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# Challenges in the Construction of the Crystal Houses Façade

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This paper presents the main challenges confronted during the construction of the innovative Crystal Houses façade in Amsterdam. Designed by MVRDV and Gietermans & Van Dijk architectural offices, the façade is a transparent reproduction of the previous 19th century masonry elevation, entirely made of adhesively bonded solid glass bricks. Even the window and door frames are reinterpreted by elaborated massive cast glass components. To obtain pure transparency, the resulting 10 m by 12 m glass masonry wall should be self-supporting. To achieve the desired structural performance of the wall a colourless UV-curing adhesive of high stiffness is selected which reaches its optimum bond strength when applied in 0.3mm thick layer. The virtually zero thickness of the adhesive and the desire of untainted transparency induced various engineering challenges, from the adhesive's homogeneous application and the dimensional accuracy of the bricks to the allowable tolerances in the entire façade. This paper records the challenges encountered and follows the innovations made from the manufacturing of the bricks to the final construction of the façade. The novel solutions include the manufacturing of glass elements of extreme dimensional precision, the development of methods for the accurate measuring and systematic levelling of the façade and the development of customized bonding techniques that lead to purely transparent and flawless connections. Based on the conclusions of the research and experience gained from the realization of the project, suggestions are made on the optimization of the developed system for its further applicability.

**Keywords:** Structural glass, Solid glass bricks, Adhesive glass connections, Glass Façade

## 1. Introduction

A novel glass brick façade has been designed and engineered for the purposes of a high-end store in Amsterdam. At the time of writing the façade has been completed and the store is expected to open within early 2016. The new façade is an accurate yet completely transparent reproduction of the building's previous 19th century elevation, entirely made of adhesively bonded solid glass bricks, reinterpreting the traditional brickwork and the typical architraves above the doors and windows. Even the elaborated original wooden frames of the openings are reproduced by massive cast glass elements. As the façade ascends conventional clay bricks intermingle in between the glass ones to create a gradual transition to standard brickwork on the top, residential floor. The standard brickwork of the last floor is structurally independent from the façade below, supported by a steel beam spanning the length of the façade. Based on the structure of the former masonry façade, the elevation of 10 by 12 meters employs more than 6000 solid glass bricks, each 210 mm thick and 65 mm high. The width of the bricks is either 105mm or 210mm to reproduce the pattern of the Dutch bond brickwork.

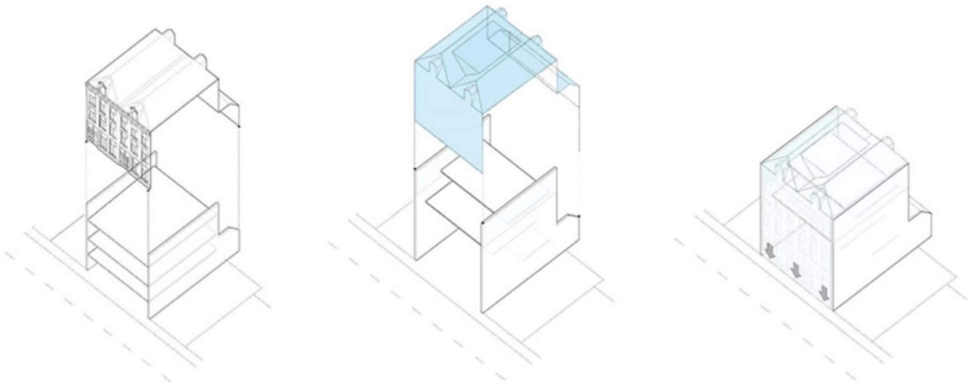


Fig. 1 Illustration by MVRDV of the concept behind the glass brick façade.

