6 Learning by building – Challenges & Innovations during the construction of the Crystal Houses façade

Continuing from the experimental validation of the adhesively bonded system, this chapter presents the main challenges confronted and records the innovative solutions implemented during the consecutive construction steps of the adhesively-bonded cast glass façade[49]. These include the manufacturing and quality control of the bricks, the set-up of the construction site, the levelling of the reference supporting beam, the bonding method used and the fabrication and installation of customized elements such as the architraves, window and door frames and the intermixing zone of glass with terracotta bricks. The experimental work on prototype elements, described in Chapter 5, resulted into the use of a colourless, UV-curing adhesive of the *Delo Photobond* family for bonding the solid glass blocks together. The tests indicated as well that the desired monolithic structural performance of the glass masonry system and a homogeneous visual result can only be achieved when the selected adhesive is applied in a 0.2-0.3 mm thick layer. In accordance, the bricks have to meet a strict dimensional tolerance of ± 0.25 mm. On the facade as a whole, this means that the overall size deviations will be limited to a few mm. The nearly zero thickness of the adhesive together with the request for unimpeded transparency introduced numerous engineering puzzles, addressed in this chapter. The fundamental difference between conventional brickwork and the developed glass masonry system is that a standard mortar layer compensates for the size deviations of the bricks, while the selected adhesive cannot. This manifests the level of complexity introduced by the manual bonding and the significance of constantly

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[49] This chapter has been published as: Oikonomopoulou F., Britogianni T., Veer F., Nijsse R. The construction of the *Crystal Houses* façade: Challenges and Innovations. Glass Structures & Engineering, 2017. (Oikonomopoulou et al. 2017a)

controlling the entire construction with high precision methods. Based on the conclusions of the research and the technical experience gained by the realization of the project, recommendations are made on the further improvement of the presented glass masonry system for future applications.

TOC

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6.1 Introduction

In the previous chapter the design and experimental validation of a novel adhesively-bonded glass block system, developed for the *Crystal Houses* façade in Amsterdam, was presented. The architectural concept of the façade is to achieve a completely transparent reproduction of the original brick façade of a former townhouse in Amsterdam. Based on the original design the resulting façade comprises more than 6500 solid glass bricks, reinterpreting the traditional brick pattern, and elaborate cast glass elements for the replication of the window and door frames. To achieve unhindered transparency, the 10 m x 12 m glass block façade has to be self-supporting. The experimental work described in Chapter 5 concluded that it was necessary to use *Delo Photobond 4468*, a clear, UV-curing adhesive of high stiffness as the bonding media. Experimental work on prototype elements indicated that the desired structural and visual performance of the glass masonry system are only guaranteed when the selected adhesive is applied in a 0.2 – 0.3 mm thick layer. To meet this requirement, the glass blocks should comply with a strict dimensional tolerance of ±0.25 mm in both height and flatness. The nearly zero thickness of the adhesive together with the request for unimpeded transparency introduced numerous engineering challenges. These include the production of highly accurate glass bricks and the homogeneous application of the adhesive to achieve the construction of the entire façade with remarkably tight tolerances. This chapter presents the main challenges confronted during the construction of the novel façade and records the innovative solutions implemented, from the production and control of the glass units to the completion of the façade.

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6.2 Manufacturing and quality control of the glass blocks

6.2.1 Manufacturing process of the glass bricks

The fabrication of approximately 7500[50] solid glass bricks in total, was assigned to the Italian company *Poesia (http://www.spaziopoesia.it)*. Each brick is manually cast by pouring molten glass in high precision, open steel moulds with a removable bottom surface (Fig. 6.1). A low-iron glass recipe is used for high optical quality. The final chemical composition of the glass, as measured by a X-ray fluorescence (XRF) spectrometer, is shown in Table 6.1. To attain the desired smooth external texture the steel moulds are preheated to a constant temperature of approximately 650°C - 750°C. If the mould's temperature falls below this range, then the hot glass coming into contact with the metal surface freezes instantly, creating a rough, wavy surface. On the other hand, if the mould is heated to a higher temperature, the glass tends to adhere to the walls of the mould. A release coating on the mould surfaces further prevents the adhesion of the molten glass to the working surface and the development of micro-cracks.

After the glass has been poured into the mould, it is left at ambient temperature to rapidly cool until ~700°C. This rapid cooling through the critical crystallization zone is essential to obtain an amorphous structure and avoid the molecular arrangement of the melt in crystals, which would result in a cloudy glass of reduced transparency (Shelby 2005). During this initial cooling phase, the glass has still low viscosity that can allow any induced thermal stress to relax out to a negligible amount immediately (Shelby 2005). After the glass temperature has dropped to its softening point (~720°C[51]), the viscosity of the glass is sufficient for it to retain its shape and not deform under its own weight (Shand 1968). At ~700°C, the glass

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[50] This figure reflects the final order for the construction of the façade and includes the production of spare blocks. The façade consists of approx. 6500 bricks.

[51] The temperatures given here for the softening, annealing and strain points are indicative for soda-lime glass and are based on research by (Albert Napolitano,Earl G. Hawkins 1964). The values may differ according to the exact composition of the glass. The exact temperatures referring to the soda-lime recipe of the glass blocks have not been disclosed to the authors by *Poesia*.

element is removed from the mould by suction at the top surface, and moved into the annealing oven.

FIG. 6.1 Left: The high precision, open steel moulds. Right: Molten glass bricks during the rapid cooling phase from 1200°C to ~700°C degrees.

