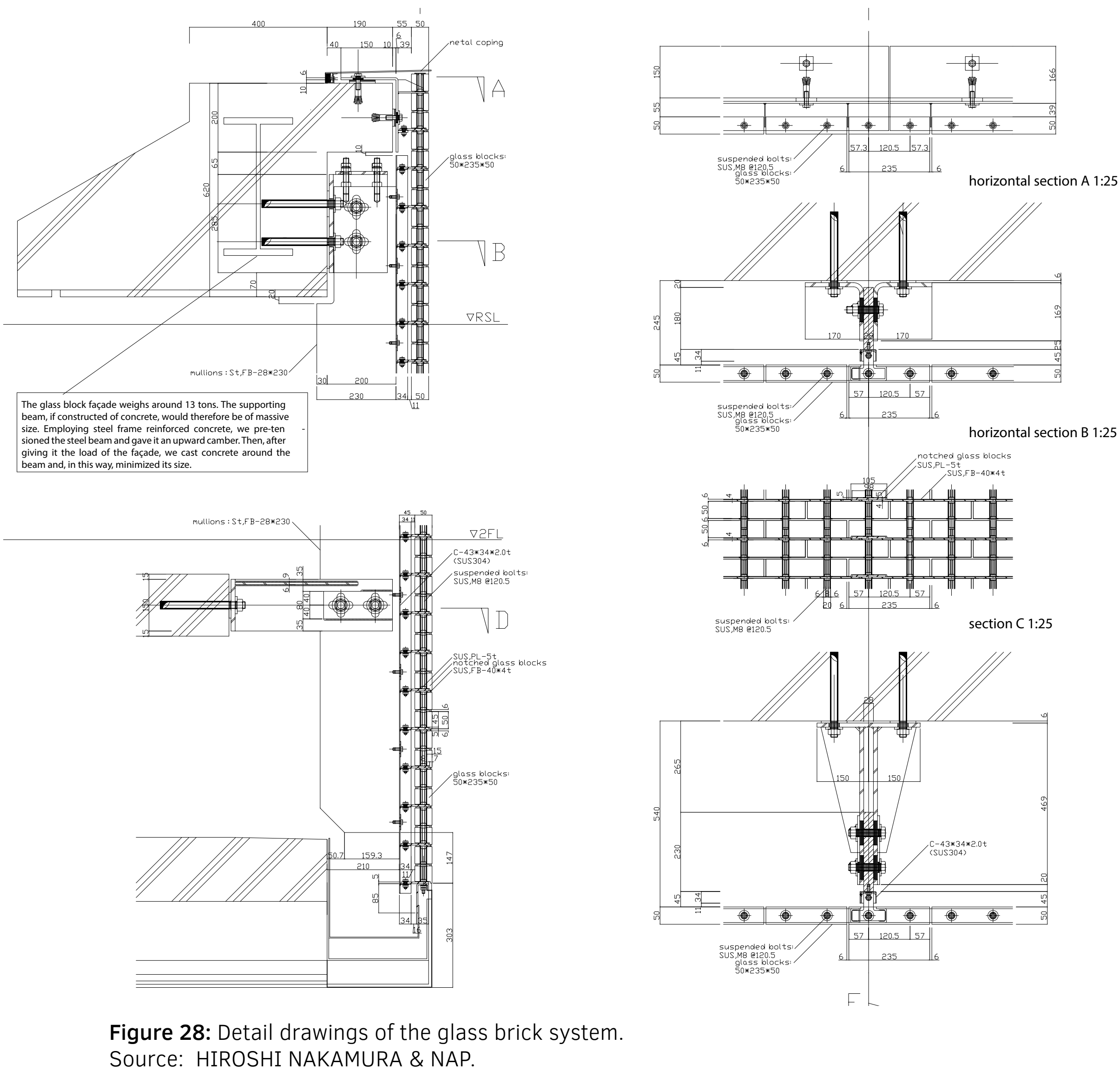



**Figure 28:** Detail drawings of the glass brick system.
Source:  HIROSHI NAKAMURA & NAP.

**Figure 29:** The glass brick facade in the Optical House. Source: HIROSHI NAKAMURA & NAP.

The 75 stainless steel rods promise the required structural efficiency mostly in tension. The glass bricks carry their own dead load, thus do not perform any structural role, since the mechanical performance of the glass unit is partially ambiguous. From a technical aspect, the tolerance is partially guaranteed since, several deviations occurred between the steel structure and the cast glass brick. As a result of the supportive substructure, the overall transparency of the facade is compromised. Moreover, in this case, the initial architectural concept was a glass façade which attributes to a translucent and a scattering effect (Yang, 2019).

Concluding, compromised transparency and required structural efficiency without the need of any additional supportive substructure, were the trigger points to select this project as the case study in this research. Even if in this project transparency is not the key issue, in other projects great transparent results are highly demanded. Furthermore, this case study presents challenging load-cases and risk scenarios, since Japan is a country where severe earthquakes and strong winds are a daily issue. This research targets to a new easy-assembly structural system which will get rid of the supportive substructure providing a sufficient structural performance while it will balance the compromised transparency.

**Figure 30:** Cast glass brick of the Optical House. Source: HIROSHI NAKAMURA & NAP.

**Figure 31:** Construction of the glass facade. Source: HIROSHI NAKAMURA & NAP.

**Figure 32:** Supportive substructure in cast glass structures in the Optical House.
Source: HIROSHI NAKAMURA & NAP.

## 3.7 Conclusions

Overall, cast glass has proven significantly its potential for constructing structural efficient glass structures meeting the highest of expectations in each project. The most prevalent glass types in the built environment are the soda-lime glass and the borosilicate since they are able to be processed under lower comparably melting temperatures, while their application leads to inexpensive manufacturing costs. Looking back to the largest cast glass components ever made, provides us with a deep comprehension concerning the potential and the technical restrictions of casting glass elements of big scale. The annealing time grows exponentially along with the dimensions of the object. Hence, the larger the object, the longer the annealing time and as a result the manufacturing costs. Moreover, the choice of the mould type mainly depends on whether it will be a mass production or not. Consequently, according to the literature review, the glass type, the casting process and the mould type are very crucial since they influence significantly the production costs, the annealing process, the stress concentrations and the shape of the element eventually ad they will be taken seriously into consideration in this research.

Furthermore, due to meticulous cooling time, the high labour costs and the on-going research, cast glass structural systems can be detected in architecture in few, yet identical realised projects. These projects have been realised either with an additional supportive substructure or with adhesively joint units. The first system, the additional substructure, offers a dry assembled structure which is reversible. The tensile forces are transferred by the metal rods while the interlayer accommodates any size deviations. However, due to the metal substructure, the overall transparency is compromised. Concerning the second system, the adhesively bonded units offer great transparency. The rigid adhesive leads to a homogeneous load transfer in the cast glass structure. Nonetheless, the total structure is non-reversible while it demands a meticulous and highly intensive labour of high precision. Nevertheless, there is a third structural system which is currently on research stage, which promises a diaphanous, reversible system by the interlocking geometry of the units. However, it is hard to achieve an accurate numerical model to simulate the structural integrity of the system.

Since cast glass structures is an innovative field in building industry, some of the required aspects are compromised and set the foundation for further development. These aspects concern the compromised transparency, the easy assembled and disassembled system and the predictability of structural performance.  Scope of this research is to propose a fourth structural system, supplementary to the existing ones, aiming to reversible and easily assembled cast glass components with less compromised transparency.

**Figure 33:** Bolted connections in  the staircase in Apple West 14th in Manhattan, New York. Source: https://www.eocengineers.com/en/projects/apple-west-14th-street-7114th-street-71

# 4 Connections

This research investigates the potential of embedding a custom-designed connection in a cast glass component pursuing the desired stiffness while it is reversible and easy to assembly, proposing in this way a new structural system. For the time being, this system is novel and thus limited research has been executed. Moreover, this chapter presents an extensive research that has been carried out, concerning the existent glass connections in float glass and few research projects employing embedded connections in laminated glass. An overall assessment of existent types of connections in cast glass structures is given on section 4.4. Furthermore, several embedded mechanisms in other materials are presented in this section, contributing to a deep understanding of the way they function while assisting significantly to the design criteria of this research.

## 4.1 Glass Connections - Current Types

The adoption of glass for load-bearing purposes is a recent relatively concept, due to the consistent need for transparency in constructions. Whereas, despite the wide variety of applications in facades, ceilings or window components, glass still stands for as a brittle, innovative material, whose potentials have not been explored to the fullest and several safe design measurements require to be considered. Connections play a fundamental role in these concepts. There is a large application of glass connections in structural glass fins and facades. The critical aspect in these applications is glass's fragility and weakness to transfer plastically the probable stresses due to external factors. Meticulous analysis is required to design suitable connection details which transfer effectively the forces between the components, mitigate tolerances and misalignments, or manage to accommodate the main structure's displacements under extreme loads (Bedon, Santarsiero, 2018). Following an extensive investigation in several books, journals and research papers the existent types of glass connections are divided in two main categories: mechanical and adhesive, with a common link the laminated adhesive (Figure 34). (Bedon, Santarsiero, 2018), (Kassnel-Henneberg, 2016), (Wurm, 2007), (Haldimann, et al., 2008), (Institution of Structural Engineers, 2014), (Eskes, 2018).

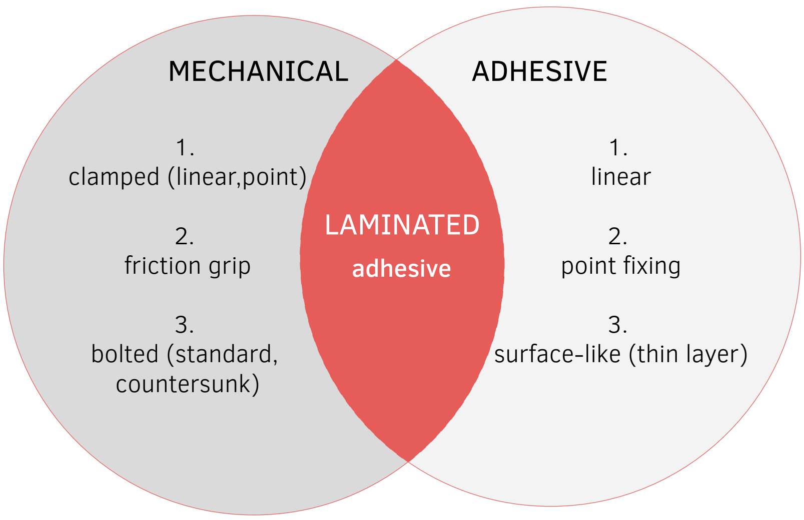



**Figure 34:** Current glass connection types. Own illustration.

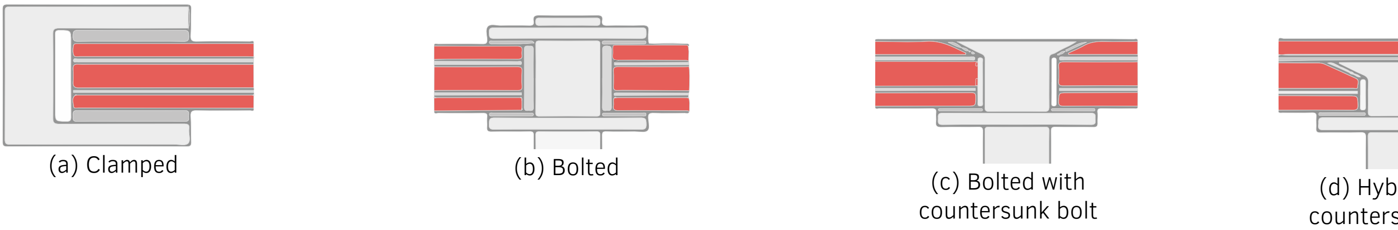



**Figure 35:** Connection typologies used in structural glass applications. Retrieved from (Bedon, Santarsiero, 2018). Edited by author.

## Mechanical: Clamped, Friction-Grip, Bolted Connections

**• Clamped**

Clamped connections are characterized by metal components which clamp the edges of a glass unit with a mechanical way. This kind of connections grant large transparent surfaces as they allow a minimum contact area with the glass unit. On behalf of this key role, local stresses and mechanisms should be crucially considered during the design process (Bedon, Santarsiero, 2018). It is important to circumvent direct contact between glass and “hard” materials such as steel, concrete or stone (Louter, 2019). For this reason, a soft plastic material, usually neoprene, or ethylene propylene diene terpolymer (EPDM) is employed as an interlayer, between the metal clamp and the glass unit, to mitigate stress concentrations due to “hard” contact. Clamped connections (Figure 37-a) can be found in a linear or point applications and usually have minor structural performance in constructions. Glass balustrades or facades employ point clamped connections to supply with local supports on glass panels. Whereas, linear connections are typically used in framing members and/or brackets providing in this way a constant translational and rotational support along the given edge of the glass panel (Bedon, Santarsiero, 2018).

**• Friction-grip joints**

In comparison to point clamped-joints, friction-grip connections take full advantage of the prestressed bolts, providing in this way an efficient transmission of in-plane loads (Figure 37 - c,f). Furthermore, the stresses distribute in wider surface, resulting to less local peaks in glass. Moreover, their load-carrying efficiency is depicted in laminated glass (LG) panels, since similar intermediate layers such as local aluminium or fiber are susceptible to temperature and creep effects. Additionally, on behalf of their wide contact surface, friction-grip joints present great results in out-of-plane deformations, since the local stress concentrations around the bolt area are restricted compared to bolted connections (Bedon, Santarsiero, 2018).

**• Bolted Connections**

Bolted connections (Figure 37 - b,e) are widely employed in structural applications of glass, such as in glass columns, fins, beams or stiffeners. They are divided into standard and countersunk and are drilled through the glass thickness, while the forces are transferred through the bolts and plates. Their difference is that, in countersunk joints, the hole’s perimeters requires tapered machining. In both cases, tempered glass is required due to high stress concentrations close to glass holes. This critical aspect combined to the brittle nature of glass, demands meticulous consideration during the design process to prevent the structure from the tolerances and the thermal movements. Usually, mortar or metallic/polymeric bushings are injected in the gap between the bolts and the glass edges, so to accommodate any misalignments in the edges, occurred during the lamination process (Bedon, Santarsiero, 2018).


## Adhesive: linear, point-fixing, surface-like (thin layer)

In adhesive connections, glass elements are adhesively bonding either to metal parts or to other glass units. The adhesive materials are mostly polymeric and present a broad area of mechanical and physical properties, resulting to great structural performances. Adhesive connections can be divided into three types: point, linear and surface-like (thin layer). In projects realised with surface-like adhesive connections, a thin layer of glue is spread over a large surface on the glass element and then is UV-cured. The total forces are transferred via the glued surfaces (Bedon, Santarsiero, 2018).

An iconic example realised with this type of connection is the Crystal Houses in Amsterdam (Figure 37 - j-i).

In contrast to surface-like connections, with linear adhesives the forces are distributed over a long linear area. Typical examples can be noticed in Structural Silicon Glazing Systems (SSGS) and hybrid structural glass elements, for instance, reinforced beams. However, in both cases, thermal movements tolerances should be taken into consideration, especially when the structure is exposed to severe weather conditions (Bedon, Santarsiero, 2018).
In point adhesive connections, loads are distributed over a reduced glued region which results to a more transparent outcome. Due to the small bonding area, an adhesive with great mechanical properties for an adequate structural performance is required. Typical examples of point adhesive connection are illustrated in (Figure 37 - n).

Furthermore, there are joints in adhesive connections both in point and in edge fittings which present high strength. Typical examples are the joints produced with the interlayer of Sentry Glass Plus (SGP). Sentry Glass Plus interlayer provides great stiffness even at thicknesses of between 1.5 and 2mm (Wurm, 2007).

It should be mentioned that the aforementioned connections are applied for both structural and non-structural purposes. The next chapters present the current types of embedded connections in laminated glass which were designed for structural reasons.

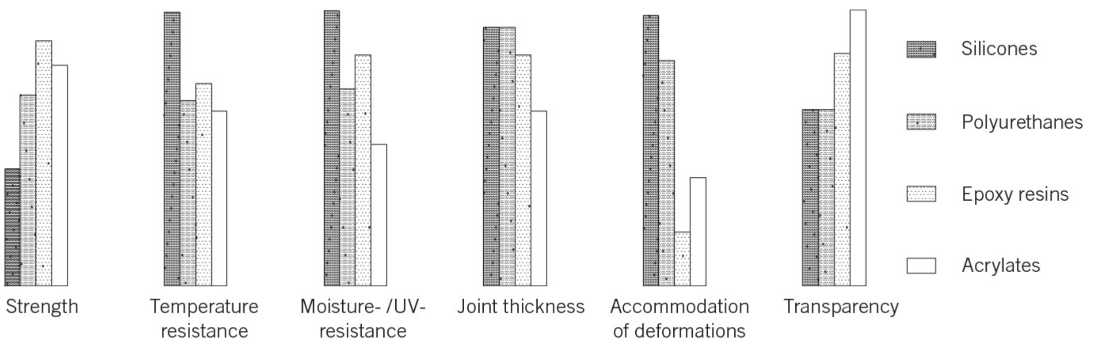
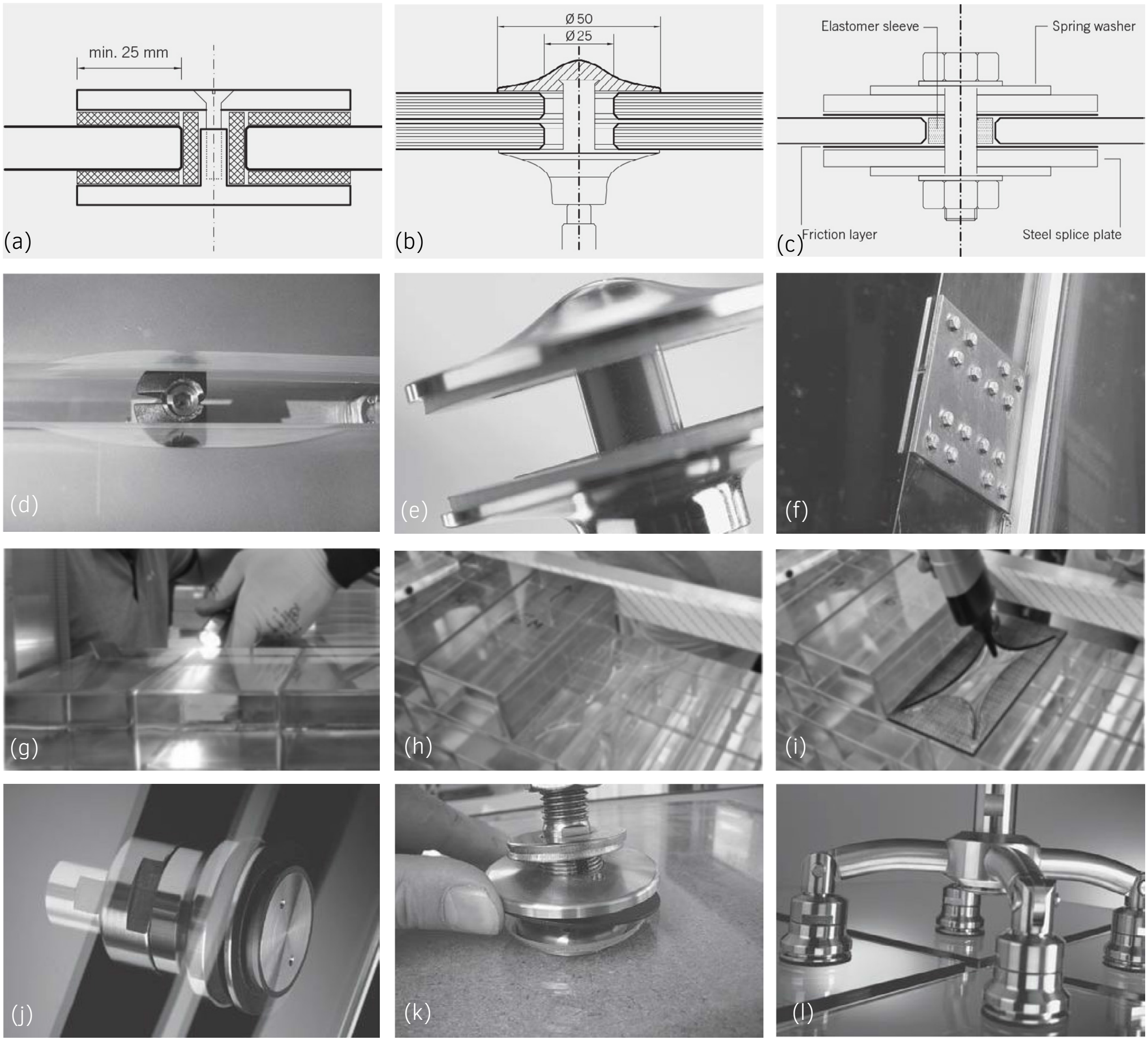
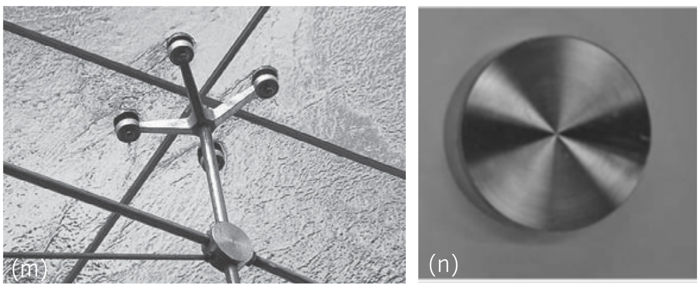



**Figure 36:** Qualitative comparison of various adhesive systems. Retrieved from (Wurm,2007).




Retrieved from**: a-f, j-m** (Wurm,2007)
**g-i** (Oikonomopoulou, et al.,2018).
**n** (Bedon, Santarsiero, 2018).

**Figure 37:** (a) Clamped connection, (b) Bolted connection, (c) Friction grip connection, (d) *Pauli und Sohn* at glasstec 2004 joint fixing. (e)*Rodan* point fixing.(f) Friction grip connection at the Educatorium Utrecht, (g-i) Bonding and curing of the adhesive at the Crystal Houses, (j) Counttersank connection for the *Dorma* Manet Construct system, (k) Typical point connection, (l) Arm connection also known as spider connection, (m) Point or plate joints prevent the leak of rainwater on hunging glazing, (n) Point adhesive connection

# 4.2 Embedded Connections in Structural Glass Existent research in laminated glass

Embedded connection in cast glass components is a novel structural system in glass structures for load-bearing reasons and limited research has been executed so far. Therefore, there are few exploratory researches and experiments which apply embedded connections either with thin or thick metal insert in laminated glass and two of them are presented in this section (Bedon, Santarsiero 2018). A full experimental study (Santarsiero, et al., 2016) is briefly presented by the end of the chapter.

Laminated glass components are fabricated by bonding together various glass layers via an adhesive transparent plastic interlayer. These specific adhesives are produced in thin film forms with an approximate thickness between 0.38-1.52mm. The most characteristic materials are Ethylene Vinyl Acetate (EVA), Poly Vinyl Butyral (PVB), and transparent Ionomers (i.e. SentryGlas, SG). A completely transparent multi-layered glass component is produced either with a post-processing (vacuum-bag) or not (Bedon, Santarsiero, 2018).

Laminated joints are produced following the same principle as in laminated glass elements. The common-use material of the connection is metal along with the adhesive foil and the glass are placed in the vacuum bag, subjected to a typical autoclave process to manufacture the final component (Bedon, Santarsiero, 2018).

The existent embedded connections in laminated glass which are fabricated slightly different[3] than the typical laminated joints are divided into two categories: embedded connections with thin metal insert and embedded connections with thick metal insert. Several research approaches have been carried out regarding embedded connections with thin metal plates while there are limited experimental explorations concerning the embedded connections with the thick inserts (Bedon, Santarsiero, 2018).

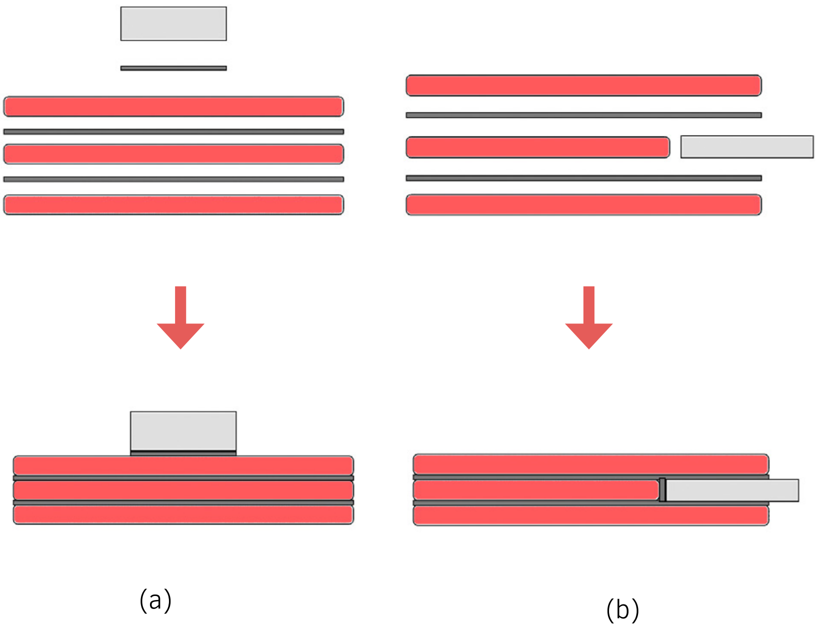



**Figure 38:** Fabrication scheme for a) laminated adhesive connections and b) embedded laminated connections. Retrieved from (Bedon, Santarsiero, 2018). Edited by author.

[3] According to (Bedon, Santarsiero 2018)., thin embedded connections need multiple intermediate layers to balance with the thickness of the glass sheet, whereas in thick embedments is not necessary. Moreover, in thick embedded connections, a slot in the middle of the glass unit needs to be cut.

The main advantage of the laminated connections is that comparing to other connection types such as in bolted or in bonded, there is no need for post-processing like mortal injection or drilling. Hence, the structural laminated connection:

1. is fully transparent
2. has a simple preparation and production method
3. can be widely used to connect various structural glass components (Bedon, Santarsiero 2018).

That's an interesting piece of information that might be beneficial for the production method of this research.

At research level, embedded connections with thin insert in laminated glass have been explored by several researchers. Multiple intermediate layers of SG material were applied to create the joint. The physical testing was accomplished by placing the final element against a reaction metal frame and then the metal template was withdrawn. The attained results presented that the temperature provoked several abnormalities in the mechanical reaction of the joint, affecting the maximum load-bearing capacity at great temperatures. Following the specific results, the maximum load-carrying capacity of the connection, at room temperature can be constrained by the plastification of the metal connection (Puller, Sobek, 2008). Apart from normal embedded metal plates, several research approaches have been conducted, embedding perforated metallic plates in laminated glass, using PVB and SG interlayers (Carvalho, et al., 2011), (Carvalho, Cruz, 2012), (Santarsiero, et al., 2013).

The research exploration concerning embedded connections in laminated glass with thick inserts are limited. (Figure 39) illustrates a research approach on a small-scale component tested under pull-out forces. The specimens were constructed by three-ply laminated joint with a thick metal plate integrated in the inner layer. Both the analytical and the numerical results showed that at temperature fluctuations, the stress states around the connection alters resulting to different effects in the connection failure and fracture conditions (Santarsiero, Louter, 2013).

(Santarsiero, et al., 2016) experimented on a full-scale study, the mechanical performance of a glass beam with embedded laminated connections under various loading cases. The main target of this research is to investigate the structural performance at the connection area. The different geometry of the connection along with the various location scenarios provided essential results concerning the mechanical behaviour of the component.

The physical testing included three different typologies of beams. (Figure 41) illustrates the three typologies with the different geometries and the locations in each type. In type A, the two metal inserts are placed in the middle, while in type B, the metal insert is placed in the

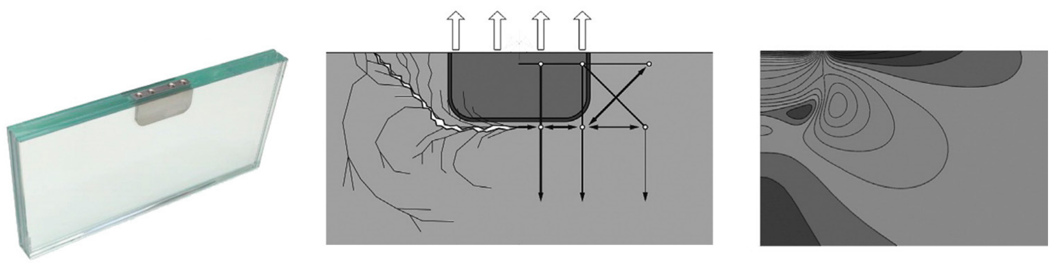


**Figure 39:** Experimental research on small-scale SG embedded laminated connection under pull-out forces. Retrieved from (Santarsiero, Louter, 2013).

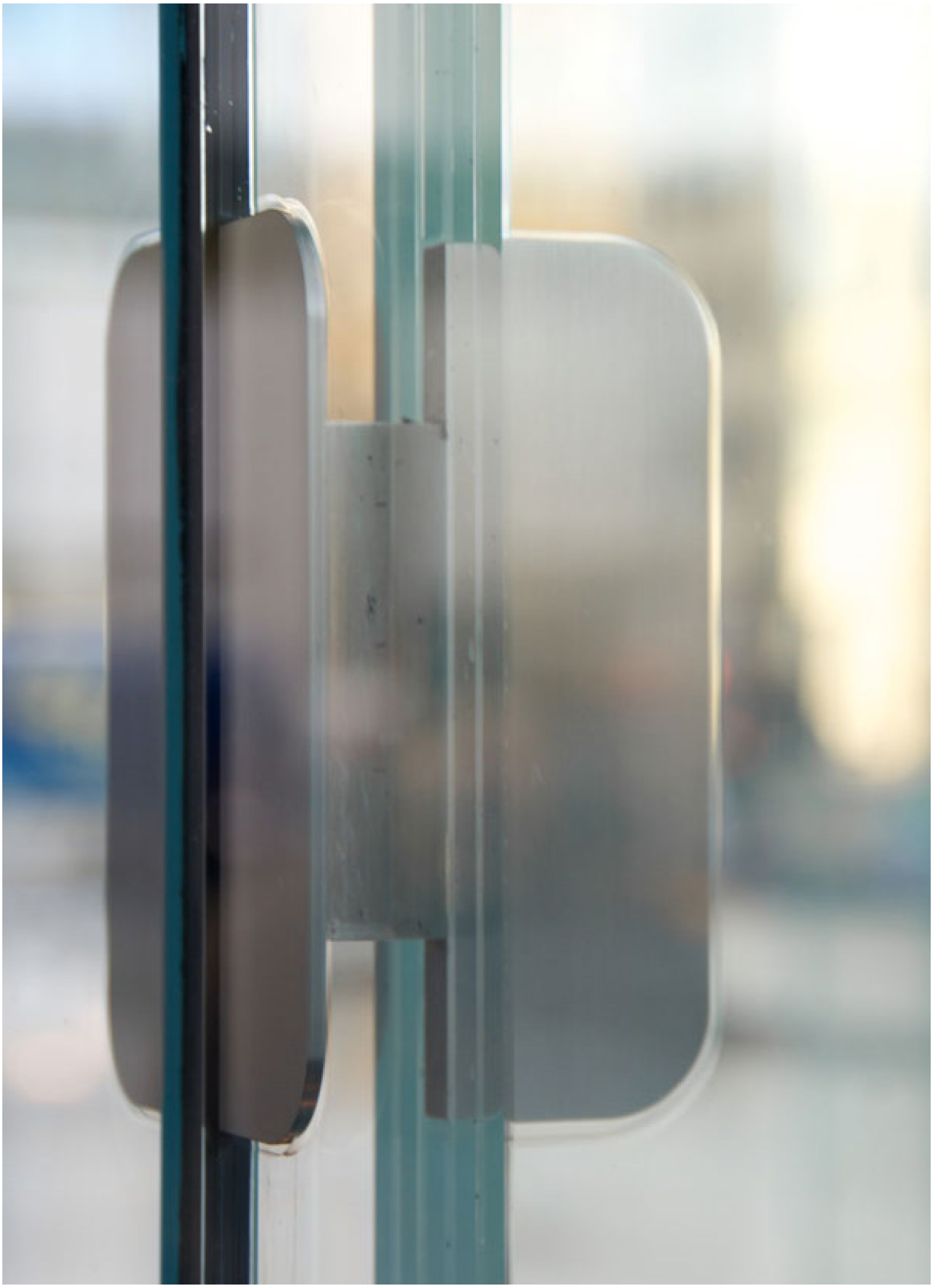


**Figure 40:** Embedded connections between column and facade panels in Apple Store in Fifth Avenue, NY. Source: https://www.eocengineers.com/en/projects/apple-fifth-avenue-mark-ii-100

centre. In type C, the metal inserts are placed in the edges connected in this way with steel reinforced bars.

Concerning the materials, the beam is composed by three glass sheets 6-10-6 mm. laminated with 1.52mm foil of SentryGlas® ionomer interlayer. The top and the bottom edges, are bonded with stainless steel reinforced bars. The beams were performed under monotonic, creep and damage test at room temperature.

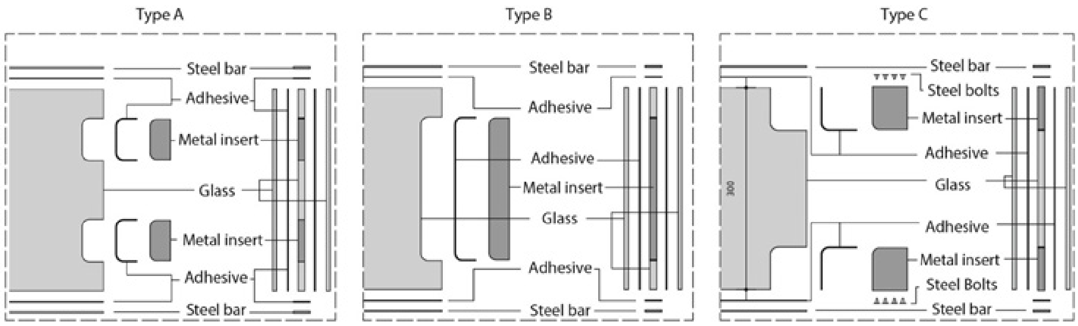



**Figure 41:** Experimental research on small-scale SG embedded laminated connection under pull-out forces. Retrieved from (Santarsiero, Louter, 2013).

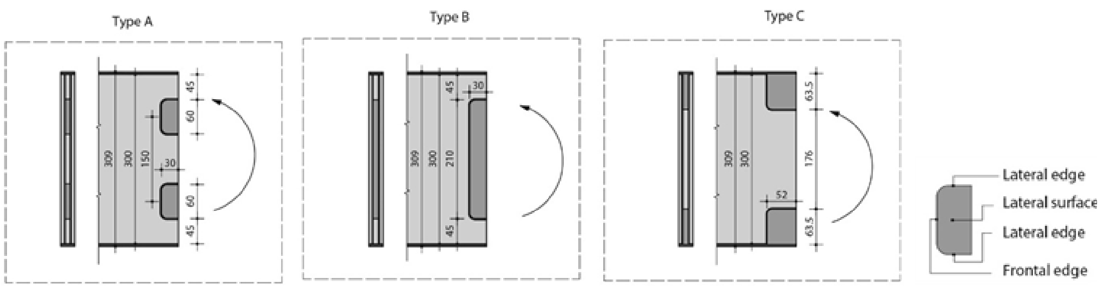



**Figure 42:** (Left): Placements and dimensions of the metal embedments. (Right): Description of the metal surface. Retrieved from (Santarsiero, et al., 2016).

According to the results, the greatest load bearing efficiency of type A and B is restricted by glass damage. The resulted fracture pattern revealed the structural performance of these connections around the joint area. Firstly, the beam of C typology, presented an adequate redundancy and ductility in contrast to type A and B. The first cracks in beam C, occurred in a distance from the connections, revealing that the connection might not me the crucial element in the beam. Secondly, the analysis demonstrated that after several cracks, the beam continued to withstand the applied force, showing a large plastic deformation. In general, type C beam presented more resistance in different load-case scenarios, even if all the glass panels are damaged.

In the built environment, embedded connections in structural laminated glass have been widely employed to connect columns with facades panels or beam-to-beam. The most representative example is the Apple Store in New York, on the 5th avenue (Figure 40), presented by Eckersley O' Callaghan in 2006. 10 x 10 m. glass portals form the main structure resulting to a fully transparent building. The connections between the structural members, such as beam-to-beam or column-to-façade are embedded connections manufactured from laminated glass with SentryGlas®[4] material (Bedon, Santarsiero, 2018).

[4] SentryGlas® material, known as SG, is a transparent ionomer polymer, broadly employed in laminated glass applications (Bedon, 2018).

## 4.3 Qualitative Comparison

Table 5 presents a qualitative comparison between the mechanical, adhesive and laminated adhesive connections based on the criteria and comparisons derived from (Eskes, 2018). These criteria correspond to the research based on different sources (Wurm,2007), (Bedon, Santarsiero,2018) concerning glass connections, both structural and non-structural.

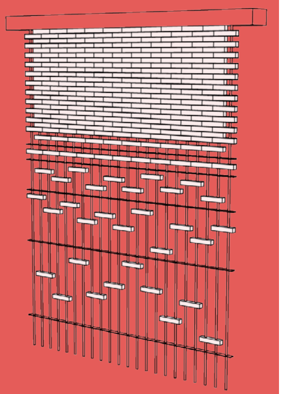
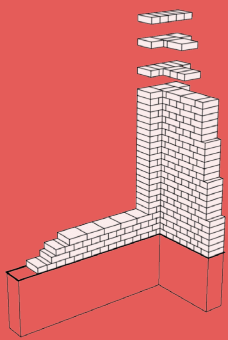
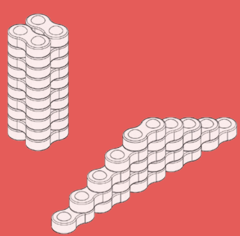
Drilling holes in bolted connections affects the overall strength since, this type concentrates high stresses, and a latter tempering is required. Moreover, this type of connection presents a great structural performance. In adhesive connections, the forces are distributed in a more homogeneous way resulting in an adequately stiff connection.  Furthermore, the overall transparency of the structure is not disturbed with the same intensity as in mechanical connections. Although, mechanical connections are easily demountable and can be recycled. In contrast, adhesive connections require a demanding pre-processing (surface pre-treatments) (Louter,2019) before the assembly on site, are hardly demountable and non-recyclable.

| Criteria / Connections | Mechanical | | | Adhesive | | | Laminated Adhesive | |
|---|---|---|---|---|---|---|---|---|
| | Bolted | Friction Grip | Clamped | Point | Linear | Thin Layer | Standard | Embedded |
| Strength* | v. high | high | low | high | high | v. high | high | high |
| Stiffness* | v. high | v. high | low | high | high | high | high | high |
| Transparency | -- | -- | - | + | - | ++ | + | + |
| Ductility | ++ | ++ | + | + | + | -- | + | + |
| No Failure Introduction | -- | ++ | ++ | + | + | ++ | ++ | ++ |
| Durability** | + | + | + | - | - | -- | - | + |
| Demountability | ++ | + | + | - | - | -- | -- | -- |
| Recyclability | + | + | + | - | - | -- | - | - |
| Simple Process | ++ | ++ | ++ | - | - | -- | + | - |
| Low Price | ++ | ++ | ++ | + | + | -- | - | - |

* For adhesive and laminated connections, the selection of the interlayer material plays an important role to define strength and stiffeness.
** This criterion concerns th ability of the connection to withstand time and exposure to various whether conditions. Steel is durable when a coating is used to prevent corrosion. Adhesives present properties that are time, temperature and radiation dependant.