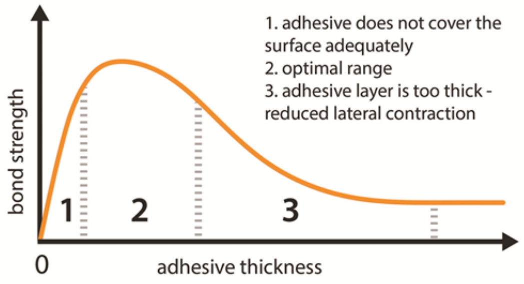

a) b)

Fig. 2. a) 3-D impression of the glass block façade; b) Photograph of the façade during construction.

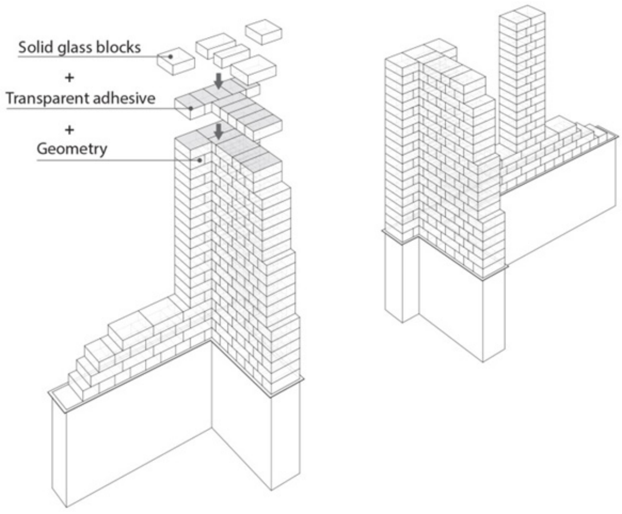
The desire of the architects for pure transparency did not allow for the use of any metal supporting structure. Thus, the glass façade had to be self-supporting. In principle this is plausible owing to the high compressive strength of glass and the considerable thickness of the masonry wall that enhances the construction's resistance against buckling. The lateral stability of the façade is further reinforced by four buttresses. Formed by interlocking bricks in the interior of the glass wall they create a continuous relief of increased rigidity. Figure 3b shows an illustration of the structural scheme followed in order to maximize transparency.

To achieve a completely transparent glass structural system the bricks are glued together by a clear adhesive. Extended research and testing of various types concluded to the choice of a UV-curing, one-component transparent acrylate designed for high strength bonding of glass to glass. Due to the low viscosity of the selected adhesive, it was determined that only the horizontal joints of the blocks are bonded; a solution that rendered optimum visual result as well. Series of four-point bending tests demonstrated that the selected adhesive leads to a monolithic behavior of the glass-adhesive assembly and to a homogeneous load distribution under loading when applied uniformly in a layer of the optimum thickness (Oikonomopoulou et al. 2015). In specific, the selected adhesive reaches its maximum bonding strength when applied in a layer of 0.3 mm. Figure 3a illustrates how a relatively thinner or thicker layer can critically affect the adhesive's strength and consequently the structural behavior and carrying capacity of the glass system.

The low viscosity and ideal thickness of the adhesive in combination with the inelastic nature of glass require various implications regarding its homogeneous application as well as the allowable tolerances in the overall façade. Not only the geometry of each brick but even the layered construction of the glass wall have to be confined within a tight dimensional precision of a quarter of a millimeter. Any accumulated deviation larger than that could lead to inhomogeneous and improper bonding of the glass components, compromising not only the visual quality, due to visible flaws in the adhesive layer, but also the structural performance, due to the initiation of local peak stresses. This particularly high level of precision has never been realized before in such a large building scale. The demand of extreme accuracy and transparency generated many challenges in the engineering of the Crystal Houses façade that required innovative solutions so that the glass masonry wall can meet both visual and structural prerequisites. These challenges and their corresponding solutions are presented below.



a)



b)

Fig. 3a. Schematic depiction of the relation between an adhesive's optimum strength and thickness.
Fig. 3b. Principle of the proposed adhesively bonded glass brick system.