TABLE 6.1 Composition of the applied cast glass based on XRF chemical analysis

compound	wt%	absolute error (wt%)
SiO_2	75.606	0.1
Na_2O	15.833	0.1
CaO	5.142	0.07
K_2O	1.836	0.04
Sb_2O_3	0.821	0.03
CuO	0.402	0.02
Al_2O_3	0.165	0.01
MgO	0.072	0.008
ZrO_2	0.043	0.006
SO_3	0.034	0.006
TiO_2	0.02	0.004
Fe_2O_3	0.01	0.003

There, a long and meticulously controlled annealing process eliminates any possible differential strain built up between casting and demoulding, as well as prevents the generation of internal residual stresses during further cooling. Upon this point, key reference temperatures are the annealing point (~545°C) and the strain point (~505°C) of soda-lime glass. The annealing point is defined as the temperature at which the viscosity of glass will allow any induced stress to relax out substantially

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in just a few minutes (Shelby 2005). The strain point is the temperature where the same stress is reduced to acceptable values in four hours (Shand, Armistead 1958; Shand 1968). The cast glass should be maintained for adequate time at the annealing point to relieve any existing strains and then cooled at a rate sufficiently slow so that residual stresses will not reappear when the glass temperature has reached equilibrium (Shand, Armistead 1958). Effectively, below the strain point, stress cannot relax in time and is considered permanent (Watson 1999). When the temperature of the entire glass component has dropped below the strain point, the component can cool at a faster pace until ambient temperature, yet still sufficiently slow to prevent breakage due to thermal shock (Shand, Armistead 1958)[52].

As already discussed in chapter 2.4 the heat transfer needed for accomplishing the desired temperature difference is influenced by multiple parameters that are challenging to accurately simulate for solid cast glass components. Instead, companies such as Poesia, use an empirical annealing schedule based on their experience and furnace facilities. In this case, the company concluded that each *Crystal Houses* brick with 65 mm x 105 mm x 210mm dimensions requires approximately 8 h of annealing, whereas bricks of double the volume (65 mm x 210 mm x 210 mm) require 36-38 h respectively to prevent the generation of perceptible permanent residual stresses. The 65 mm thickness of the components hindered -at that time- an accurate through-the-thickness stress measurement by a *Scattered Light Polariscope* (SCALP) stress-meter using the current hardware/software. Instead a qualitative analysis of strain concentration was performed using a polarized white light source and a crossed polarized film that blocks the transmission of light. If glass is subjected to stress, it exhibits optical anisotropy. Glass without any stress will appear completely dark (Schott AG 2004). If the specimen presents besides black only grey-scale spectral composition, it has low residual stresses. When the colour spectrum appears the amount of stress is higher but cannot be quantified[53]. This method was used by Poesia to control all produced bricks. Bricks such as the one on the left of Fig. 6.2, with a clear indication of internal stresses by a coloured spectrum, were discarded. Only bricks such as the one on the right of Fig. 6.2, with dark and white areas were used in the façade. The fracture pattern of tested specimens also suggested low residual stresses – there was no excessive fragmentation or branching observed in the components.

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[52] For a detailed explanation of the annealing process of cast glass objects refer to Chapter 2.4

[53] See chapter 2.4 for a more detailed explanation.

During the initial rapid cooling, natural, inevitable shrinkage occurs to the glass volume during the material's transition from liquid to solid state. The shrinkage causes dimensional differences between units, uneven surfaces especially on the top, open surface of the cast component owing to the additional gravity force (see Fig. 6.1 and Fig. 6.3).

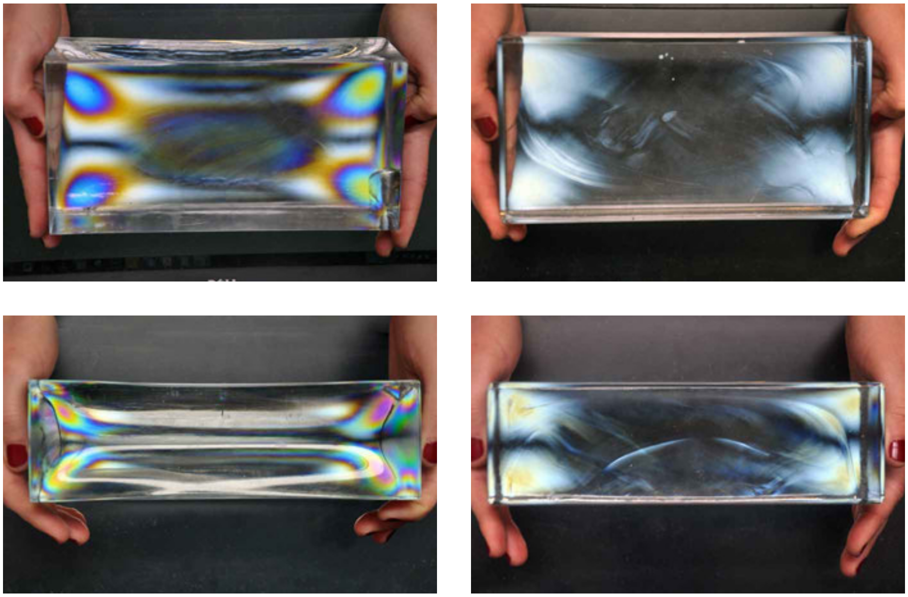

FIG. 6.2 Qualitative analysis of strain concentration by polarization test. Bricks such as the ones shown on the left image, with a clear indication of residual stresses, were discarded. Specimens such as the one on the right, with no visible considerable strain concentration, were employed in the façade.

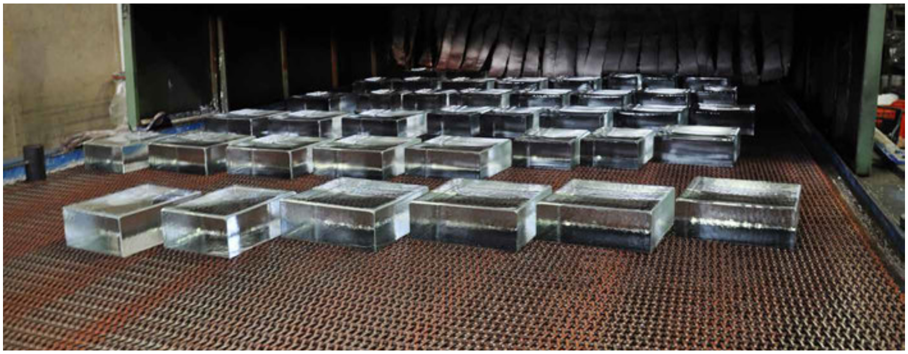

FIG. 6.3 Glass bricks of 210 mm x 210 mm x 65 mm coming out of the annealing oven after circa 36-38 h. The natural shrinkage is visible on the top surface.

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Different casting orientations were tested for minimizing the resulting shrinkage in the larger, bonding surfaces of the bricks. Fig. 6.4 demonstrates that even when molten glass is rapidly cooled in a vertical orientation, there is still visible shrinkage on the larger, bonding faces of the components.