**Table 5:** Qualitative Comparison of the existent glass connections. v. stands for very.
All the criteria derived from (Eskes, 2018).

# 4.4 Current connection types in cast glass structures. Overall assessment.

| Connection types | Buildability | Transparency |
|---|---|---|
| Mechanical Connection Additional Substructure  | + the dry assembly connections assist to an easily assembled structure | - the metal steel rods lead to compromised transparency |
| Adhesively bonded  | - meticulous and high intensive labour of high precision | + the diaphanous adhesive leads to a highly transparent connection |
| Interlocking Geometry  | + the dry connectioned interlocking geometries assist to an easily assembled structure<br><br>- susceptibility to eccentricities during the construction | + high transparency is achieved by the construction method |

| Reversibility | Structural efficiency | Accommodation of size deviations |
|---|---|---|
| + the dry assembly connections leads to demountable structure | + the metal structure carries the tensile forces | + size deviations are accommodated from the interlayer |
| - non-demountable connection | + the rigid adhesive assists to a homogeneous transfer of the loads in the cast glass structure. hence, no peak stresses. the appropriate choice in thickness achieves the maximum strength | - high precision in the unit size required from the adhesive's thickness |
| + reversible structure | (still on research stage)<br>- pre-compression is required<br>- hard to achieve an accurate numerical model to simulate the structural efficiency of the system | + the interlayer between the glass units accommodates tolerances |

## 4.5 Embedded mechanisms in other materials

The present research explores the potential of applying an embedded connection in cast glass components. Even if this system is novel in cast glass structures, embedded mechanisms are widely applied in other materials for various reasons. This section divides the embedded mechanisms into four main categories: furniture manufacturing, façade panels, load-bearing structures, medical purposes (Figure 46). Since connections is a vast field in construction, the literature research of this section is mostly empirical and based mainly on articles and internet sources through construction companies' catalogues.

Embedded connections can be found in timber, concrete, sandwich panels or metal structures. Starting from furniture, simple but quite delicate mechanisms are applied in furniture design such as beds, tables, bookshelves. Most of the times, the integrated mechanism is manufactured by plastic or metal material without the presence of interlayer. Locking bed rail or rail connector are very common and quite interesting mechanisms concerning the scope of design (Figure 43).

Following, embedded mechanisms are applied successfully in load-bearing structures, usually employed in cast or pre-cast concrete and timber constructions. In cast or pre-cast concrete the embedded mechanism is a metal insert capable to present sufficient load-bearing capacity in: wall-to-slab applications, beam-to-column or beam to slab-application. The concrete cast component is capable to withstand both in-plane and out-of-plane forces (Connections for Architectural Precast, ND). In pre-cast concrete there is a vast range of embedded anchors designed exclusively for special conditions (Figure 45).

**Figure 43:** From left to right: Connecting rail in furniture.
Source: https://shop.titanbuildingproducts.com/rail-connector-level.php

**Figure 44:** Hidden wooden connection embedded in wood.
Source: https://www.core77.com/posts/50862/More-Knockdown-Fasteners-This-Time-from-Festool

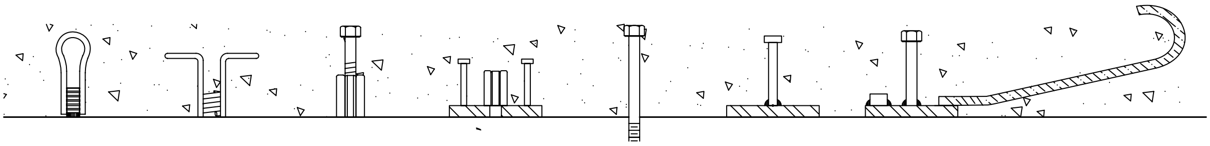


**Figure 45:** From left to right: Coil thread loop insert, coil thread wing nut, coil thread coupling nut and bolt, coil thread coupling nut plate and studs, coil bolt, flush plate with studs or hand welded bolt blanks, bearing lug and/or tension bar supplement on flush plate with studs or hand-welded bolt blanks ( Connections for Architectural Precast, ND).

Additionally, hidden joints are widely applied in façade panels. For aesthetical reasons, sandwich panels are connected either to each other or to beam through a hidden connection. Lastly, a very interesting sector which employ embedded connections is prosthetics. In this implant systems, the loads are distributed from the artificial limb to the abutment, then from the abutment to the fixture and lastly from the fixture to the human bone (Figure 51). These artificial limbs are manufactured from a strong titanium alloy commonly used for medical reasons (Thesleff, et al., 2018).

Consequently, there is a wide variety of embedded mechanisms in multiple materials. For the time being, this investigation stayed in preliminary phase and based mainly in the design concepts and the purposes that these mechanisms serve. Some of these hidden mechanisms, present interesting ideas that might be included during the design process of this research respecting the design constrains defined by this paper.

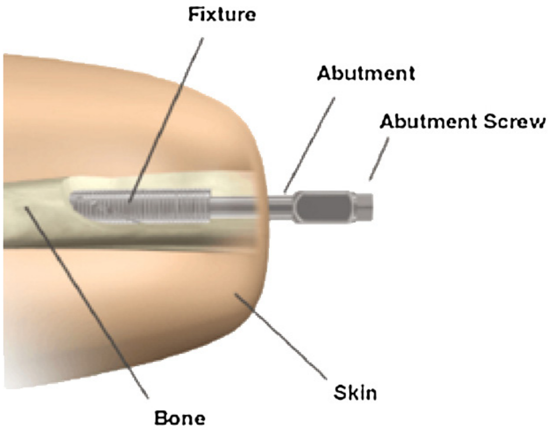



**Figure 46:** Schematic image of OPRA implant system in an amputated limb (Thesleff, et al., 2018).

## Observations:

Comparing the embedded connections in glass to embedded connections in other materials is quite challenging as far as concerned the structural efficiency of the joints. Moreover, there are several differences regarding the materials and the mechanisms.
In glass, embedded connections have been constructed and tested only in laminated glass, while embedded mechanisms in other materials such as wood or concrete are quite prevalent. Thick or thin metal inserts are the most common shape of connections in laminated glass. In contrast, in other materials, embedded mechanisms can be found in multiple concepts (i.e. clicking, railing connector).
Concerning the production method, embedded connections in laminated glass requires a meticulous process. In other materials, it is a purpose dependent factor because for instance, in timber structures the embedded connection can be simply drilled to the structural member, while in prosthetics a more attentive procedure is required.
From a material perspective, embedded connections in glass are up to now metal components. Moreover, in other materials, apart from metal, embedded mechanisms could be found in titanium plastic or wood.

## 4.6 Conclusions

Overall, the connections in float glass are divided into two categories: mechanical and adhesive with a common link between them the laminated adhesive, categorized in standard (bonded on surface) and in embedded, respectively. Mechanical connections offer the advantage of reversibility and usually are preferred for structural purposes since the forces are distributed through the pre-stressed metal elements. The most critical point in these connections, is the need of interlayer between the metal component and the glass, so the forces to be homogeneously distributed. However, adhesive connections are quite favoured for structural reasons and for transparency. Nonetheless, they lead to an irreversible structure, while it is hard to accommodate size deviations. The Crystal Houses in Amsterdam, constructed entirely from a thin layer adhesive, creating in this way a self-supporting glass structure. Concerning the embedded connections, in glass can be found only in laminated glass panels. The type and the material of the connections are quite restricted in contrast to a broad spectrum in other materials. The key aspects derived is the need of interlayer for a "hard"-to-glass contact, the pre-stressed element for greater structural efficiency, the application on the large surface for a better stress distribution and the temperature fluctuations which can cause several abnormalities in the mechanical reaction of the joint.

In cast glass structures, the connections are divided into three categories, mechanical, adhesive and interlocking connections with several advantages and disadvantages.
In mechanical connections the tensile forces are carried by the additional supportive substructure. The dry-assembled mechanical connections lead to demountable structure. Although, the metal rods compromise the transparency significantly. In adhesively bonded, the diaphanous rigid adhesive offers a highly transparent and structurally efficient connection. However, this type of connection contributes to an irreversible structure. The dry joint interlocking geometries assist to an easily assembled and highly transparent structure. Nevertheless, it is hard to achieve an accurate numerical model to predict the structural efficiency of this connection.

Within this research's context some of the unfavoured aspects will be addressed, targeting to a structural system with easy to assembly, structural predictable and less intrusive connections.

# 5 Design Criteria

Considering the sub-question (Chapter 2.2) below imposed in the research framework and the information derived from the literature review, this section establishes the design criteria related to embedding a connection into a cast glass component.

Sub - question:

**- What are the design principles for designing an embedded connection in cast glass components?**

Regarding the findings collected from previous chapters, the design criteria are divided into two categories related to casting of the unit and the connection type: More specifically the criteria concerning the casting are: limited volume, rounded shape and uniform mass distribution while for the connection type: material compatibility with glass, need of intermediate material, ease of assembly, minor visual impact, structural efficiency, novelty. Next to the research sub-question, these design criteria would assist significantly the design development.

**Design criteria related to cast glass unit:**

- **Limited Volume**

The meticulous and essentially prolonged cooling process of cast glass can increase significantly the cost of the components and address them as financially inappropriate. For this reason, mass is a critical aspect. The larger the volume of the unit, the longer the annealing time in an exponential way. For instance, in Crystal Houses, glass units with weight 3.6 kg and overall dimensions 65mm x 210 x 105 mm required 8 hours of cooling, while components of two times larger volume, needed 36-38 hours respectively (Oikonomopoulou, et al., 2018 ). Accordingly, for this research, the dimensions of the glass unit will not exceed significantly the current dimensions (235mm x 50mm x 50mm) since the volume is approximately 1.3 kg, which means that the annealing time will be to a certain extent in normal levels. Of course, this is dependent to the final choice of glass type.

- **Rounded shape and homogeneous mass distribution**

A shape with curved corners and a uniform mass distribution are two critical aspects for the avoidance of condensed residual stresses. Rounded geometries are recommended over rectangular and pointy edges, where non-uniform shrinkage is developed from the internal residual stresses. An analogous cross-section throughout the entire unit, results to a steady annealing, homogeneously, avoiding any further development of residual stresses (Oikonomopoulou, et al., 2018 ).

**Design criteria related to the embedded connection:**

- **Ease of assembly**

This concept targets to a reversible new structural system in cast glass components. The ease of assembly will alleviate the labour during both in construction and in the dis-assembly. Time and cost are two key aspects that will be benefit from this criterion. For this reason, a delicate and effortless to connect component such as those with the "railing connectors" is favourable.

- **Minor visual impact**

Balance of the compromised transparency in cast glass structures, imposed by the additional substructure, is one of the main goals of this master thesis. Hence, the desired connection should be a small- scale component embedded in the cast glass unit, with the minimum dimensions respecting the rest of the criteria (i.e. structural efficiency, ease of assembly).

- **Structural efficiency**

The structural efficiency will reflect on the ability of the structure to withstand the various load-cases such as the lateral loads, wind load or any risk scenario. Based on the literature findings, this interprets to no rotation allowance and capability to withstand the applied forces.

- **Material compatibility with glass**

The choice of the material for the connection should fulfil the limitations imposed by the glass's mechanical properties. Hence, the selected material should perform in a similar way under certain circumstances with glass and most importantly to have similar thermal expansion coefficient.

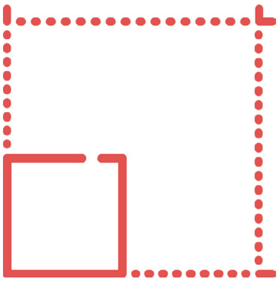
- **Need of intermediate material**

Glass-to-metal contact or any other contact with "hard" material is restricted due to stress concentrations. For this reason, the need of an interlayer between the connection and the glass brick is vital, to mitigate the loads to the glass unit uniformly. This is a significant aspect to take into consideration not only during the design process of the joint but also during the design constraints of the glass block. Nonetheless, the glass-to-glass contact should be avoided as well, hence, the choice of a secondary interlayer between the cast glass bricks would be necessary during the assembly process (Chapter 9).

- **Novelty**

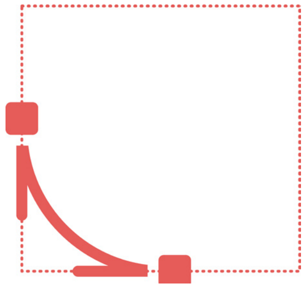
Novelty stands as a very beneficial and meaningful criterion both in architectural and in product design, since applying new ideas will create an extra value to the design process. Moreover, seeking for novelty in the design development will boost the creative thinking during the design stage.

## CAST GLASS BRICK



### Limited Volume

less annealing time
less cost



### Rounded Shape

less residual stresses
avoid non - uniform
shrinkage

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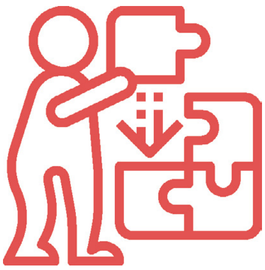
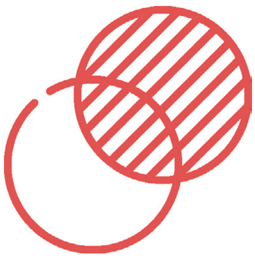
## EMBEDDED CONNECTION



### Ease of Assembly and Dissasembly

time and cost efficiency
in labour

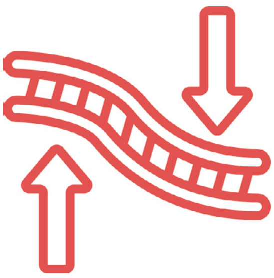


### Minor Visual Impact

balance compromise
transparency

### Structural Efficiency

withstand the various
loads - homogeneous
distribution of the loads



### Need of interlayer

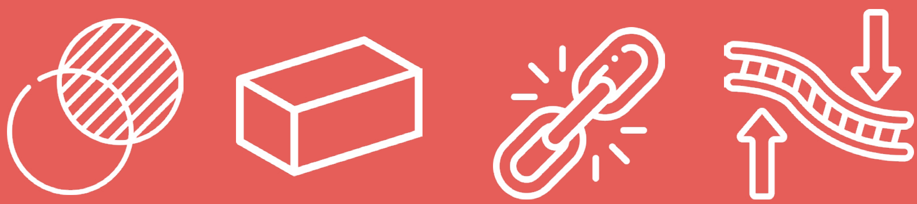
mitigate loads
distribution

### Material Compatibility

similar thermal
expansion coefficient
with glass

### Novelty

new ideas during the
design procedure



# 6 Material exploration on embedded connection

Engineering design broadly pursues to achieve maximum performance. The term performance can refer to many aspects such as stiffness for a specific weight or it could refer to maximum strength, or safety or cost-efficiency. The determination of the structural/mechanical performance depends significantly on three aspects: on the type of load (tension or compression, bending or torsion, or combination of them), on the shape of the section (solid, tubular, I-section and such like), and on the properties of the material of which it is manufactured (modulus, strength, toughness, cost per unit, volume). Among the extensive range of the materials and the section forms, the trigger point is to select the one which maximizes the performance. (Ashby M. F., 1991).

Following this, the formulation of the main research question based upon three sub-questions. One of them, is related to the restrictions imposed by the material. More specifically:

-Which are the constraints of the material used for an embedded connection in a cast glass component? Which are the main principles and challenges involved in the material compatibility between a cast glass component and the desired connection?

This research is based on a new system, which explores the potential of embedding a connection in a cast glass unit for load-carrying purposes. This investigation will be based mainly in "free searching" using a software library of materials, CES (2019). Nonetheless, the starting point for the identification of the desired material is answering the questions related to: function, constraints and objectives, as stated in (Ashby, et al., 2003).

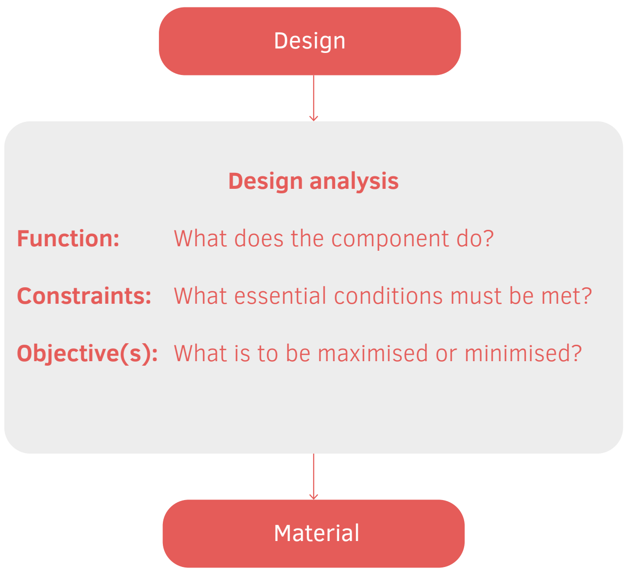



**Figure 47:** A first investigation of the desired material (Ashby, et al., 2003).

This material will be employed in a structural connection (function) for a cast glass component. Based on the findings from the literature research, the structural performance of this cast glass component is dependent on the load-carrying efficiency in lateral loads, and in compressive and shear stresses. One crucial constraint is the thermal expansion coefficient. Since, the joint will be embedded in the cast glass, it is essential that in any temperature fluctuations, the volume of the materials to be transformed (either expand or compress) in a similar manner. Certainly, the objective of this exploration is the choice of the material and its cross-section area, suitable enough to demonstrate efficient structural performance. These questions will attenuate the “free scanning” in the material software and assist significantly with the choice of the material.

Nonetheless, the embedded component will be consisted of two classifications: the joint and the interlayer. Since, it is restricted to contact glass-to any hard material due to high stress concentrations, an intermediate layer seems crucial.

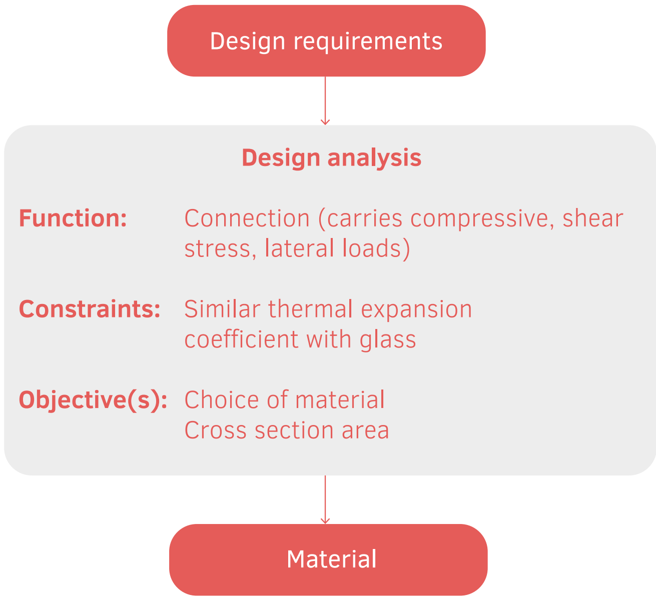



**Figure 48:** Addressed requirements of the connection.

## 6.1 Connection

The material library in (CES Software, 2019) is vast. During the "free scanning" procedure, the candidate materials had to be limited. The starting point in the material exploration based on the materials applied in existent types of glass connections. According to the research findings, stainless steel (ferrous metal) is a dominant material in mechanical, adhesive and laminated adhesive connections. Moreover, non-ferrous metals present great mechanical properties too. Consequently, the material exploration starts with the first material category that crosses the mind when you consider about connections in cast glass. Moreover, designing a novel system in an already innovative area like the cast glass structures, requires thinking out of the box. The Ceramic and Glasses section includes apart from the glasses, the non-technical ceramics. This section includes many "hard" materials which are expected to present similar mechanical properties with glass. Following the desire for innovation solutions, PMMA is also involved in the research for its optical properties. Concluding, borosilicate and soda-lime glass, with their mechanical properties known from previous chapters, completed the research.

Targeting to a limited number of materials with similar thermal expansion coefficient as the two types of glass (borosilicate and soda-lime), the information derived from Table 6, applied into CES Software. More specifically, according to the values of Table 6, the values of thermal expansion coefficient cover a range from 8 μstrain/°C to 9 μstrain/°C. The most compatible materials with soda-lime glass appeared to be some titanium alloys.

Moreover, an investigation about the applicability of titanium in structural connections, showed that titanium bars have been employed in restorations works with marble in Acropolis monuments in Greece. The choice of titanium based on its great resistance to weather conditions and its high great mechanical properties. Furthermore, the Poison Ratio of titanium (=0.32) is similar to the Pentelic marble, a reason why titanium bars have been employed for connecting together the marble pieces (International RILEM Symposium on Connections Between Steel and Concrete, 2001). According to (Engineering ToolBox, 2003), marble's thermal expansion coefficient covers a range of 5.5 - 14.1 μstrain/°C, depending on the type of the marble and its mechanical properties. Nonetheless, due to its high brittleness, it is challenging to be taken into consideration according to this project's requirements.

However, same analysis in (CES Software, 2019) conducted for borosilicate glass. Chromium, high alloy steel, and zirconium cover a similar range in thermal expansion coefficient with borosilicate glass, but their Young's Modulus is comparably higher.

| Glass type | Mean melting Point at 10 Pa.** [°C] | Soft. Point [°C] | Anneal. Point [°C] | Strain Point [°C] | Density kg/m³ | Coeff of Expan. 0°C - 300°C 10-6 / °C | Young's Modulus GPa |
|---|---|---|---|---|---|---|---|
| Soda-lime (window glass) | 1350 - 1400 | 730 | 548 | 505 | 2460 | 8.5 | 69 |
| Borosilicate | 1450-1550 | 780 | 525 | 480 | 2230 | 3.4 | 63 |

* 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 different recipes resulting into different properties.

**Table 6:** Approximate chemical compositions and typical applications of soda-lime and borosilicate glass as retrieved from (Oikonomopoulou, et al., 2018).

Titanium embedded connections are widely employed in the built environment for structural purposes. The most identical examples can be detected in Apple Stores (Figure 40) where structural embedded connections manufactured by titanium, connect columns with façade panels. Furthermore, titanium inserts have been already employed in façade glass panels in the New Medical School of Montpelier. The titanium connections are embedded in vertical glass fins, laminated with SentryGlas® interlayer in multiple heat-strengthened glass panels. The total design of the façade ensures the overall stability even in the most threatening risk scenario (Torres, et al., 2017)

The wide applicability of titanium in embedded connections in laminated glass, along with the great compatibility in thermal expansion coefficient with soda-lime glass, render titanium as the selected material for this research. Figure 49 presents the selected materials and their values in thermal expansion coefficient. The information related to glass properties derived from the extensive research of (Oikonomopoulou, 2019). The values related to titanium's thermal expansion coefficient derived from (Hsueh, et al.,2006).

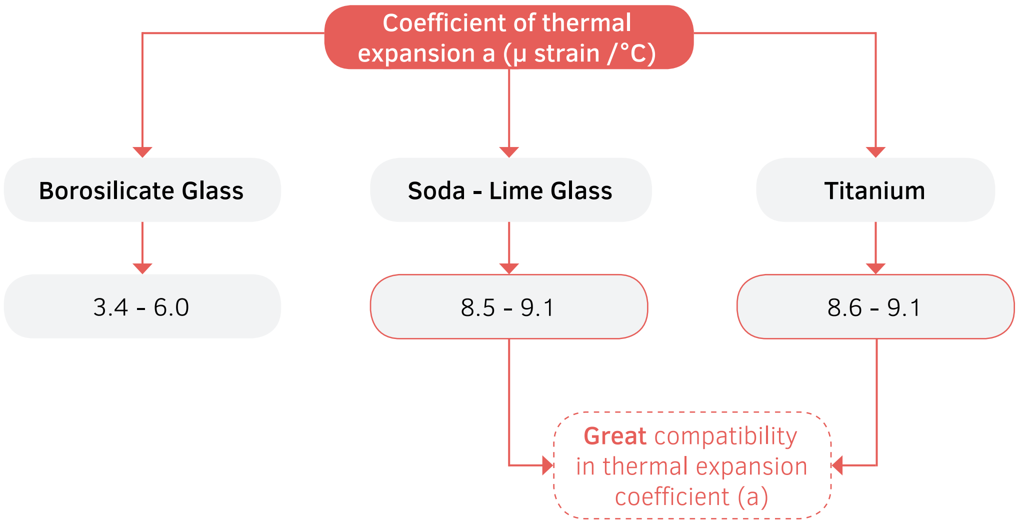



**Figure 49:** Mechanical properties of the chosen materials.

## 6.2 Interlayer

Considering that the direct "hard" material-to-glass contact is not approved, the placement of an intermediate layer between glass and the metal connection is essential. The choice of interlayer is differentiated in every kind of glass connection and predominantly depends on the magnitude of tolerances.

For instance, in bolted connections, neither too elastic nor too hard material are considered as the most appropriate solution for the interlayer. On behalf of this, materials that present a proper compromise between compliance and resistance are usually distinguished through experiments and numerical studies (Bedon, Santarsiero, 2018). Typical examples of such interlayer materials are polymeric or soft aluminium plates. These intermediate materials are used in case of accommodating small tolerances in the hole or the magnitude of load transfer is small (Bedon, Santarsiero, 2018). In case of larger tolerances, injectable mortar material is preferred, as their low viscosity contributes in a uniform distribution of the load or manages to accommodate tolerances more suitably (Bedon, Santarsiero, 2018).

For laminated adhesive connections, two are the main materials that are used: The Transparent Structural Silicon Adhesive (TSSA) and the SentryGlas® (SG) ionomer. The main difference with the standard silicon adhesives is their increased mechanical performance. The TSSA is manufactured from Dow Corning and provides greater stiffness and strength capacity comparing to standard silicon adhesives. Moreover, TSSA is not suitable neither for embedded laminated connections nor for laminated glass components (Dow Corning, 2014), hence it is essentially employed in metal-to-glass adhesive laminated connections, bonded to the glass surface. In this regard, through-out the literature review, it was not clear the reason why TSSA is not suitable for embedded laminated connections, but several experiments proved a complicated stress-distribution in the adhesive layers. In contrast to TSSA, SG is widely applied in laminated glass applications as foils in the intermediate layer.

In comparison to PVB or EVA, SG in general terms presents greater stiffness and mechanical resistance, it is durable while has already proven its resistance in temperature fluctuations and in time-loading (Bedon, 2018).Moreover, SentryGlass® has been widely used in laminated connections with metal inserts for structural purposes especially in Apple Retail stores.

Concluding, the selection of the interlayer material in this research will depend largely on the degree of the loads and tolerances, while the durability and the mechanical strength are also significant factors. Moreover, the compatibility with the main material of the embedded connection is very crucial as well. Existing examples and applications will play an important role in the material assessment. Hence, the combination between glass, interlayer and selected material for the connection should provide an adequate load carrying capacity and uniform distribution of the forces.

## 6.3 Conclusions

Consequently, this happened to be an approach concerning the material of the embedded connection. The specific research conducted by taking into consideration the similar thermal expansion with glass. Titanium has a great compatibility with soda-lime glass and appears to be very promising since it is already employed as an embedded insert in laminated glass. Important factors, such as the cost, have not been taken into consideration. However, the need of interlayer seems inevitable. Moreover, the final selection of the interlayer will be determined in the same time with the definition of the overall loads and the final selected material of the connection.

**Figure 50:** Small puzzle game. These are all the elements used during the design procedure. The answer lays between the components. Shot taken by author.

# 7 Design Development

The main focus of this chapter is to provide the design development – the story - behind the final proposal. Based on the established criteria, the design of this embedded connection has been quite challenging, since this system targets to an easy assembly structural system which can reassure for its structural integrity while it imprints the minimum possible visual impact. Without doubt, the final design eventuated after multiple design concepts which, during the process assessed based on the design criteria. Depending on this assessment, two candidate concepts which stand for two different connection types have been selected and filtered to choose the prevailing system. In the next chapter, the detailed design of the embedded connection in the cast glass elements is presented.

## 7.1 Preliminary designs

The main difference between the desired system and the third one, the interlocking cast glass elements, is the connection between the cast glass units. This connection will ensure the structural efficiency of the system, something that is still on research stage in the interlocking elements, while it leads to an easily assembled and disassembled system. Hence, we are seeking for a connection which creates an interlocking between the cast glass, yet is difficult to be achieved by glass. Transparency is also a key aspect. Moreover, it is challenging to accomplish the high transparency offered by the adhesively bonded or the interlocking cast glass bricks. However the requested system will balance the compromised transparency introduced by the additional substructure.

Based on the literature review and the established design criteria (chapter 5), the first experimentations concerned a **bolted system** both as a linear and as a point connection. Moreover, the linear dry assembled connections even though they are on research stage in standard bricks[4], and they would efficiently transfer the loads homogeneously, discarded because the transparency would be significantly disturbed.

The target is a small-scale mechanism, embedded in the cast glass unit, which can be easily assembled and disassembled.

### System fundamental principle:

Various bolted systems in other materials (chapter 4.5) and especially in wood are accessible from the side. Analogous approach in this project would generate several obstacles.
The access either from the side or from above would complicate the assembly and the disassembly of the structure while it would affect the mechanical properties of the cast glass unit. Based on the literature review, the existence of a small notch on the cast glass brick would possibly create peak stresses around the hole (Oikonomopoulou, et al.,2018). Besides, it would affect the overall transparency. In this way, a fundamental principle concerning the assembly and the accessibility has been established:

A system with **no** access from outside through the glass brick.

[4] There is not much literature yet, moreover there is adequate information here: http://drystack.nl/

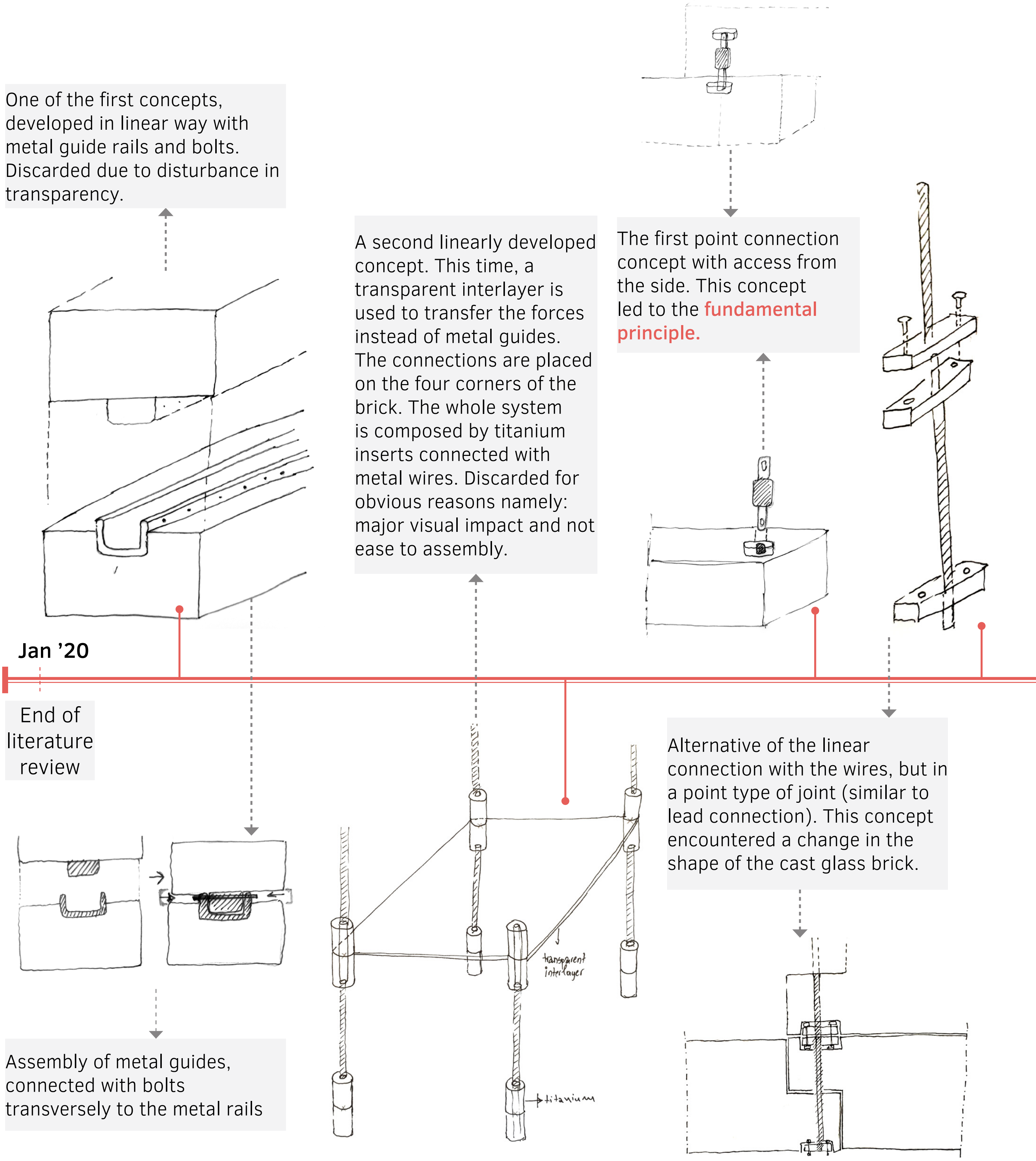
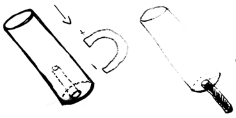
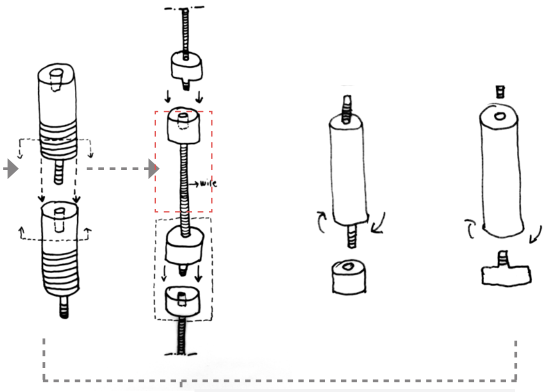



**Figure 51:** Time-line of the whole brainstorming and ideas developed after the end of literature review. Respecting the established design criteria, the prevailing concepts are briefly presented as well.

(+) A very easy to assembly and dissassemmbly concept.
(-) Same visual impact with the additional substructure.

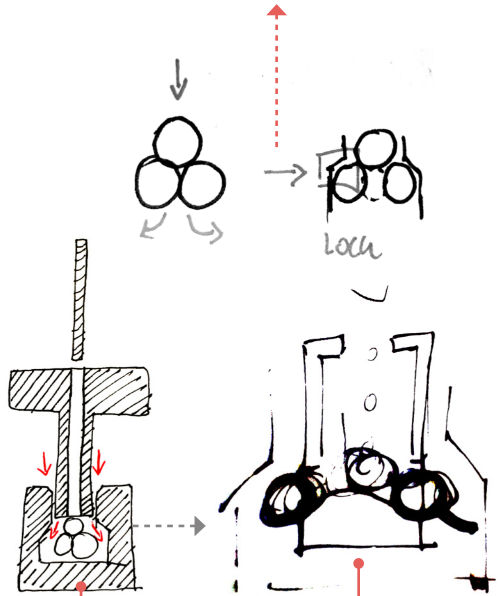


The only concept developed in angle.



Various alternatives led to **Concept 1:**

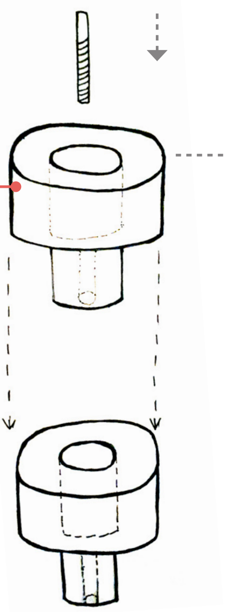
**Concept 2:** A locking mechanism, an alternative of a mechanism, already employed in constructions. The difference? Gravity will lock the components!

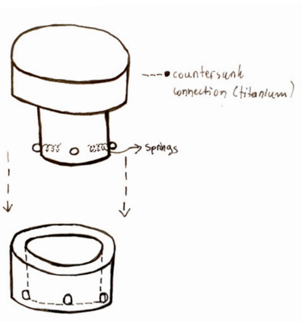



**Mar-Apr '20**

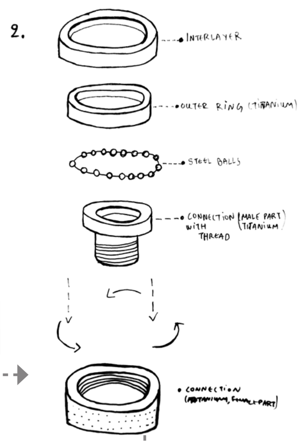
**Two prevailing systems**

**Concept 1:** A bolted system, assembled and disassembled with magnets, facilitates the "no access from the side" principle and has minor visual impact. At first point the concept include access from above.

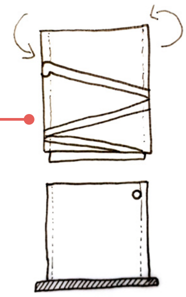





Alternative of concept 1. The metal springs without external pull-out force would not be functional.




Alternative of concept 1. Over-engineered concept for this project's requirements.



This mechanism (bayonet) gave the idea for a locking system. Moreover, this system could work with one connection per brick, something that could not be functional in this project as the necessary number of connections per cast glass unit is two.

## 7.2 First concept - Bolted system

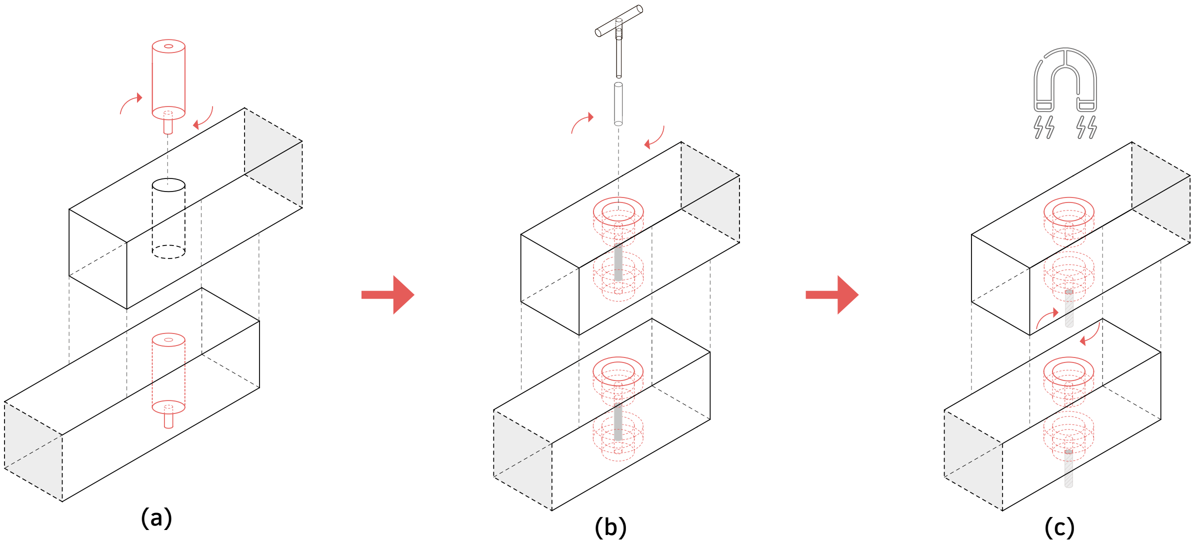



**Figure 52:** Design development of concept 1. (a) Major visual impact (b) A notch in the middle creates an access to bolt the system (c) The system is bolted with the assistance of magnets.