## 2. Fabrication and controlling of the bricks

In previous realized examples of façades employing solid glass bricks, such as the *Atocha Memorial* (Christoph,Knut 2008) and the *Optical House (Hiroshi,NAP 2013)*, borosilicate glass was opted for the fabrication of the bricks. Due to its low thermal expansion coefficient, borosilicate presents a much higher resistance in rapid temperature changes; as well as much less shrinkage and thus, higher dimensional accuracy during the annealing of the blocks. In contrast, in this project soda-lime glass was chosen for the fabrication of the bricks(Oikonomopoulou et al. 2015), which is characterized by a higher thermal expansion coefficient than borosilicate, and consequently larger volume changes due to temperature variations. As the required ±0.25 mm tolerance necessitates the post-casting processing of the blocks regardless if they are made out of borosilicate or soda-lime glass, the latter was preferred due to its considerably lower raw material cost.

The fabrication of the approximately 6000 solid glass bricks was assigned to the Italian company *Poesia* specialized in cast glass components. Each brick is manually cast by pouring molten glass in high precision open steel moulds. A low-iron glass recipe is used in order to obtain completely colorless bricks. To acquire the desired smooth surface texture the moulds are preheated to a constant temperature. If a mould is too cold, then the hot glass coming into contact with the cold metal surface freezes instantly, creating a rough, wavy surface. On the other hand, if a mould is too warm, the glass tends to stick to the walls of the mould. After the glass is poured into the mould it is left to cool by air temperature to 700 °C before it is removed and placed into an annealing autoclave. There, a long and meticulously controlled cooling process prevents the development of internal residual stresses. In specific, every brick with 65 mm by 105 mm by 210 mm dimensions requires approximately 8 hours of cooling, while a brick of double volume requires 36-38 hours respectively. During the annealing process, natural, inevitable shrinkage occurs to the glass volume. This mainly appears on the top face basically due to gravity force. This top layer is trimmed by a CNC machine which processes the block to the precise height. Finally, the two horizontal faces of each block are polished to a smooth flat surface to minimize any local projections.

The final glass bricks are then subjected to two controls to verify if they meet the desired dimensional precision. First, a cut-out metal plate is used as a jig to control the bricks' total length and width (see Figure 4a). Only if a brick can go through the cut-out, it can be used in the façade. The accepted bricks are then controlled by a specially developed measuring system that evaluates if they meet the 0.25 mm precision in height and flatness. Five LVDT sensors with 1 micrometer (0.001 mm) measuring accuracy, fixed on an aluminium frame, take height measurements at the edges and center of each brick (see Figure 4b). If not all five points are within the desired 0.25 mm tolerance in height the brick has to be re-polished or discarded.

Besides the measuring control, the glass bricks are also submitted to a visual inspection in-situ for minute cracks and defects on their bonding surfaces, commonly caused by the handling and transportation processes. Bricks with even minor cracks have to be discarded, as the almost 10% shrinkage of the adhesive during its curing triggers the propagation of cracks even less than one millimeter deep due to introduced tension, resulting to visible cracking of the brick (see Figures 4c and 4d). Only the glass components that pass both the measuring and visual controls are used for the construction of the façade.

a) b) c)

Fig. 4 a), b). Measurement controls of the final bricks. Fig. 4c. Propagation of a minor crack after it the curing of the adhesive.

## 3. Construction of the glass brick wall

### *3.1. Levelling the starting surface*

The construction of the glass masonry wall started above a 0.60 m high by 0.20 m wide reinforced concrete zone. The concrete base guarantees the impact resistance of the lower part of the façade against hard objects and has been calculated to withstand a car impact with 50km/h speed. To match the texture and color of the glass wall, the plinth is coated along its height with a stainless steel sheet laminated with SentryGlas® to a hardened glass pane. A 30 mm thick stainless steel plate bolted on the top of the concrete plinth forms the base of the glass masonry wall.