Considering that regardless of orientation of the mould, the bricks' bonding surfaces required further processing, the horizontal position was favoured in terms of aesthetics, where the non-bonding sides are not visibly distorted. Thus, to achieve the desired ±0.25 mm precision, the blocks are originally cast slightly higher. After the annealing process, a CNC machine mills the top layer of each block to remove the natural convex and obtain the precise height and flatness. Finally, both top and bottom faces of each block, i.e. the bonding surfaces, are polished to a smooth flat surface of the desired dimensional accuracy. The four vertical surfaces remain unprocessed as they do not influence the structural system. Mechanical testing on both CNC polished and unpolished bricks showed no deterioration of the mechanical properties of the former.

FIG. 6.4 Glass bricks rapidly cooled down to the annealing point in vertical orientation. The natural shrinkage is evident besides the top surface, also across the larger surfaces.

6.2.2 Quality control of the glass bricks

The processed glass bricks are then subjected to two separate dimensional controls to verify their conformity. Both controls were performed first at *Poesia* and then again at *TU Delft* for verification. The first control is accomplished by a cut-out metal plate jig that controls the total length and width of the bricks in 1.00 mm accuracy (Fig. 6.5). The second control employs a customized electromechanical measurement bench with five *Linear Variable Differential Transformer* (LVDT) sensors of 1 μm accuracy attached to an aluminium frame (Fig. 6.6). By taking point measurements close to the four edges and at the center of each unit, the sensors check if the bricks meet the required 0.25 mm tolerance in both height and flatness from the nominal height of 65.00 mm. It should be clarified that the range of acceptable height varies between 64.75 - 65.25 mm but within each particular brick the height deviation cannot exceed 0.25mm. Accordingly, through this measuring control, the acceptable bricks are sorted in two groups based on the point with the maximum height:

- Group A comprises bricks between 64.75 mm and 65.00 mm high
- Group B comprises bricks between 65.00 mm and 65.25 mm high respectively.

Only bricks of the same group were used per row of construction to maintain the 0.2-0.3 mm requirement for the adhesive thickness.

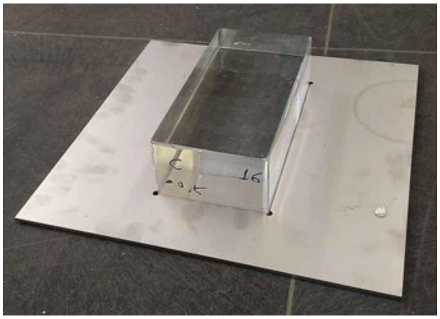

FIG. 6.5 The jig used in the first dimensional control.

FIG. 6.6 Set-up of the second control for checking the height and flatness of the components.

Besides the dimensional controls, a visual inspection of the bricks is performed. Flaws on the bricks' bonding surfaces, usually in the form of minute cracks or scratches, even less than 1 mm deep, commonly caused during the handling and transportation, can trigger the propagation of visible cracks after the adhesive's curing process. In specific, during curing the adhesive shrinks by max. 9% vol at

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ambient temperature (Delo Industrial Adhesives 2014) because of polymerization triggered by UV-light (Delo Industrial Adhesives 2007), inducing a considerable amount of tension to the minute cracks that can start to propagate, eventually resulting in visible cracking[54] (see Fig. 6.7). Only the glass components that pass both the measuring and visual controls were used in the construction of the façade.

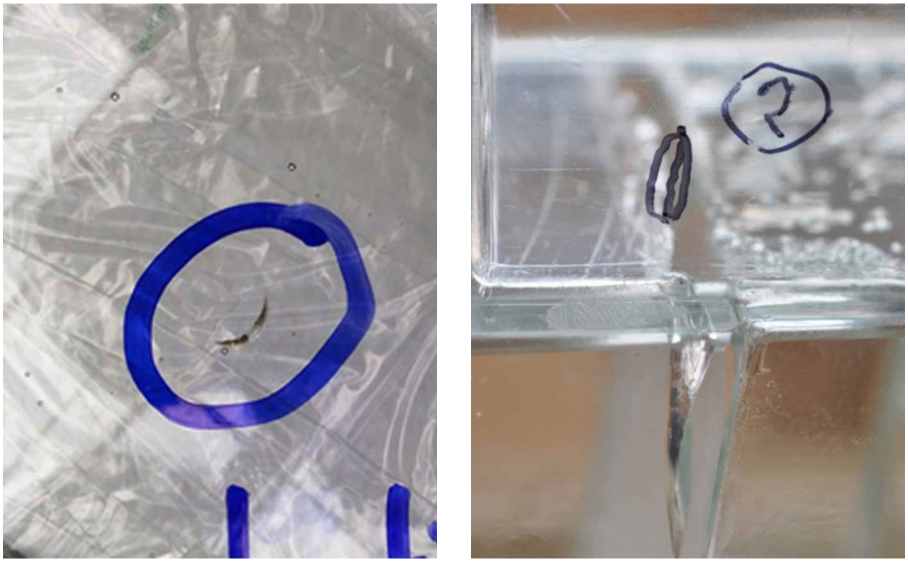

FIG. 6.7 Left: A minor crack on a brick's bonding surface. Right: The propagation of such a minor crack after the curing of the adhesive.

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[54] According to the research and experimental work conducted by (Prautzsch 2015), a curing process of increased duration and decreased intensity, carried out in steps, allows for better settlement of UV-curing adhesives and results in less internal stresses. As described in chapter 6.3.3, the curing process followed in the façade's construction follows a two-step curing process. The duration of the curing and intensity have been chosen in consultancy with Siko B.V. Still, the resulting tensile stresses at the adhesive layer were sufficient to cause crack propagation from surface damage.

6.3 Construction of the glass brick wall

6.3.1 Construction site set-up

The upper conventional masonry façade of the top residential floor, based on a steel beam spanning its length, was completed 6 months prior to the construction of the glass elevation (Fig. 6.8). The level of complexity of the manual bonding process of the glass façade, called for a highly skilled building crew and a strictly controlled construction. A 12 h working schedule was established, five days per week. 7-9 highly skilled workers bonded and sealed an average of 80-100 glass blocks per day under the supervision of 2 quality control engineers and the construction site supervisor.