Figure 51 presents a timeline of the all design concepts and the evolution of the two prevailing according to the design criteria. The approaches which developed with point connections, suggests two connections on the wide side of the glass bricks, to avoid rotation in lateral forces, a principle established according to literature review findings.

Figure 52(a-c) illustrates the design development of the first concept. The design has been arisen from the concept illustrated in Figure 52 (a). This concept lays in the fact that two cast glass bricks are connected through a titanium rod with a protrusion and a niche which has the same height as the cast glass brick. The connection is bolted firstly in the threaded interlayer between the connection and the cast glass brick, and then interlocks with the connection below. This served significantly the ease of assembly since there is no need for extra bolts yet would have the same visual impact as the additional supportive substructure in the Optical House.

By isolating the "female and male" segment of this connection, the first concept concluded with a bolt which connects the two interlocking parts, ensuring in this way the structural efficiency of the system. The access occurs through a notch created vertically under the connection (Figure 52-b). Moreover, such an operation would not follow the established principle which encountered in the beginning of this chapter. Therefore, a novel solution considered as more appropriate.

According to Oxford dictionary:

**Magnet *(noun)*:**

"a piece of iron that attracts objects made of iron towards it, either naturally or because of an electric current that is passed through it"

Accordingly, the idea of the magnets assists perfectly in the interlocking of the system.

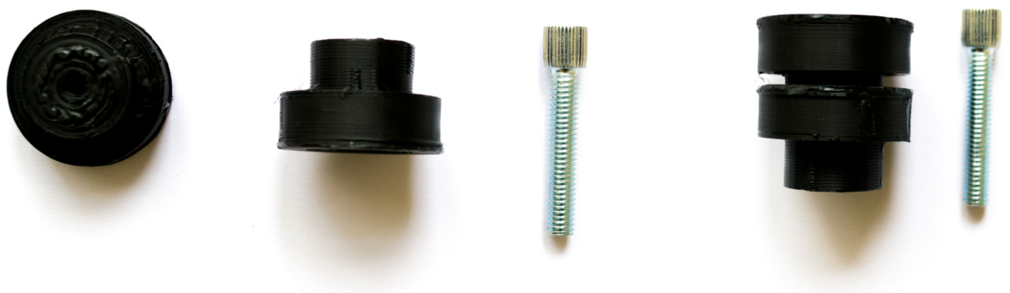
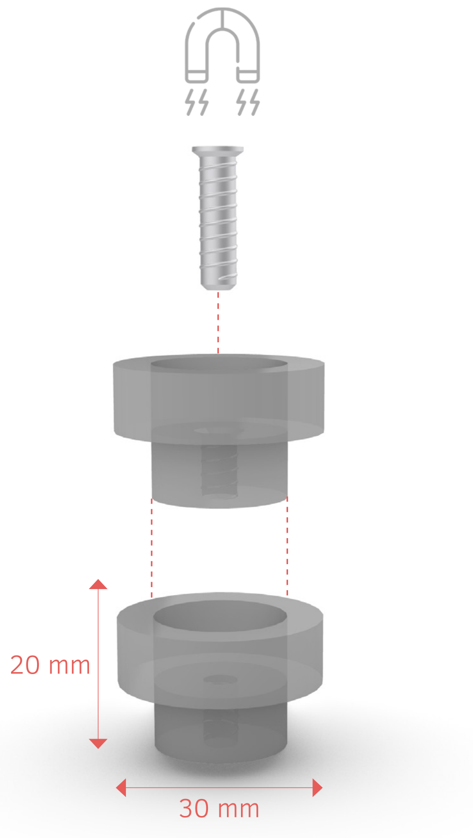


**Figure 53:** 3D-printed mock-ups of the first concept.

In the construction industry and especially in the wood joining, the Invis Mx2 developed by Lamello is a magnet-guided joining fittings. The components, in this case the wood units have no visible slots, can be easily demounted and re-assembled via its magnet drive. The MiniMag (see Appendix) is then attached to the drill and operates a rotations on the wooden surface near to the connection with a clamping force of up to 250 kg per connector (Lamello AG Joining Technology, n.d.).

Concluding, the first concept would be operated with the same principle as the Invis Mx2. A bolt would be magnet – driven from outside and the system would be successfully interlocked while it would guarantee for its structurally efficiency. It is a connection with circular cross section which reminds slightly a countersunk fitting. Concerning the dimensions, a first approach with 20x30x20 mm (w x l x h) as it is illustrated in Figure 54 and Figure 55 is proposed.

However, does it follow all the design criteria?



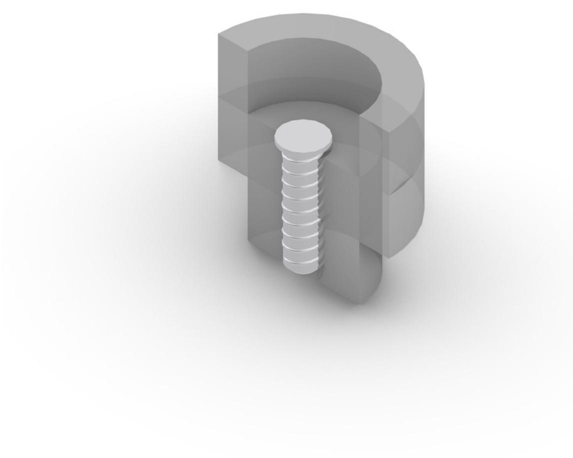



**Figure 54:** Left: Exploded view of the connection with a first approximate dimensioning.

**Figure 55:** Right: Section illustrating the interlocking between the glass bricks.

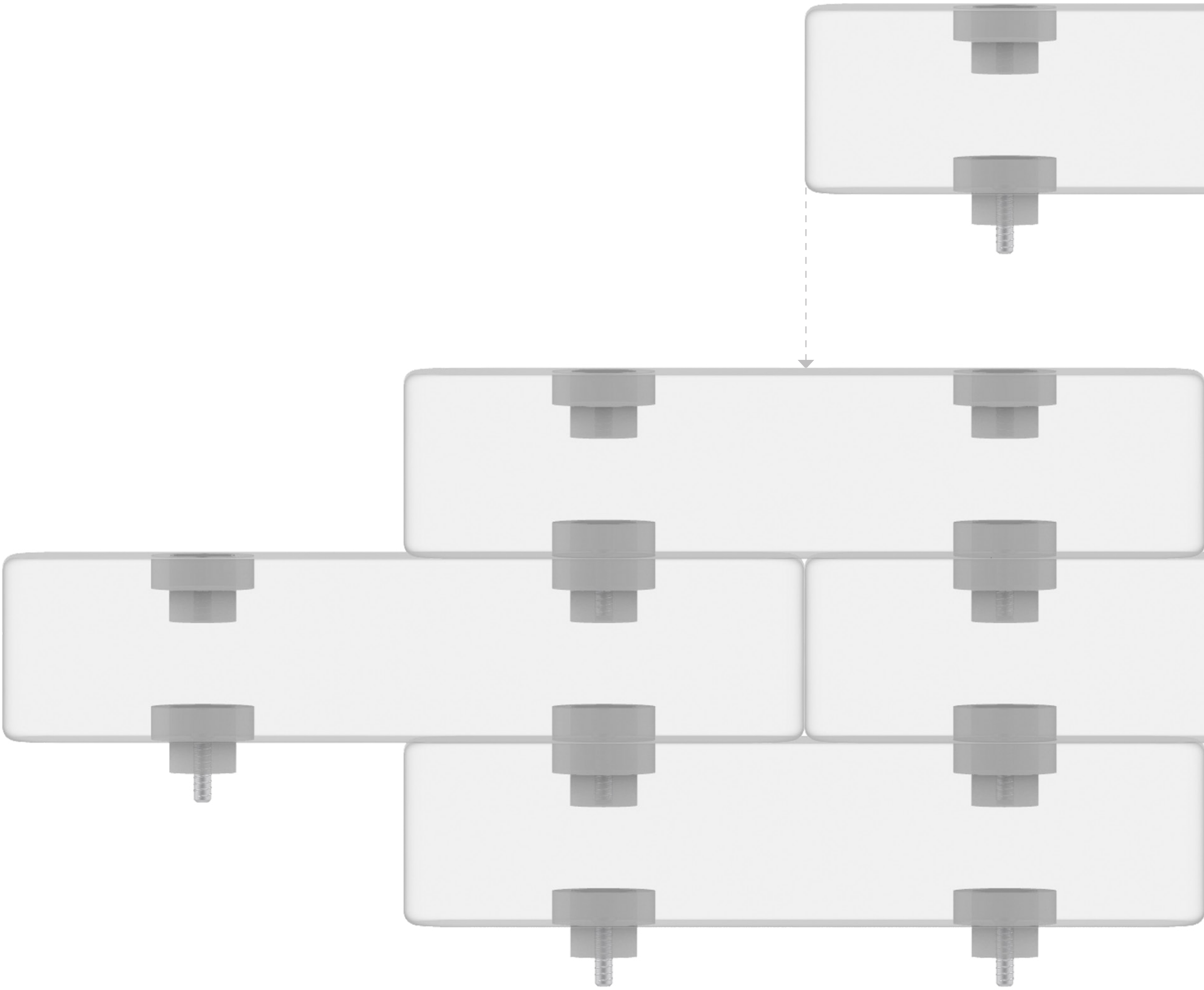
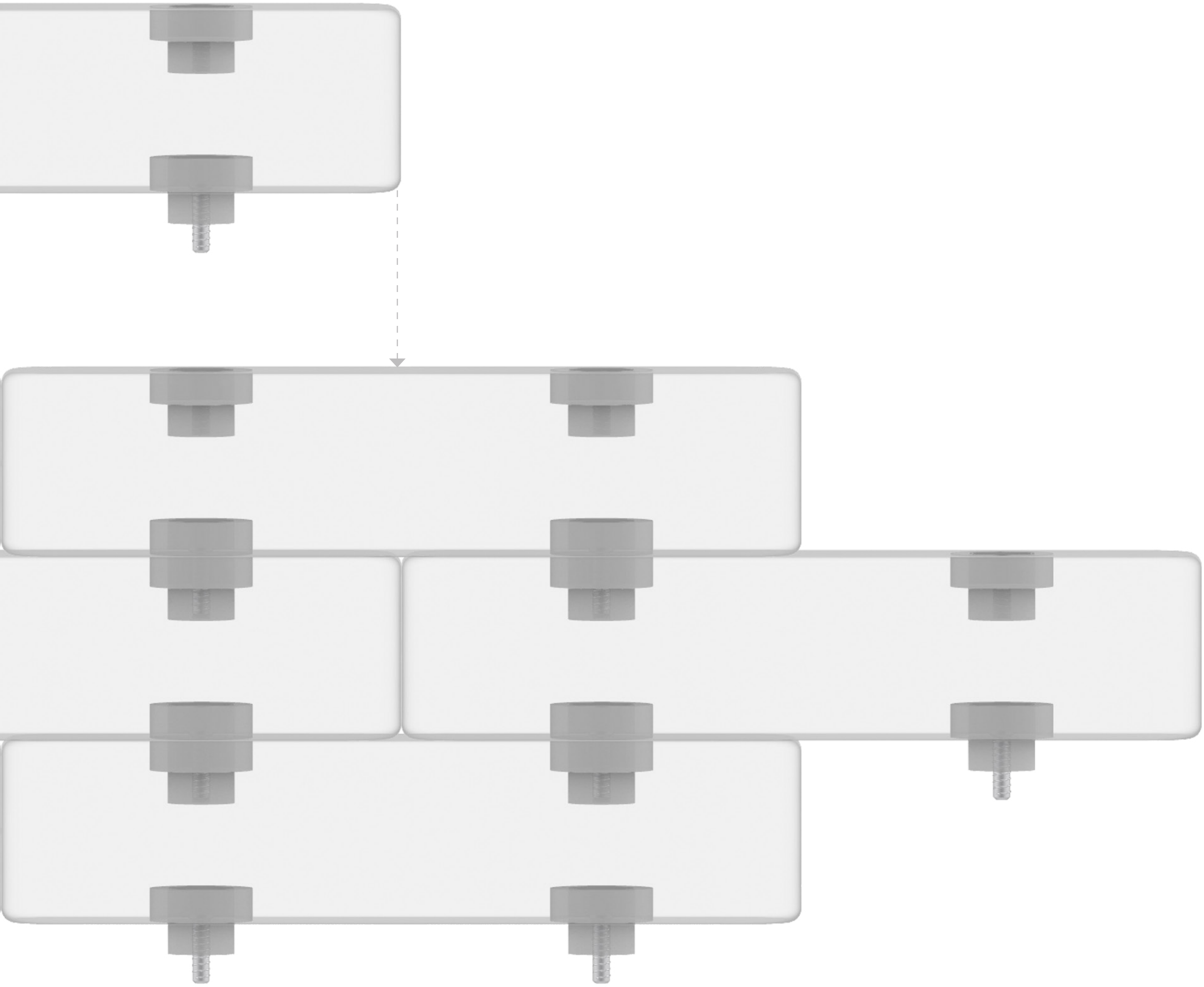


**Figure 56:** Cast glass units assembly of the first concept.



# 7.3 Second concept - Locking mechanism

Cast glass have emerged in the built environment as a very competitive material, as it stands as an innovative solution against brittleness, shape and thickness limitations imposed by float glass. Hence, in an attempt to conform with this novelty along with the desire for new ideas, the ambition for a novel design in the connection established as well. In contrast to the first concept, this endeavour targets to introduce a new system which performs more effectively in assembly and disassembly while it imprints minor visual impact.

Undoubtedly, a mechanism which would contribute to an easily assembled component, without the need of bolts or access from outside, is a locking mechanism. In the engineering world, locking mechanisms are widely applied in automotive, aeronautics, space, nuclear or renewable energy. Furthermore, locking mechanisms are significantly employed in architectural applications for easily securing, adjusting and locking components.

These systems constituted an inspiration for the second concept. In addition, their already application in the built environment would guarantee for their structural efficiency.
The second prevailing concept borrowed the locking idea from a system in which three stainless steel balls lock the system with the use of a piston and access from above (Figure 57,left). Since, the access from the side of from above does not follow the design principle established in the beginning of this chapter, **gravity** and **magnets** have been selected as the two main parameters of this design concept. Gravity would assist in locking the stainless-steel balls while the use of magnets would provide an easily disassembly of the structure.

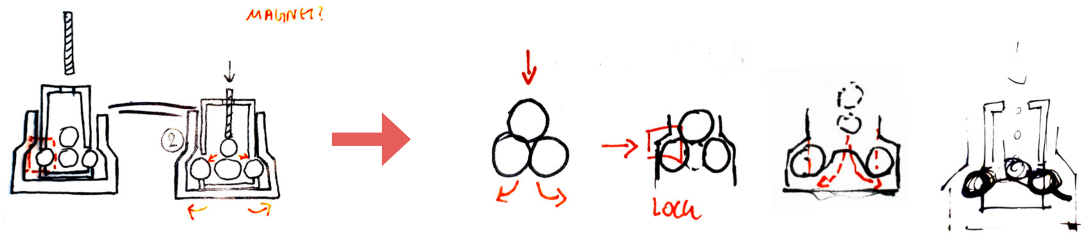


**Figure 57:** Left: The mechanism which already exists in the market. Right: The embedded connection concept.

The development of this concept has been quite a challenge during the design process, since assorted concerns and thoughts have been arisen. These concerns were related to the locking and unlocking efficacy of this connection. Moreover, the structural effectiveness of this connection especially because the selected case study is in Hiroshima, in Japan, a country which always experiences severe winds and earthquakes have constituted a major concern as well.

More specifically, the design development of this concept based on the following considerations:

1. In case of any motion (lateral loads), will the system be still locked?

2. Will the balls roll effectively in the “correct” path each time?

3. Are we going to have a successful disassembly (unlocking)?

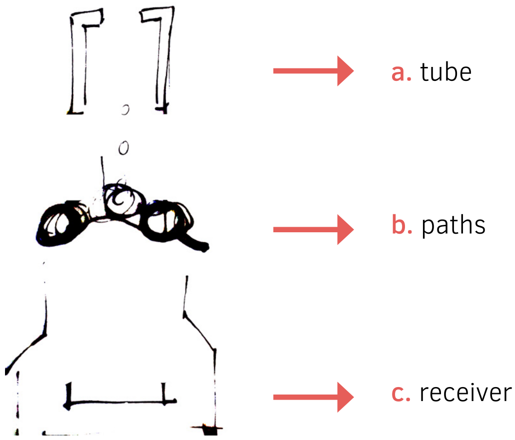



**Figure 58:** Preliminary sketch of the concept. Exploded view.

The evolution of this concept based exclusively on these considerations while the design has been divided in three parts as it is illustrated in Figure 58, a exploded view of a preliminary sketch of this idea.

a. The tube or shank is the part which will locate the balls after the uplifting. In this case, the geometry and especially the width of this part will play an important role since it needs to ensure that the balls will not be lodged while the geometry will assist the balls to "roll" in the correct path and eventually lock.

b. The curved paths have been a challenging part of this concept. In this case, this segment seeks for the most appropriate inclination, so the balls will roll effectively during the lifting while its geometry will reassure the accurate location of the balls after their releasing from the magnet. Besides, their design needs to ensure the structural efficiency against lateral loads.

c. The receiver is the segment which will interlock with the upper part (shank and curved paths) while the inner section will be designed in a way that it would "receive" the rolling stones and eventually lock the components.

Answering the considerations stated above constituted the trigger point of the design procedure.

**Consideration1:** In case of any motion (lateral loads), will the system be still locked?

The answer is yes. The design of the curved paths is at a rotational distance of 120° (Figure 59). Basically, it follows the same principle used in tripods for photography. This arrangement will provide stability against horizontal and vertical forces while it will secure

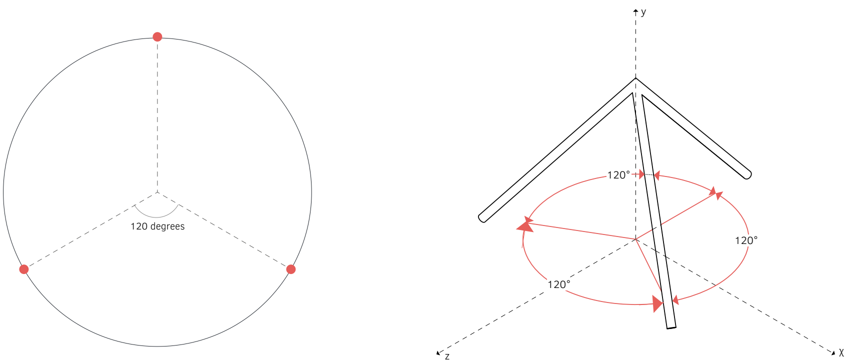



**Figure 59:** Explanatory diagrams illustrating the arrangement of the curved paths

from moments around the horizontal axes.

**Consideration 2:** Will the balls roll effectively in the “correct” path each time?

The answer is yes. For this part, the investigation based on two alternatives.
The first alternative incorporated two balls in each path, six in total. This alternative would ensure that each ball will be in the correct path while from a structural point of view, in any downward forces the weight of the second ball would assist to maintain the system locked.

Experimenting on various inclinations (Figure 60), a 30° angle considered as the most appropriate.

The second alternative included four balls in total (Figure 62 - left). The balls are distributed from the shank, rolling in their spot while the fourth ball is pressing the three balls beneath. Each path is designed with a length that could host only one ball, a principle which ensures that each ball would be in the correct path each time.

(Figure 62 - right) represents a preliminary physical testing with modelling clay and plastic balls that carried out and contributes to better comprehension of the concept.

In contrast to the first alternative, the considerably smaller diameter of the paths encountered two aspects: Firstly, it would assist to a minor visual impact which is preferable, since seeking for less compromised transparency is on of the key aspect of this master thesis. However, it is ambiguous if the four balls would ensure for a locked system, since in any possible vertical loads it would not be adequate to maintain the rest of the balls locked in their locations.

Concluding, in each alternative, every path is designed in a way that the end of the segment offers an horizontal location for the ball to lock, long enough so half of the ball would be inside the one part of the connection and the rest inside the receiver (Figure 63).

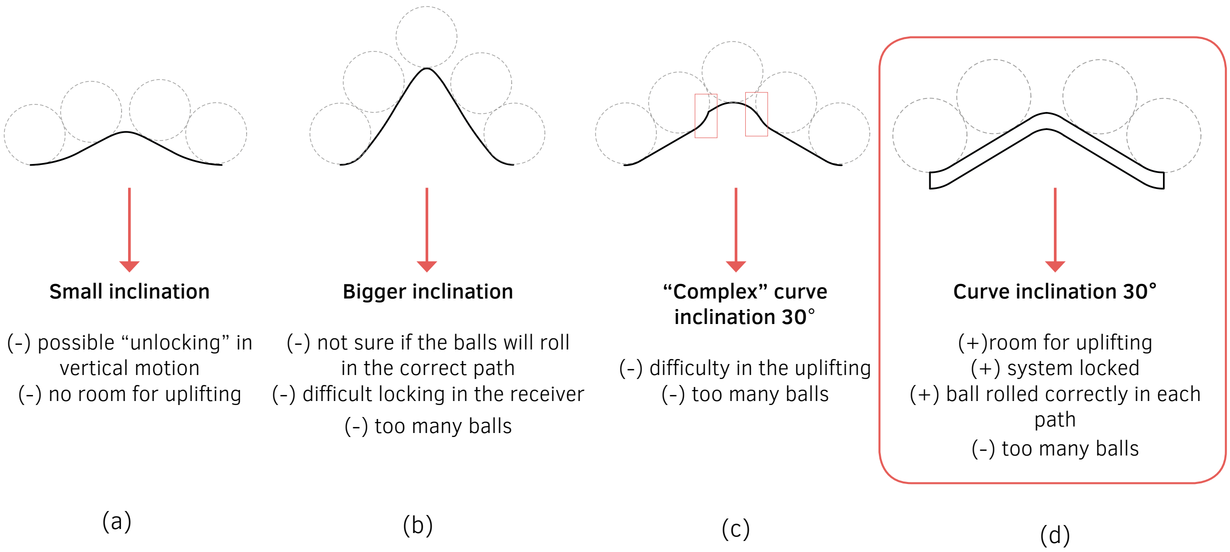



**Figure 60:** Illustrations (a-d) provide an insight on the multiple configurations concerning the design of the paths. The (d) considered as the most appropriate.

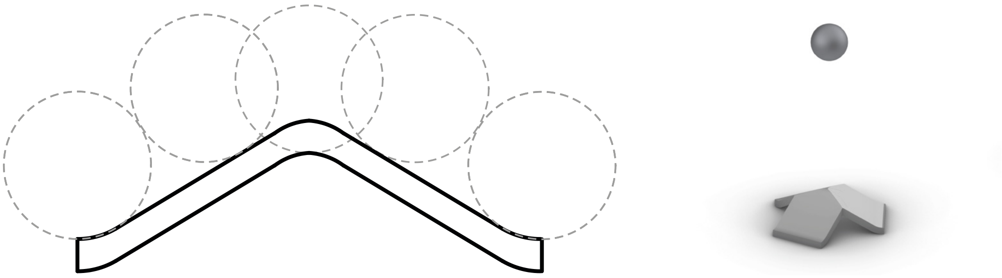


**Figure 61:** Left: Section of the first alternative with the six balls. Right: Animation of the rolling balls.

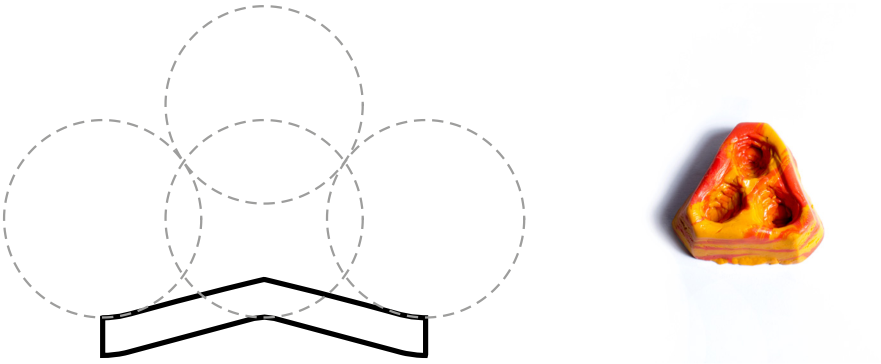


**Figure 62:** Left: Section of the first alternative with the four balls. Right: Animation of a preliminary mock-up representing the way the balls roll to their spot.

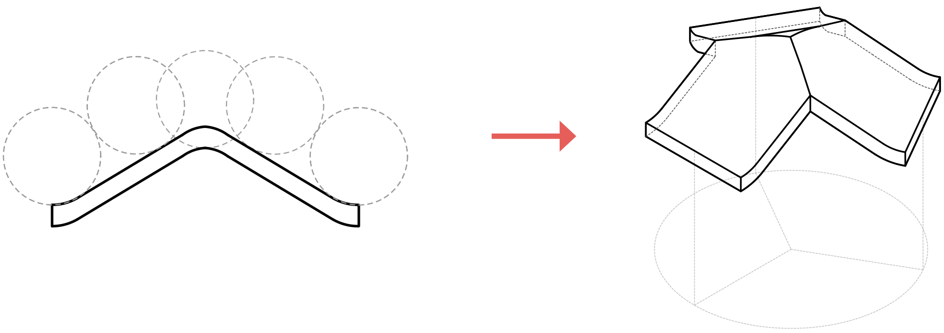


**Figure 63:** From left to right: Design evolution of the lower part with the curved paths from 2D to 3D.

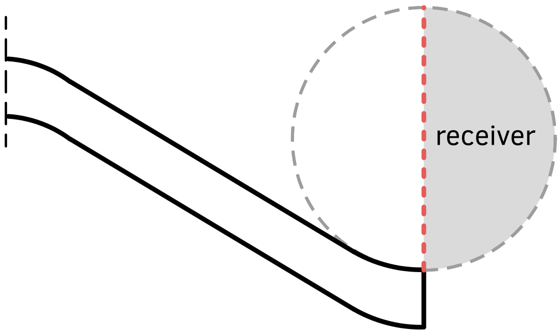



**Figure 64:** The settlement of the balls between the connection and the receiver.

**Consideration 3:** Are we going to have a successful disassembly (unlocking)?

The answer is yes. This part of the design incorporated various physical experiments, firstly with basic materials such as modelling clay, plexi glass and plastic balls. These experiments assisted significantly in the design process of this part, since two basic observations have emerged:

1. Need of adequate space in vertical direction between the shank and the paths

2. Need of adequate space in horizontal direction for successful uplifting.

The successful disassembly translates into the condition where the balls will roll effectively upwards during uplifting when the magnet will secure them, and instead they will not be lodged. This condition will lead to a successful unlocking. For this reason, the design embodies the idea of the gradual delay (Figure 66) in the uplifting. This involves that the inner section of the tube is designed with three different inclinations, which in - the uplifting state – each ball will be in different location each time and gradually will be uplifted correctly inside the tube. Besides, this part should be designed in a proper way, that the balls would roll correctly in the paths after the demagnetisation.

Based on the multiple configurations stated above concerning the segments of the connection, the design of this concept progressed with the first alternative which encounters six balls in total and an inclination 30° degrees in the path. The design of the tube settled down after two more physical experimentations which incorporated stainless-steel balls and magnets. The way the balls collaborate with the magnet was the posed issue.

It should be mentioned that the first designs included stainless steel balls of 8 millimetres diameter. Moreover, this diameter would lead to a tube with considerably great length which translates into an intrusive connection. For this reason, the design progressed with six stainless-steel balls of 6 millimetres diameter.

The second physical testing carried out with a plexi glass, a magnet and stainless-steel balls relieved that when magnet force occurs, the stainless-steel spheres line up immediately in a vertical direction. This encounters that possibly, the different magnitude in the inclinations would not be necessary.

Hence, the final inclinations of the tube have arisen after the third physical testing which included three different types of inclinations: the first alternative with a magnitude of 30°-40°-50°, the second alternative with a magnitude of 40°-45°-50° and the third alternative

(a) (b) (c) (d) (e)

**Figure 65:** First physical experimentations with modelling clay and plastic spheres. Due to lack of a magnet , gravity was the leader of the experiment. (a) **test 1** with circular diameter: rotate the model, only one ball fell, (b) section photo of the adjusted clay, more open tube, (c) **test 2** better, at least the balls “tried” to fall (huge friction from clay), (d) **test 3** adjust more the clay, second ball fell, (e) after many test better results but better expected from a decent test with a magnet.

with same 50° degree inclination above each path.

The physical testing (Figure 68) proved that all the alternatives are feasible. However, the second selected as the most appropriate since, the balls responded successfully when the magnet secured them while in the first and in the third alternative the balls uplifted but with some complications. These included extra attempts placing the magnet in various locations around the connection or in some cases one ball out of the six remained in its initial position. Without a doubt these deficiencies would affect the final assembly and disassembly of the structure.

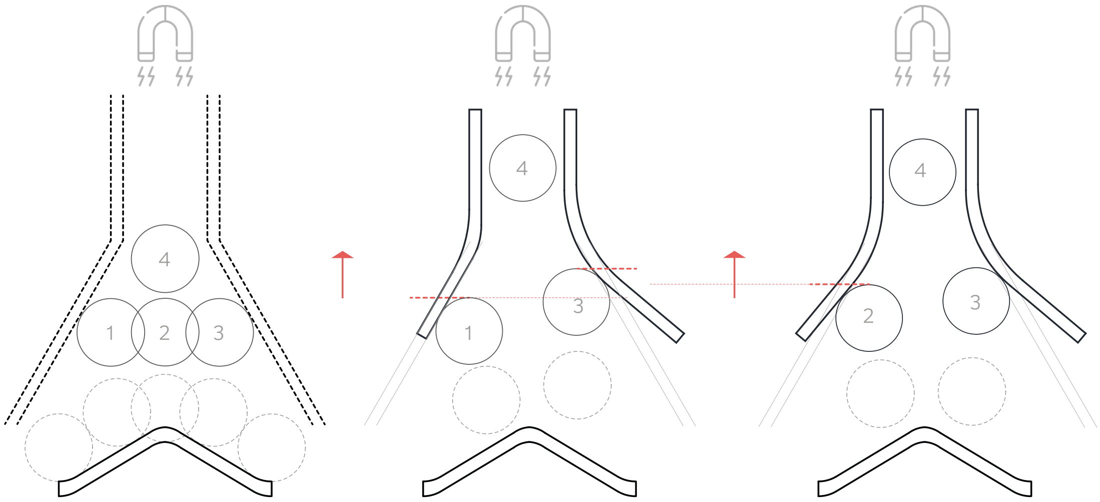



**Figure 66:** Explanatory diagrams of the gradual delay idea. Due to different inclinations the spheres are "forced" to uplift. In these diagrams the tested incilinations are 30°-40°-50°.

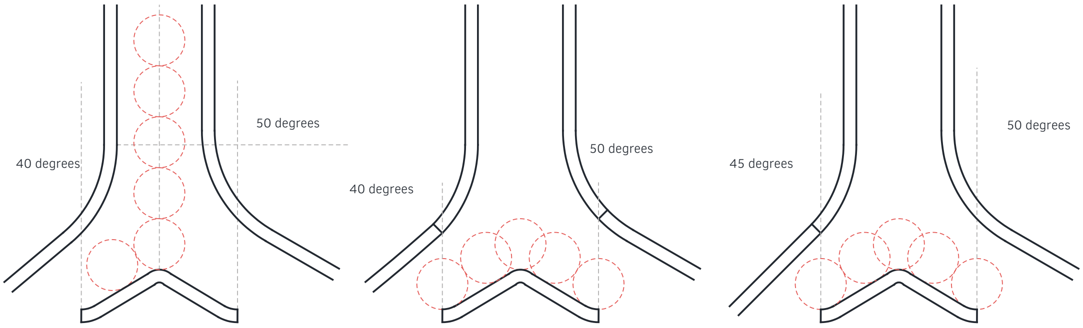



**Figure 67:** Left: The expectation during uplifting! Middle and right: The chosen inclinations and the location of the spheres when the system is locked.

**Figure 68:** Left: Photo of the first alternative 30°-40°-50°. Middle: Photo of the second and selected alternative with the 40°-45°-50°. Right: Photo of the third alternative with the same inclinations in the inner section.

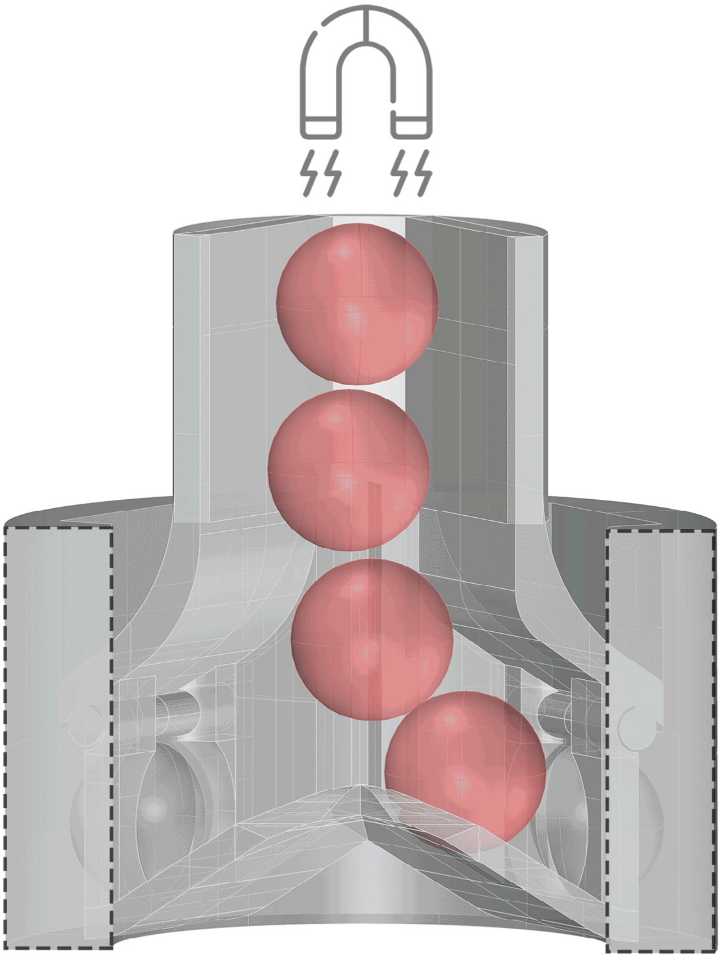


**Figure 69:** Locking between the tube and the receiver. At first, the balls are secured with the magnet.

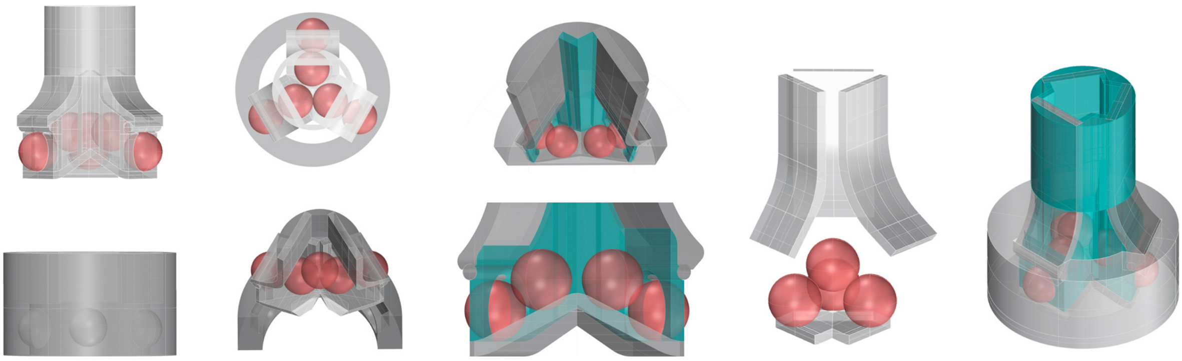


**Figure 70:** Various 3D - configurations before the final selection.

# 7.4 Assessment of the two prevailing concepts

During the design procedure an overall assessment on the established design criteria between the two prevailing systems considered as appropriate in order to select the dominant concept. The results of this evaluation are presented in (Table 7). Undoubtedly, the second concept, named Rolling in Transparency, outclasses the first one in the easy assembly criterion and in novelty while in the rest criteria perform equally. Moreover, even though the economic aspect is out of this research scope, the cost also included as well in the overall assessment in case there is a further development.

Concluding, concept two, the locking mechanism is selected as the most prevailing for this project. In the next chapter, the final designs are presented.

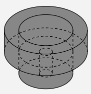
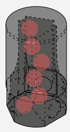
| Concepts / Criteria | Easy Assembly | Transparency | Novelty | Structural Efficiency | Cost* |
|---|---|---|---|---|---|
| 1: Bolting the Transparency  | + | + | + | + | ++ |
| 2: Rolling in Transparency  | ++ | + | ++ | + | + |

**Table 7:** Assessment of the two concepts according to the established design criteria.
*Note: The economic aspect is out of this research scope. The concepts assessed in this criterion in case of a further development.

# 7.5 Conclusions

Design an embedded connection in cast glass units is undoubtedly a very challenging task. When it comes to connections, cast glass elements present a very different philosophy than what already exists in float glass or in different materials. From what it has been derived from this design development is that, in order to preserve the mechanical properties of cast glass respecting in the same time the design criteria, novel principles are rendered as more appropriate. A system with no access from outside through the cast glass considered as the most suitable in order to achieve this thesis's goals. For this reason, a locking mechanism magnet driven from outside is the most prevailing concept for design a small-scale embedded connection in cast glass components targeting to a greatly easy to assembly system which is reversible and structural predictable.