The extreme accuracy of the developed system necessitates a starting building surface with a flatness of matching precision. Consequently, the stainless steel plate had to meet a 0.25 mm height precision over a total length of 12 meters. This measurement accuracy is much higher than the one achieved even by high precision survey methods and called for the development of an innovative measuring and calibrating system in order to obtain the desired flatness on the starting surface.

In specific, bolts set every 275 mm support and allow for the levelling of the stainless steel plate in consecutive steps. By using conventional levelling equipment the plate is initially levelled above the concrete to an accuracy of a few millimeters. Figure 5 shows the measuring laser system developed to further level the stainless steel plate to a flatness of less than 0.25 mm. A continuous plastic open conduit with both ends sealed is elevated from points fixed on the concrete surface essentially parallel to the stainless steel plate. The conduit is then filled with a non-transparent liquid. At its balance state, the liquid will achieve nearly absolute horizontal flatness, establishing the reference level for calibrating the stainless steel plate. A laser machine with a precision of one micrometer, fixed on an aluminium frame with three legs stepping on the stainless steel plate (see Figure 5c) takes measurements on the liquid's surface, mapping the plate along its complete length. Then, by tightening or loosening the counternuts of the bolts the plate is levelled according to the reference liquid surface to the desired accuracy. When the stainless steel plate is successfully levelled, the gap between the concrete base and the stainless steel plate is filled with non-shrinking concrete and left to cure. By using this method, the stainless steel starting surface was successfully levelled to a maximum total height deviation of 0.24 mm.

a) b) c)

Fig. 5 a), b), c): Images of the stainless steel base and the measuring system developed for its levelling.

### *3.2. Bonding*

The special characteristics of the adhesive required the construction of the façade inside a UV-filtering tent to provide protection against sun-radiation, the weather elements and dust. To ensure controlled levels of temperature and humidity, heating equipment was installed inside the tent so that the adhesive is maintained in workable temperatures during winter. During the summer, when the ambient temperature exceeded 30°C the construction was stopped.

Structural and visual tests suggested that the complete contact surface between blocks had to be bonded. The uniform application of the adhesive not only ensures the homogeneous load distribution, but it is also essential for maximizing transparency in the connections. Indeed, the high transparency of the solid glass bricks reveals any small defect in the adhesive layer. Air bubbles and gaps in the spread of the adhesive, overflow, as well as capillary action of the liquid along the vertical faces of the bricks can disturb the optical result. Therefore, a customized bonding method was developed in order to minimize the occurrence of these defects.

Initially, the surfaces to be bonded have to be cleaned with 2-propanol. Special PURE® (self-reinforced polypropylene) moulds are used to distribute the adhesive in an X shape, leading to a controllable and uniform spreading and the minimization of air bubbles and overflow when pressed by the weight of the block (see Figure 6a). To avoid any capillary effect between adjacent bricks each brick is placed in such a way so that the excessive adhesive is directed towards the free sides. This is achieved when the first side of the brick to touch the bonding surface is the one corresponding to the adjacent, already fixed, brick. Once the adhesive is evenly distributed an initial 5 seconds UV exposure in low intensity stabilizes the brick in position but still allows for the easy removal of any overflow of adhesive. After cleaning, the adhesive is further exposed to UV radiation in an intensity between 20-60 mW/cm2 for 60 - 120 seconds depending on the brick size. Once a complete brick layer is bonded all horizontal and vertical joints are sealed so that the façade becomes water- and moisture- tight. For the sealing, a more elastic, clear UV-curing adhesive of the same family, specially designed for outdoor applications is selected.