FIG. 6.8 The masonry wall was already constructed prior to the glass elevation.

The special characteristics of the adhesive required the construction of the façade inside a UV-filtering tent for protection against solar radiation, adverse weather conditions and dust. To ensure a controlled level of temperature and humidity, heating equipment was installed inside the tent so that the bricks and the adhesive be maintained within workable temperatures during winter. During the summer, when the ambient temperature exceeded 30 °C the construction would temporarily stop. Due to limited space in the construction site, the glass blocks were stored in pallets in a separate warehouse and were gradually transported to the site upon demand.

A scaffolding with a mast climbing working platform was installed for the construction of the glass brick wall. Simultaneously, three mobile elevated working platforms were placed at the inner side of the wall for the construction of the buttresses. Bricks for one full row of construction were loaded and lifted each time on the mast climbing working platform, from where they were distributed for bonding. An elaborate network of horizontal aluminium guides was utilized to prevent any misalignment during the erection of the wall (Fig. 6.9). Customized vertical aluminium frames were temporarily installed as place holders of the wall openings.

FIG. 6.9 Left: the installed aluminium place holders of the opening. Right: The mast climbing working platform and one of the three mobile elevated platforms.

6.3.2 Levelling the starting bonding surface

The erection of the glass masonry wall started on top of a 0.60 m high by 0.20 m wide reinforced concrete plinth, essential for the protection of the lower part of the façade against hard body impact; it has been calculated to resist a vehicle collision travelling with a velocity of 50 km/h. To match the texture and colour of the glass wall, the vertical faces of the concrete base are coated with a laminate of a stainless steel sheet and annealed patterned glass, laminated together by *SentryGlas®* foil. A

30mm thick stainless steel plate fixed by bolts on top of the plinth forms the base for the glass masonry wall (Fig. 6.10).

FIG. 6.10 On the left the bolts used for levelling the stainless steel plate, seen on the right.

The prerequisite for extreme accuracy of the developed glass block system necessitates a reference building surface of corresponding flatness. Accordingly, the stainless steel plate had to be levelled to an accuracy of 0.25 mm for the entire 12 m length of the façade. Such high measuring accuracy called for the development of an innovative measuring and levelling system. Specifically, the bolts, set 275 mm apart (Fig. 6.10) allow for the levelling of the stainless steel plate in consecutive steps. By employing standard levelling equipment the plate was initially levelled to an accuracy of 3 mm over the 12 m length. Fig. 6.11 demonstrates the principle of the measuring system developed to further level the stainless steel plate to the desired precision: A continuous open metal conduit with both ends sealed, supported directly on the concrete surface, is filled with a non-transparent, reflective liquid. When still, a liquid will achieve absolute horizontal flatness, establishing the reference level for calibrating the plate. A laser scanner with a sensor of 1 μm precision, fixed on an aluminium frame with three legs is then moved over a set of consecutive points on the stainless steel plate, taking measurements in reference to the liquid's surface, mapping the plate along its entire length. The use of an opaque reflective liquid (e.g. full fat milk) is essential for ensuring that the laser beam will take all measurements exactly at the same reference level. After the entire surface of the plate is mapped, by tightening or releasing the nuts and counter nuts of the bolts the plate was successfully levelled with a maximum height deviation of 0.24 mm for the total 12 m length. The resulting gap between the concrete base and the plate was filled with non-shrinkage concrete and left to cure.

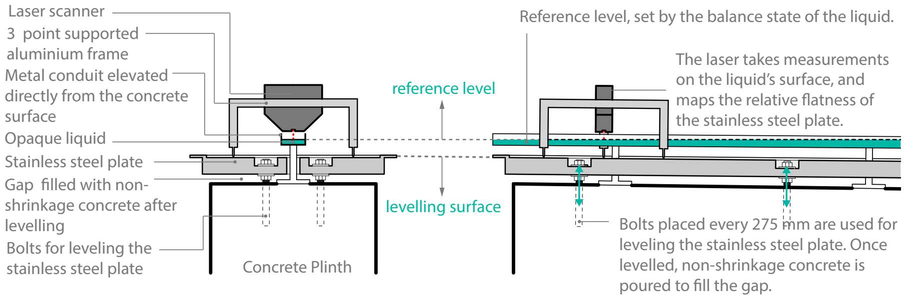

FIG. 6.11 Principle of the developed levelling system.

6.3.3 Bonding Process

The 0.2-0.3 mm optimum thickness of the adhesive layer demanded extreme precision in each construction layer. In traditional terracotta brickwork the mortar plays the dual role of bonding and compensating for tolerances in the size of the bricks. However, the selected adhesive's inability to compensate for any dimensional discrepancies in the construction can result to an accumulated offset of a few centimetres in the total height of the façade, even when the allowable tolerance per glass component is only ±0.25 mm. To eliminate the development of fluctuations in the height of the construction, all the glass bricks of a new row are laid down prior to bonding. The thickness of the resulting horizontal joint between the laid bricks and the bonded ones below is then checked by a feeler gauge (Fig. 6.12). When the seam is larger than the suggested 0.25 mm, the corresponding brick is replaced with another one that accomplishes better contact in the specific location. The final selection of bricks is then numbered to guarantee their correct bonding sequence.

Previous structural and visual tests by (Oikonomopoulou et al. 2015b), described in Chapter 5, suggested the bonding of the complete contact surface between blocks. The uniform application of the adhesive besides ensuring a homogeneous load distribution is also essential for maximizing transparency. Indeed, the façade's visual result is deeply affected by any form of air gaps and bubbles in the adhesive layer, as well as from stains caused by the adhesive's overflow or capillary action. To eliminate such defects, a customized bonding procedure was applied.