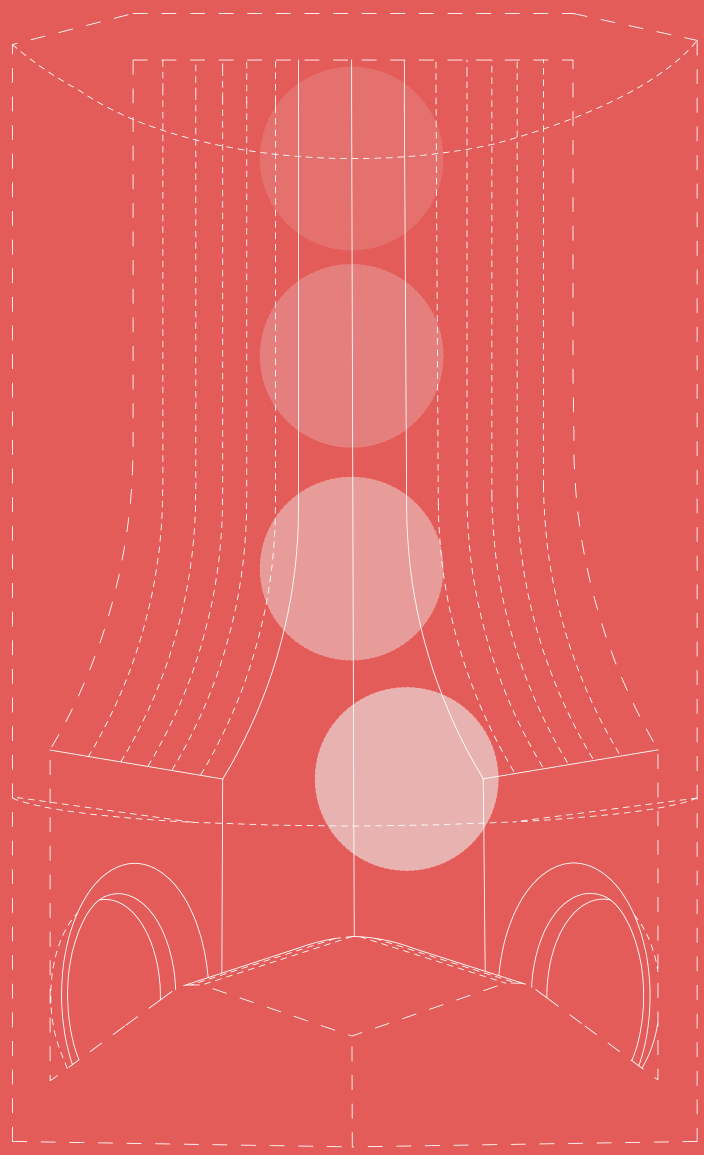


**Figure 71:** Small overview of the embedded connection. This illustration gives a first comprehension of the final geometry.

# 8 Final Design

Ensuing the whole brainstorming, the physical experimentations with the mock-ups and the design development resulting eventually, this chapter presents the final proposal of the embedded connection.

Respecting the established design criteria, the first impression is a very clear and elegant geometry on the outside with simple lines and curves. This will ensure that less peak stresses will be concentrated around the connection, while it will not affect the visual result significantly. Moreover, beginning from the top, this connection encounters three different inclinations in the inner section of the tube 40°-45°-50°, three paths with 30° inclinations and developed in a rotational distance of 120°.The receiver is designed in a way that the half part of the balls will be nested there while the other half will be inside the connection. This condition will ensure that the system will be locked. It should be mentioned, that these specific inclinations in the tube have been selected not only because they achieved an accurate and immediate uplifting but also, they eventuate in a second locking of the connection. This locking has not been predicted during the design development but was an accidental, yet pleasant discovery during the 3D-printed physical testing.

Concerning the dimensions, the total length is 36 mm including the interlocking of the connection with the receiver. The total diameter of the connection is 22 mm while the receiver designed with a diameter of 30mm. The inclined paths have a total width of 10mm, wide enough to allow the balls to roll but also not to get stuck. The total dimensions decided not only for functional reasons (have successful uplifting and locking) but also considering that this connection should imprints the minimum visual impact on the glass wall. Hence, the drawings in the following pages illustrate the design explicitly.

As it is discussed in previous chapters, to avoid any movements from lateral loads two connections will be embedded on the longitudinal side of the cast glass brick. The receiver will be fully nested on the upper part of the brick while the one third of the connection which is placed on the lower part of the brick will not be embedded in order to interlock with the embedded receiver in the cast glass unit below.

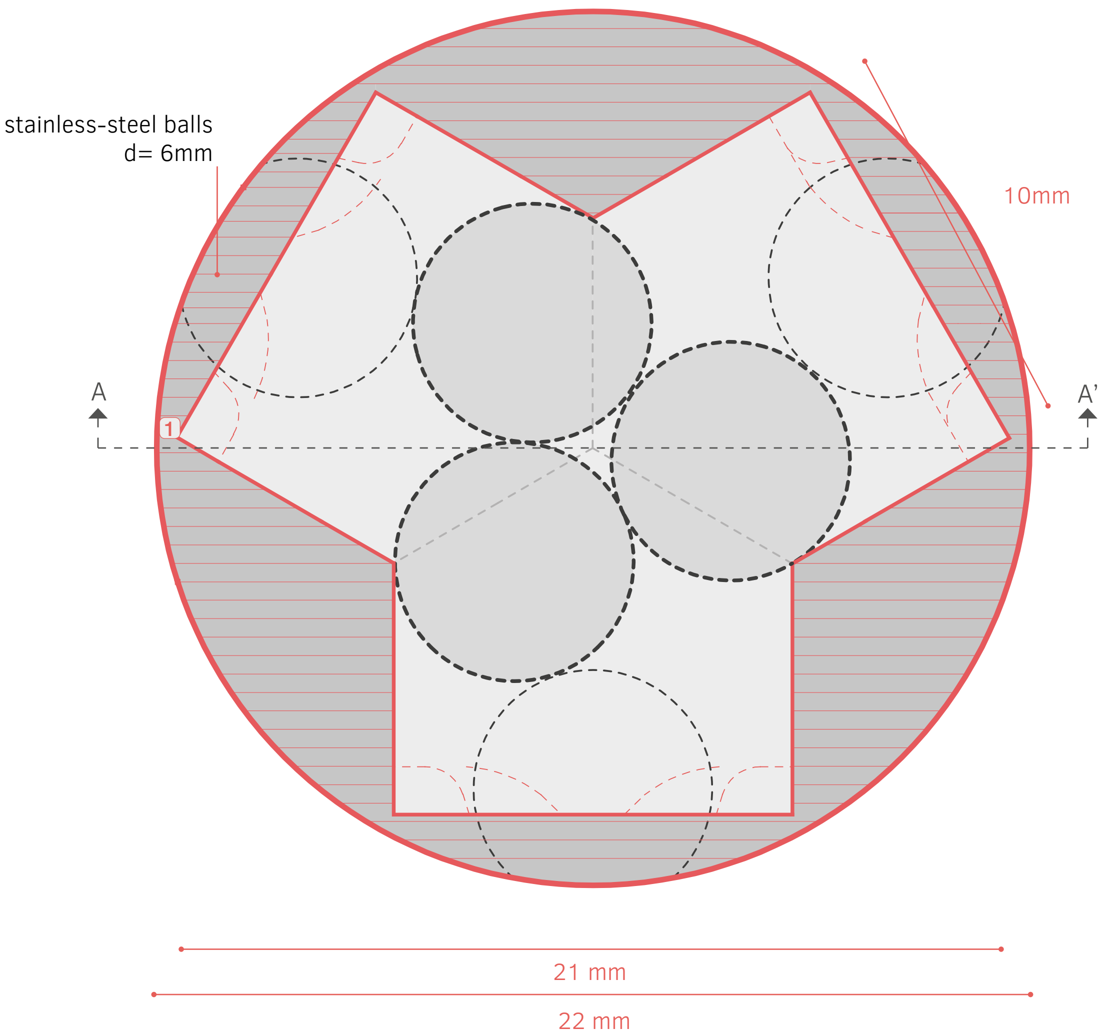
Prior to the assembly the stainless-steel balls are secured with a magnet. At first point, the system achieves a motion restrain when the connection and the receiver interlock. After the magnet is pulled out, the balls “roll” and lock the system. However, the assembly order will be analysed more in Chapter 10.2.

**Figure 72:** The 3D-printed mock - up, a neodymium magnet and stainless-steel balls assisted to the decision of the final design.

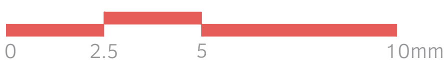
# Plan View

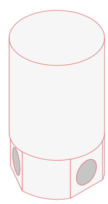
## Connection (upper part):

The design based significantly on several physical testings with basic materials, which gave an insightful idea how this system could work.




• 1: This part offers a first locking when the interlocking between the two parts occurs. It also helps to restrain from any rotational movements due to lateral loads.

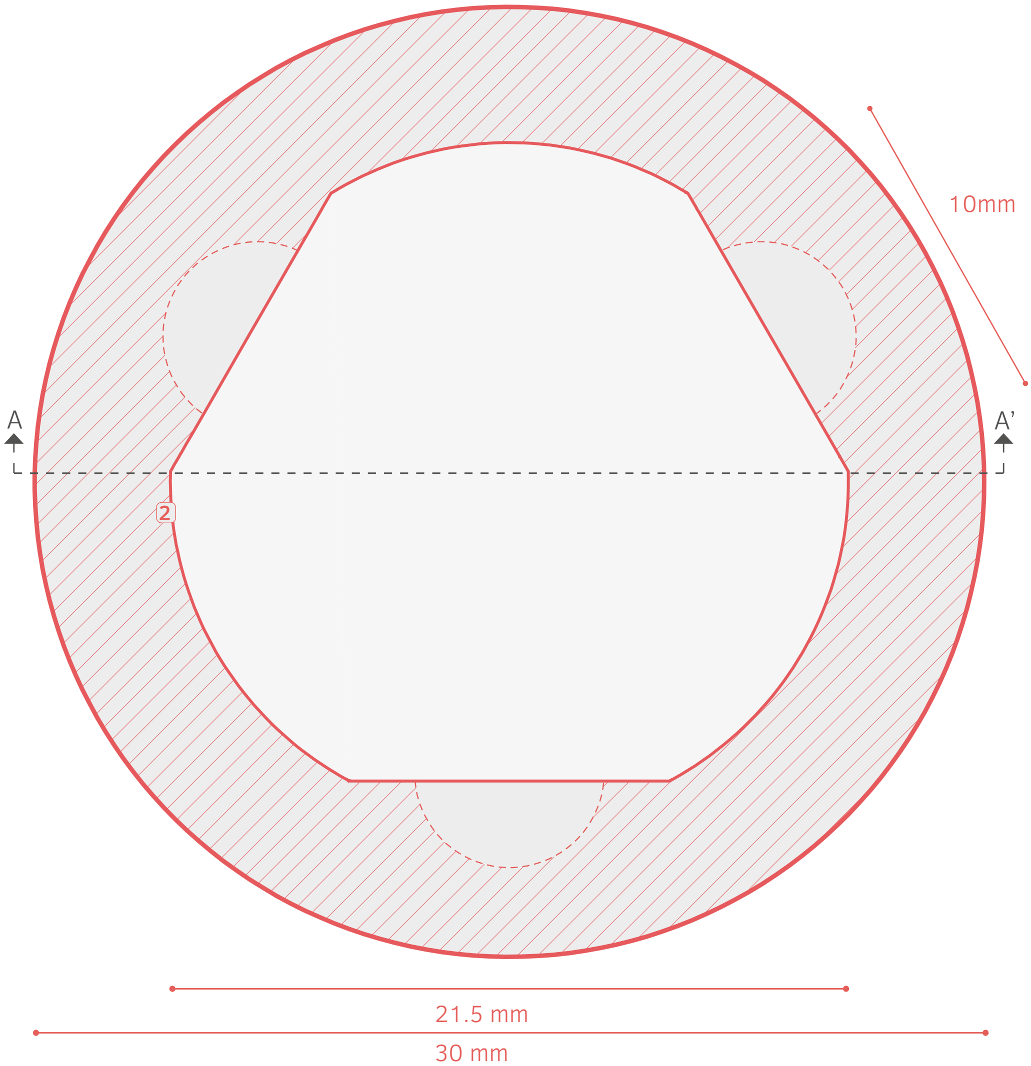


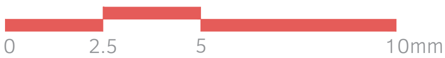
## Plan View

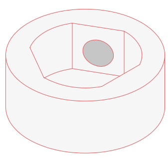
### Receiver:

The design derived from the low part of the connection, where the curved paths have been evolved. The 3 hemispheres have the same diameter as the stainless steel balls, so to nest them during locking. Although, for the 3D printed physical experiments the hemispheres designed 0.2mm wider.




• 2: The section has been selected in a way that the inner line (which is 0.5 millimetre wider) to be identical with the bottom part so the connection can interlock successfully. The outer respecting the principle of seeking for a simple design that could assist to transfer the loads homogeneously and imprints minor visual impact.

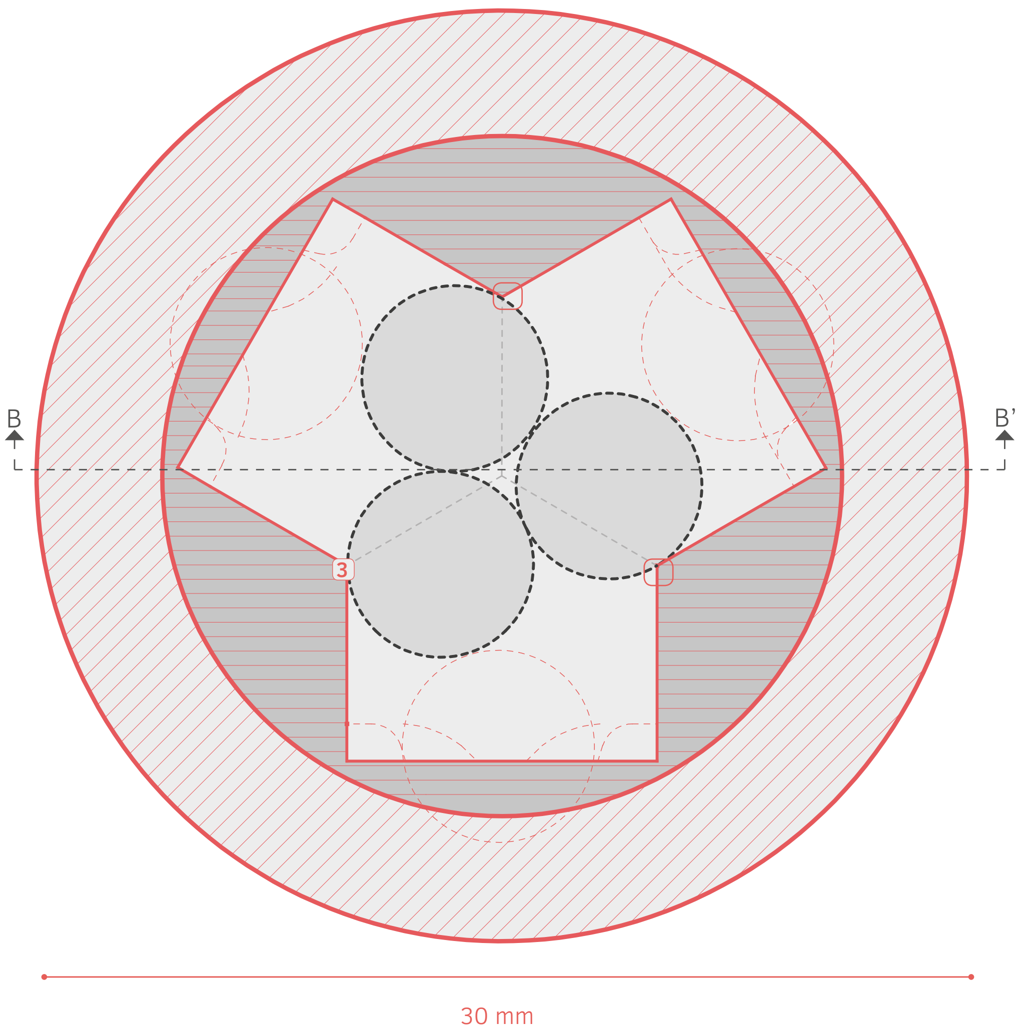


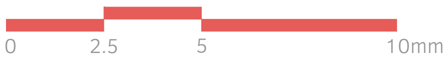
## Plan View

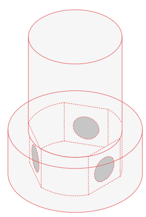
### Interlocking:

This drawing gives a full comprehension of how the system is locked in a plan view. Half of this sphere lays inside the receiver while the other half is inside the upper part of the connection. This guarantees that the system is locked.



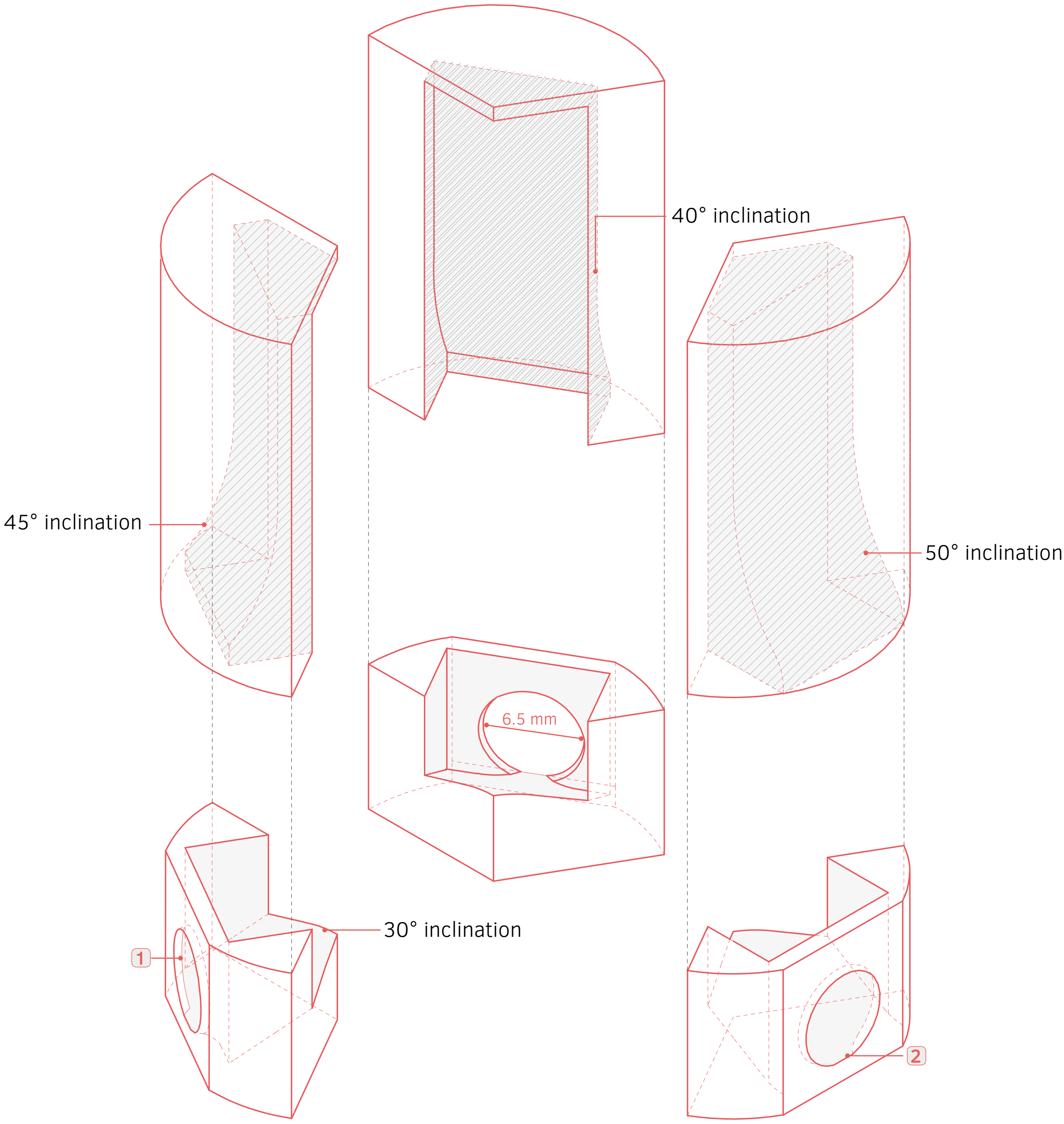

• 3: The extra locking occurred from the chosen inclinations, the design and of course from gravity! The overall geometry assists the three balls on top to rest slightly some degrees on the left and lean on the inner walls. In case of any vertical movements this locking will provide an adequate structural efficiency, since their weight will keep the spheres beneath to stay in their initial spot. This principle actually was the reason why the design progressed with six "rolling stones" instead of four. And the mock - up proved its feasibility.



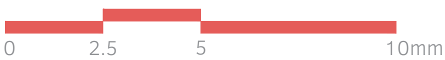
## Exploded view: Tube

Exploded isometric view of the upper part of the connection. This drawing gives a clear overview of the three different inclinations in the tube and the 30 degrees inclination on the bottom part.




•**1**: This opening designed with a diameter of 6.5 mm, 0.5mm wider from the one balls have. This guarantees a freedom to tolerate with misalignments during manufacturing.

• **2**: This is the only part which is in horizontal alignment and was discussed in the previous chapter. It is the part in which the ball settles between the receiver and the upper part after rolling.

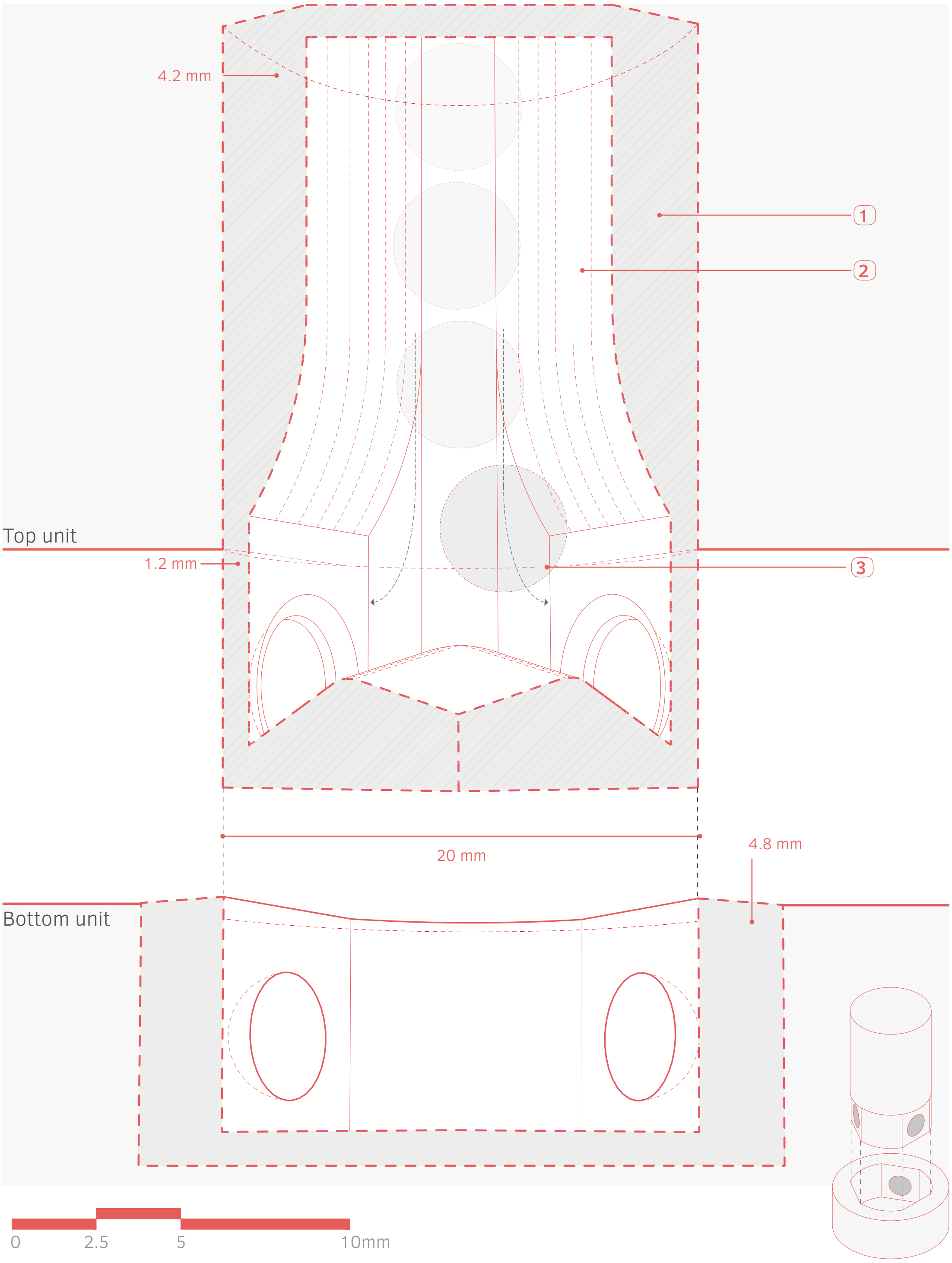


# Section A-A'

## Connection: Unlocking position

Transverse cross-section of the system. The faded balls give an overview of how the balls fall and lock the system. Once the balls are uplifted, the system can be easily disassembled and unlocked.

- 1: Tube
- 2: Different inclinations allow for successful uplifting (and disassembly).
- 3: Set of stainless-steel balls

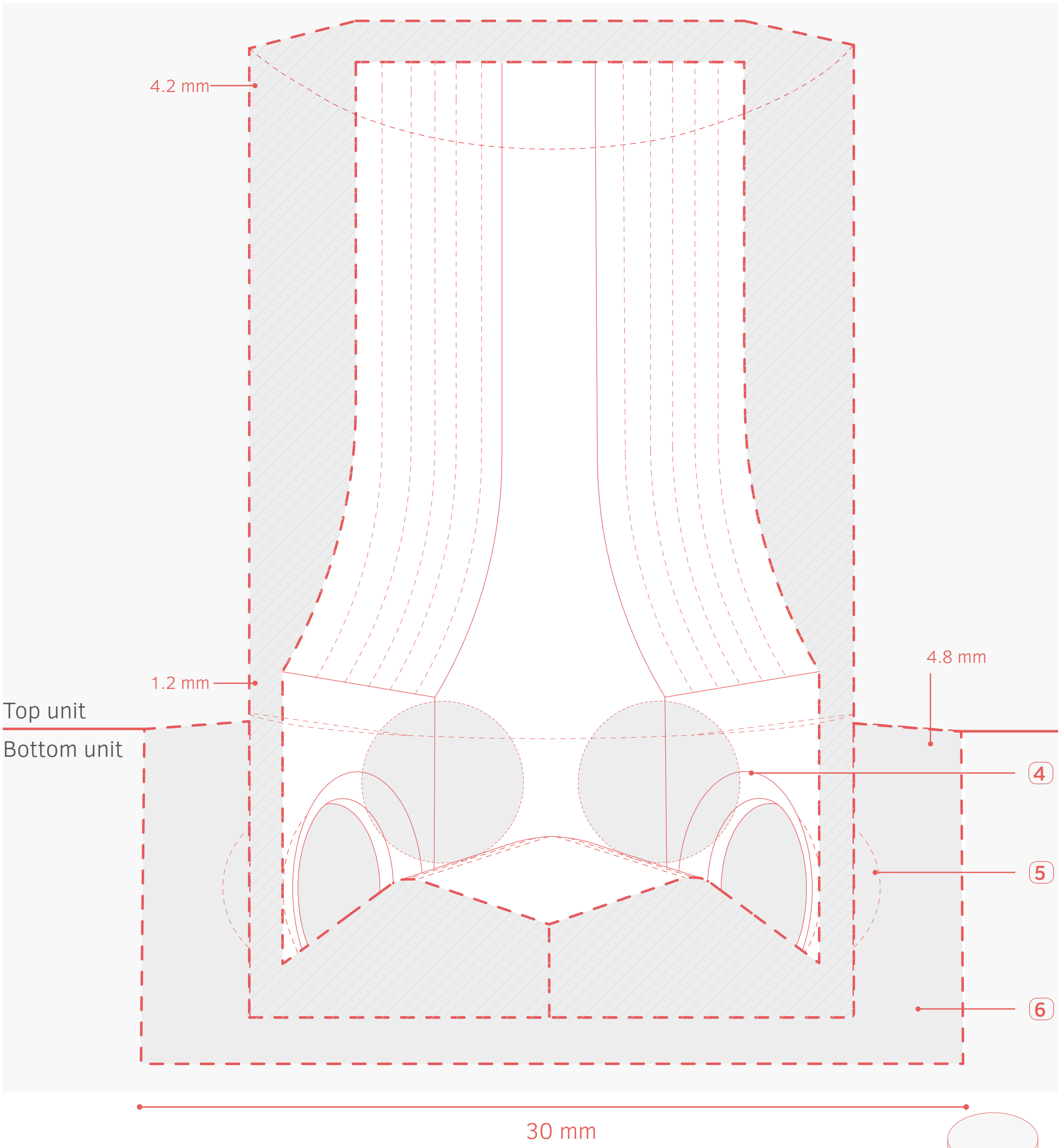


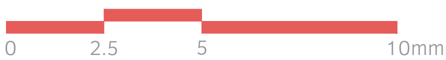
## Section B-B'

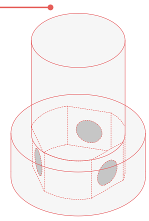
### Connection: Locking position

System is locked. The inner section of the tube is designed in such a manner that the balls will always end up to the desired location. The balls' location partially in the tube and partially in the shank locks the two pieces together.

• 4: The inner curves of the opening designed with a diameter of 7mm. The inner walls were filleted with a magnitude of 20mm  to ensure that the ball will not lodge in the upper part before locking with the receiver.
• 5: The inserts at the receiver are matching the diameter of the stainlesss steel balls.
• 6: Receiver



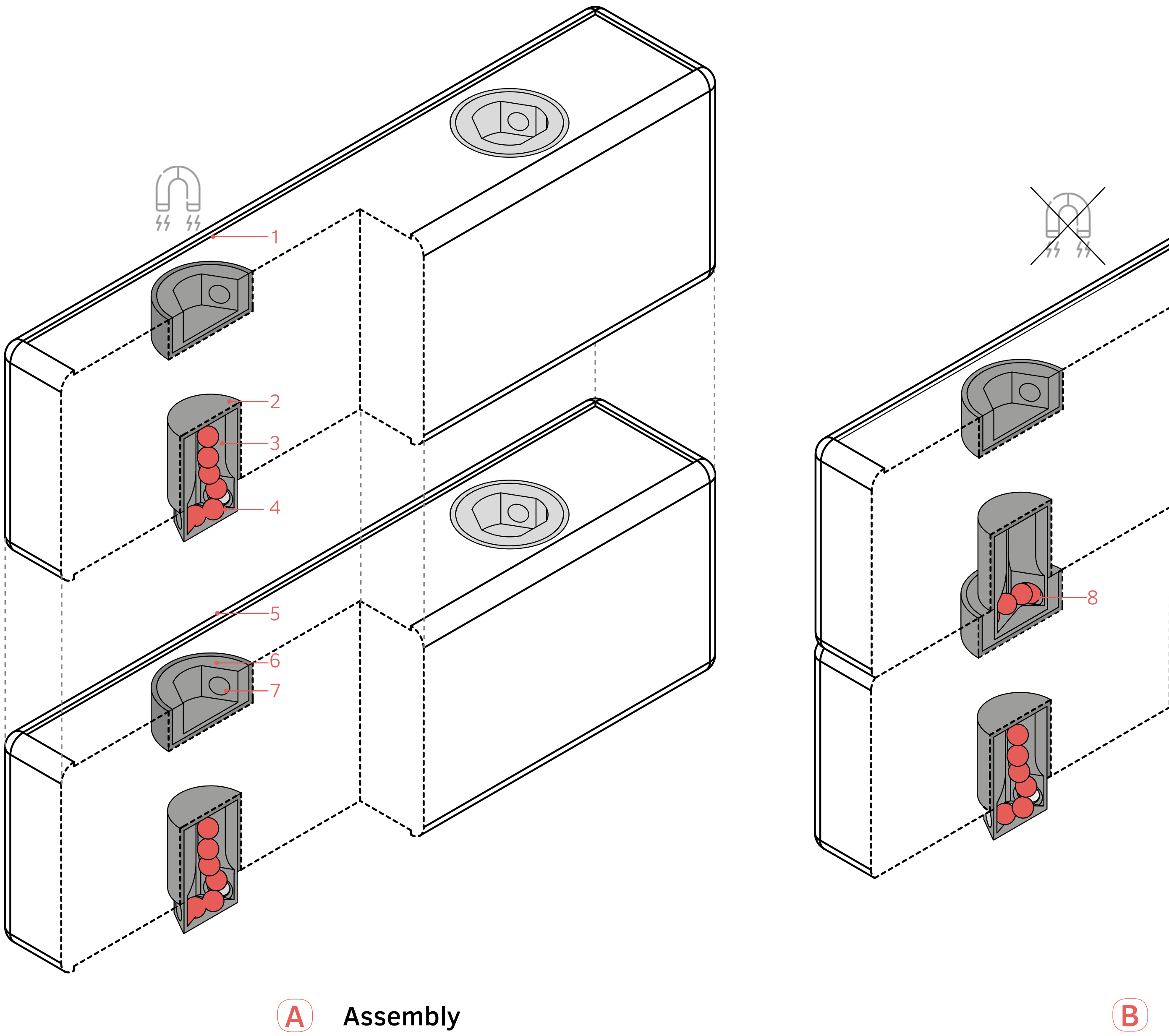



## Assembly and disassembly sequence of the novel connection:

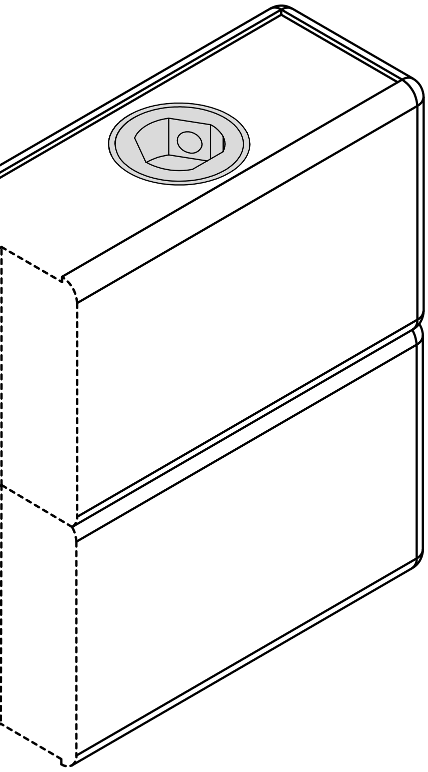
### Conditions:

• A: Once magnetic field is activated, the stainless-steel balls are charged and are uplifted in the tube.
• B: Condition where the magnetic field is de-activated and the stainless-steel balls drop to the desired locations and lock the system and accordingly the two units together.
• C: During the disassembly the stainless-steel balls are uplifted contributing to a successful unlocking of the system.

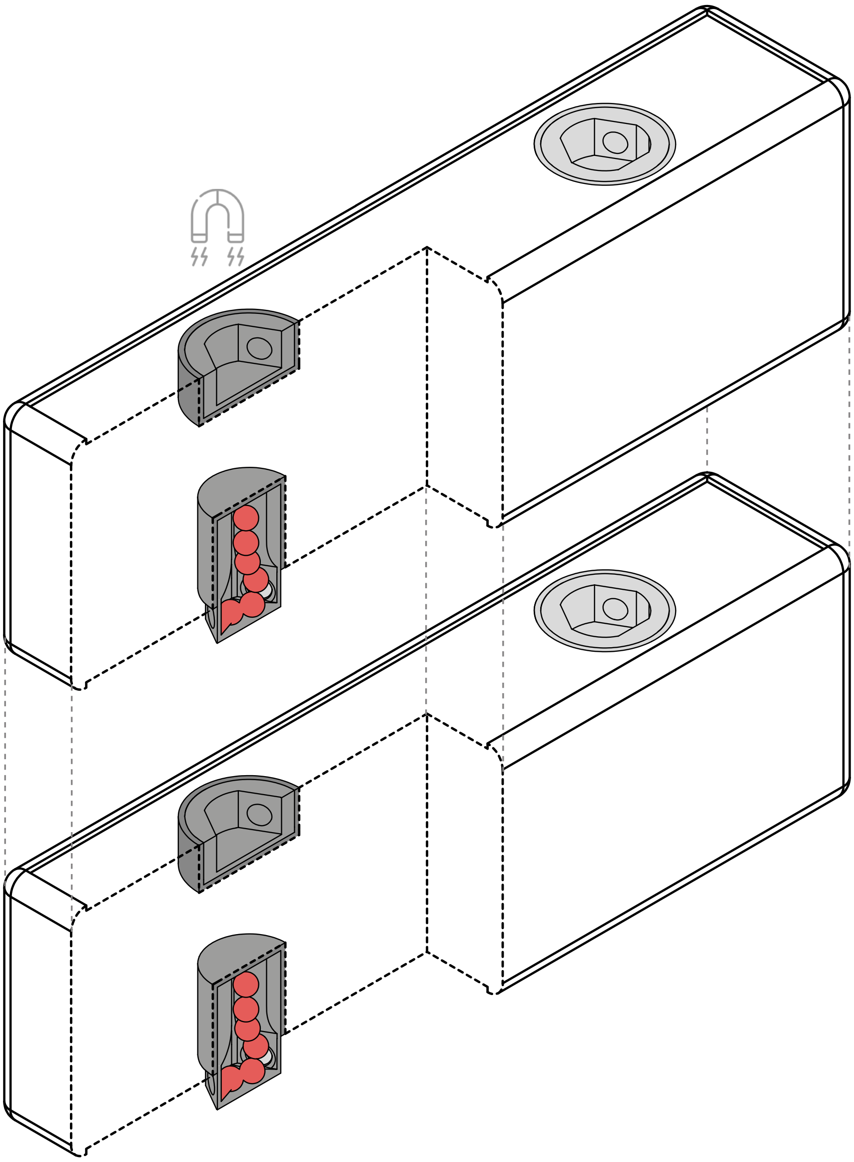


INDEX

1. Top unit
2. Tube
3. Different inclinations allow for successful disassembly.
4. Set of 6 stainless - steel balls. They are kept upwards during the installation due to magnetic field.
5. Bottom unit
6. Receiver
7. Insert of matching the diameter of balls so that they can settle successfully and eventually lock the system.
8. Condition where the magnetic field is de-activated and the magnetic balls drop to the desired locations and lock the system and accordingly the two units together.