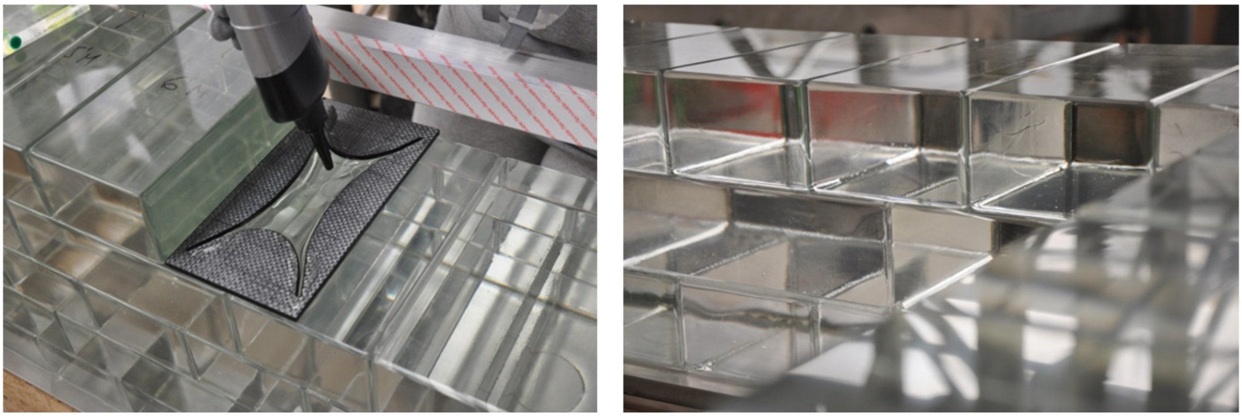

a) b)

Fig. 6 a) Mould used for the bonding of the bricks. b) End result after bonding.

The virtually zero thickness of the adhesive layer, essential for the desired structural performance, meant that the façade had to maintain a tight height precision per layer of construction as the adhesive itself cannot compensate for any dimensional intolerances. Even the allowed ±0.25 mm tolerance per block can accumulate to an offset of a few centimeters in the total dimensions of the construction. This reveals the level of complexity of the manual bonding process and called for a highly skilled building crew and a strictly controlled construction process, as follows. To avoid accumulated deviations along the height of the construction, before starting to bond a complete row of bricks, all of its glass elements are laid down. The occurring horizontal seam between the laid brick and the bonded ones below is checked with a feeler gauge. If the seam is larger than 0.25 mm, a brick that achieves better contact is chosen for the specific location. The final selection of the bricks is then numbered in order for the correct sequence to be kept. Every two meters of elevation, the levelling along the total length of the façade is recorded using a high accuracy total station. In the case of accumulated deviations, bricks with a 0.5mm or a 1 mm smaller height were manufactured to be used for levelling the wall. These bricks were specifically employed to level the elevation of the wall before the architraves bridging the wall segments were installed.

### *3.3. Construction and installation of the architraves*

The architraves, placed above the window and door openings, were pre-manufactured in the TU Delft Glass and Transparency Lab into one single component each. They comprised special tapered glass bricks that were bonded together by the same adhesive system along their vertical surfaces. Due to the low viscosity of the selected adhesive the architraves had to be assembled in a special rotating steel mould, shown in Figure 7a. The rotating mould ensures that the adhesive is always horizontally applied and that the final architrave would have the desired arch geometry, with a straight top line, complying with the maximum 0.25 mm deviation rule. The finished components were transferred on site and installed in situ by a crane, as shown in Figure 7b.