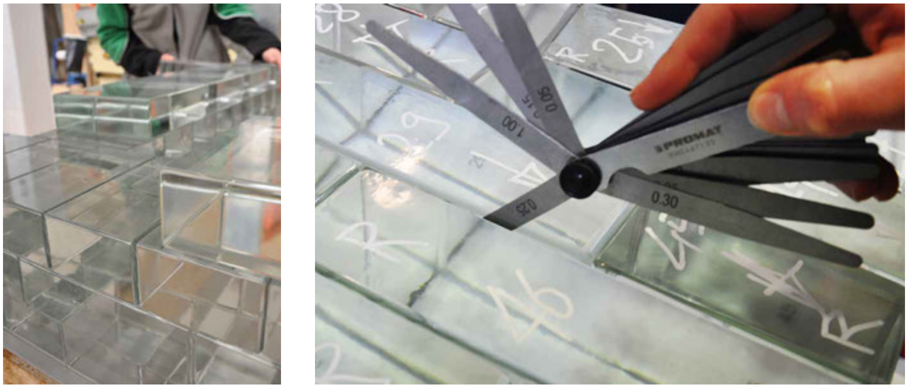

FIG. 6.12 Bricks of a new row laid down prior to bonding (left). Afterwards, a feeler gauge is used for checking the thickness of the resulting seam (right). The blade of the feeler gauge is sufficiently flexible and round not to induce any surface damage on glass.

Initially, the bricks are visually inspected on site for any defects, as explained in section 6.2.2. Then, the surfaces to be bonded are cleaned with 2-propanol. Specially designed self-reinforced polypropylene forms out of *PURE*® (DIT b.v. 2016) are placed for the distribution of the adhesive in an X pattern, controlling the flow, spread and amount of the adhesive (Fig. 6.13 and Fig. 6.14). To prevent any capillary effect along the vertical faces of the glass bricks, a special, UV beam light is used to locally harden the liquid adhesive in case it arises on the vertical seams.

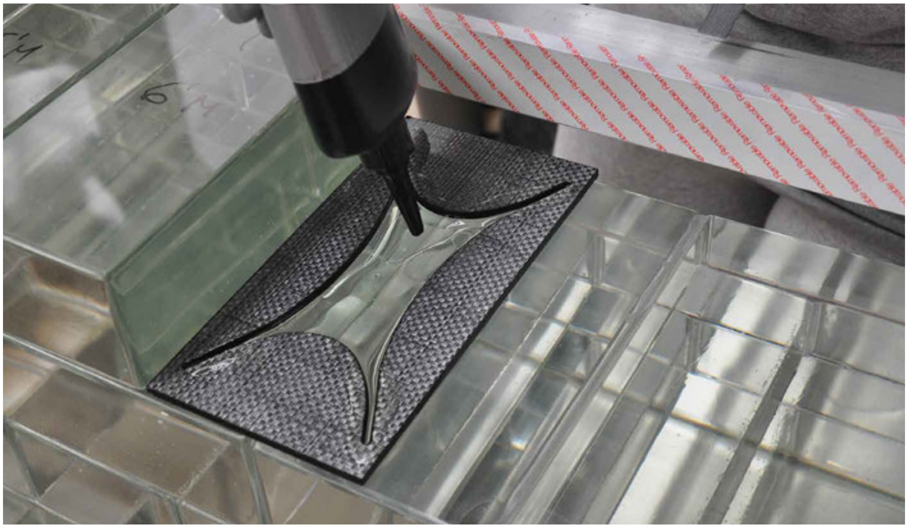

FIG. 6.13 *PURE*® mould used for the application of the adhesive on the final façade wall.

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FIG. 6.14 Bonding steps from left to the right: 1. Application of the adhesive with the aid of the *PURE*® form. 2. Resulting X pattern. 3. Local hardening of the adhesive by a UV beam light for preventing capillary action. 4. UV-lamp used to cure the adhesive for 60—120 seconds.

Once the adhesive is evenly spread, it is initially exposed to low intensity UV-light for 5 s while the brick is kept in position and under pressure. This partial pre-curing step was introduced for practical reasons[55]. It allows for the stabilization of the glass brick; at the same time the wiping-off of adhesive overflow can be easily made. After cleaning, the adhesive is further cured by low and medium intensity UV-radiation in the range of 20-60 mW/cm^2 and for a period of 60 - 180 s, according to brick size. Once a complete brick layer is bonded, all joints are sealed in order to guarantee the dust, water- and moisture- tightness of the façade. For the sealing, *Delo Photobond 4497* (Delo Industrial Adhesives 2016b), a more flexible and viscous, clear UV-curing *Delo Photobond* acrylate, specially designed for outdoor applications, is selected due to its good visual performance, compatibility with *Delo Photobond 4468* as well as for its easy and quick application (Fig. 6.15). This adhesive requires only 10 s of UV-curing to be completely cured.

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[55] This pre-curing time was set experimentally. Testing of specimens cured in this way did not reveal any differences with specimens cured once off.

FIG. 6.15 Left: Sealing of the already bonded bricks. Right: the final, visual result achieved by the novel bonding method.

The first row of glass blocks was directly bonded onto the stainless steel base by *Delo Photobond 4468*. As previously mentioned, *Delo Photobond 4468* is recommended by the manufacturer for glass to metal bonding as well. Previous research on such a bond has been conducted by (Puller,Sobek 2008; Tasche 2007). The established rigid connection was considered imperative by the structural engineers in order to eliminate any horizontal movements of the free-standing façade. Any movements due to temperature strains in the structure are compensated by the flexible connections at the sides and top of the façade (see section 6.3.6).

FIG. 6.16 The top connection is completely masked by the ceramic strips.

Every 2 m of elevation, the levelling along the total length of the façade is recorded using a high accuracy total station survey equipment. Bricks with a 0.5 mm or 1.0 mm reduction in height were specially manufactured for the levelling of the wall in case of height deviations. Such bricks were required to level the wall segments when reaching the level of the architraves of the ground and first floor. At the top of the elevation, the glass wall is connected to a steel beam by a 22 mm thick structural modified silane (MS-) polymer bond. This flexible connection can accommodate displacements due to the different thermal expansion and stiffness between the upper construction and the glass wall. A flexible waterproof tube filled the gap towards the interior of the wall, to further prevent water leakage. As ceramic strips cover the entire top row, the connection details are fully hidden (Fig. 6.16).

6.3.4 Construction and installation of the architraves

The architraves above the window and door openings of the original 19th century elevation are also reinterpreted into glass components by special tapered glass bricks bonded together by the same adhesive across their vertical surfaces. Due to the low viscosity of the *DP 4468* each architrave had to be pre-assembled into one single component in a custom made rotating steel fixture. The rotating fixture ensures the horizontal application of the adhesive, as well as the desired arch geometry, with a straight top line in accordance to the maximum 0.25 mm deviation rule. The finished components, preassembled in the *TU Delft Glass & Transparency Lab*, were then transported to the building site and installed one by one in situ with the aid of a jib fixture on the fork lift, as shown in Fig. 6.17.