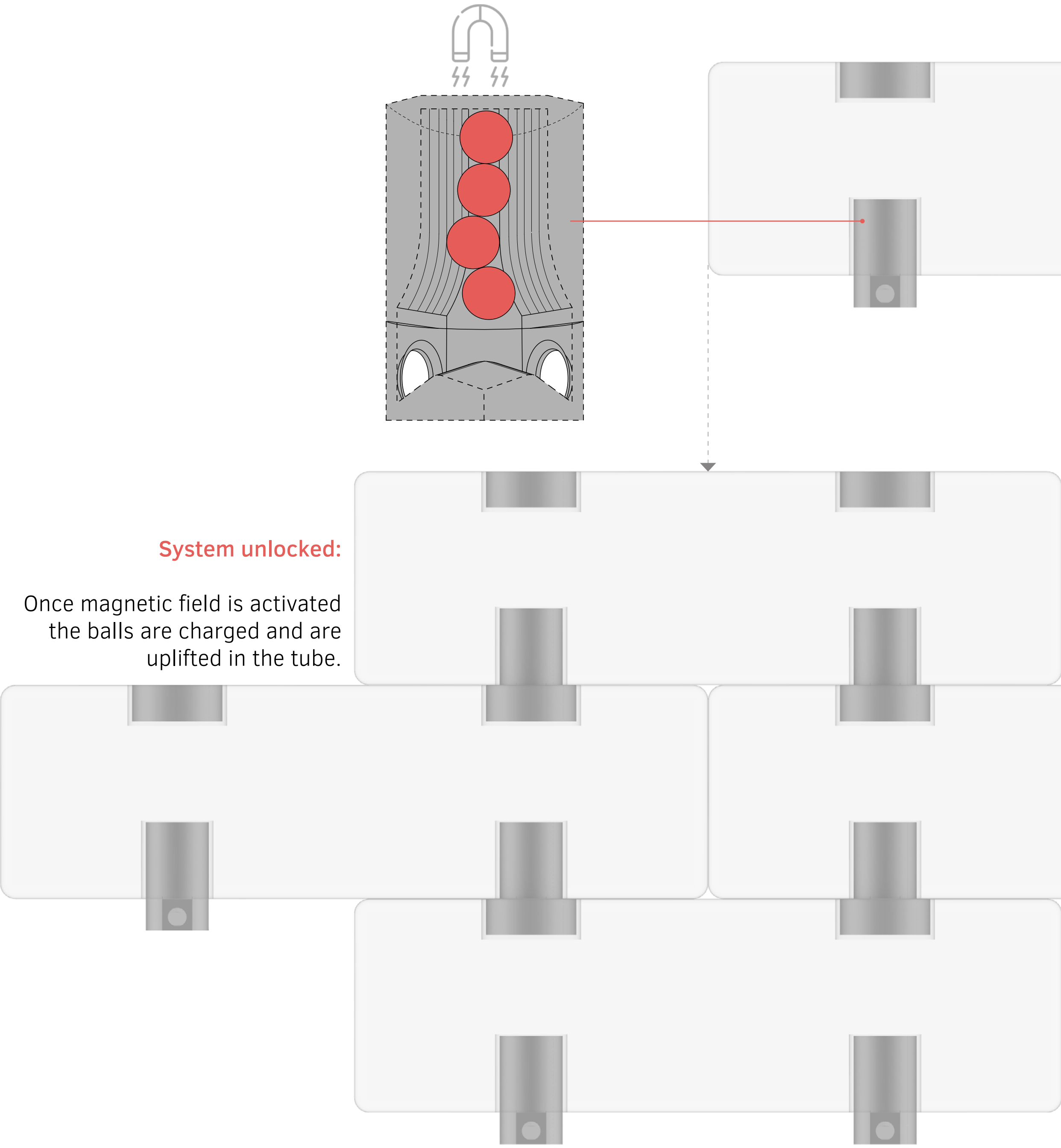
**Locking position**



**C Disassembly**

## Small overview of the glass wall: Cast glass units interlocking

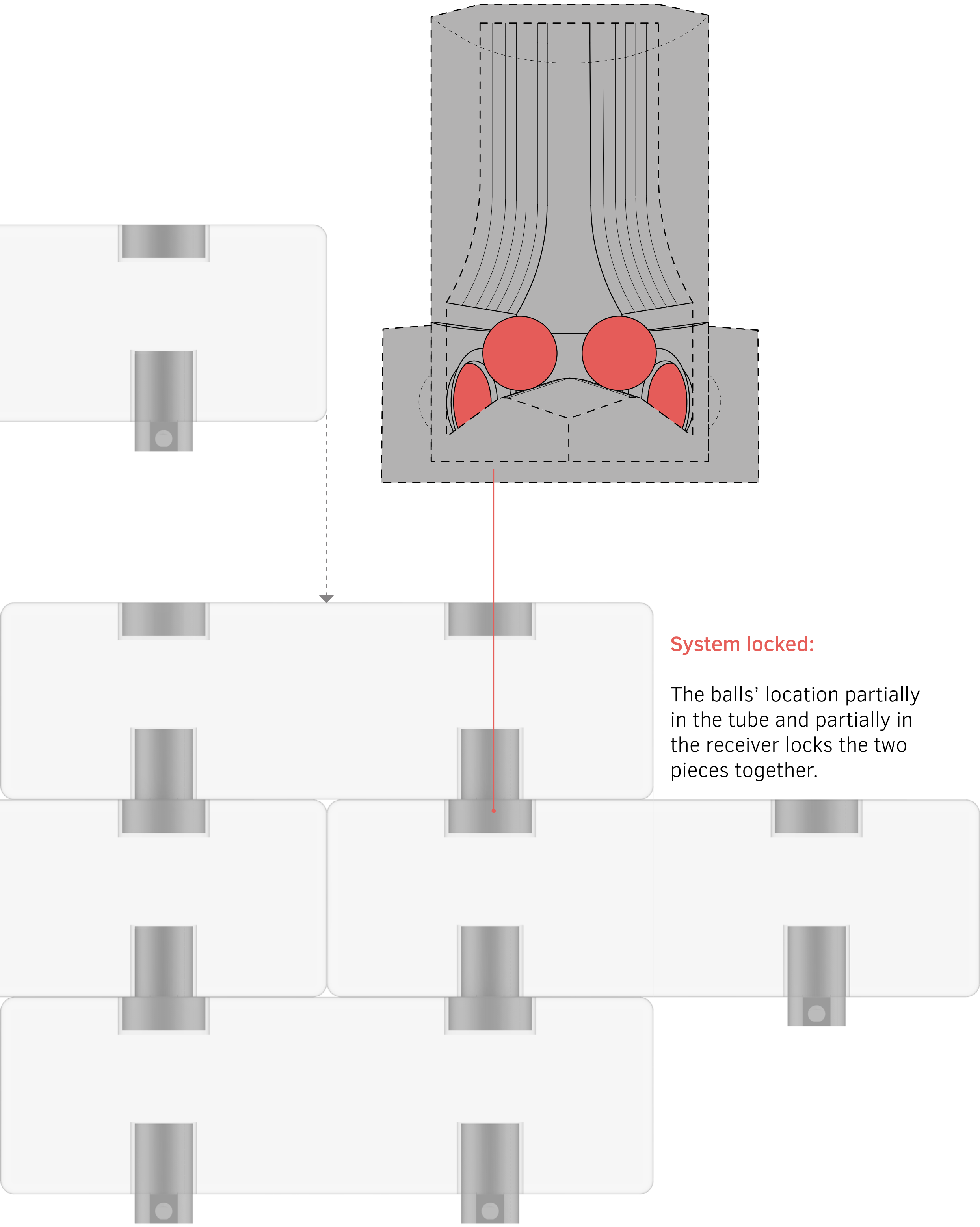
This is an overview with the embedded connections in the cast glass brick and the interlocking between the cast glass units. In this 3D - visualisation two are the basic conditions that ensure whether the system is locked or not:



**System unlocked:**

Once magnetic field is activated the balls are charged and are uplifted in the tube.

**Figure 73:** Cast glass units assembly with the embedded connections.



**System locked:**

The balls' location partially in the tube and partially in the receiver locks the two pieces together.

# 8.1 Structural Investigation

This chapter presents a short investigation about the structural performance of the proposed system, while it addresses the main challenges that need to be encountered.

As it is discussed in previous chapter, the design of the proposed connection derived from mechanisms and locking systems that are broadly used in several fields including construction, aeronautical or in automotive industry. Concerning the aforementioned purposes, a brief inspection related to the dimensions of these mechanisms, revealed that in relation with some of them, this proposed system follows similar dimensions in its circular cross section and in its length.

However, since the selected case study is located in Hiroshima, Japan, this translates that the glass façade will be subjected into severe lateral loads. Hence, the main challenge is to ensure that the proposed connection is capable to withstand the wind load and that the shear stress values are at acceptable levels.

For this reason and as it is already mentioned, the proposed design incorporates the three inclined paths, where their design arrangement is developed at a rotational distance of 120°. This arrangement will provide stability against horizontal and vertical forces while it will secure from moments around the horizontal axes. It should be mentioned that this is a primary prediction about its structural efficiency in gravitational and horizontal loads. Accordingly, this connection along with titanium as the selected material will be sufficient to transfer the loads that occur from the overall dead load and the lateral loads of the glass wall, homogeneously. Lastly, considering the final design, the simple outer geometry ensures that it can tolerate the concentrated peak stresses around the connection created by the horizontal and vertical forces acting on it, accordingly.

Concluding, and what it is intriguing about this structural system from a structural point of view, is the promising performance under earthquakes. In case an earthquake occurs, the kinetic energy will be transfered from the ground to the cast glass bricks and by extension to the titanium connections. Correspondingly, the stainless - steel balls will take charge of the situation by absorbing the energy released by the earthquake.

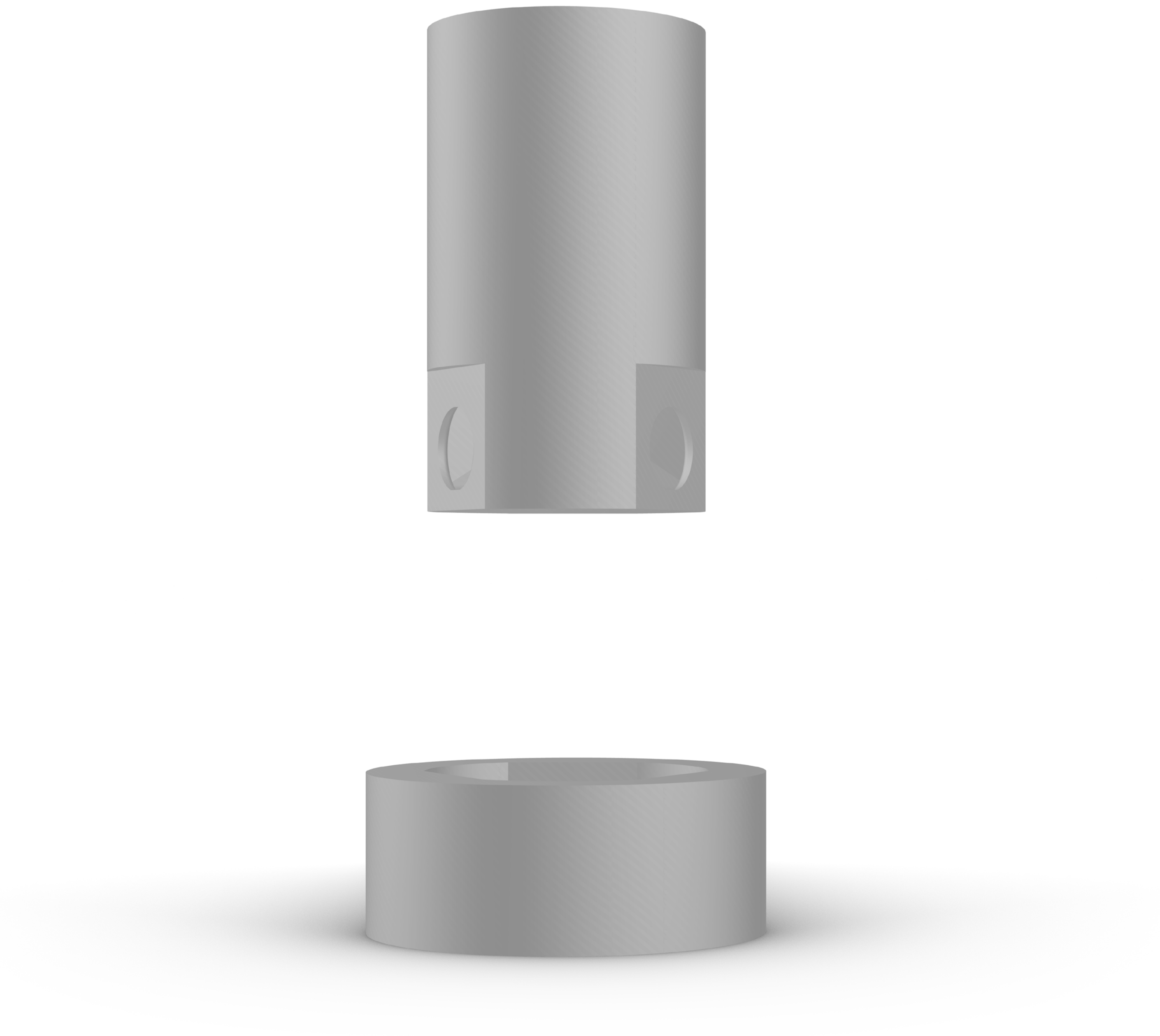


**Figure 74:** 3D Visualisation of the novel connection.

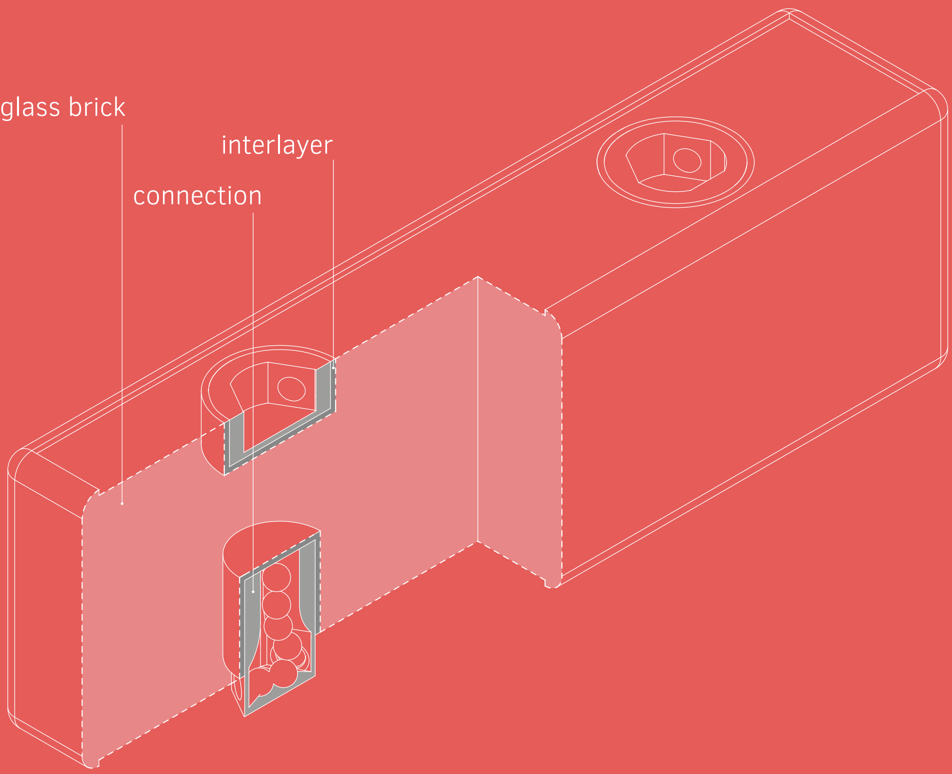



**Figure 75:** Explanatory section of the parts that are embedded in the cast glass unit.

# 9 Fabrication

This chapter focuses on the fabrication of the proposed component with the connection embedded in the cast glass unit. The suggested system has been developed as an alternative structural system in cast glass structures targeting to an easy to assembly and disassembly structure, structurally efficient and not visually intrusive. Firstly, a material assessment will present the final choices of the materials and then the fabrication of the unit will be introduced in steps. Soda-lime glass is selected for the fabrication of the glass bricks due to material compatibility with the titanium connection. Furthermore, a short configuration about the geometry of the cast glass brick has been carried out and will be briefly analysed. The selection of two interlayers will be discussed as well, based on the findings of the literature review. A primary interlayer between the glass brick and the connection and a secondary. The secondary interlayer is opted for the glass-to-glass connection during the assembly of the façade on site. The selection of the secondary interlayer based on the findings of (Dimas, 2020). The fabrication of the component will take place into two phases: firstly the fabrication of the cast glass unit and then the joining process with the connection which will lead to the final component.

### Choice of glass and connection

Soda-lime has been favoured over borosilicate glass due to compatibility with the connection in thermal expansion coefficient. Furthermore, soda-lime is an inexpensive type of glass and comparing to borosilicate glass, demands lower working temperature. However, because of the greater thermal expansion coefficient of soda the annealing -and manufacturing- time of the components would be considerably higher (Oikonomopoulou, 2019).

After the material exploration on Chapter 6, titanium has been selected as the most appropriate material for the connection because of the great compatibility in thermal expansion coefficient with the soda-lime glass and its already employment as embedded insert in structural laminated glass applications.

### Primary Interlayer (glass-to-connection contact)

Based on the literature findings (Chapter 6.2) SentryGlas® has been selected with a thickeness of 1.52 mm (see Appendix for more specifications) as the primary interlayer between cast glass brick and connection. The SentryGlas® interlayer is a structural interlayer initially generated for glazing in hurricane affected regions. It is 100 times stiffer than PVB, castin resin or EVA. SG's mechanical properties hardly change in high permanent temperatures. The most identical use of SentryGlas® intrlayer is in the Apple Stores, where metal inserts are laminated into glass sheets to circumvent mechanical connections(Wurm, 2007). Moreover, TSSA could be also appropriate because of its flexibility in working temperatures especially during lamination process.

### Secondary Interlayer (glass-to-glass contact)

Neoprene owes its wide use in long-term constructions such as in bridge bearings, façade detailing or glass connections (chapter 4.1), to its durability and to the minimum requirement if any to maintenance.  Especially in bridge design it is an appealing choice, since it presents great ability to dampen vibrations. Furthermore, it presents resistance to tearing, it is flexible, and it is developed in sheets of multiple thicknesses. During neoprene application, a 25% – 30% compression factor is suggested, so to perform properly. Moreover, neoprene can be found in the market mostly in black colour, while white neoprene is also available, but not as broadly as black (Dimas,2020).

The total thickness of the interlayer is 5 mm. Following the same principle as in Optical House, the upper and the down surface of the cast glass unit will be casted with a small slot of 1.5 mm. In this way, the cast glass units will not come into contact while only 2 millimetres will be visible on the glass wall. Lastly, to avoid glass to glass connection in the horizontal direction, a void of 1 mm is recommended as applied in the vertical joints of the cast glass bricks at the Crystal Houses. This grants for thermal expansion as well. (Oikonomopoulou, 2019).

Concluding, respecting the design criteria related the cast glass unit as they established in Chapter 5, a new configuration on the cast glass brick carried out. These changes encompass round edges, so to avoid non - uniform shrinkage and concentrate fewer residual stresses (Oikonomopoulou, 2019). Furthermore, since it would not affect significantly the annealing time since the critical dimension is the thickness (see Appendix), a slight change in the brick height could enhance the transparency on the glass wall. Hence the new brick has total dimensions 50x235x71 mm.

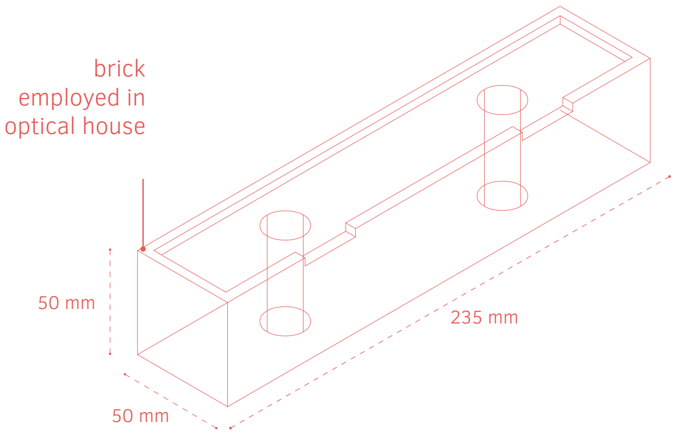



**Figure 76:** The brick employed in the Optical House. Own illustration.

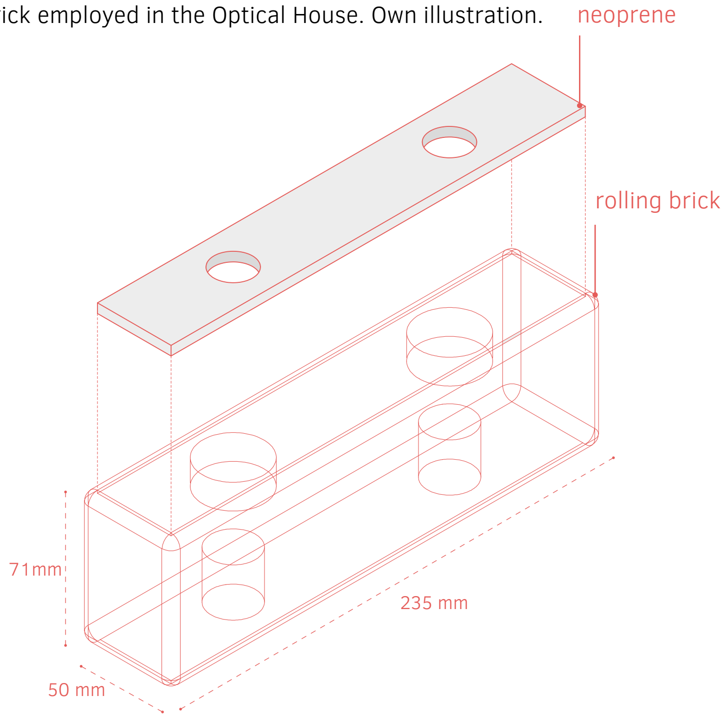



**Figure 77:** The “rolling” brick, with new height and rounded edges. On top the neoprene interlayer, so to avoid glass-to-glass contact.

# 9.1 Cast glass unit manufacture

The first phase of the fabrication includes the manufacture of the cast glass unit. According to this project's prerequisites the glass wall requires approximately 4700 normal bricks and 120 side bricks. Concerning the dimensions, the side bricks are half of the normal bricks (see Table 9 at Appendix). According to *© Bullseye Glass Co.*[5] guideline for annealing of thick slabs and comparing to realised projects the total cooling time would be around 8 hours. The total annealing time depends on the brick mass, since it grows exponentially when the mass changes (Oikonomopoulou, 2019).

For mass fabrication as if this project would be realised, hot pouring as casting method and metal moulds are recommended. The metal moulds would contribute to a highly accurate result with no post-processing. Based on the proposed shape with the four notches for the connection, an open metal mould has been favoured for higher accuracy (Oikonomopoulou, 2019). During the annealing time the natural shrinkage would be inevitable and for this reason the cast glass units would be cast in the horizontal direction facing the flat surfaces. The shrinkage would not affect the notches around the connections and therefore this would lead to a great dimensional result.

The suggested open metal mould consists of two parts as it is illustrated in Figure 78. The upper part is divided into two pieces (Figure 78 - right) , achieving in this way a successful de-moulding. In each segment, special protrusions and nooks have been designed, in order to interlock precisely, targeting to a highly accurate result in the cast glass unit. Subsequently to the pouring of the soda-lime glass, four short metal rods secure the upper parts with the bottom part, accordingly. This ensures that, during the annealing time, the molten glass will not escape from the metal mould. Towards to an accurate alignment of the metal parts,special sockets are proposed on the upper and the bottom part, respectively.

This project demands two types of metal moulds, one for the side bricks and one for the normal ones. In reality, more than two moulds would be more appropriate because they decay after a certain amount of uses (Barou, 2016). In order to avoid any rough result on the glass surface and achieve a glossy result, the moulds are preheated prior to casting (Oikonomopoulou, 2019).

In the following page the proposal for casting the cast glass units is introduced in steps.

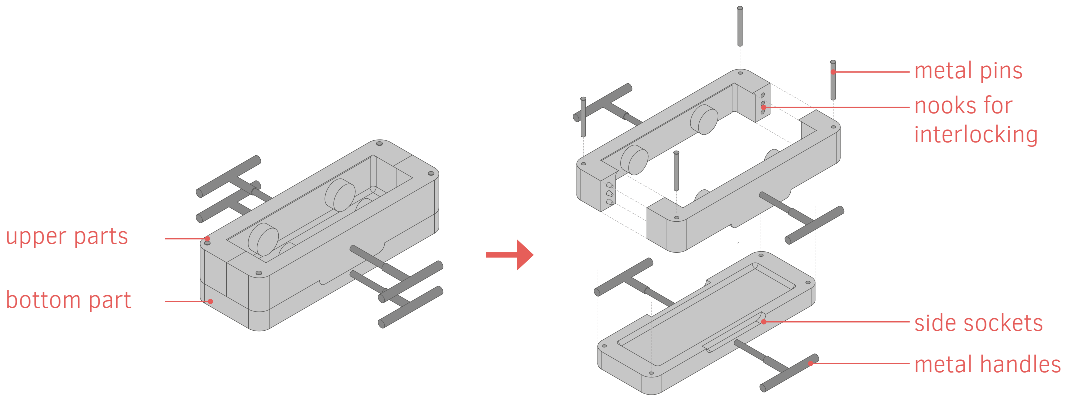
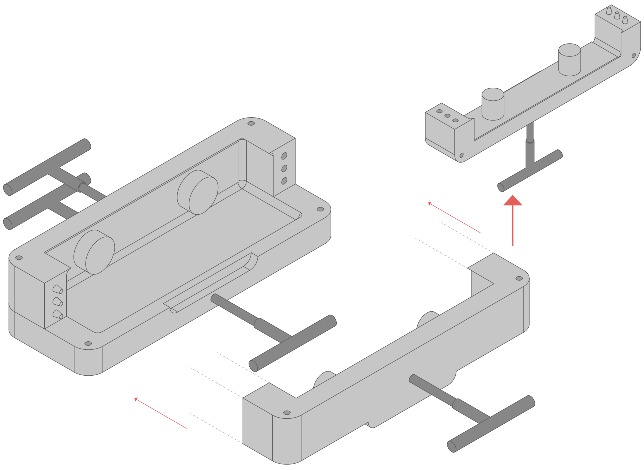
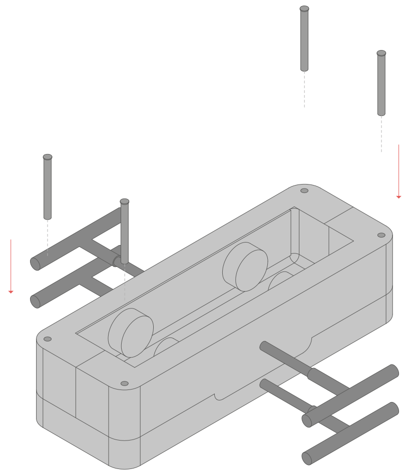



**Figure 78:** From left to right: The suggested open metal mould prior to casting. Exploded illustration of the recommended open metal mould.

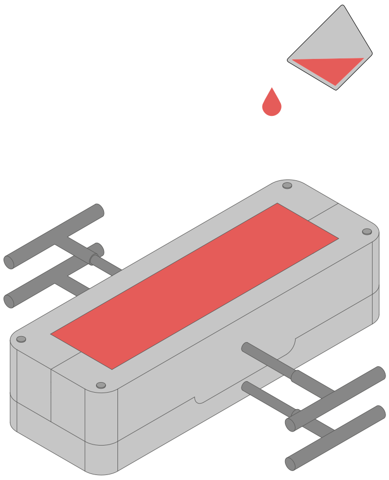
[5] A more detailed overview regarding the annealing time of slabs in various thicknesses, is provided at the Appendix.



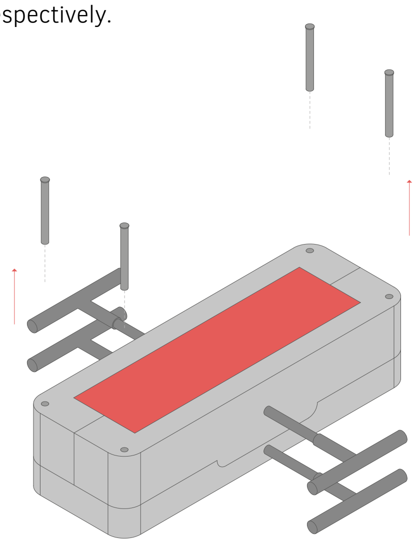
**Step 1:** Preheat the bottom and upper metal parts constantly to approximately 650°C - 750°C and assemble them.



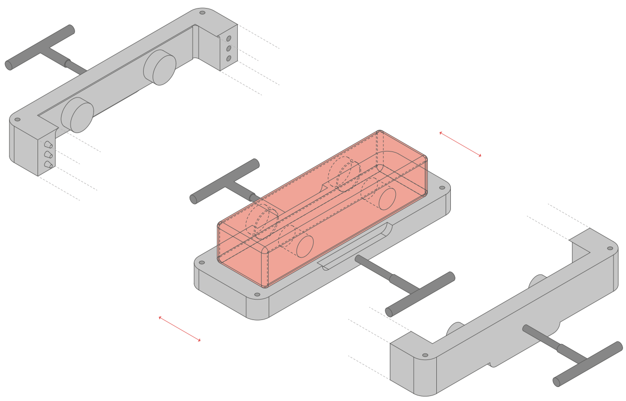
**Step 2:** Insert the four metal pins to secure the upper and the bottom part, respectively.



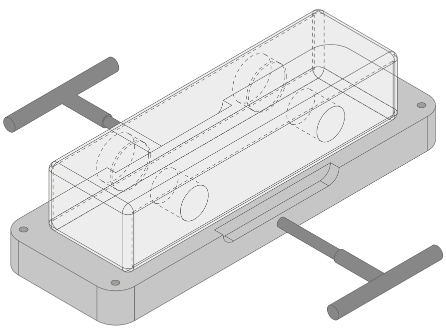
**Step 3:** Pour the molten soda-lime glass. Leave the unit to cool down. The cast glass unit starts getting the desired shape.



**Step 4:** Around the ~700°C and since the cast glass block is able to maintain its shape, the metal pins are removed.



**Step 5:** De-mould the cast glass brick by removing the bottom and the upper parts, deliberately and transfer into the annealing oven.



**Step 6:** Leave the glass unit to cool down and release the internal stresses.

## 9.2 Build-up the component

The second phase of the fabrication incorporates the lamination of the connection directly to the cast glass unit and the build-up of the final component. Lamination was favoured as a joining process over drilling holes on the cast glass unit, since the later will provoke significant stress concentrations around the notch (Oikonomopoulou et al., 2018).

Considering that lamination between a cast glass unit and a connection has not been realised yet, this phase is based on literature review and existent examples of joining metal inserts (both embedded or not) in laminated glass (Chapter 4.2). Laminated joints are produced following the same principle as in laminated glass elements. The common-use material of the connection is metal along with the adhesive foil and the glass are placed in the vacuum bag, subjected to a typical autoclave process to manufacture the final component (Bedon, Santarsiero, 2018). Accordingly, the cast glass unit along with the primary interlayer and the connection, would be placed in the vacuum bag and then they would be subjected to an autoclave process.

The titanium connection would be manufactured by a standard CNC milling machine. Subsequently to the lamination process and once the component has cool down, the cast glass unit with the embedded connections remains with the receiver facing downwards, so the stainless-steel balls could be inserted and then secured with two plastic cups, so the balls could not fall out. Consequently, the components are ready for transportation.

The following page describes the whole procedure in a more diagrammatic way.

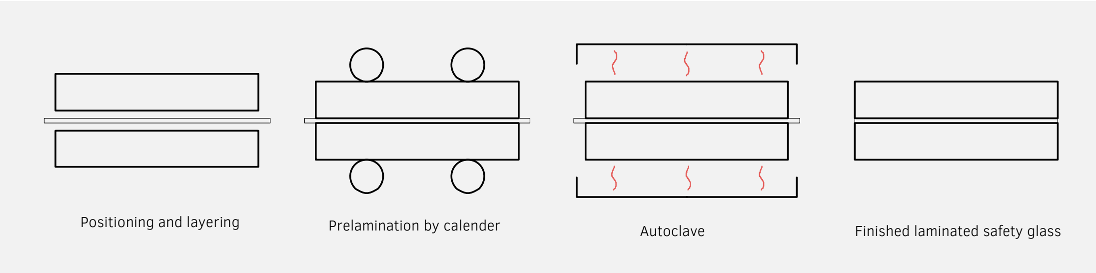
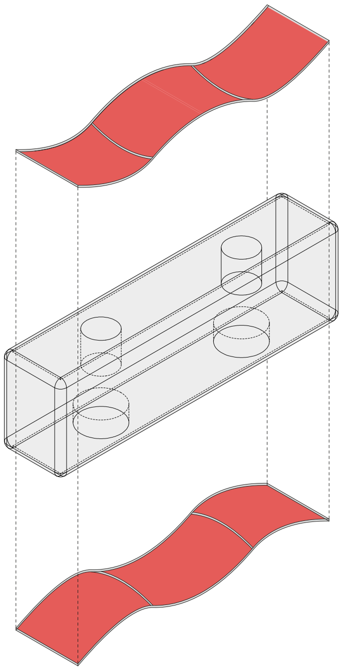
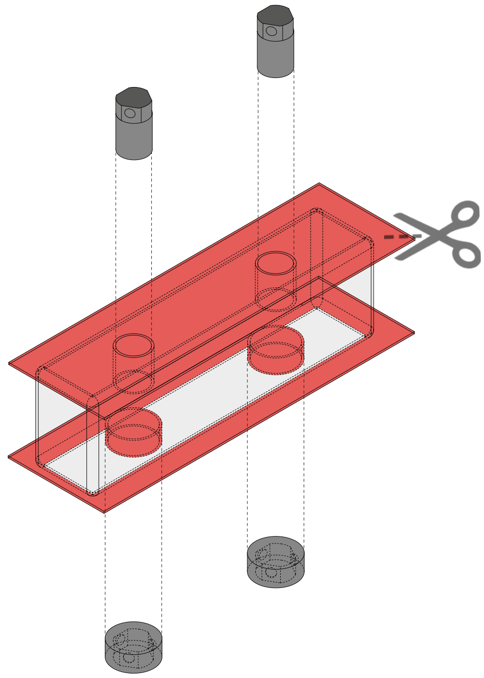



**Figure 79:** The followed procedure of laminated safety glass. Retrieved from (Wurm,2007).

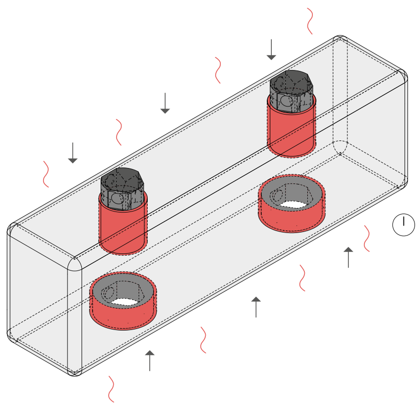
**Figure 80:** From left to right: PVB film is positioning, placement of the next glass layer on top, pre-lamination. Retrieved from (Wurm,2007).



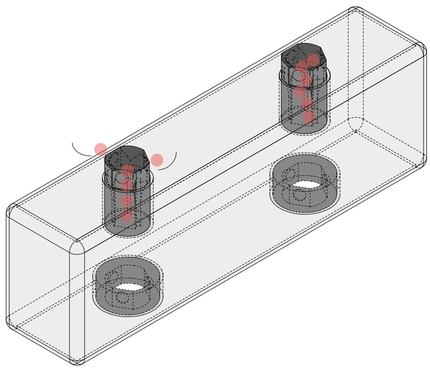
**Step 1:** Remove any dust from the cast glass unit and place the interlayer (as a proposal SG -1.52mm).



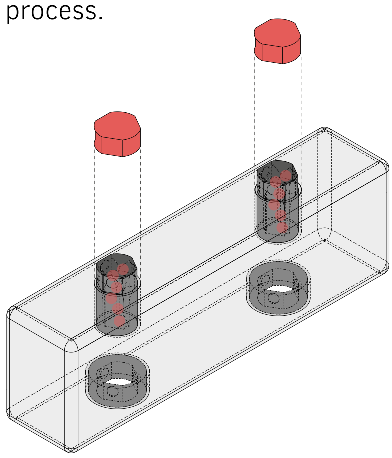
**Step 2:** Place the titanium connections and trim the unnecessary parts of the sheet.



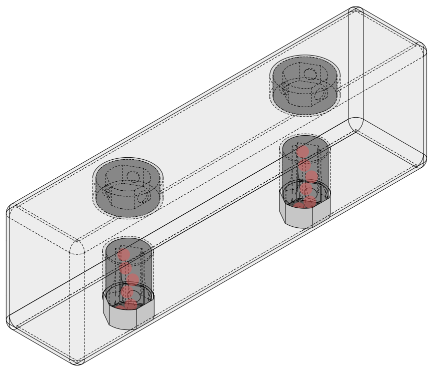
**Step 3:** Insert the component in a vacuum bag and subject to autoclave process.