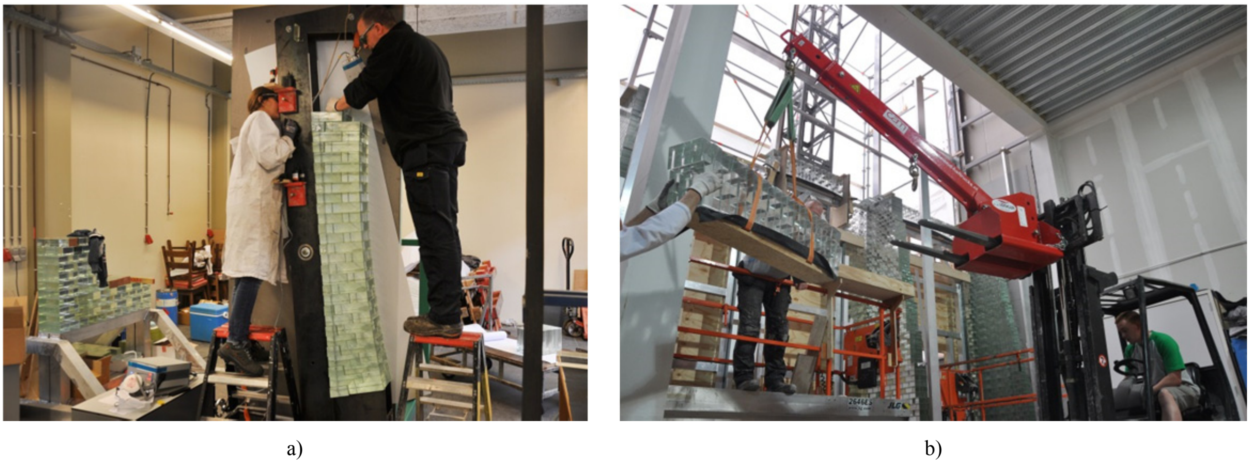

a) b)

Fig. 7 a) Bonding one of the architraves in a special rotating table at the TU Delft. b) Installing the architraves of the ground floor.

### 3.4. Transition layer between standard and glass masonry

The desire of the architects was to create a transition zone of glass and normal clay bricks towards the top of the façade, in order to create a smooth, gradual connection to the standard brickwork of the final, residential floor of the building. Nevertheless, the combination of the two different materials proved to have various practical implications. Apart from their different mechanical properties that would result in an inhomogeneous structure in the transition zone, there is a great difference in the size of acceptable tolerances between the two types of bricks. But most importantly their bonding together necessitates the use of various adhesives, involving the risk of their intermixing when they came in contact with each other. Moreover, the strongly alkaline character of most mortars used for the bonding of standard ceramic bricks attacks the glass surface and must be avoided. For these reasons an innovative solution was applied: glass bricks, 40 mm narrower covered with an 18 mm thick ceramic tile at each visible side would be placed instead of standard bricks at the specific locations. The cladded glass block does not differentiate from a standard masonry brick even if one looks at it from an angle. Although one can see completely through the horizontal bonded surfaces, the air trapped in the non-bonded vertical sides of the glass bricks creates a mirror surface that does not reveal what lies behind. The result provides a monolithic glass structure, and simultaneously gives the impression of a ceramic and glass masonry intermix zone. Shear tests on various different adhesives were conducted to evaluate their bonding degree to ceramic and glass and their load-bearing capacity before failure. Tests included specimens left into water for two hours and specimens wetted and then frozen prior to testing to observe if increased moisture and frost can decrease the bonding strength. From the tests it was concluded that the adhesive with the optimal combination of carrying capacity and visual performance was a brown colored modified silane polymer, as shown in Figure 8a. After their bonding, the seams around the ceramic tiles are sealed using a special acrylic-based mortar of less than 3% volume shrinkage after curing and with similar texture and color to the mortar used for the standard masonry on top (see Figure 8b). The ceramic tiles were applied on the façade after all the glass blocks had been bonded in place (see Figure 9), to avoid adhesive stains on the exterior surface of the ceramic tiles. The end result of the intermixing, gradient zone can be seen in Figure 10.


a) b)

Fig. 8 a), b) Bonding and sealing of the ceramic tiles

Fig. 9 Completed glass brick wall with the 40 mm narrower bricks bonded on location.

