Glass Monument in Remembrance of the Terrorist Attacks in Madrid of March 11, 2004

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1.- Introduction

On March 11, 2004 in Madrid 191 people were killed in terrorist bomb attacks on four suburban trains. 1824 people were partly severely injured. The monument for remembrance of the victims is situated next to the Atocha Railway Station in the centre of Madrid and was inaugurated and presented to the public by Juan Carlos I, King of Spain and Queen Sofía on the third memorial day.

Fig. 1 - Monument at the Atocha Railway Station

2.- Design

The competition design by the young architects FAM from Madrid consists of a translucent aboveground structure atop an underground, 500 m² large meditation room that is painted in cobalt blue. The aboveground structure is situated on a large traffic island next to the Atocha Railway Station where the terrorist attacks took place. Through the outer shell, daylight floods in the meditation room below the street level. At night the effect is inverse: The outer glass shell becomes a luminous artwork. A transparent inflated ETFE foil, that is stabilized by an air-overpressure in the memorial room, forms the second major element of the memorial. Expressions of condolence in many different languages are printed on the amorphous shape in remembrance of the attacks.

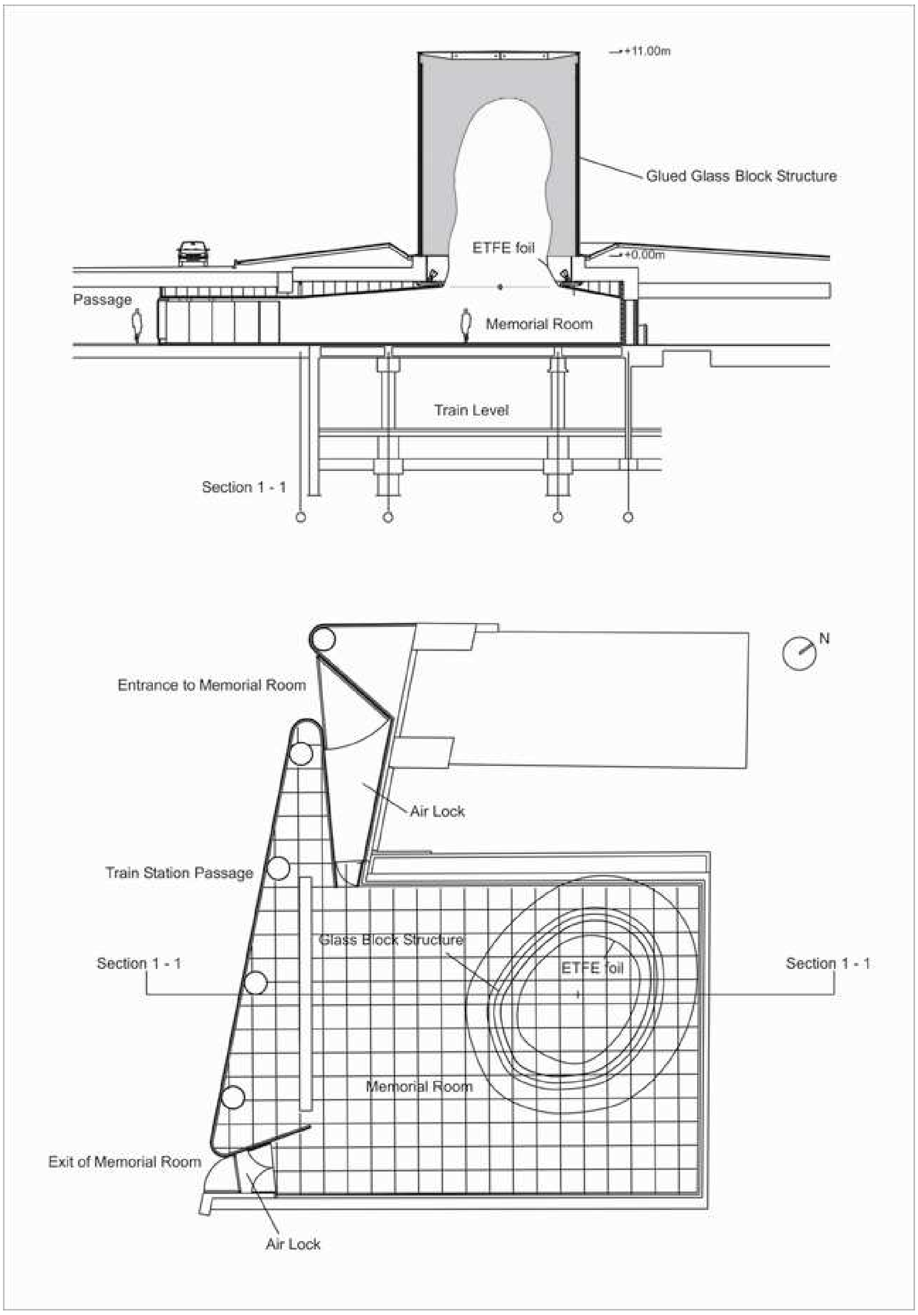


Fig. 2 - Sectional and plan views of the monument

3.- Glass shell structure

The outer shell is eleven metres high and has a free-form baseline close to an elliptical shape measuring eight metres by eleven metres. It consists of 15.100 massive glass blocks that are glued together using a transparent acrylic adhesive. The curvature gives the glass wall its rigidity and the monument becomes a shell structure of structural glass, eliminating the need of visually disturbing steel elements and providing unimpeded transparency. The roof is connected to the glass block structure in a rigid way to stiffen the upper free edge and to prevent the ovalisation of the section.