**Step 4:** After the unit is cool down, insert the stainless-steel balls (6 in total).



**Step 5:** Secure the bottom part with protective caps to prevent the accidental drop of the balls.



**Step 6:** The cast glass unit with the embedded connections is ready for transportation.

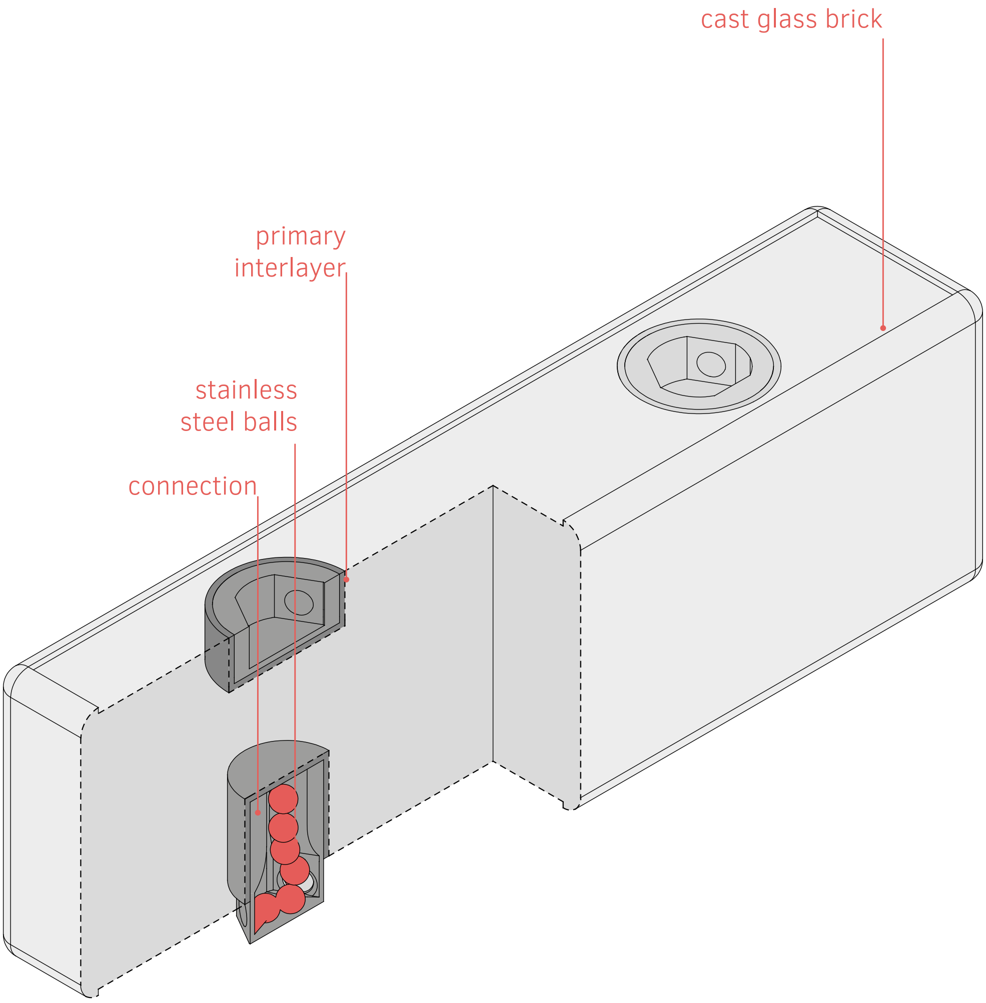



**Figure 81:** Explanatory section illustrating the materials employed for the final component.

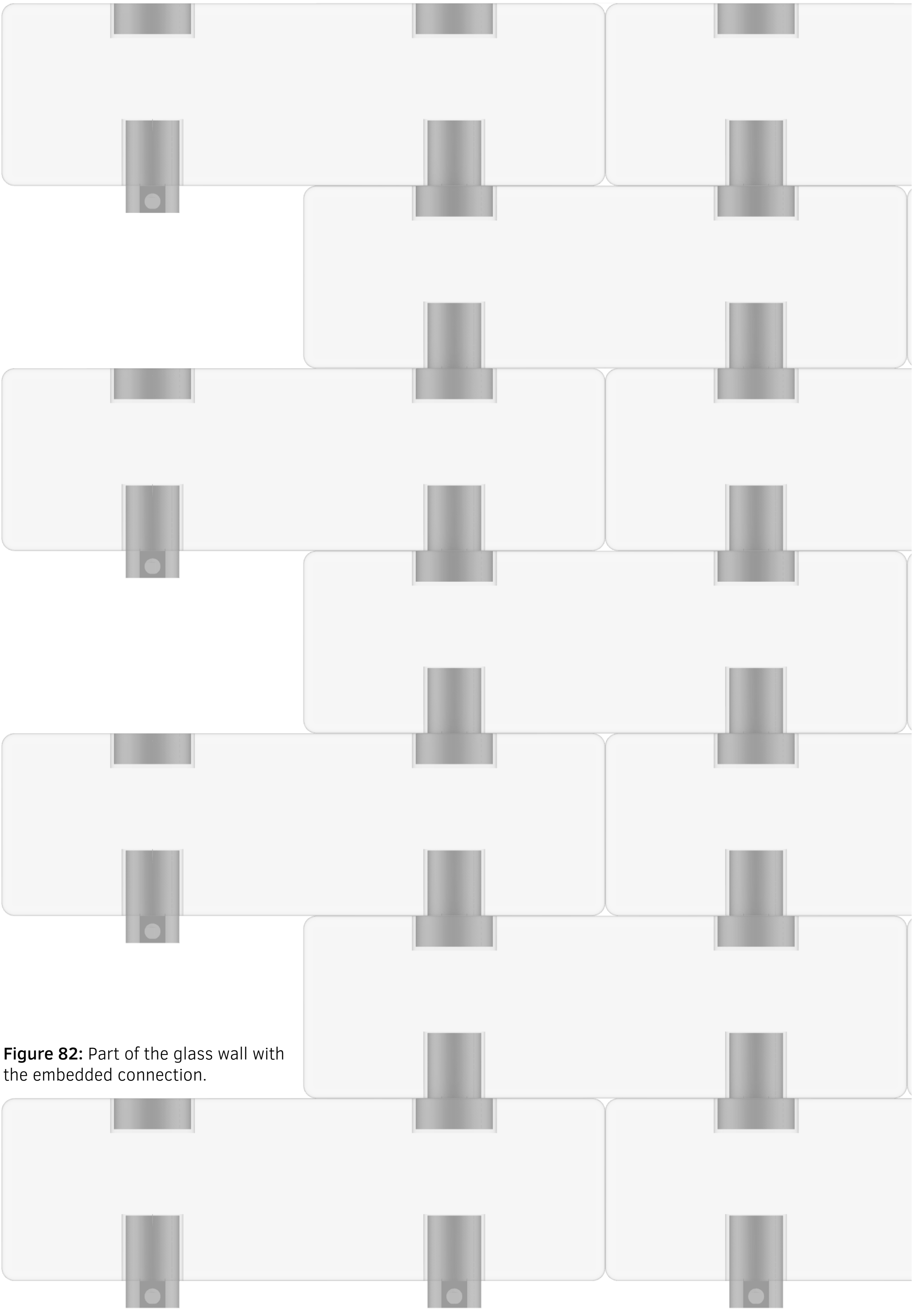


**Figure 82:** Part of the glass wall with the embedded connection.

# 10 Facade detailing and assembly

This chapter provides an insight of the construction details and the glass wall assembly adapted to the requirements of the selected case study. As presented in Chapter 3.6, Optical House in Hiroshima, with the additional supportive substructure has been chosen as a case study, providing a more realistic depiction in this proposal. The total façade dimensions 8.6 by 8.6 metres and the whole structure is suspended from a metal beam on top which is cast in concrete. Lastly, some recommendations addressing the maintenance and the sealing of the system are given by the end of this chapter.

## 10.1 Detailing

The presented alternative system will not follow the same principle as the whole concept is based on gravity. Hence, the brick layering will start from bottom to top, seeking in this way to stiff enough, yet unobtrusive and elegant connections to the concrete frame. Furthermore, dry assembly connections are favoured over adhesives since this will enhance the concept of easy assembly and disassembly of the structure. Furthermore, the ability to adjust the tolerances will be taken into consideration as well.

At the beginning of this design phase, the idea of adapting again embedded connections eventuated, so to avoid the use of metal parts to the minimum and enhance transparency eventually. However, this concept discarded because producing new types of embedding connections and new types of bricks would increase the manufacturing cost significantly. Besides drilling holes in the glass brick would affect intensely the mechanical properties of glass.

Consequently, metal frames and titanium units are opted for connecting the glass wall with the concrete frame. The titanium elements have been selected due to the same thermal expansion coefficient with the soda-lime glass. The construction details include aluminium panels for cladding, in order to cover the intrusive parts of the metal framing where is necessary. Accordingly, the next page presents an overview with the selected elements as well as a first impression of the chosen approach to attach the glass facade on the concrete frame. The final connections are presented in the following pages, correspondingly.

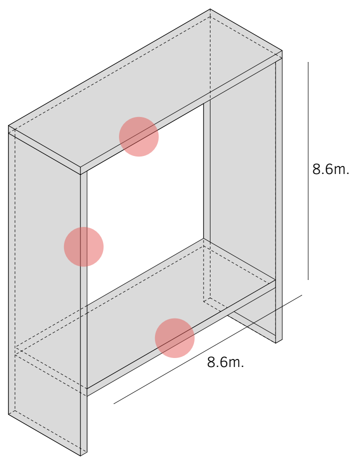
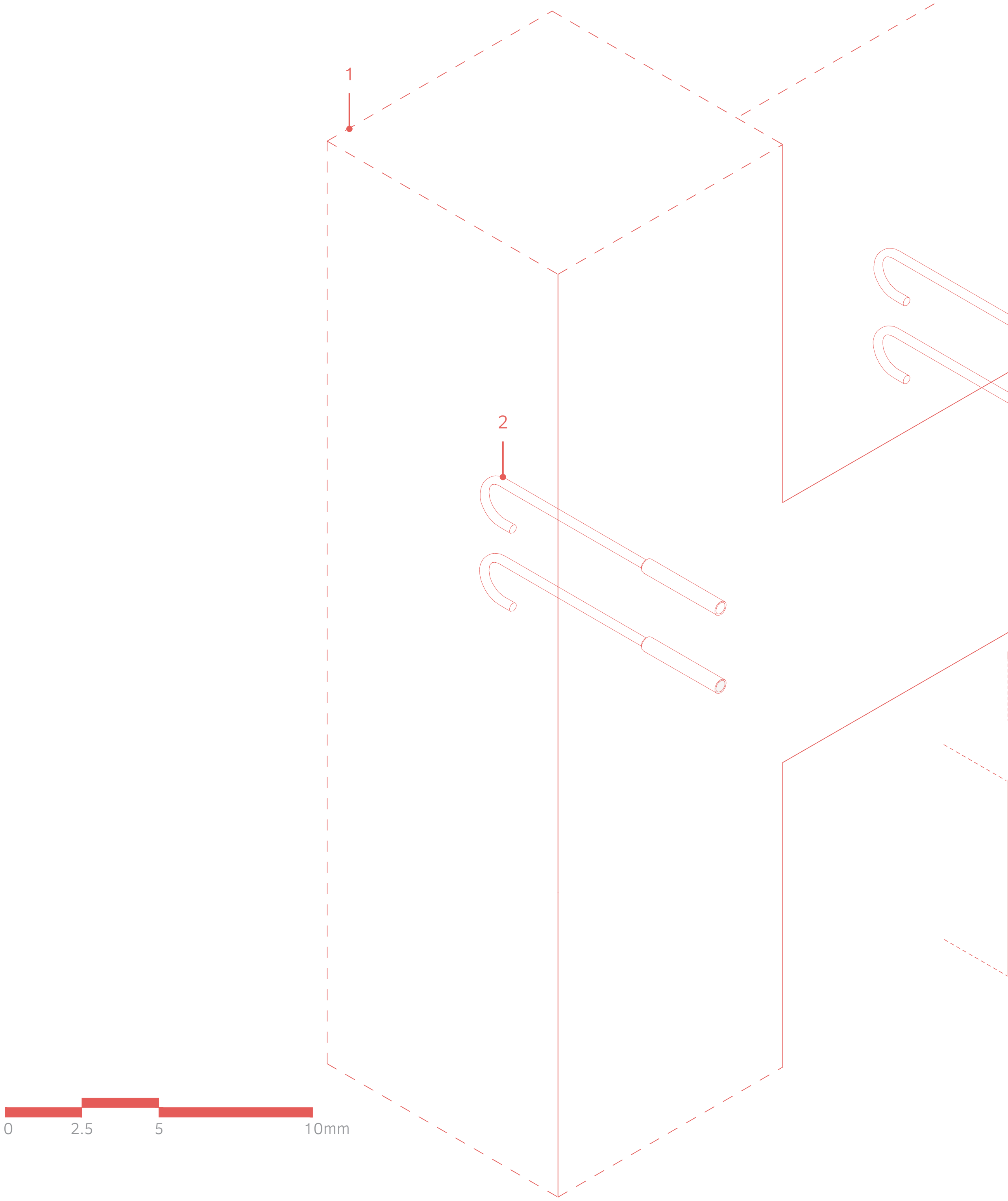


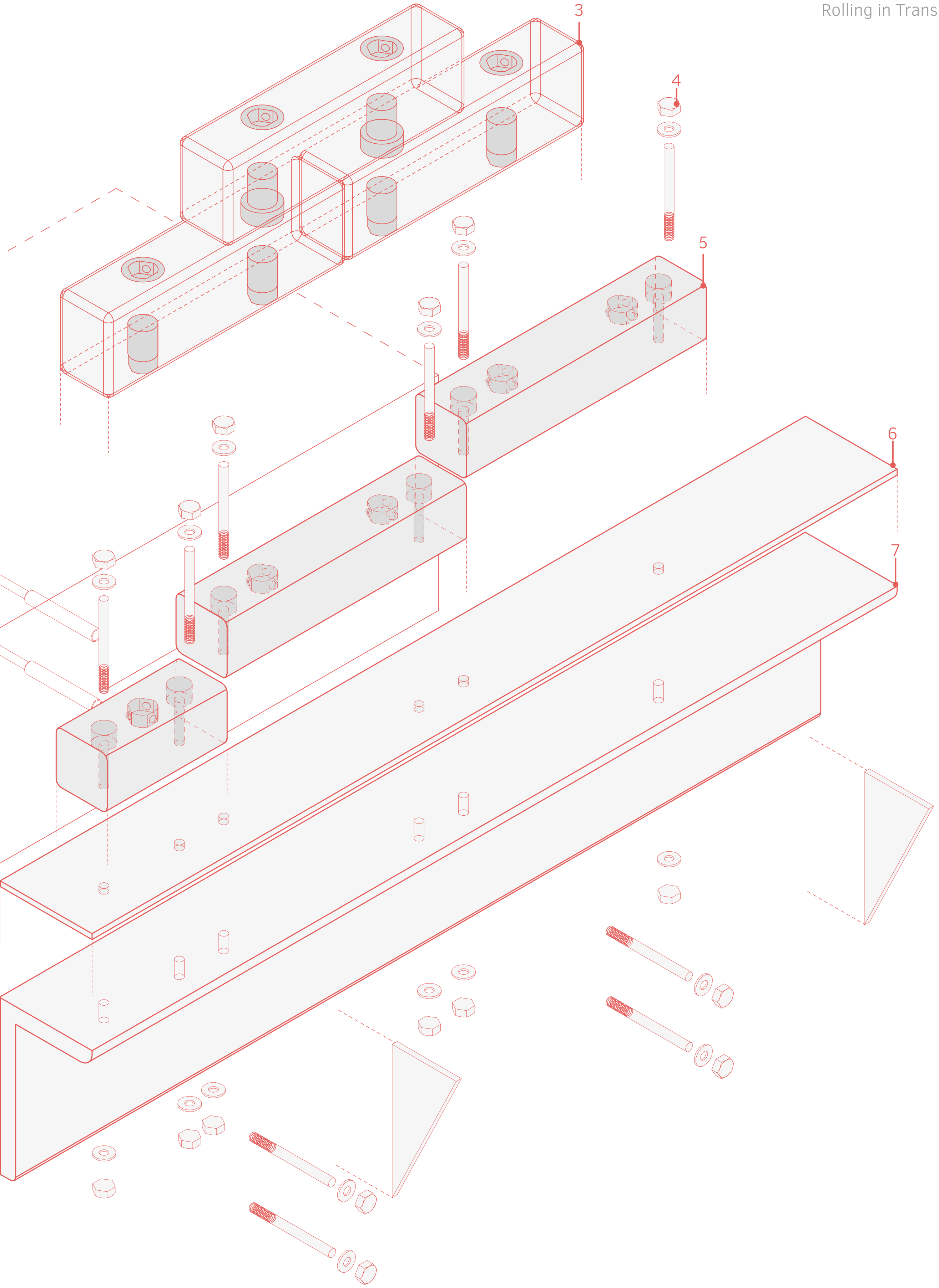

**Figure 83:** The 8.6 x 8.6 m. concrete frame where the glass wall will be attached.

## Facade detailing: Overview

**INDEX**

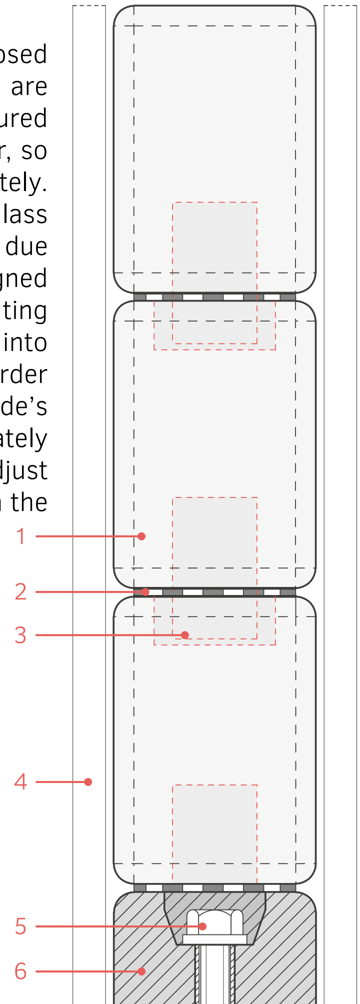
1. Existing concrete frame
2. Cast - in concrete brackets
3. Cast glass components with embedded connections
4. Steel bolts
5. Titanium units
6. Metal plate to accommodate tolerances
7. Metal frames




3
4
5
6
7

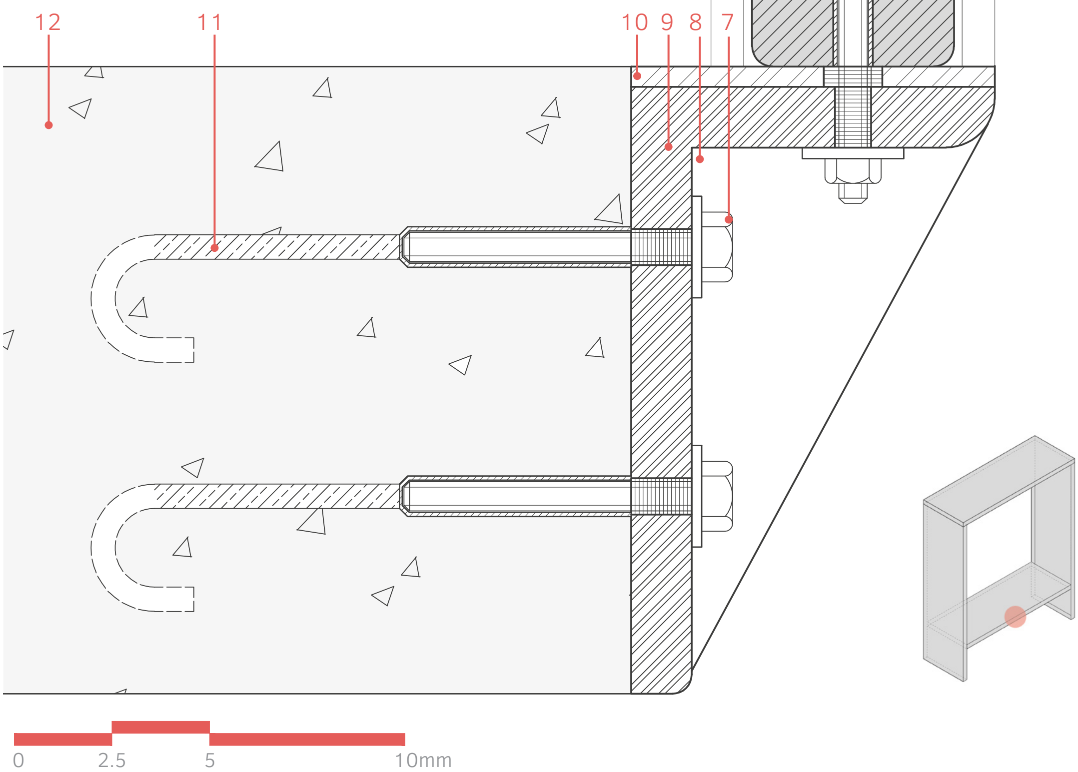
## Bottom connection

Accordingly, for the bottom connection, the proposed connections are composed by titanium bricks, which are bolted firstly in a L – profile and would be manufactured with notches with identical dimensions as the receiver, so the first row of the cast glass bricks will interlock accurately. The titanium bricks are bolted axially down of the glass wall, so to avoid any occurrence of bending moments due to lateral loads. The titanium units have been designed significantly shortly than the cast glass bricks, contributing to unobtrusive visual imprint. The L- profile is divided into segments, so to assist the assembly procedure. In order to reassure that the structure withstands the façade's deadload, metal angle plates are placed approximately every 1 meter. Metal plates have been selected to adjust tolerances where is necessary, both on bottom and on the top connection respectively.



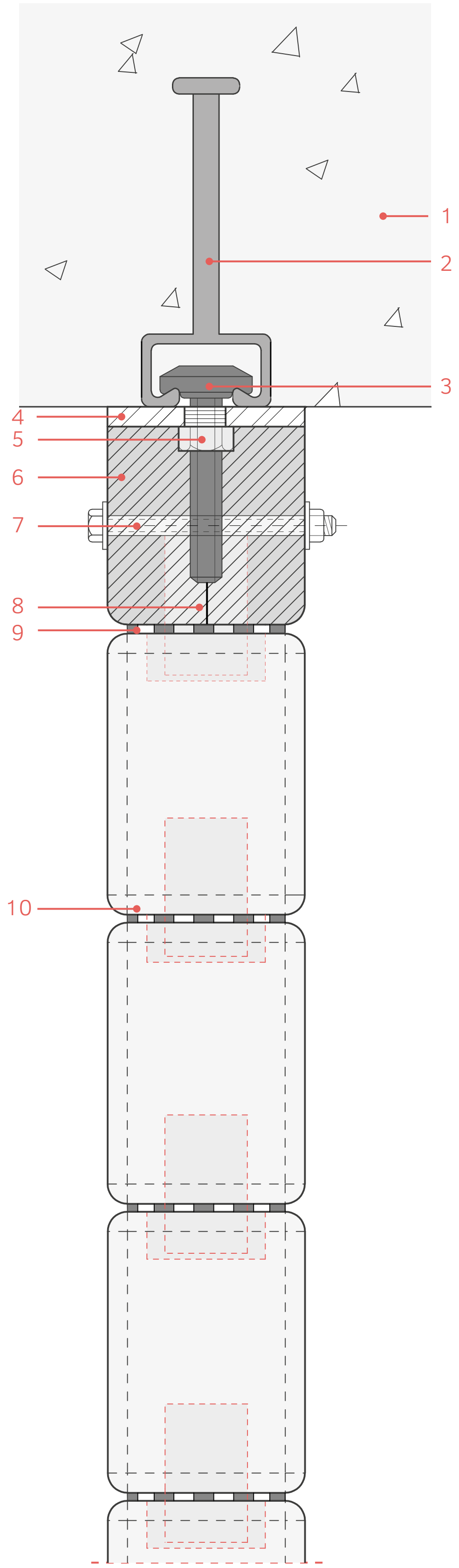

**INDEX**

**1.** Cast glass unit (235x71x50mm)
**2.** Neoprene interlayer (thickness 5mm)
**3.** Titanium embedded connection
**4.** Side UPN - metal profile
**5.** M8 bolt (for axial joining with the L -profile)
**6.** Titanium unit 235x40x50mm)
**7.** M9 bolt (for joining the L - profile with the concrete frame)
**8.** Metal angle plate
**9.** L - profile (150x90x15 mm)
**10.** Metal steel plate (for tolerance adjustments)
**11.** Cast in concrete brackets
**12.** Concrete frame (existing building)



## Top connection

The top connection is designed in a similar way incorporated titanium bricks but consisted of two segments. Prior to brick layering, on the top part, T – framing channels with rails are cast in concrete. Ahead of this decision, an idea of just casting metal rods emerged, but this condition could not guarantee the alignment with the glass wall, since several deviations could result from casting. The two titanium segments are manufactured with slots that can enclose both the T-head bolts from the T-channels and the titanium connections which will be employed to bridge the titanium bricks with the cast glass components. Consequently, the glass wall with the embedded connections stands below the concrete frame, contributing in this way to a protection from severe weather conditions.




**INDEX**

**1.** Concrete frame (existing building)
**2.** T - channel cast in concrete
**3.** T -head bolt M20 x 50mm
**4.** Metal steel plate for 50 x 5mm for adjusting the tolerances
**5.** M10 steel nut for fastening the T head bolt with the steel plate
**6.** Titanium unit (235x50x50mm)
**7.** Steel bolt M8 for fastening the titanium brick with the T Head bolt and the titanium connection transversely
**8.** Titanium connection (for bridging the glass wall with the T - channel)
**9.** Neoprene interlayer (thickness 5mm)
**10.** Cast glass unit (235x71x50mm)

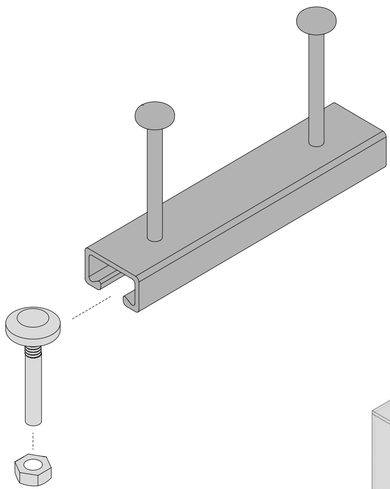
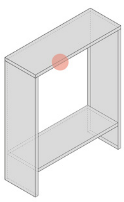


**Figure 84:** Exploded view of the T channel.

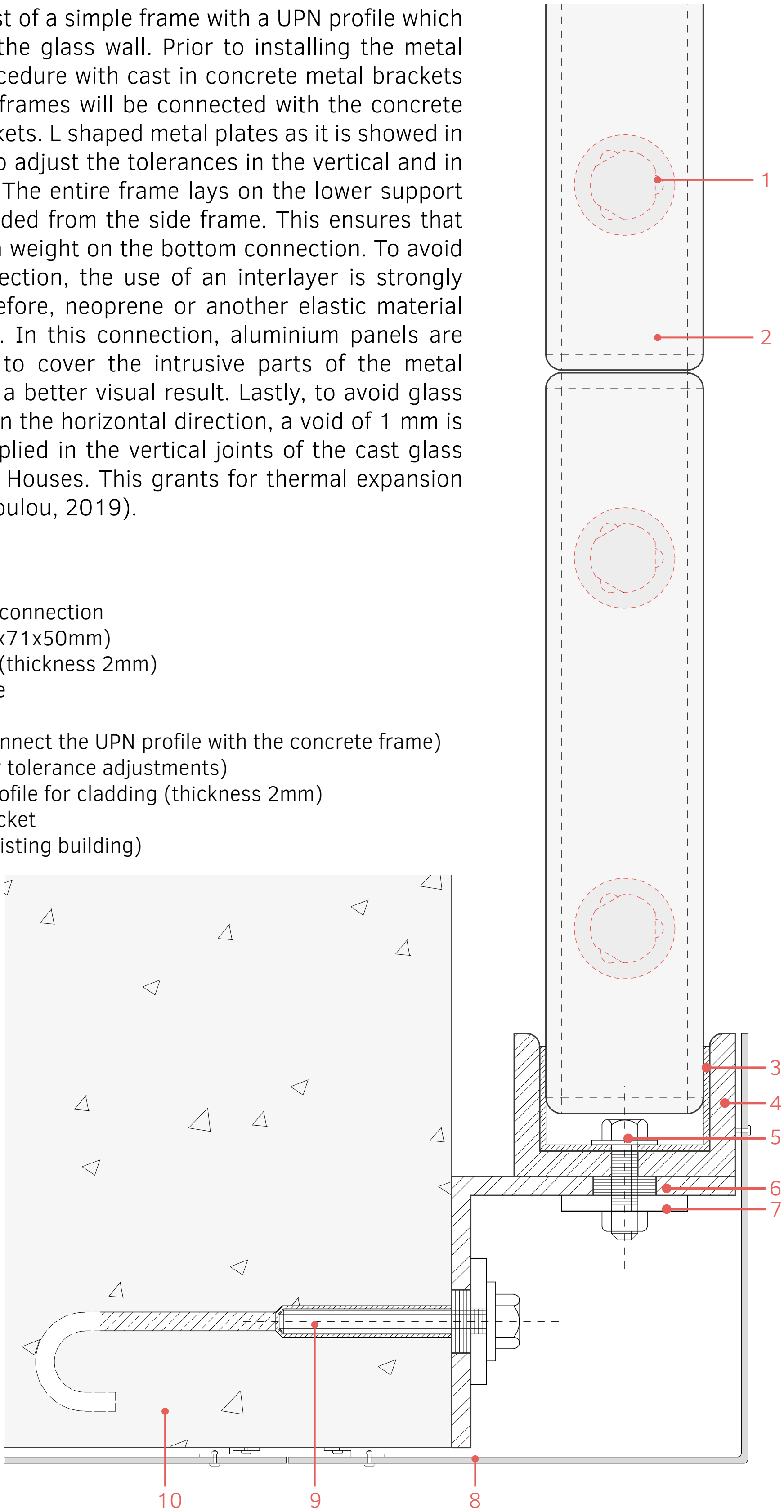


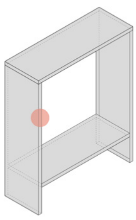
## Side connection

The side parts consist of a simple frame with a UPN profile which embodies a part of the glass wall. Prior to installing the metal frame, the same procedure with cast in concrete metal brackets followed. The metal frames will be connected with the concrete frame via these brackets. L shaped metal plates as it is showed in the drawings allow to adjust the tolerances in the vertical and in horizontal direction. The entire frame lays on the lower support but it is fully suspended from the side frame. This ensures that there will be no extra weight on the bottom connection. To avoid metal to glass connection, the use of an interlayer is strongly recommended. Therefore, neoprene or another elastic material should be employed. In this connection, aluminium panels are opted for cladding, to cover the intrusive parts of the metal framing and achieve a better visual result. Lastly, to avoid glass to glass connection in the horizontal direction, a void of 1 mm is recommended as applied in the vertical joints of the cast glass bricks at the Crystal Houses. This grants for thermal expansion as well. (Oikonomopoulou, 2019).

### INDEX

1. Titanium embedded connection
2. Cast glass unit (235x71x50mm)
3. Neoprene interlayer (thickness 2mm)
4. Metal UPN 65 profile
5. M10 steel bolt
6. Steel angle plate (connect the UPN profile with the concrete frame)
7. Metal steel plate (for tolerance adjustments)
8. Aluminium corner profile for cladding (thickness 2mm)
9. Cast in concrete bracket
10. Concrete frame (existing building)

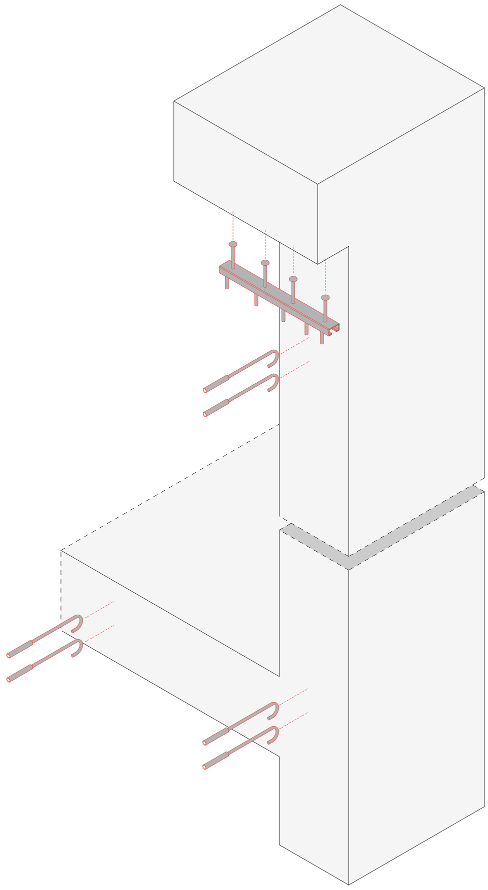


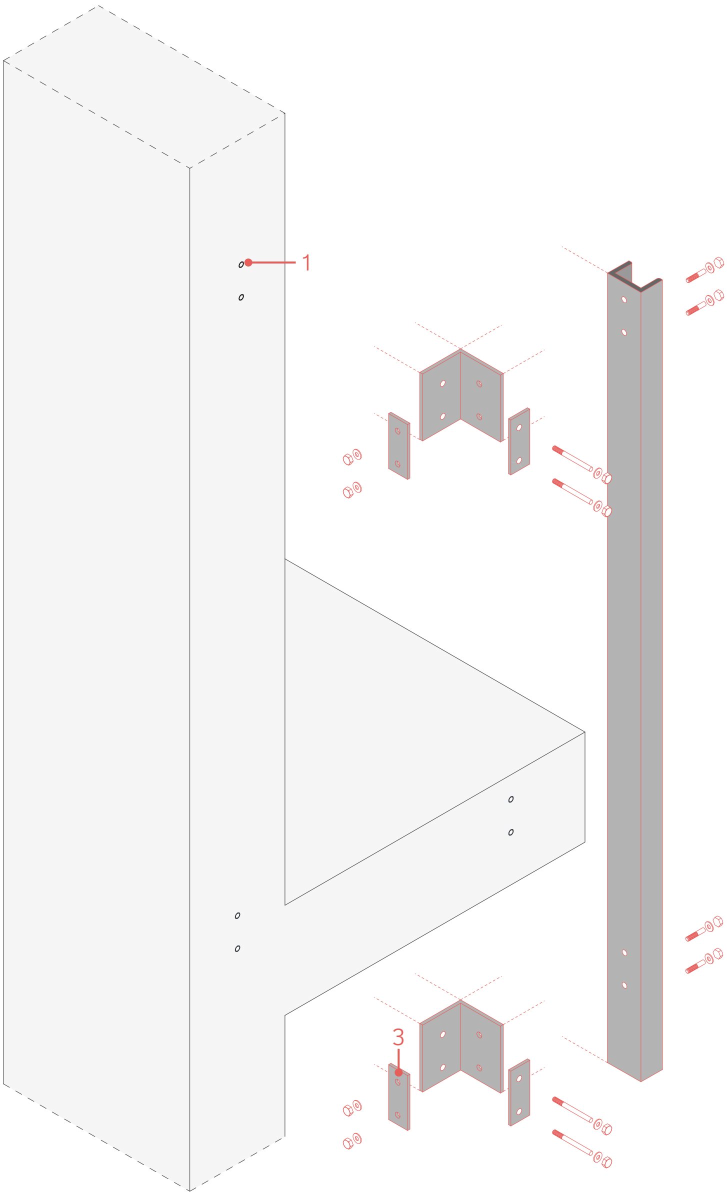



# 10.2 Assembly Sequence

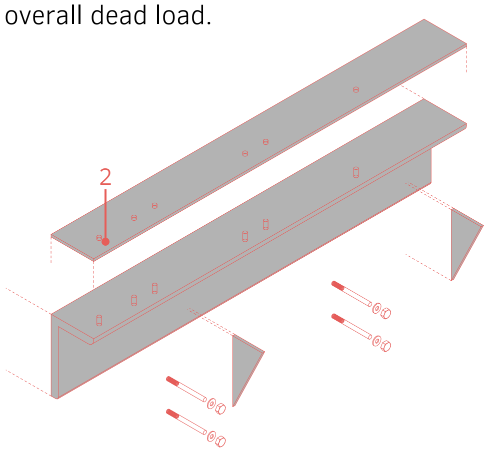
**Step 1:** The first step of the assembly is to cast the metal brackets and the T - channels on the sides on the bottom and on top accordingly. As a proposal, the brackets on the bottom and on the sides are cast approximately every 1m in two rows to ensure the stability of the system.

1.The metal brackets ready to support the metal frames
2. On top of the L -profile, a metal steel plate with countersinks is placed to adjust the tolerances.
3. Metal plates in order to adjust the tolerances are employed on the side connections correspondingly.

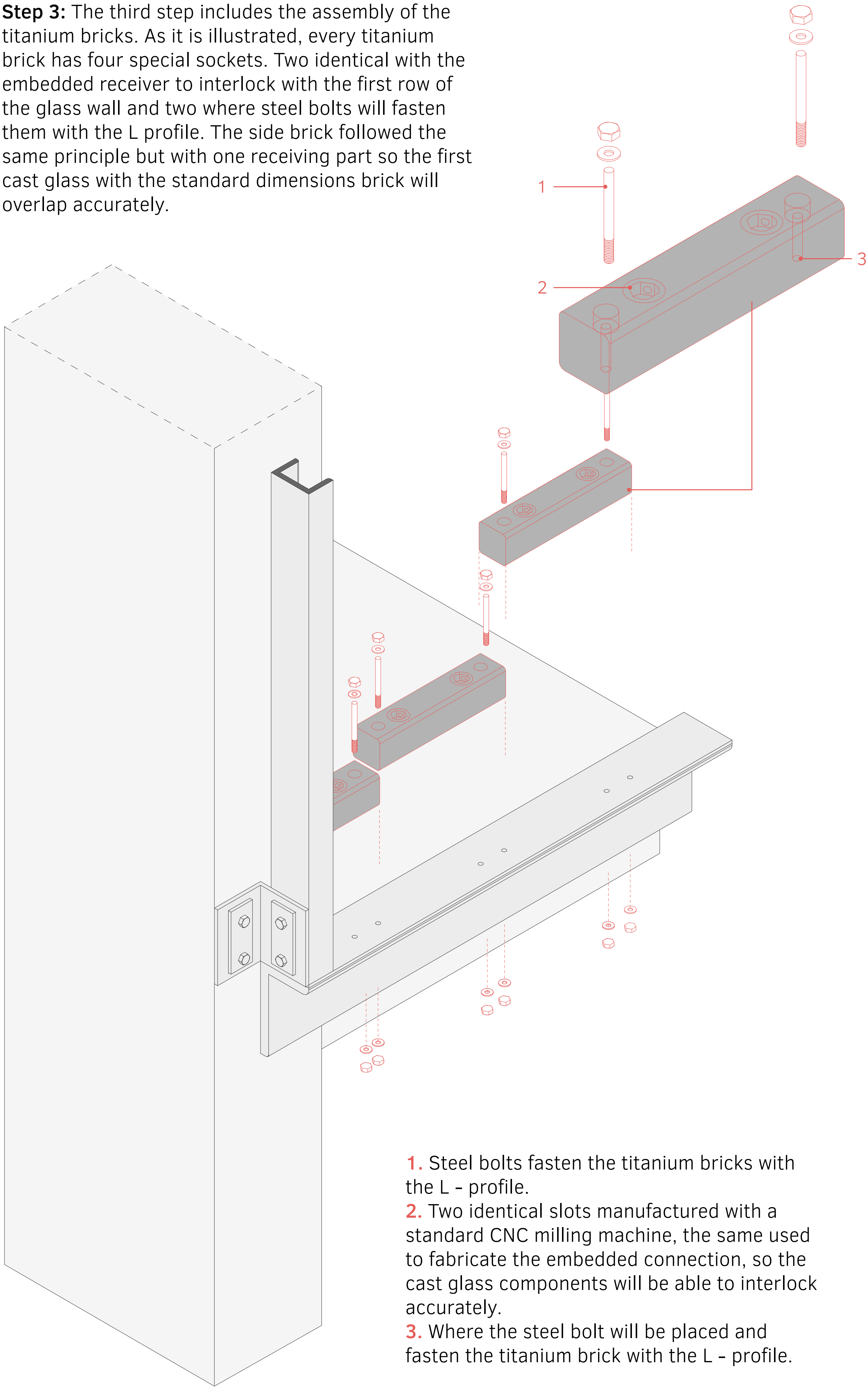




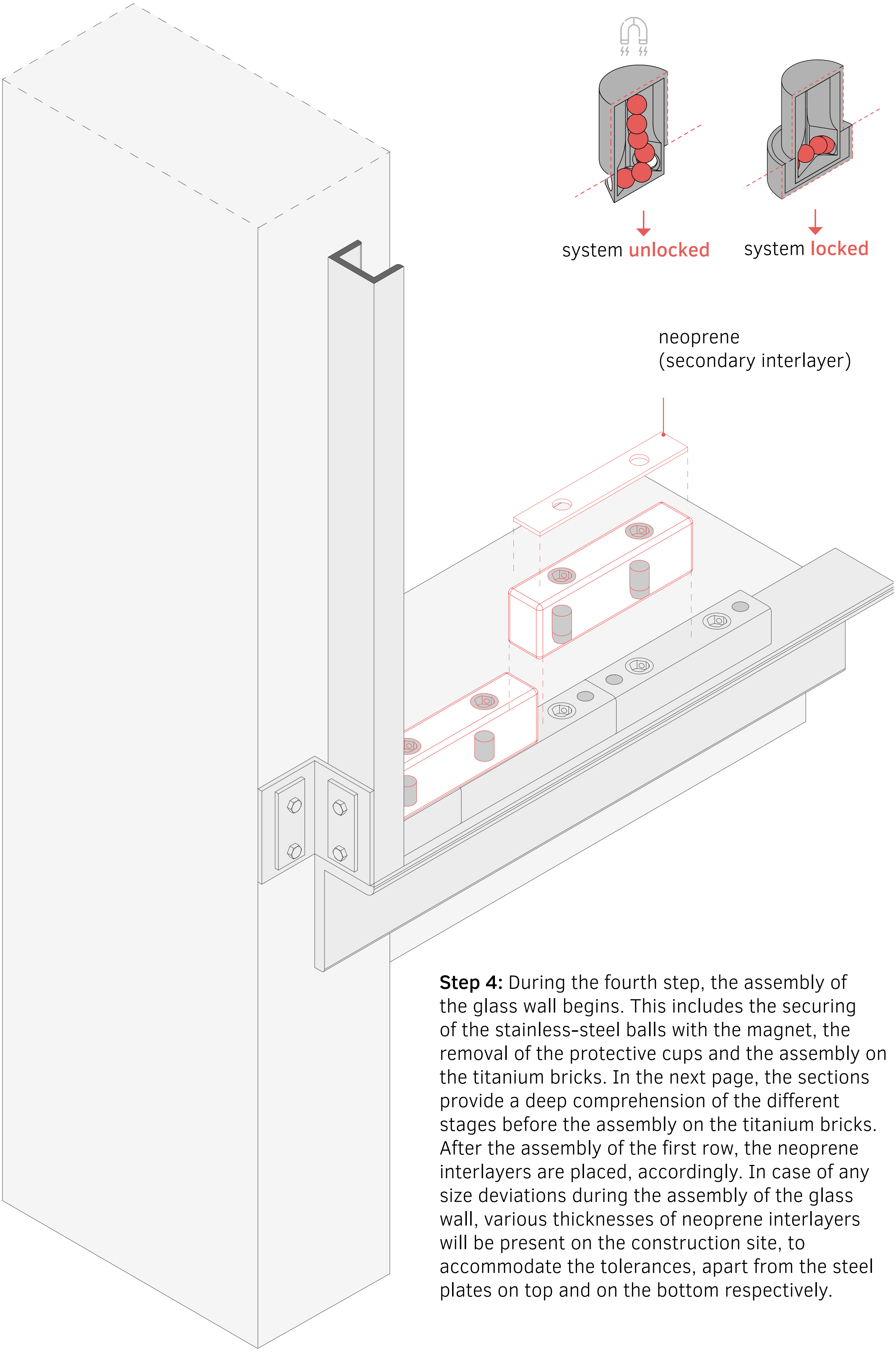

**Step 2:** Since the brackets and the T – channels are cast into concrete; the second step incorporates the placement of metal L and the UPN profile on the bottom and on the sides respectively. In order to facilitate the assembly, the L profile is segmented into several parts. As it is shown in the diagram, metal angle plates are proposed to be placed and withstand the deflections from the overall dead load.