Fig. 10 The façade after the bonding and sealing of the ceramic tiles

### *3.5. Installation and bonding of the glass window and door frames*

The traditional, wooden window and door frames of the previous 19th century façade were also reinterpreted entirely in glass by massive cast components (see Figure 14). The frames comprised various components that had to be connected via completely transparent connections to each other as well as to the glass masonry wall. The challenge in this case was achieving a completely flawless vertical adhesive connection of maximum transparency and at the same time of the desired structural capacity. In this case, the adhesive should also account for horizontal deviations in the glass masonry wall as well as for small dimensional variations in the cast frame components. A clear silyl-terminated semi-elastic polymer was chosen due to its relatively high viscosity, colorless nature and easy application. Shear tests were conducted on a series of prototypes, bonded by an 8 mm thick polymer layer on a surface of 130 mm x 157.5 mm to test the structural performance of the selected adhesive. The experimental set-up is illustrated in Figures 11, 12 and a graph with the results is presented in Figure 13. The chosen adhesive provided consistent results. All specimens failed when reaching a load of approximately 4 kN and a deformation of 11 mm. At these values, the force started to drop gradually while the polymer layer started to tear in the exterior, while visible delamination was occurring in the interior. It should be noted that the shear tests were conducted one month after the production of the specimens. At that point only an exterior peripheral adhesive zone of circa 20 mm had been fully cured, as this product cures in reaction to atmospheric moisture and thus the curing of the interior core is a prolonged process. Therefore the resulting strength values are considered conservative, as a higher shear strength of the adhesive on the actual window frames is expected after a curing period of a few months. Even so, the deducted values were considered satisfactory by the structural engineers against the accounted windload case. The window and door frames were installed after the glass masonry wall had been completed and all ceramic tiles had been bonded and sealed. Special temporary aluminum frames were made to place and hold the glass frame components on their exact location. First, the various components were bonded together along their horizontal surfaces by a more elastic UV-curing adhesive of the same family as the one used for the masonry to form the complete frame. Then, the polymer was applied along the vertical connections. To achieve a completely uniform distribution of the polymer without any trapped air gaps, the polymer was applied simultaneously from both sides of a glass frame. The polymer connections were left to cure for several days to reach a satisfactory strength before the supporting aluminium frames were removed. Finally, the glass panes were adhesively bonded to the frames by the same transparent elastic polymer, completing the façade.