A block geometry with two oposed concave and convex sides was developed specifically for this structure. This particular shape allows the irregular curved surface to be created from a single block geometry. The massive blocks of 200 mm x 300 mm x 70 mm were produced under pressure in special moulds. The tolerance requirements were tight (±1 mm) in order to guarantee the applicability of the transparent adhesive and an uniform glue thickness.

As the massive glass elements experience high temperature differences (rain on a sun-heated glass block) and resulting high surface tensions, the 8,4 kg glass blocks are made out of borosilicate glass. Their low thermal expansion coefficient of 4,3 x 10^{-6} 1/K is half of the value found in conventional soda-lime glass, which halves the thermal stresses in the blocks.

On site, the glass blocks were glued together with an UV-curing acrylic adhesive. The one-component product was created especially for this application by the manufacturer. Small and large samples were tested and verified with regard to the ageing resistance and long and short term resistance for different temperature levels.

The structural analysis showed that deflections in the post-tensioned concrete flooring could create high shear forces in the glued joints of the 140 ton monument. In order to reduce this effect, the glass blocks are placed on a total of 200 elastomer pads (160 mm x 100 mm x 45 mm). This also compensates for differences in temperature strains between the glass and the substructure. The elastic deflection of the post-tensioned flooring was compensated by applying a preload before the erection of the glass structure. The necessary preload was removed in stages according to the progression of the construction of the glass wall.