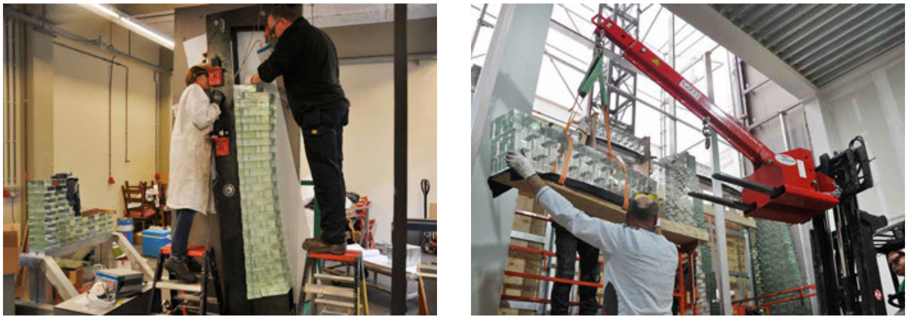

FIG. 6.17 Left: The special rotating fixture for the preassembly of the architraves. Right: The installation of the bonded architraves on site.

6.3.5 Transition layer between standard and glass masonry

To obtain a smooth, gradual connection to the standard brickwork of the final, residential floor of the building, the initial intention of the architects was to realize a transition zone of intermixing glass and normal terracotta bricks towards the top of the façade. Nonetheless, the structural blend of the two materials presented various practical implications, as can be seen in Fig. 6.18. Besides having different mechanical properties, the two types of bricks vary substantially in acceptable tolerances. Whereas in the glass bricks the required precision in height is ±0.25 mm, for the terracotta bricks is at least ±1.0 mm. Most importantly, the bonding between the two brick types necessitates the application of different adhesives, involving the risk of their intermixing. Lastly, the strongly alkaline character of most mortars used for the bonding of standard ceramic bricks attacks the glass surface and must be avoided. It should be mentioned that, as the upper conventional masonry façade was completed 6 months prior to the construction of the glass elevation and the mortar was fully cured, there was no hazard of alkaline reaction between the mortar and glass.

FIG. 6.18 Practical implications were encountered when combining terracotta and glass blocks.

Due to all the aforementioned reasons the option of combining terracotta and glass was rejected. The following solution was applied instead: Glass bricks, 40 mm shorter in width, clad with an 18 mm thick ceramic strip at each external side, replace the traditional bricks in the intermixing zone. The ceramic strips are bonded on the façade after all glass blocks have been bonded in place, preventing the occurrence of adhesive stains on their exterior surface. *Tec 7* (Novatech N.V. 2016), a brown coloured modified silane polymer is applied for bonding the strips to the glass units. With an application thickness of circa 3 mm the adhesive compensates for any difference in thermal strains between the two materials. Once all the ceramic strips have been bonded to the façade, the seams around the strips and the glass are sealed by *Zwaluw Joint Fix 310 ml lichtgrijs (Den Braven 2017)*, an acrylic based mortar of similar texture and colour to the mortar used for building the wall above (Fig. 6.19). The selected mortar is less brittle than conventional mortar due to its acrylic content and features considerably less volume shrinkage (5%)(Den Braven 2017) after hardening in comparison to standard mortar types, preventing thus its delamination from the glass blocks. The completed intermixing, gradient zone can be seen in Fig. 6.20.

FIG. 6.19 Left: Bonding of the ceramic strips to the shorter bricks. Right: The final visual result.

FIG. 6.20 End result of the intermixing, gradient zone.

6.3.6 Boundary connections of the façade

The façade forms a free standing wall firmly connected to the concrete plinth. To allow for displacements due to the different thermal expansion and stiffness between the glass wall and its boundaries, the façade is joined via flexible connections to the top metal beam, supporting the residential level above, and to the stainless steel columns on the vertical sides. The top connection of the two structures is realized by a modified silane (MS-) polymer adhesive bond as described in Section 6.3.3.

Regarding the connection along the vertical sides, this varies between the right and left (as seen from the street) side of the wall at the ground floor, since the left side is self-supported by a buttress. On the right side at the ground floor, as well as on both sides at the first floor, the glass masonry wall is connected by a 10 mm thick layer of a clear silyl-terminated semi-elastic polymer to the stainless steel L-shaped columns to compensate for thermal displacements of the wall. Since for the curing of the specific MS-polymer adhesive the contact with atmospheric conditions is essential, the adhesive was applied gradually with a glue-kit dispenser using compressed air row by row, so that each glue layer can set until the next row of bricks is completed (Fig. 6.21). The bricks at the right side of the ground floor are each clad with two 1mm thick stainless steel strips at their adjacent to the L-shaped column sides, to mask the rough detailing of the welded stainless steel structural components (Fig. 6.21). The cladding is applied to the bricks prior their bonding to the façade. For such a connection, *DP 4497* is used, to ensure impact resistance.

FIG. 6.21 From left to right: Bonding of the steel plate to the corner brick. Positioning of the brick by a suction cup holder. Application of the semi-elastic polymer.

6.3.7 Installation and bonding of the cast glass window and door frames

The reproduction of the previous, historic elevation's wooden openings in cast glass was an extra challenge added to the engineering and construction of the *Crystal Houses* as it included the manufacturing and bonding of massive cast glass elements. The glass frames were cast by *Poesia* in open graphite moulds (Fig. 6.22), ground along their open surface to remove the material shrinkage layer and polished with a rotational band manually. As such pieces present larger tolerance problems, *DELO*

Photobond 4494 (Delo Industrial Adhesives 2016a) was chosen to bond the frame elements together due to its higher viscosity and application thickness that allow for easier tolerances, while maintaining a clear optical result. This adhesive has a comparatively lower mechanical resistance to *DP 4468,* yet sufficient for integrating the glass frames into the construction.