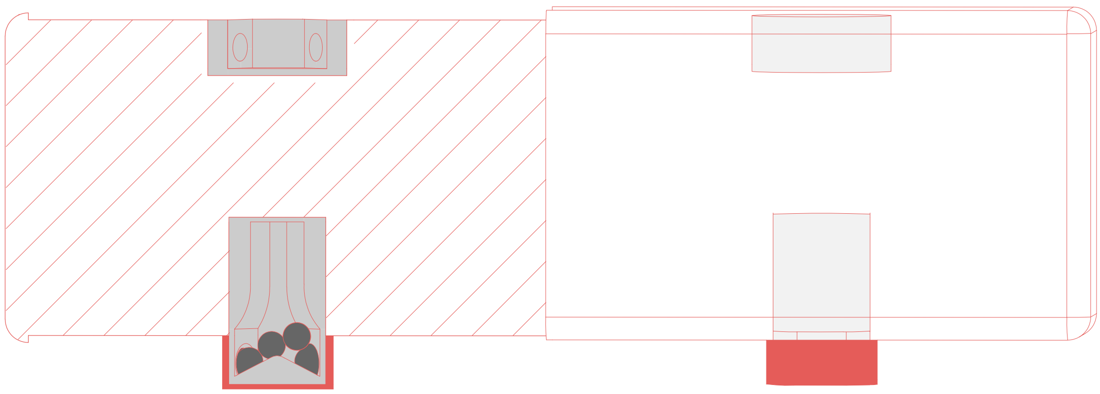
**Step 3:** The third step includes the assembly of the titanium bricks. As it is illustrated, every titanium brick has four special sockets. Two identical with the embedded receiver to interlock with the first row of the glass wall and two where steel bolts will fasten them with the L profile. The side brick followed the same principle but with one receiving part so the first cast glass with the standard dimensions brick will overlap accurately.



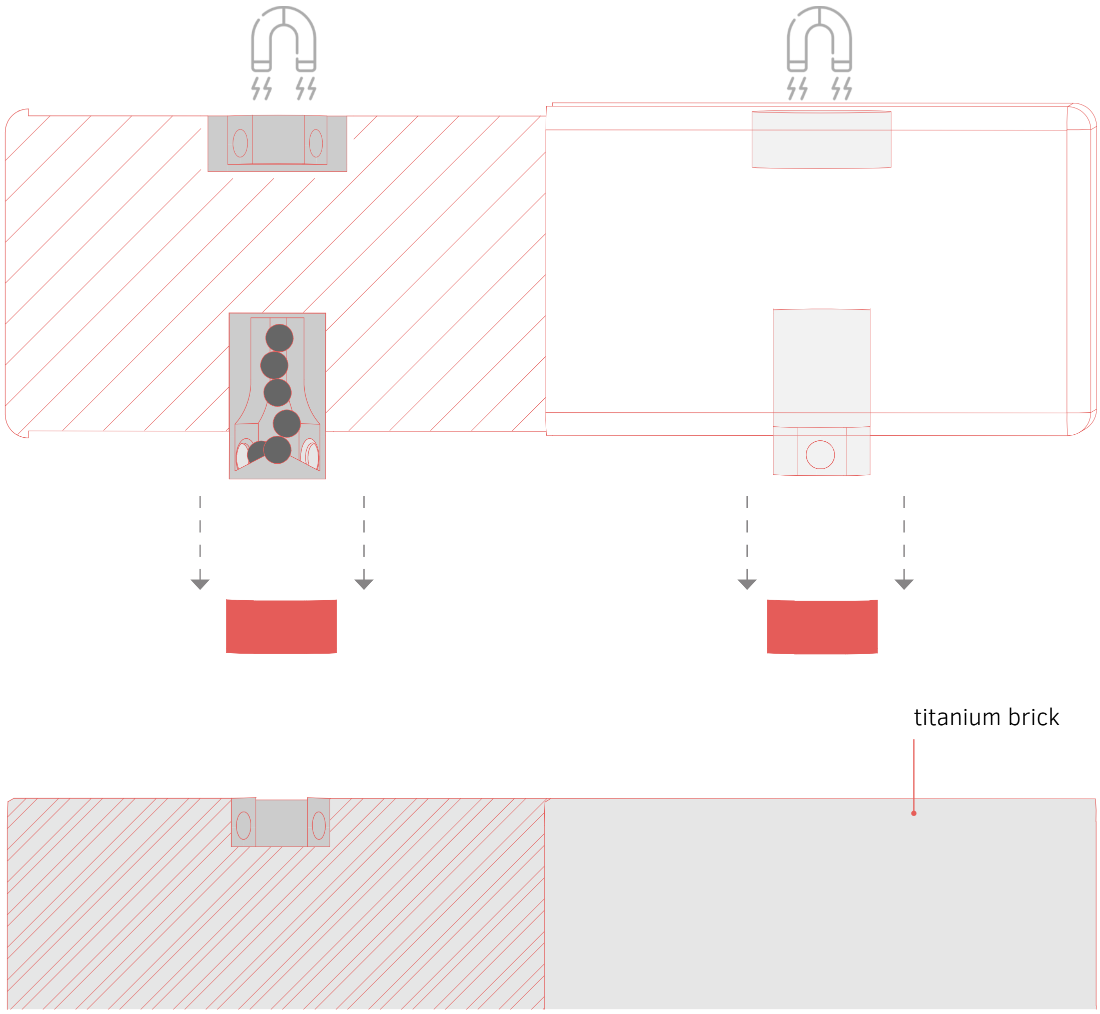

1. Steel bolts fasten the titanium bricks with the L - profile.
2. Two identical slots manufactured with a standard CNC milling machine, the same used to fabricate the embedded connection, so the cast glass components will be able to interlock accurately.
3. Where the steel bolt will be placed and fasten the titanium brick with the L - profile.



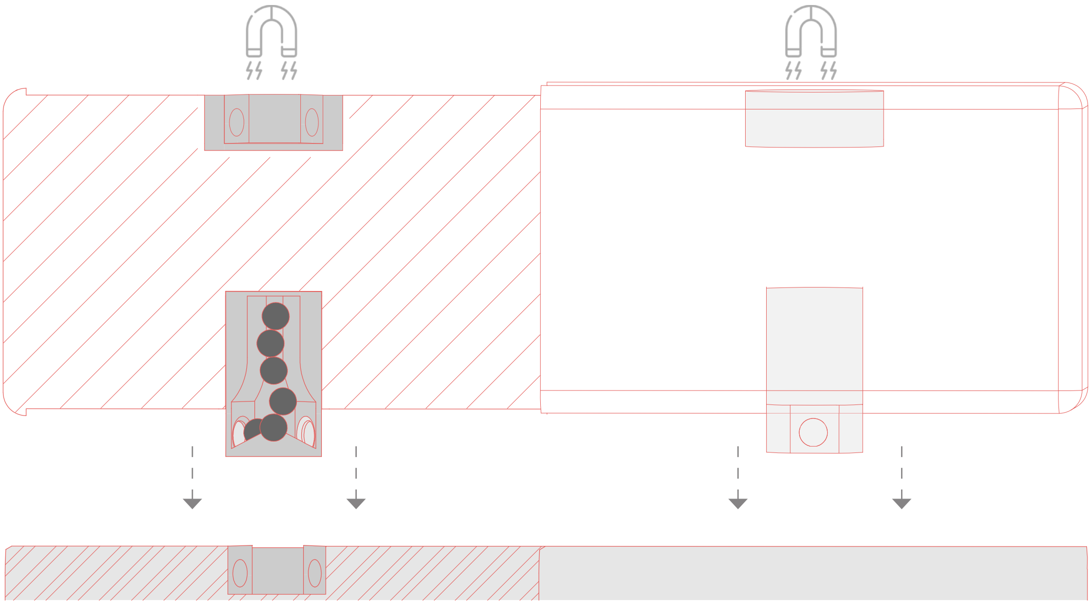

**Step 4:** During the fourth step, the assembly of the glass wall begins. This includes the securing of the stainless-steel balls with the magnet, the removal of the protective cups and the assembly on the titanium bricks. In the next page, the sections provide a deep comprehension of the different stages before the assembly on the titanium bricks. After the assembly of the first row, the neoprene interlayers are placed, accordingly. In case of any size deviations during the assembly of the glass wall, various thicknesses of neoprene interlayers will be present on the construction site, to accommodate the tolerances, apart from the steel plates on top and on the bottom respectively.



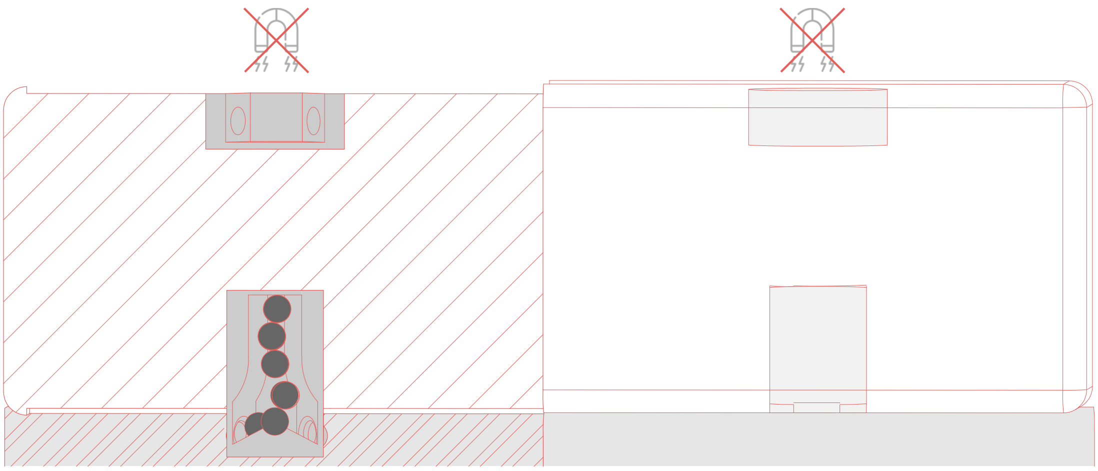
**1.** The components arrive on site with the plastic caps securing the stainless-steel spheres. In the meantime, the spheres are laying randomly inside the connection.



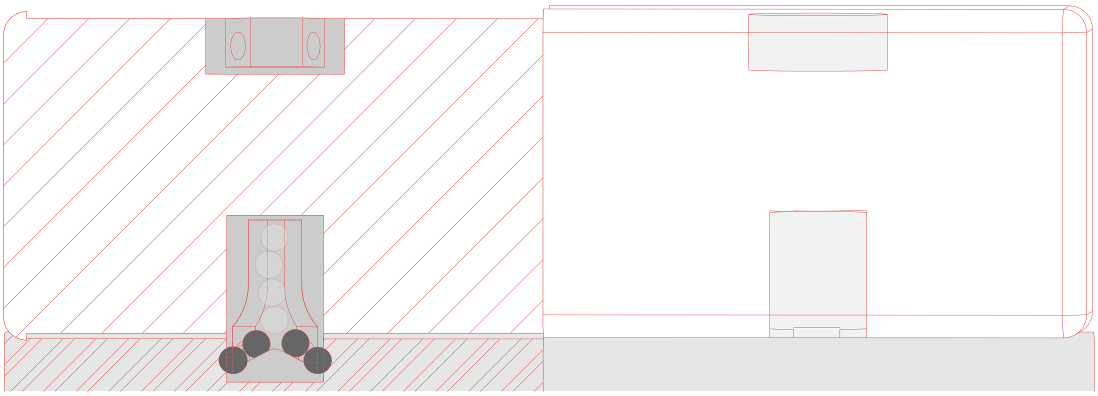

**2.** A magnet is placed above the component (from the side is also an option), secures the stainless - steel balls and the plastic cups are removed. The spheres line up immediately as it is shown in the illustration.



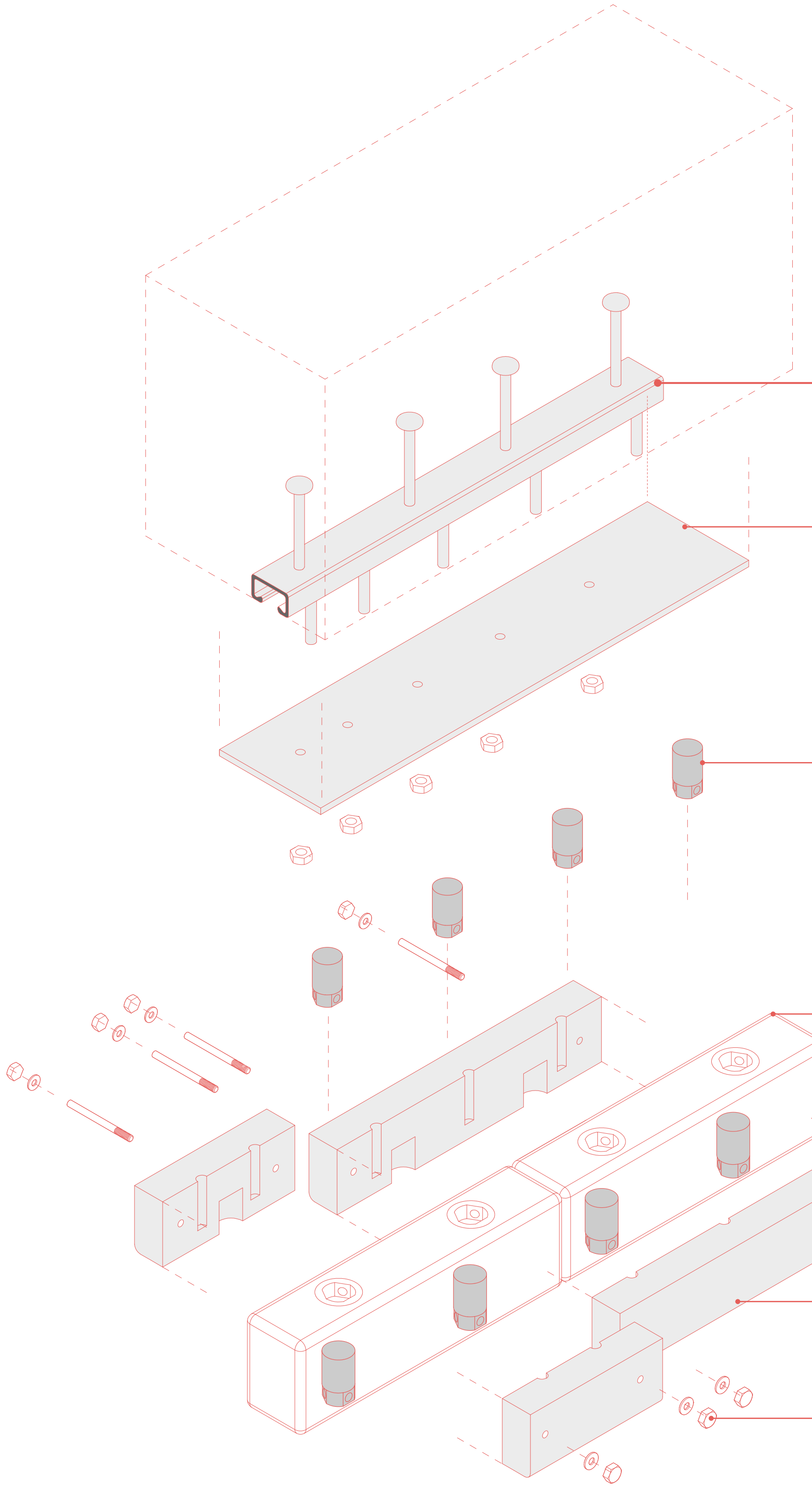
**3.** The plastic cups are removed and saved in case the disassembly of the total structure occurs. The magnets are still securing the spheres and the assembly of the glass wall begins.



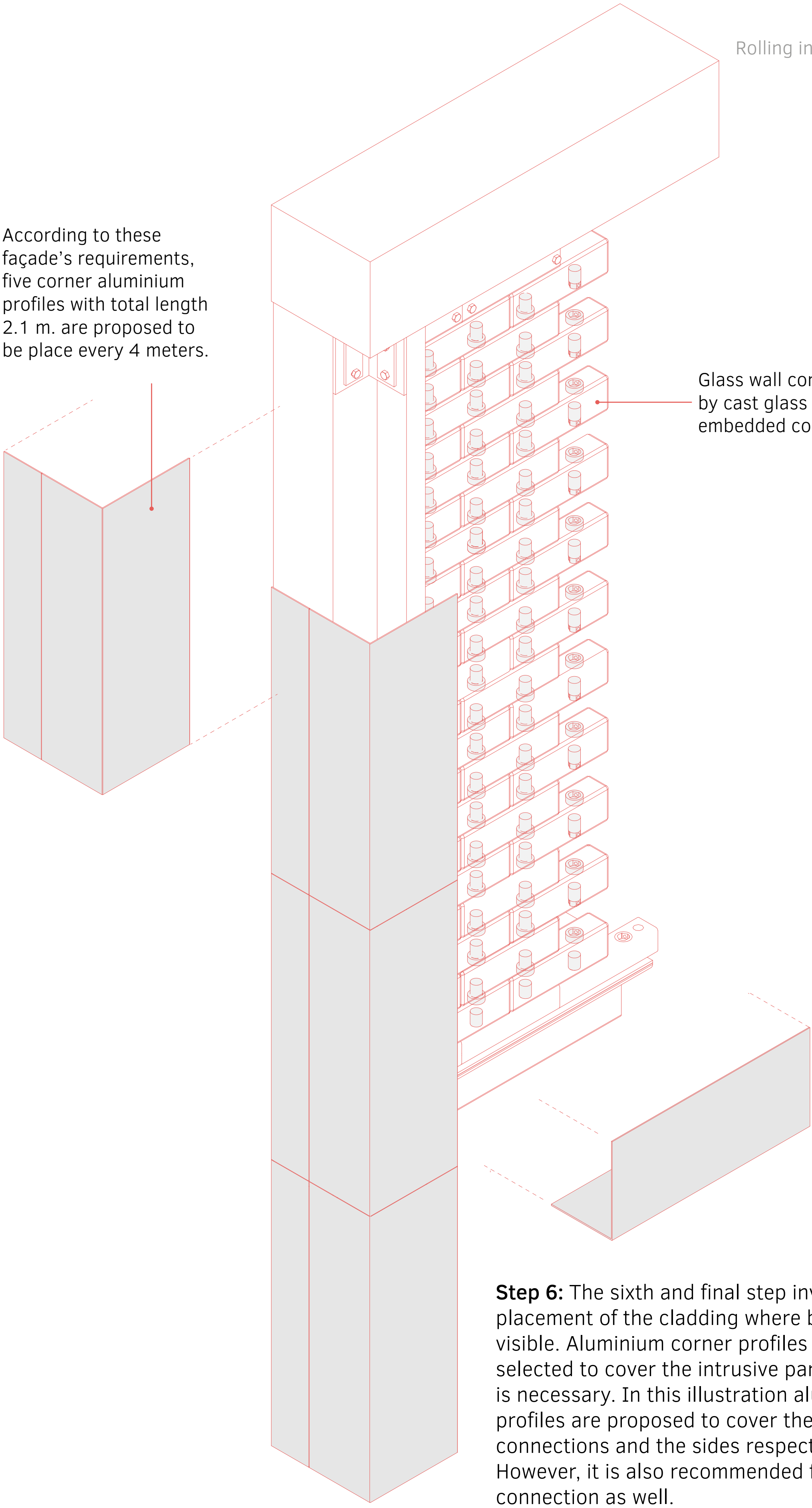
**4.** The cast glass units with the titanium bricks interlock. The magnets are withdrawn after some seconds and the spheres start rolling.



**5.** Thanks to gravity and the deliberated inclinations the balls roll to their spot and settle between the receiver and the upper part. The system is successfully **locked.** The same procedure is followed until the glass wall is fully assembled. In case of disassembly, the magnets secure the balls, the system is **unlocked** leading to an easy disassembly.




**Step 5:** After the assembly of the glass wall comes the fastening with the top connection. This step includes the titanium connections which will bridge the glass wall with the segmented titanium bricks and the T – head bolts. The titanium bricks are split into two segments in order to enclose both the T – head bolts and the titanium connections. Firstly, the titanium connections are interlocking with the cast glass units (the system is locked with the same procedure discussed in the previous step). Then, the metal steel plate is placed to adjust the tolerances accordingly. Following this, the titanium bricks are placed, enclosing in this way the T head bolts and the connections. Lastly, the system is fastened with the steel bolts vertically.




**Step 6:** The sixth and final step involves the placement of the cladding where bolts are visible. Aluminium corner profiles have been selected to cover the intrusive parts where is necessary. In this illustration aluminium profiles are proposed to cover the bottom connections and the sides respectively. However, it is also recommended for the top connection as well.

# 10.3 Maintenance of the glass wall

The glass wall with the suggested structural system, offers a convenience to be maintained against weathering. Considering the literature review or existing applications on realised projects, the selected materials - cast glass along with titanium - are very durable materials, against severe weather conditions. Concerning the selection of the intermediate material, SentryGlas® is also durable. SentryGlas® retains its clarity, after a long-term exposure to sunlight or rain and it does not easily discolour. However, some recommendations addressing the maintenance and the sealing of the system are provided in this section.

The maintenance of the glass façade against moisture or dust could be achieved by applying a hydrophilic coating on the external face. This will reduce the cleaning requirements, since the rainwater will keep the glass wall clean. The selected coating is necessary to be replaced after some years (e.g. 10 years). In order to restrain moisture and dust settling between the connections of the cast glass units, a water-resistant adhesive sealant is recommended. The selected adhesive is suggested to be aging resistant and durable when it is exposed to sunlight. The presented proposals based on the principles and recommendations applied in the glass wall of *The Crystal Houses* in Amsterdam, as established by (Oikonomopoulou, 2019) in her PhD dissertation.

Lastly, an anti – corrosion coating is recommended to be applied on the metal parts (UPN and L profiles) of the construction. This coating ensures that the metal parts will not corrode during their exposure to rainwater and humidity.

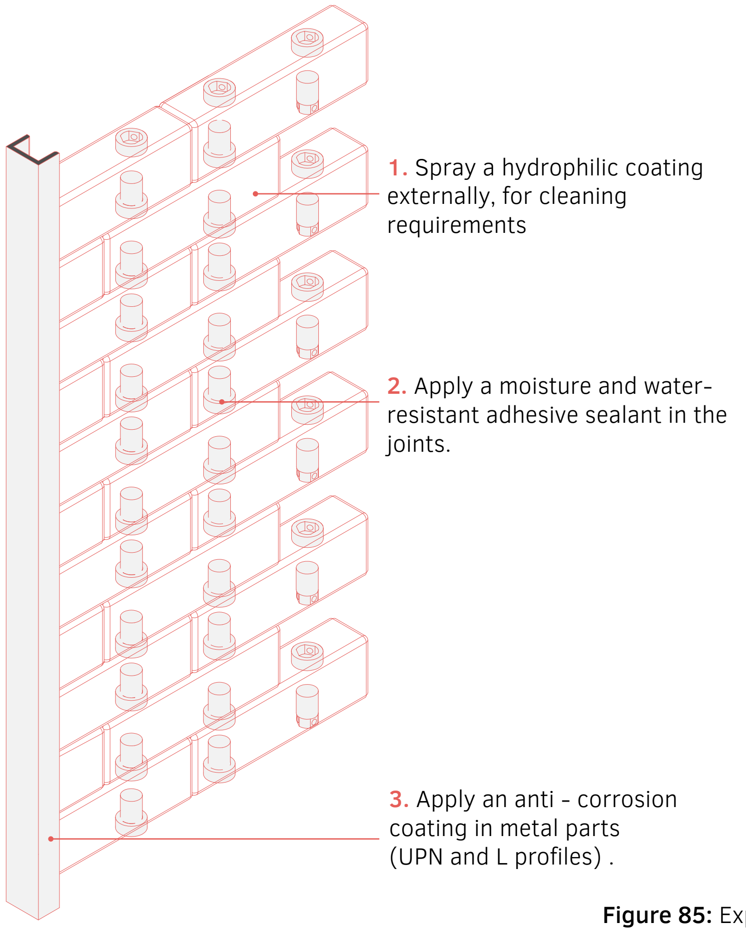



**Figure 85:** Explanatory diagram addressing the main techniques to maintain / seal the system.

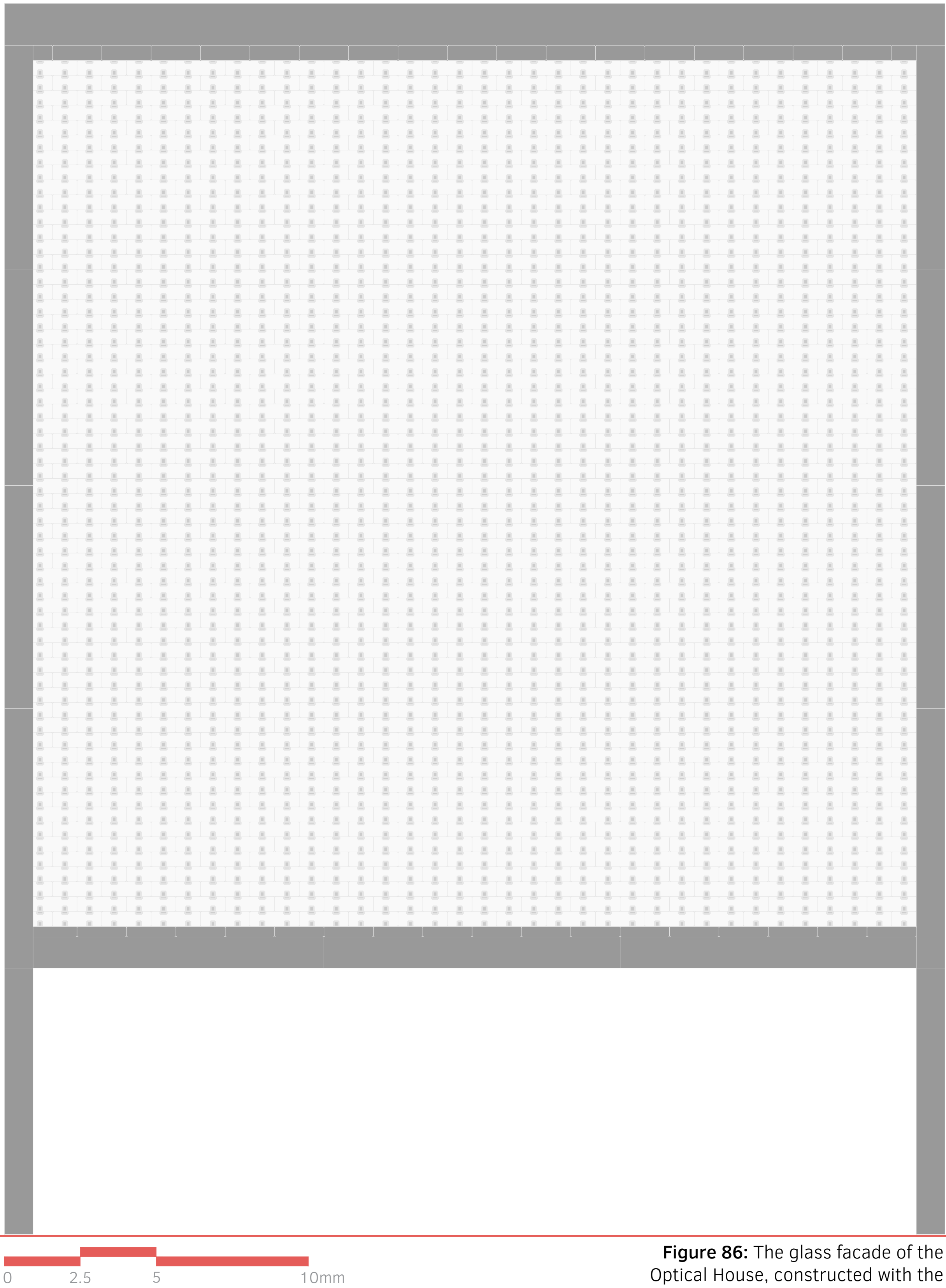



**Figure 86:** The glass facade of the Optical House, constructed with the proposed structural system.

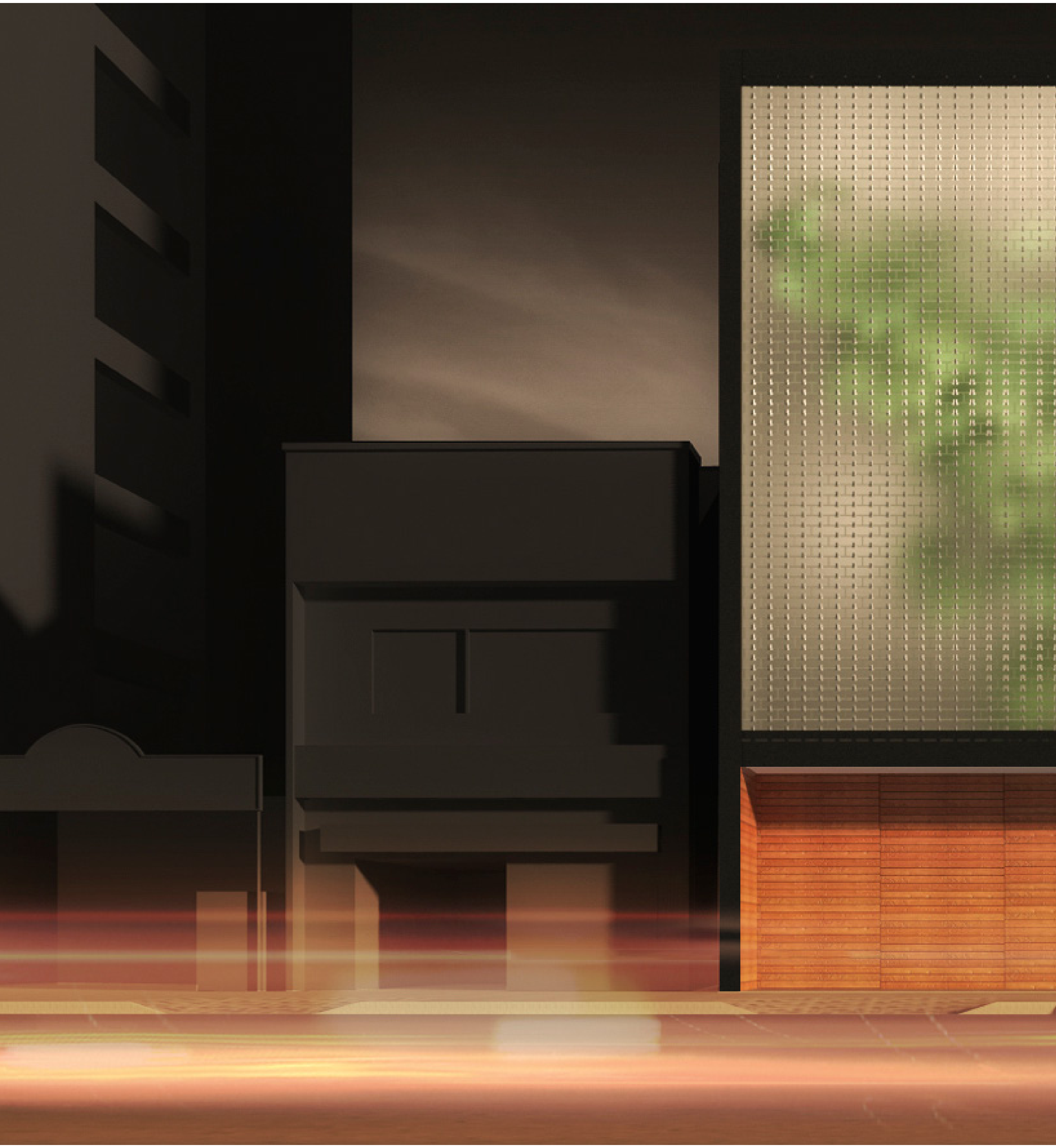
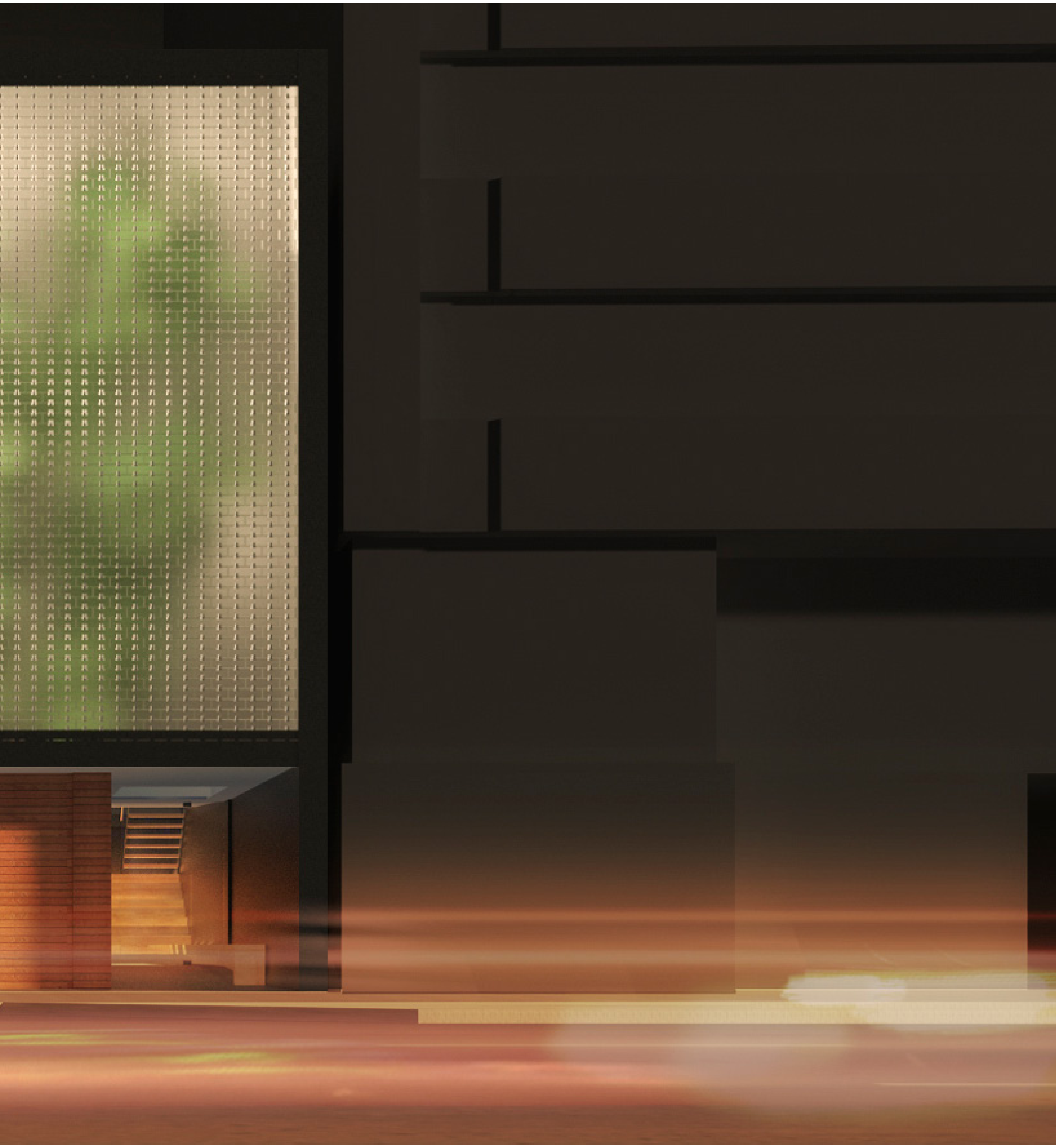


**Figure 87:** Night impression of the glass wall from a road view. The proposed structural system leads to a more transparent optical result. Source of road view: http://www.voyd.co.kr/



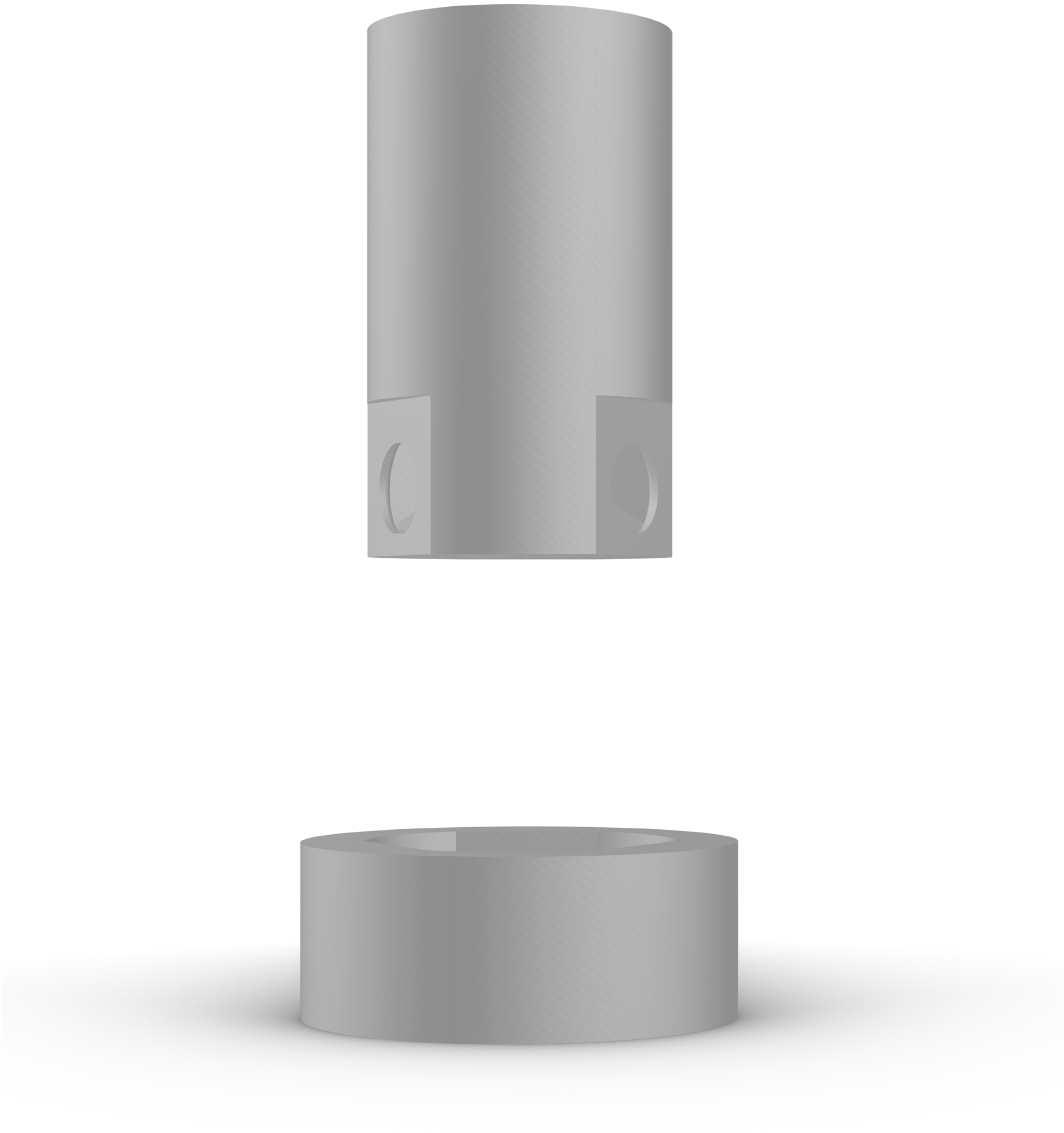


**Figure 88:** 3D Visualisation of the novel connection.

# 11 Conclusions

The present master thesis introduced the potential of a new structural system in cast glass structures by employing embedded connections in cast glass components. This chapter provides the main conclusions and the results of this research by giving answer to the main research question and sub-questions posed in the beginning of this research. An overall assessment with the main achievements of this system is presented and discussed as well. Consequently, a brief discussion with recommendations for further development, along with possible other applications are given on sections 11.2 and 11.3, respectively.