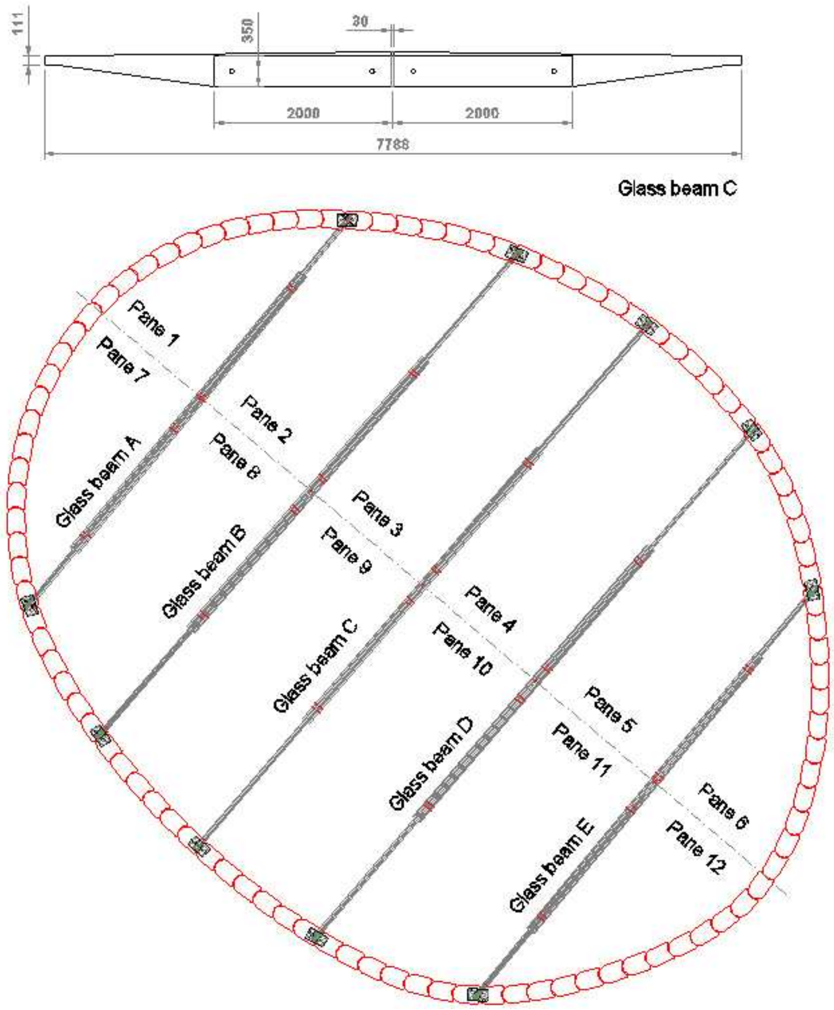


Fig. 3 - Monument's roof structure

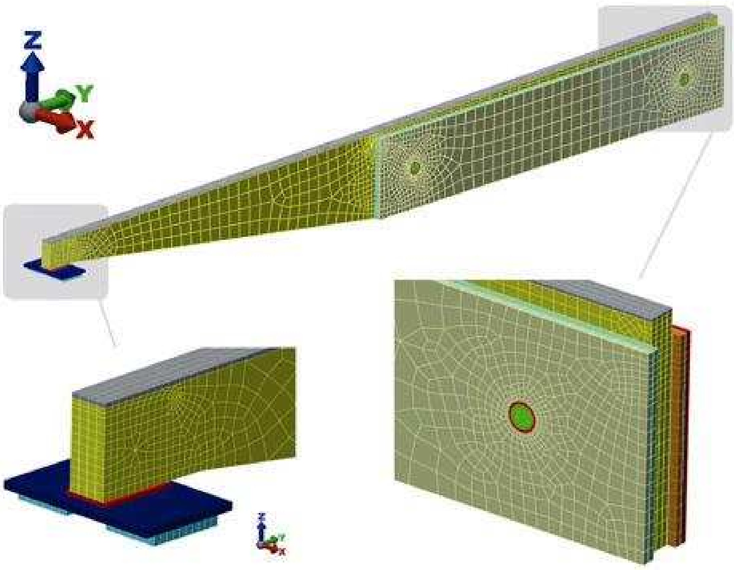
4.- Glass Roof

The design concept of maximising transparency continued into the design of the roof structure. Borosilicate glass was chosen for the entire roof structure in order to minimise the stresses due to different temperature expansion coefficients.

Five glass girders support the twelve cladding panels, which in turn serve as an horizontal diaphragm for the glass block structure. The girders have a total length of maximum 7,80 m and are spaced at approximately 1,75 m centres. The shape of the girders reflects the moment diagram and are elastically supported on the glass block structure. Borosilicate glass is just fabricated in limited dimensions, which led to the girders to be fabricated from four individual elements. The two central elements (laminated fully tempered lites, 4 x 12 mm) have a maximum span of 3,90 m and depth of 0,35 m. These elements are joined by two four metre long glass pane splices (laminated fully tempered lites, 2 x 12 mm). All contact areas between glass elements were laminated in the workshop using a transparent polyester resin.

Four stainless steel pins are placed at a maximum spacing between one another. This large level arm minimises the magnitude of the force couple due to the bending moment. The opaque metallic cross section of the pins can thereby be minimised to 40 mm, reducing its visual impact.

A detailed finite element model of the girders was built, as shown in fig. 4. The areas around supports and stainless steel pins were carefully modeled in order to capture stress concentrations. Loads were determined according to Eurocode 1 and the Spanish standard "Código Técnico de la Edificación". A nonlinear calculation of the girders was carried out, which was used to determine the their safety factor, well above code requirements.