The window and door frames were placed after the completion of the glass wall. During the bonding process, aluminium place holders were used to secure temporarily the location of the openings. First each frame was assembled in place by *DP 4494*. Based on the UV-measurements per m^2 done by *Siko b.v.* the sill of each window frame, of 1145 mm x 143 mm footprint, required 4 minutes of total curing by two UV-lamps travelling back and forth along its length.

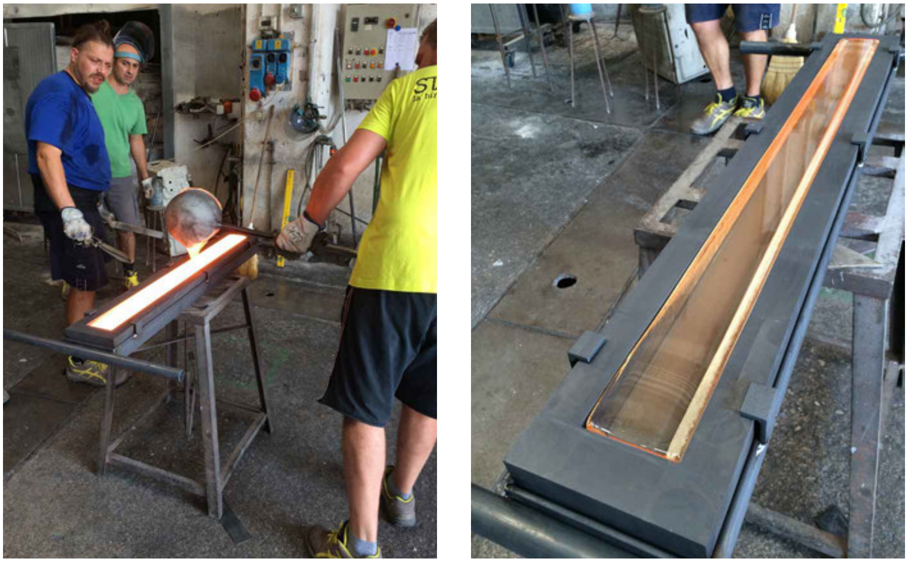

FIG. 6.22 The graphite moulds used for the fabrication of the frames.

Once the frame was in place, the side and top connection to the glass masonry wall was established. The thickness of this connection was designed to be 8 mm, to compensate for horizontal and vertical deviations in the glass masonry wall, and was achieved by the same clear silyl-terminated semi-elastic polymer used also at the top and side connections of the wall. To avoid the entrapment of air, the polymer was injected at both sides simultaneously from bottom to top (Fig. 6.23). After a few days, when the polymer had reached a satisfactory strength, the aluminium frames were removed. Then the cast glass mullions were bonded to the glass frames via the same polymer applied in a 2mm thick layer. Finally, the glass panes were bonded to the mullions by a standard transparent silicone, completing the façade. The end result can be seen in Fig. 6.23.

FIG. 6.23 Left: The simultaneous application of the polymer from both sides. Centre and right: The final result of the bonded glass frames.

6.3.8 Maintenance

The proposed system is practically maintenance free. Glass block are durable building components and is generally not subject to weathering (Dietrich et al. 1995). In order to minimize the cleaning requirements of the facade, a spray of hydrophilic coating (e.g. Vindico (Vindico 2014)) can be externally applied to the wall as a soft coating, so that the rainwater will clean the facade. The coating needs to be re-applied every ten years. To avoid moisture and dust entering the joints of the glass blocks, they are sealed with a moisture- and water-resistant adhesive of the same UV-modified acrylate family, yet with a significantly higher viscosity. This adhesive is also resistant to glass detergents. Both adhesives are aging resistant and do not discolour when exposed to direct sunlight.

The façade was completed in May 2016 and has been since exposed to weathering. Neither discolouring of the *DP 4468* interlayer nor penetration of moisture has been observed up to the date of this dissertation.

6.4 Conclusions

A novel, completely transparent self-supporting glass masonry wall system has been developed and realized through pioneering research in the *Crystal Houses* façade (Fig. 6.24). With the exclusive use of solid cast glass elements bonded together by a clear, high stiffness, adhesive and with the aid of geometry for enhancing the lateral stability, the 10 m x 12 m façade combines the desired structural performance with pure transparency. Previous experimental work indicated *DP 4468*, a one-component, UV-curing acrylate for attaining both the desired monolithic structural performance and high transparency level. The experiments also demonstrated that the desired structural and visual performance is only guaranteed when the adhesive is applied in a uniform layer of a mere 0.2-0.3 mm thickness. This in turn leads to an allowable dimensional tolerance of a quarter of a millimetre in the height and flatness of the cast glass components. This demand of extreme dimensional precision introduced new challenges in the engineering of the façade from the manufacturing of the bricks to their bonding method, calling for pioneering solutions.

Due to the inevitable natural shrinkage of molten glass, such dimensional accuracy could only be attained by CNC-cutting and polishing of the bricks' horizontal faces to the desired height. Since the post-processing of the bonding surfaces was considered unavoidable, soda-lime glass and open, high precision moulds were preferred over borosilicate glass and precision press moulds to reduce the manufacturing cost. Special measuring equipment was developed for controlling the dimensional accuracy of the components.

Nonetheless, even blocks of such high dimensional accuracy can still lead to a significant offset in the façade's total height. Considering that the maximum allowable deviation per layer of construction is ±0.25 mm, this mere fact manifests the level of complexity deriving from the manual bonding and the significance of constantly controlling the entire construction with high precision methods.

A completely transparent façade is moreover linked with the inability to hide any possible flaws in the construction. The development of a novel bonding method for the homogeneous and flawless application of the adhesive resulted in imperceptible connections in the constructed façade.

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FIG. 6.24 The completed *Crystal Houses* façade.Source: *MVRDV Architects / Image copyright: Daria Scagliola and Stin Brakkee.*


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6.5 Recommendations

Overall, the innovative glass masonry system developed for the *Crystal Houses* façade illustrates the great potential of adhesively bonded cast glass blocks as an answer to the quest of structural transparency and can form the basis for novel architecture applications. The system can be further engineered in order to simplify and accelerate its application, minimize the interlinked challenges and decrease the cost.

Most of the engineering puzzles elaborated in this paper can be solved with the use of a thicker transparent adhesive of equal structural performance that in turn can allow for larger tolerances. The fundamental difference between a conventional brickwork and the developed glass masonry system is that a standard mortar layer compensates for deviations in the size of the bricks, while the selected adhesive cannot; this leads to a meticulous and strictly controlled building process.