## 11.1 Answers to the main research question and sub-questions

Starting from giving answers to the sub-questions, this section provides a deep comprehension of the posed problems that consisted the trigger point of this thesis. Eventually, the answer to the main research question will present the overall result.

**Sub – questions:**

1. **Which are the advantages and disadvantages of existing connections types in cast glass structures?**

The existent structural systems in cast glass technology employ cast glass components in the shape and size range of typical masonry bricks, assembled on site. These systems have been accomplished either with mechanical connections or a rigid structural adhesive. However, the third structural system, which is on an early research stage, achieves the desired connections by the interlocking geometry of the units. The mechanical connection is translated into an additional supportive substructure which carries the tensile forces while it promises the desired resistance against buckling and lateral loads. This type of connection employs dry assembly connections which assist to an easily assembled and disassembled structure. In terms of tolerances, the size deviations are accommodated from the interlayer. However, the metal steel rods have a major visual impact leading to a compromised transparency. The structural rigid adhesive lead to an excellent diaphanous connection in which the applied loads are transferred homogeneously. Nonetheless, because of the construction method, this type of connection is non-reversible while it demands a meticulous and highly intensive labour of high precision. Lastly, the interlocking connection promises a reversible structure which is highly transparent. Additionally, the need of interlayer between the cast glass units accommodates any tolerances during the construction. Nonetheless, its structural efficiency is still on research stage.

Reacting to the challenges imposed from the current connection types, this research targets to a novel and easily assembled and disassembled structural system in cast glass structures, mitigating the compromised transparency resulting from the supportive substructure system. This will be achieved by employing embedded connections in cast glass components.

**2. What are the design principles for designing an embedded connection in cast glass components? What are the practical design limitations involved in this endeavour?**

This question is consisted of two parts based on two chapters. Chapter 5 introduced the design criteria as they have been established following the literature review. The design criteria divided into two categories, concerning the cast glass unit and the embedded connection respectively. More specifically, based on the principles concerning the connection, the desired structural system inquires a novel connection which is easily assembled and disassembled leading to a time and cost-efficient labour. Furthermore, the requested connection should be opted for its minor visual impact balancing in this way the compromised transparency imposed by the additional substructure. Moreover, ensuring for its structural integrity translates that the system will be able to withstand various loads. Lastly, the chosen connection should present material compatibility with the glass, so to circumvent any failure and distribute the various loads homogeneously.

From these criteria, the ease of assembly and disassembly, the minor visual impact, the predictability of structural efficiency and the novelty have played an important role during the design procedure. In Chapter 7.1, a major design limitation derived and concerned the accessibility of this system.  The aforementioned criteria consisted the driven factors for establishing the system's fundamental principle: a system with no access from outside. This has been a very challenging to follow principle during the design development, yet necessary to be respected.  The access either from the side or from top would complicate the assembly and the disassembly of the structure. Bolting two connections in approximately 6000 cast glass bricks on a glass wall would be a very time-consuming and demandable task. Moreover, it would affect the mechanical properties of the cast glass unit. Based on the literature review, the existence of a small notch on the cast glass brick would possibly generate peak stresses around the hole. Besides, the existence of a small notch would be visually intrusive affecting eventually significantly the overall transparency.

The answer for a system which is not accessible from outside though the cast glass unit, found in the principle of magnetic force. This encountered a locking mechanism that is magnet driven and could lock and unlock the cast glass components under these circumstances, generating in this way a very easy to assembly and disassembly structural system in the cast glass components.

**3. Which are the constraints of the material used for an embedded connection in a cast glass component? Which are the main principles and challenges involved in the material compatibility between a cast glass component and the desired connection?**

Embedding connections in cast glass units is an endeavour that has not been realised yet, so the material compatibility between the cast glass unit and the desired connection is an aspect that studied in two levels. To begin with, from what has been derived from the material exploration in Chapter 6, one crucial constraint was the thermal expansion coefficient. Since the aim is an embedded connection in cast glass units, it is crucial that in any temperature fluctuations, the total volume of the two materials will behave in a similar way. Hence, titanium met the aforementioned criteria and since it is already employed as an embedded insert in laminated structural glass selected as the most appropriate material for this research.

However, one of the main challenges in glass connections is the avoidance of glass to metal contact since the latter would provoke stress concentrations around the connection. Hence, concerning the material compatibility between the cast glass component and the requested connection, the main principle involved the selection of an intermediate material that could mitigate the loads and would not lead in cracking failure. The selection of the interlayer based on a combination between literature review and intermediate materials that are already employed in structural glass applications. The main challenge involved in this selection is that the selected interlayer should be able to respond to any structural challenges that may be occurred in this system. TSSA and SentryGlas® considered as the most appropriate materials for this endeavour. Based on existent structural applications, this proposal progressed with SentryGlas® as a primary intermediate material. However, TSSA presents great potential as well.

**4. Which are the main challenges affecting the structural behaviour of a system employing embedded connections in cast glass components?**

The chosen type of the embedded connection is broadly used in constructions and thus ensures that it is capable to withstand the loads applied in this structural system, as well. Besides, the selected geometry ensures that it can tolerate the concentrated peak stresses around the connection, generated by the gravitational and horizontal forces acting on it, respectively.

The main challenge that could affect the structural stability of a system which employs embedded connections in cast glass units, as introduced in Chapter 8.1 is the ability of such a system to withstand any lateral loads. Especially when the selected case study is located in a region which is seriously affected by strong winds and typhoons, the main objective is to ensure that the shear stress values are at acceptable levels. Addressing on this, the inner section of the proposed connection is engineered in a way that the metal balls lock the system in a rotational distance of 120°. This predicts significantly the ability of the introduced structural system to withstand any lateral or gravitational loads.

Main research question:

- **What is the potential of employing an embedded connection in cast glass components in order to accomplish an easily assembled and disassembled load bearing cast glass structure, which is structurally efficient, and it is not visually intrusive?**

The main aim of this master thesis was to explore the potential of embedding connections in cast glass elements targeting in this way to balance some of the technical obstacles derived from the existent structural systems in cast glass structures. The few realized projects are introduced with cast glass bricks in the size and dimensions of typical masonry bricks and employ either additional supportive substructure or a structural rigid adhesive. The third structural system which is still on research stage promises that the desired stiffness is achieved by the interlocking geometry of the units. Undoubtedly, the present structural systems are very promising, still they challenge some technical difficulties, summarizing to the meticulous and intensive assembly, the non-reversibility and the compromised transparency. These disadvantages were the trigger point of this research. The new structural concept introduces embedded connections in cast glass units.

This proposal introduces a novel embedded connection which performs as a locking mechanism between the cast glass units, achieving in this way no access through the glass brick. The connection is consisted of two parts, the upper part and the receiver. The inner section of the upper part designed after deliberated research and physical experiments and it embodies six stainless steel balls with a diameter of 6 millimetres which lock and unlock the system. The system is easily assembled and disassembled since the stainless-steel spheres are magnet – driven from the outside. Besides, the concept proved its locking and unlocking feasibility with 3D printed mock-ups of the connection, a magnet and stainless-steel balls. Concerning the geometry, the connection has been designed meticulously, so during the securing of the balls with the magnet, there is not only adequate length for the uplifting but also the exact width so the spheres will not lodge. Gravity is the parameter which assists to the lock of the system. For this reason, three inclined paths designed with 30° angle degrees contributing to a successful rolling of the spheres when the magnet is pulled out. Three out of six stainless steel balls are settled between the receiver and the upper part of the connection creating a successful locking. The three remaining balls rest on top of the others guaranteeing with a second locking. The whole system designed in a way that ensures its structural integrity as it is capable to withstand any lateral and gravitational loads.

Functionality along with minor visual impact were the driven factors for settling in the final dimensions of the embedded connection. Hence, the final design comes with a total length of 36 mm and an overall diameter (incorporated the receiver) of 30 mm, which in practice translates to a small – scale component. Comparing to the additional supportive substructure, this embedded connection could balance successfully the compromised transparency.

Table 8 consists a refined edition of Table 4 (Chapter 3.5.2 ). This table summarizes with a refined qualitative comparison what it could be achieved in this master thesis with the embedded connections in cast glass units. Developing further some disadvantages of the current structural systems, the new structural system seems very promising. Concerning the reversibility, the alternative structural system is reversible. However, due to the fact that the connection is laminated, de-lamination is achievable, but in contrast to the interlocking system or the additional supportive substructure, this includes a more meticulous procedure. Towards re-usability and since the structure is entirely reversible, the units could be successfully reused.

Consequently, from what it can be derived from this extended conclusion is that embedded connections in cast glass structures present a great potential steering to an easy assembled and disassembled structure which is structurally efficient and mitigates the compromised transparency imposed by precedent structural systems.

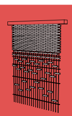
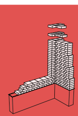
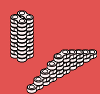
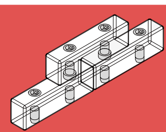
| Criteria / Systems |  Additional Supportive Substructure |  Adhesively Bonded Blocks |  Interlocking Cast Glass Untis |  Embedded Connections in Cast Glass Units |
|---|---|---|---|---|
| Buildability | + | - | ++ | ++ |
| Transparency | - | ++ | ++ | + |
| Reversibility | ++ | - | ++ | + |
| Predictability Of Structural Performance | ++ | + | -still on research stage- | + |

**Table 8:** Refined qualitative comparison of Table 4 with the new proposed structural system.

## 11.2 Recommendations for further research

Scope of this research is to present an alternative structural system in cast glass structures as an attempt to balance some of the technical obstacles posed by the existent ones. This endeavour proposes embedded connections in cast glass elements. Based on extended research by design and several physical experiments which proofed its feasibility, the proposed system appears to be very promising. However, some recommendations for further development are given in this section.

To begin with, seeking for a small – scale component which is capable to transfer the various loads while it affects to the minimum the visual result on a cast glass structural element has been one of the main principles during the design development. For this reason, the proposed connection tested within various alternatives in order to achieve the more feasible one. One of the alternatives suggested 4 instead of 6 stainless-steel balls inside the connection. As it is discussed in previous chapters, the 3 out of 4 balls would lock the system and the 4th would rest on top of them. In the beginning this alternative was more preferable since with 4 spheres, the connection could be even smaller than the suggested one, if we considered that the necessary length for a successful uplifting could be approximately 25mm. However, this alternative did not progress as the final proposal, considering that the existence of the fourth sphere may not be sufficient enough to maintain the system locked. As a recommendation, the inner section could be different by adopting a design approach where the inner walls apply pressure to the stainless- steel balls. This possibly would eventuate to a different approach regarding the three inclinations which were designed to accomplish a successful uplifting.

Furthermore, for several weeks, the first ideas, incorporated that the stainless-steel balls are enclosed to the connection and they are not inserted after the fabrication of the component. During the design procedure, there were several attempts to create a stopping around the three openings, so the balls could be placed prior to the lamination, eliminating the need of plastic cups for their transportation. These attempts confused the design procedure for weeks and led to complicated drawings and results which in such a small scale they may not even be successful. However, as a recommendation for further research, this idea could be implemented in case that similar connections but with bigger cross section need to be adapted. In this case, this attempt will be more feasible to be achieved. Besides it will facilitate to the maximum the assembly of the structure, since there will be no need of plastic covers.

Lastly, embedded titanium inserts are already applied for joining structural elements in laminated float glass. Such structural applications confirm that, glass and titanium cooperate successful and guarantee the structural integrity of the system. However, in cast glass structures this application has not been realised yet, since the concept of embedded connections in cast glass components is firstly proposed with this master thesis. In Chapter 8.1, the structural efficiency of this system has been primarily investigated revealing a promising structural performance. Nonetheless, as a further recommendation, a proper structural physical testing with titanium connections and cast glass units (or a chosen material with similar mechanical properties) would provide a deeper understanding of how the system operates under various loads. Towards to the verification of its structural integrity, an accurate numerical simulation related both to earthquake's and to lateral loads would provide a better comprehension of how the system performs under these circumstances.

## 11.3 Possible applications in alternative systems

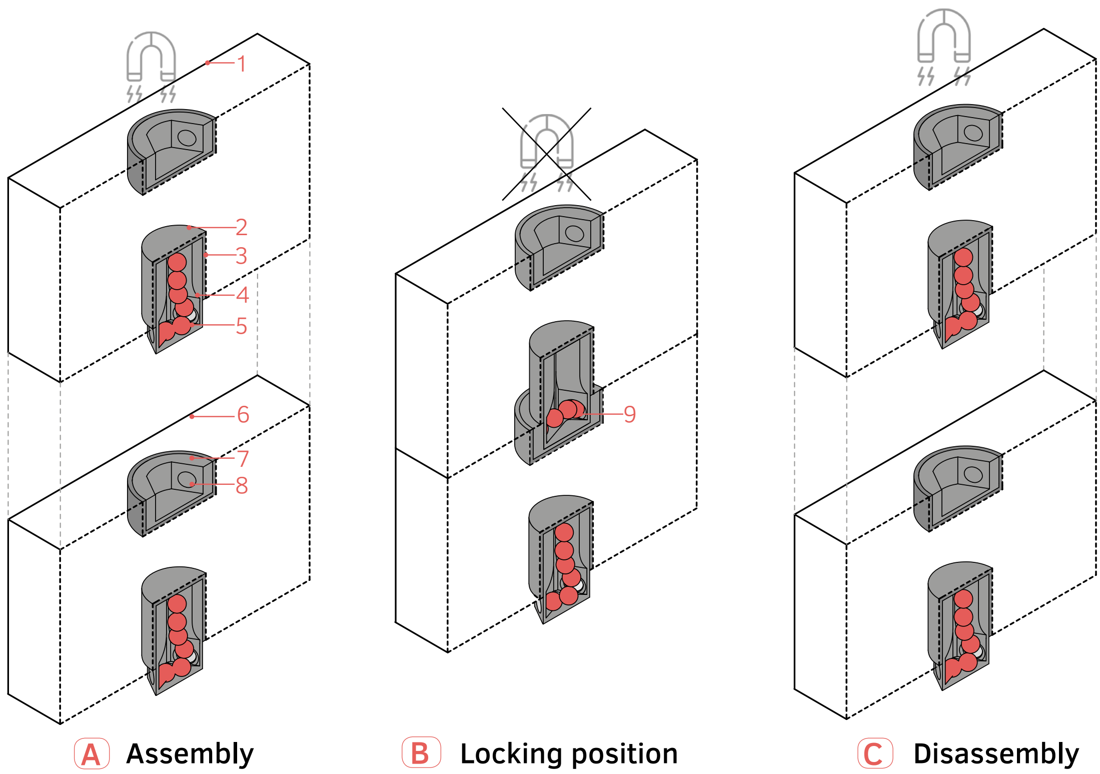
The conducted master thesis provides a novel answer to the persistent request for more diaphanous structures in the built environment, expanding simultaneously, the dynamism of the existing structural systems in cast glass structures. Embedded connections in the cast glass units, address some of the technical difficulties imposed by the former systems since they promise an easy to assembly, structurally predictable, with less compromised transparency cast glass structure. Considering that embedded connections in cast glass units is an endeavour that is firstly presented within the context of this master thesis, the final connection designed, by following explicitly the established design criteria. This ensures that the proposed metal connection will collaborate successfully with the cast glass unit. However, considering the functionality and the overall geometry, the potential of applying this mechanism as a hidden structural or non-structural connection in alternative vertical or close to vertical systems and materials, is given in this section.

Firstly, the proposed design could be successfully applied in typical masonry bricks as dry-assembled connections for cladding. Considering the applicability in alternative materials, the different thermal expansion coefficient indicates a freedom to a material selection of the embedded connection, not necessarily titanium, yet for instance, plastic or 3D printed. Although, metal (magnetic material) should remain at the spheres not only to ensure the structural integrity of the system, but also to be efficiently stimulated by the magnet, leading to a successful unlocking. The alternative material gives the opportunity for a cost-efficient system in masonry bricks, in contrast to cast glass structures in which the titanium embedded inserts consist an expensive proposal. Approaching circularity, the dry-assembled connections lead to a reversible system and totally recyclable. Considering the joining process, the connection with the unit could be achieved either with adhesion or direct material collaboration.

Although challenging, yet with an attention to not accidentally tilted or overturned the structure, the proposed connection could be implemented in furniture and in wood constructions, as well.  Chapter 4.5 provided a small overview of the existing embedded mechanisms in wood construction where there is access mainly through the material from outside. This novel connection eliminates the need of external access for fastening the system with bolts or alternatives joining methods. Flexibility in selection of a more cost-efficient non - magnetic material, such as wood, or plastic is also possible. In a similar way as in cladding, this provides a freedom in the joining process between the unit and the embedded connection. However, considering an alternative approach in the design by integrating magnets in the inner section of the receiver, so to sustain the magnetic balls locked in any rotation, provides a great potential to achieve easily assembled wood structures without the need of any bolts, and limits the possibility of a disassembled structure in case of an accidental overturning.

Furthermore, the suggested connection could be a very promising solution in façade engineering. The proposed small-scale component with the magnet driven stainless-steel spheres could stand as an innovative answer for connecting façade panels. Once more, the embedded joints could be produced by other materials, apart from titanium. Considering the small geometry, along with the potential of developing further the overall dimensions (Chapter 11.2), the connection could be embedded and perform successfully to various thicknesses that the façade panels may be produced.

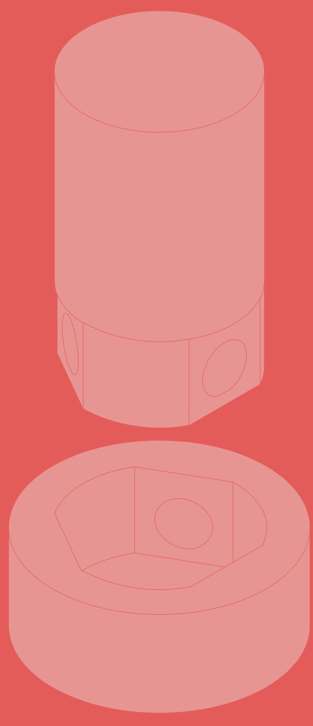
Consequently, the diagrams below illustrate the assembly and disassembly sequence of the novel connection in a possible application in alternative systems as a structural or a non-structural connection. Correspondingly, there is a flexibility in material choice regarding the tube and the receiver. The two components could be manufactured from a non-magnetic material of any choice, according to each project's requirements. The balls should remain from a magnetic material in order to be efficiently triggered from the magnet. Since the present system could be potentially applied in a great variety of alternative systems, the joining process could be either lamination or adhesion. In some cases (e.g. concrete), it could be even a direct collaboration with the material.




- **A**: Once magnetic field is activated the magnetic balls are charged and are uplifted in the tube.
- **B**: Condition where the magnetic field is de-activated and the magnetic balls drop to the desired locations and lock the system and accordingly the two units together.
- **C**: During the disassembly the magnetic balls are uplifted contributing to a successful unlocking of the system.

**INDEX**

1. Top unit
2. Tube manufactured of non-magnetic material.
3. Connection to unit can be achieved through adhesion / lamination / direct material collaboration (cohesion).
4. Different inclinations allow for successful disassembly.
5. Set of balls made of magnetic material. They are kept upwards during the installation due to magnetic field.
6. Bottom unit
7. Receiver manufactured of non-magnetic material.
8. Insert of matching the diameter of balls so that they can settle successfully and eventually lock the system.
9. Condition where the magnetic field is de-activated and the magnetic balls drop to the desired locations and lock the system and accordingly the two units together.



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# List of figures

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# Appendix

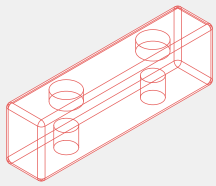
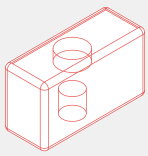
| Specifications<br>-<br>Bricks | Dimensions (mm)<br>l * w * h | Volume (mm³) | Number of units | Type of glass |
|---|---|---|---|---|
|  Normal Brick | 235x50x71 | 780189.64 | appr. 4700 | soda-lime |
|  Side Brick | 117.5x50x71 | 388880.439 | appr. 120 | soda-lime |

**Table 9:** Overview of dimensions, materials and processes concerning the fabrication of the cast glass unit the embedded connections.

| Material of the connection | Material of the interlayer | Joining process | Type of casting process |
|---|---|---|---|
| titanium | SentryGlass 1.52mm (TSSA also possible) | lamination | hot pouring |
| titanium | SentryGlass 1.52mm (TSSA also possible) | lamination | hot pouring |

| | | POLYMERS | | | ELASTOMERS | |
|---|---|---|---|---|---|---|
| | | PU | PVC | VIVAK® | NEOPRENE | SILICONE |
| PRIMARY | COMPRESSIVE STRENGTH ≥ 20MPa | YES | YES | YES | YES | YES |
| | CREEP RESISTANT | UNKNOWN | NO | UNKNOWN | UNKNOWN | NO |
| | SLIGHTLY LESS STIFF THAN GLASS | NO (MUCH LESS) | NO (MUCH LESS) | YES | NO (MUCH LESS) | NO (MUCH LESS) |
| | ABILITY TO BE SHAPED IN FINAL GEOMETRY & THICKNESS | YES INJECTION MOLDING | YES INJECTION MOLDING | YES VACUUM FORMING | NO N/A | YES INJECTION MOLDING |
| | CIRCULARITY | YES | YES | YES | YES | NO |
| SECONDARY | OPTICAL QUALITY | TRANSPARENT/ TRANSLUCENT | TRANSPARENT/ TRANSLUCENT | TRANSPARENT/ TRANSLUCENT | OPAQUE WHITE | TRANSLUCENT |
| | THERMAL EXPANSION COEFFICIENT* GLASS: 4-10 MSTRAIN/ ° C | 90-92 | 45-180 | 120-130 | 110-240 | 250-300 |
| | DURABILITY: WATER, FIRE & UV | YES | YES | YES | YES | WATERTIGHT FOR APPROX. 20 YEARS YES YES |

**The values for the thermal expansion coefficient have been retrieved from CES EduPack 2019*

POSITIVE — DEBATABLE — NEGATIVE — CHOSEN

**Table 10:** Overview of the materials explored for an interlayer study between interlocking cast glass units. Retrieved from (Dimas,2020)

| | METALS | | | HYBRIDS | | |
|---|---|---|---|---|---|---|
| TEFLON | COPPER | ALUMINIUM | LEAD | METAL FOAM SANDWICH | LAMINATED PU | SOFT CORE ALUMINIUM |
| YES | YES | YES | YES | YES | YES | YES |
| MAYBE | YES | YES | YES | YES | MAYBE | YES |
| MAYBE | NO (MORE) | YES | YES | YES | MAYBE | YES |
| MAYBE/ NO MILLING | YES PRESS FORMING | YES PRESS FORMING | YES PRESS FORMING | MAYBE/ NO *COMBINATION* | MAYBE *COMBINATION* | MAYBE *COMBINATION* |
| MAYBE | YES | YES | NO | MAYBE/ NO | MAYBE/ NO | MAYBE/ NO |
| TRANSLUCENT | REFLECTIVE RED-BROWN | REFLECTIVE SILVER | OPAQUE ASH GRAY | REFLECTIVE | TRANSLUCENT/ OPAQUE | REFLECTIVE |
| 120-180 | 15-23 | 18-26 | 18-30 | UNKNOWN | UNKNOWN | UNKNOWN |
| YES | YES *DISCOLORATION FROM WATER* | YES | YES | MAYBE *CONSIDER THE EDGES* | YES | YES |

# SentryGlas®

IONOPLAST INTERLAYER

## SPECIFYING AND TECHNICAL DATA

The following information is presented to help you evaluate or order SentryGlas® ionoplast interlayers.
SentryGlas® interlayer is available on roll or as sheet and has a Yellowness-Index (YID) of < 2.5.

## SHEET DIMENSIONS

| Caliper mm (mil) | Width cm (in) Ordered, -0 +10 mm (-0 +0.4 in) | Length m (ft) |
|---|---|---|
| **0,89** (35) | **61-216** (24-85) | **up to 600** (up to 236) |
| **1,52** (60) | **61-216** (24-85) | **up to 600** (up to 236) |
| **2,28** (90) | **61-216** (24-85) | **up to 600** (up to 236) |
| **2,53** (100) | **61-183** (24-72) | **up to 600** (up to 236) |
| **3,04** (120) | **61-183** (24-72) | **up to 600** (up to 236) |

In addition to the standard stock sizes above, SentryGlas® can be ordered as 'cut-to-size', 'cut-to-fit' or 'cut-to-form' sheet, which means that none of the material is wasted. In all cases, sheet thickness is 0.89 mm (35 mil), 1.52 mm (60 mil) or 2.28 mm (90 mil). As these custom sizes require special handling/cutting, lead times are longer.

For details about the 'cut-to-size', 'cut-to-fit' or 'cut-to-form' sheet offering feel free to contact us.

## ROLL DIMENSIONS

| Caliper mm (mil) | Width cm (in) Ordered, -0 +10 mm (-0 +0.4 in) | Length m (ft) |
|---|---|---|
| **0,76** (30) | **122** (48) | **200** (656) |
| **0,76** (30) | **153** (60) | **200** (656) |
| **0,76** (30) | **183** (72) | **200** (656) |
| **0,76** (30) | **153** (60) | **50** (164) |
| **0,89** (35) | **122** (48) | **200** (656) |
| **0,89** (35) | **153** (60) | **200** (656) |
| **0,89** (35) | **183** (72) | **200** (656) |
| **0,89** (35) | **153** (60) | **50** (164) |
| **0,89** (35) | **225** (88) | **50** (164) |
| **0,89** (35) | **225** (88) | **200** (656) |
| **0,89** (35) | **240** (96) | **50** (164) |
| **0,89** (35) | **240** (96) | **200** (656) |



www.sentryglas.com
Contact: safetyglass@kuraray.com

# SentryGlas® Elastic Properties (SG5000)

In general, 0,76 mm (30 mil) is specified for easy processing when double stacking and not intended to be used as a single ply. Single ply use has not been tested to determine performance against any safety glazing codes or standards. 0,89 mm (35 mil) interlayers typically require high quality tempered glass for flatness. 1.52 mm (60 mil) interlayers are specified as the standard thickness for minimally supported applications. 2.28 mm (90 mil) thickness interlayers are normally specified for anti-intrusion, hurricane and other types of security applications. Glass producers and laminators require interlayers to be supplied either in sheet form or on rolls. SentryGlas® Ionoplast interlayers are available in both formats. For faster deliveries, SentryGlas® ionoplast interlayer is stocked in standard thicknesses (calipers) of 0.89 mm (35 mil), 1.52 mm (60 mil) and 2.28 mm (90 mil) sheets. SentryGlas® ionoplast interlayer on roll is available in 0,76 mm (30 mil) and 0.89 mm (35 mil) thickness.

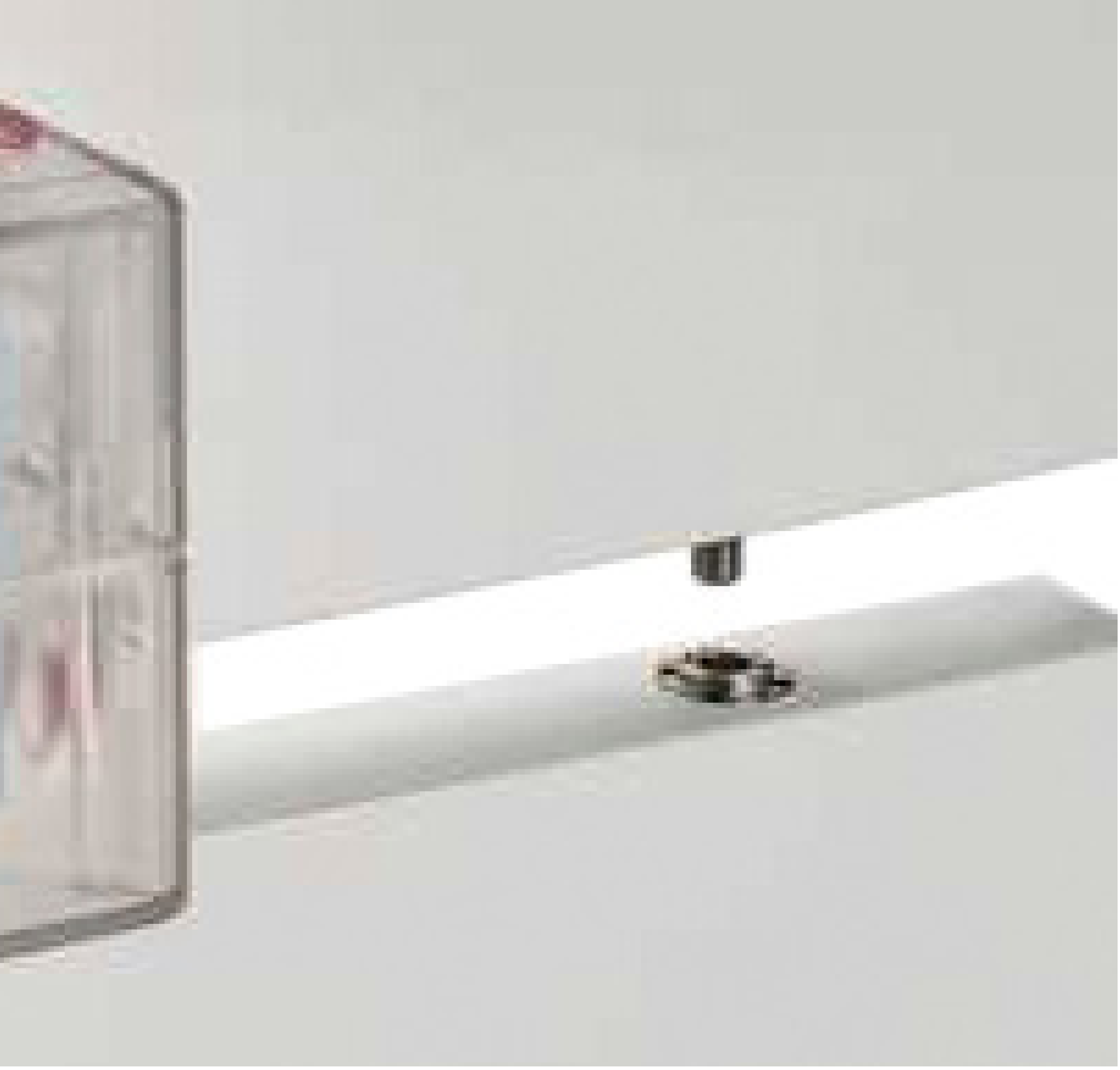
## TABLE 1 — LAMINATE PROPERTIES

| Property | Units Metric (English) | Value | Test |
|---|---|---|---|
| Haze | % | < 2 | ASTM D1003 |
| Impact test<br>0,23 kg (0.5 lb) | **m** (ft) | > 9.14 (> 30) | ANSI Z26.1 |
| Boil test<br>2 hr | - | No defects | ANSI Z26.1 |
| Bake test<br>2 hr/100 °C | - | No defects | ANSI Z26.1 |

## TABLE 2 — INTERLAYER TYPICAL PROPERTIES

| Property | Units Metric (English) | Value | ASTM Test |
|---|---|---|---|
| Young's Modulus | **Mpa** (kpsi) | **300** (43.5) | D5026 |
| Tear Strength | **MJ/m3** (ft lb/in3) | **50** (604) | D638 |
| Tensile Strength | **Mpa** (kpsi) | **34.5** (5.0) | D638 |
| Elongation | **%** (%) | **400** (400) | D638 |
| Density | **g/cm3** (lb/in3) | **0.95** (0.0343) | D792 |
| Flex Modulus<br>**23 °C** (73 °F) | **Mpa** (kpsi) | **345** (50) | D790 |
| Heat Deflection Temperature (HDT)@0.46 MPa | **°C** (°F) | **43** (110) | D648 |
| Melting Point | **°C** (°F) | **94** (201) | (DSC) |
| Coeff. of Thermal Expansion (-20 °C to 32 °C) | **10-3 cm/cm °C** (mils/in °C) | **10 - 15**<br>(0.10 - 0.15) | D696 |
| Thermal Conductivity | **W/M-K**<br>(BTU-in/hr-ft2 °F) | **0.246** (1.71) | |

**Figure 89:** The Lamello Invis Mx2 System.
Source: https://www.lamello.com/product/bohrenfraesen-verbinder/invis-mx2/



BULLSEYE
GLASS CO.

# ANNEALING THICK SLABS

This annealing chart has been formulated for use with Bullseye clear glass. It is derived from Corning's method as shown in McLellan and Shand.* It is based on a flat slab of uniform thickness that is set up in such a fashion that it can cool equally from top and bottom.

If the piece is not set up in such a fashion that it can cool equally from top and bottom or is anything besides a flat slab of uniform thickness, select an annealing cycle for a piece that is twice the thickness of the thickest area of the piece. Even a very conservative annealing cycle may not work if the kiln is not capable of cooling the work uniformly.

For more Bullseye technical and product information see **www.bullseyeglass.com**

| THICKNESS | ANNEAL SOAK TIME | INITIAL COOLING RATE | INITIAL COOLING RANGE | 2nd COOLING RATE | 2nd COOLING RANGE | FINAL COOLING RATE | FINAL COOLING RANGE | TOTAL MINIMUM TIME |
|---|---|---|---|---|---|---|---|---|
| inches | @ 900 ˚F | ˚F/hr | ˚F | ˚F/hr | ˚F | ˚F/hr | ˚F | Hours |
| mm | @ 482 ˚C | ˚C/hr | ˚C | ˚C/hr | ˚C | ˚C/hr | ˚C | |
| 0.5 in | 2 hr | 100 | 900–800 | 180 | 800–700 | 600 | 700–70 | ~5 hr |
| 12 mm | | 55 | 482–427 | 99 | 427–371 | 330 | 371–21 | |
| 0.75 in | 3 hr | 45 | 900–800 | 81 | 800–700 | 270 | 700–70 | ~9 hr |
| 19 mm | | 25 | 482–427 | 45 | 427–371 | 150 | 371–21 | |
| 1.0 in | 4 hr | 27 | 900–800 | 49 | 800–700 | 162 | 700–70 | ~14 hr |
| 25 mm | | 15 | 482–427 | 27 | 427–371 | 90 | 371–21 | |
| 1.5 in | 6 hr | 12 | 900–800 | 22 | 800–700 | 72 | 700–70 | ~28 hr |
| 38 mm | | 6.7 | 482–427 | 12 | 427–371 | 40 | 371–21 | |
| 2.0 in | 8 hr | 6.8 | 900–800 | 12 | 800–700 | 41 | 700–70 | ~47 hr |
| 50 mm | | 3.8 | 482–427 | 6.8 | 427–371 | 22 | 371–21 | |
| 2.5 in | 10 hr | 4.3 | 900–800 | 8 | 800–700 | 26 | 700–70 | ~70 hr |
| 62 mm | | 2.4 | 482–427 | 4.3 | 427–371 | 14.4 | 371–21 | |
| 3.0 in | 12 hr | 3 | 900–800 | 5.4 | 800–700 | 18 | 700–70 | ~99 hr |
| 75 mm | | 1.7 | 482–427 | 3.1 | 427–371 | 10 | 371–21 | |
| 4.0 in | 16 hr | 1.7 | 900–800 | 3.1 | 800–700 | 10 | 700–70 | ~170 hr |
| 100 mm | | 0.94 | 482–427 | 1.7 | 427–371 | 5.6 | 371–21 | |
| 6.0 in | 24 hr | 0.75 | 900–800 | 1.3 | 800–700 | 4.5 | 700–70 | ~375 hr |
| 150 mm | | 0.42 | 482–427 | 0.76 | 427–371 | 2.5 | 371–21 | |
| 8.0 in | 32 hr | 0.42 | 900–800 | 0.76 | 800–700 | 2.5 | 700–70 | ~654 hr |
| 200 mm | | 0.23 | 482–427 | 0.42 | 427–371 | 1.4 | 371–21 | |



* McLellan and Shand (1984), *Glass Engineering Handbook*, 3rd Edition, New York, McGraw Hill.

WWW.BULLSEYEGLASS.COM