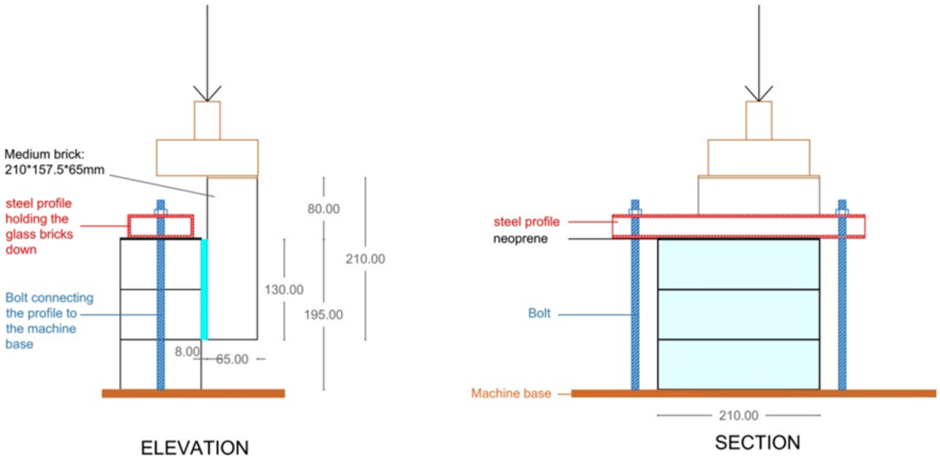


Fig. 11 Experimental set-up of the shear tests of the window frame connection

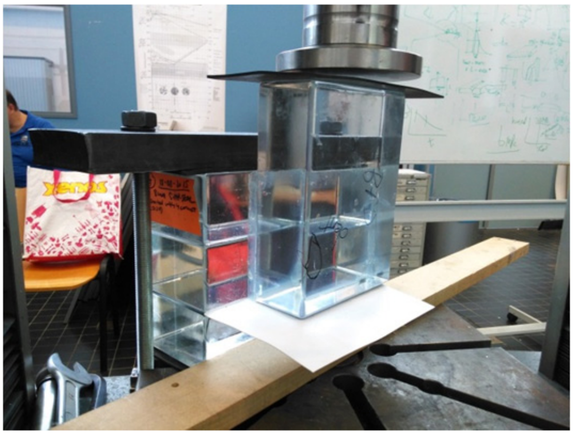


Fig. 12 Experimental set-up of the shear test

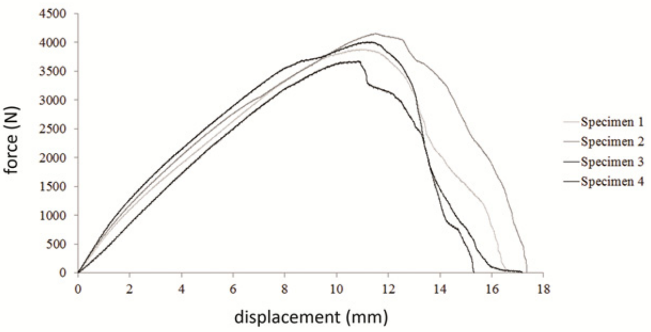


Fig. 13 Force to deformation graphs of the specimens tested in shear

## 4. Conclusions and discussion

An innovative, completely transparent adhesively bonded glass masonry wall has been realized in Amsterdam, setting a new example on the structural potential of glass and stretching the level of transparency that can be achieved in a wall construction. By bonding cast glass elements with a clear adhesive of high stiffness, the 10 m by 12 m façade is an entirely transparent masonry wall that can carry its own weight and support wind loads without the need of any supportive substructure. This is only plausible when the adhesive-glass assembly functions as one rigid unit against loading. Testing of various different adhesives pointed out that the desired monolithic behavior under loading was achieved only by a UV-curing one-component acrylate. However, the optimum thickness of the selected adhesive is a mere 0.3 mm, introducing new challenges in the engineering of the façade from the manufacturing of the bricks to the bonding method. The fundamental difference between a conventional brickwork and the developed glass masonry system is that a standard mortar layer can compensate for deviations in the size of the bricks, while the selected adhesive cannot. This lead to an allowable tolerance of a quarter of a millimetre in the glass bricks. Due to the inevitable natural shrinkage of molten glass, such dimensional accuracy could only be achieved by CNC-trimming the bricks to the desired height after casting. Each brick was subjected to meticulous measuring controls by specially developed jigs and equipment to verify that they meet the dimensional prerequisites. Still, even this virtually zero allowable tolerance per glass brick can accumulate to a considerable offset in the total height of the façade. This reveals the level of complexity of the manual bonding and the importance of a strictly controlled and precise construction process from the levelling of the starting supporting surface to the installation of the window and door frames. A completely transparent wall bears yet another challenge: any defect on the masonry system is visible. Therefore, besides a visual inspection of each brick for surface defects, a new bonding method had to be developed in order to allow for the completely homogeneous distribution of the adhesive, without any visible gaps, bubbles or overflow. The end result is a completely transparent, self-supporting glass masonry skin with virtually invisible connections.

Overall, the adhesively bonded glass masonry system presented in this paper can set the base for new architectural applications where structural transparency is desired. Owing to the experience gained through the realization of the Crystal Houses project, the engineering of the system can be further developed to simplify its application and reduce the involved challenges in future designs. Most of the engineering challenges presented in this paper can be confronted if a thicker adhesive that accounts for larger tolerances could be used as the bonding media or if a new casting method is found that can result to bricks with acceptable tolerances without further processing. By improving the geometry of the wall, the façade can obtain the desired rigidity even by a more elastic, thicker adhesive. In the same context, by using bricks of smaller dimensions, the shrinkage during the cooling down process would be within acceptable limits, rendering post-processing unnecessary.

Fig. 14 Close up of glass masonry wall, the architraves and the cast glass window frames.

Fig. 15 Transparency level of the wall.

Fig. 16 The glass masonry façade.

## Acknowledgements

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