In this direction, different envelope geometries can enhance the rigidity of the structure, allowing for thicker, more elastic adhesives and correspondingly for larger tolerances in the brick units. A good example on this direction is the *Atocha Memorial*, where the elliptical, almost cylindrical, shape of the adhesively-bonded structure allowed for a less rigid adhesive of 2 mm thickness (Goppert et al. 2008).

In another direction, the development of a casting method of glass units of higher accuracy without the need of post-processing would significantly facilitate the entire production and building process, enhance the structural and architectural result and reduce the corresponding manufacturing costs.

Likewise, the choice of glass recipe plays a crucial role in the total annealing time and in the scale of resulting natural shrinkage. Although a faster and more accurate casting process can be achieved with borosilicate glass instead of soda-lime, the total manufacturing cost and dimensional precision prerequisites should be considered prior to the glass recipe choice.

Another important aspect to be addressed is the permanent nature of an adhesively bonded glass structure. As described in Chapter 5, *DP 4468* has no known solvent besides heat, rendering the structure irreversible. In turn, this means that the blocks cannot be retrieved intact at the end-of-life of the building, nor can they be easily recycled due to adhesive contamination. Taking into account the global drive

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towards circularity, it is crucial to further investigate the development of solid glass block systems that can be reversible, and thus, reusable and recyclable.

Lastly, glass casting can provide the designer with a great freedom in the shapes and sizes of the building component. Owing to the architectural concept of the *Crystal Houses* façade, it was determined that the glass block unit should follow the geometry of the original masonry bricks. Nonetheless, the rectangular geometry of the blocks is not compatible with casting as a manufacturing process – as discussed in chapter 2.4 sharp edges result to uneven cooling rate and concentration of residual stresses. In view of that the choice of shapes that follow more organic, curvy shapes is highly recommended for future applications.

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Interlocking cast glass prototypes made of recycled art glass at the *Glass & Transparency Lab* of TU Delft.

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Interlock [verb]

(of two or more things) Engage with each other by overlapping or by the fitting together of projections and recesses.

Definition by the Oxford English Dictionary

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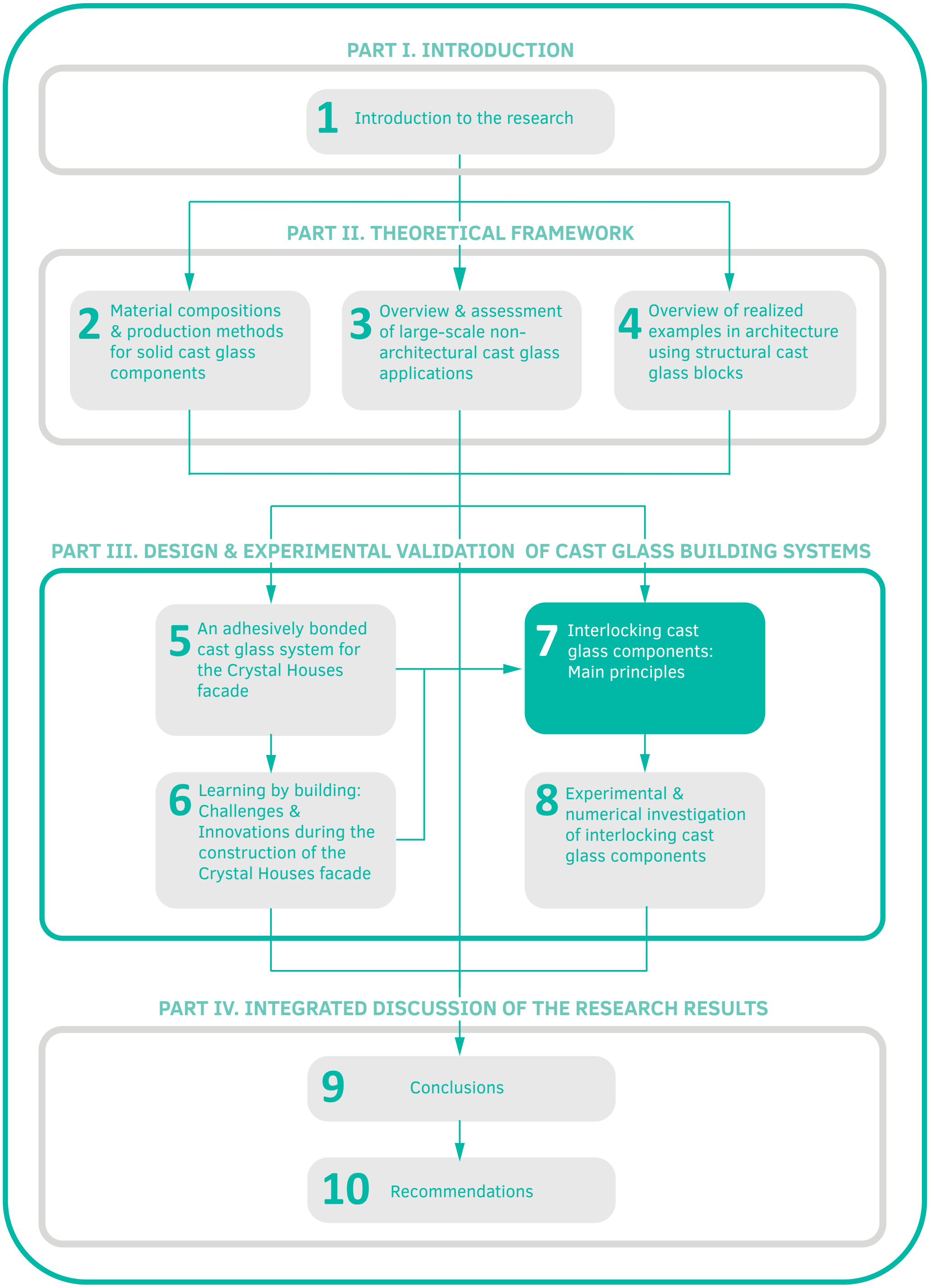
Exploring the third dimension of glass



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4 Overview of realized examples in architecture using structural cast glass blocks

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