Hyp.	SLS	ULS
Max. disp. (mm)	11.1	--
$\sigma_{pr,max}$ (N/mm^2) Central panes	20.8	27.1
$\sigma_{pr,max}$ (N/mm^2) Lateral splices	24.0	31.2

Fig. 4 - Finite element model of the glass girders

The continuously edge supported glass cladding creates the roof surface. The panes have a maximum length of 3,98 m. The cladding follows the geometry of the monument in plan. A slope of approximately 1,5 % and an edge overhang of 40 mm provide drainage. The overhead cladding is created by 3 lites of 10 mm fully tempered glass, as heat strengthened glass is not available for borosilicate glass. In order to brace the upper free edge of the glass block wall, the glass panes are glued on the top surface of the glass blocks using a structural silicone. The advantage of structural silicone compared to the acrylic adhesive is that a thicker glue layer is possible, allowing tolerances to be evened out and also to facilitate the replacement of the roof panes for the case of any damage.

5.- Construction of the primary glass structure

5.1 Construction of the stacked glass wall

5.1.1 Perimeter steel ring and elastomer pads

The construction of the glass wall started with the fabrication and installation of the perimeter steel ring which supports the monument. The ring was designed as a curved U-shaped profile of steel grade S355. In order to facilitate fabrication and transport, it was divided in ten sections, each with a different curvature, which were welded together on site and fixed to the concrete base of the monument by means of chemical anchors.

Two hundred elastomer pads were installed between the ring and the first row of glass blocks. Vertical loads are transmitted by compression while horizontal loads are transmitted by friction. Only a low-modulus silicone seal was installed between the glass blocks and the flanges of the steel ring in order to protect the elastomer pads from rain water and pollution.

5.1.2 Bonding

The special characteristics of the glue required the monument to be built inside a tent which protected the construction site from the radiation of the sun, rain water and pollution. In the tent, both temperature and humidity were controlled. Heating equipment permitted to work within the glue's temperature limits even in the coldest nights of January, while works were interrupted when humidity surpassed the limits recommended by the glue's manufacturer.

The average thickness of the adhesive layer is 2mm, which permits a good structural performance of the adhesive while absorbing the tolerances of the moulded glass blocks. The correct spacing was guaranteed by sticking eight small transparent polyurethane spacers at specific locations under each glass block.

Fig. 5 - Distribution of adhesive on the glass blocks

According the structural design, a maximum bonding area of 2 x 15.000 mm^2 per block was required in some areas of the wall. This meant that, in these areas, almost all the contact surface between blocks had to be filled with glue while at the same time overflow had to be minimised as glue was difficult to clean even before curing.

Therefore, several tests were carried out in order to determine the dose of adhesive and the best distribution of the glue. Finally, a distribution of twelve heaps of glue per block with two different diameters was chosen, which permitted to minimise both overflow and air bubbles when the glue was splashed by the weight of the next glass block. Some aluminium templates were fabricated to help positioning and sizing the glue heaps. The dose of adhesive was controlled by weighing the glue cartridge before and after bonding each block.

The surface preparation consisted in a simple cleaning of the two surfaces to be bonded with isopropanol. No primer was required.

According to tests, curing was guaranteed with 4 minutes of exposition to UVA radiation with a wavelength of 320÷380 nm and an intensity between 15 and 30 mW/cm^2. The intensity of all lamps was checked twice a day and light bulbs were replaced when necessary.

Fig. 6 - Glass wall during construction

5.1.3 Logistics and personnel

The limited space at the construction site required the glass blocks to be stored in a separate warehouse near the site. Every few days some glass pallets were transported to the site, where they were stored in a small stock area outside the tent. Then, glass pallets were entered into the tent, in which 100% of the blocks were visually inspected and transferred to an intermediate stock area.

All bonding tasks were carried out from a working platform on top of a scaffolding situated inside the monument. This scaffolding was supported by the meditation room floor slab and was laterally restrained by the glass wall. The working platform was lifted as the construction of the glass wall progressed, so the scaffolding was continuously being extended. The free-form perimeter of the glass wall required to fabricate some customised aluminium platforms to avoid any open gaps in the platform, while the glass wall was used as a balustrade.

From the intermediate stock area the glass blocks were distributed in small pallets which were lifted up to the working platform on top of the internal scaffolding by means of an overhead travelling crane. There, the blocks were distributed on top of the previous row after sticking the polyurethane spacers on their lower surface.

Once the distribution tasks had finished, bonding started. One by one, the 15.100 blocks were (1) removed from their position, (2) the bonding surfaces were cleaned, (3) the glue was applied on the top surface of the last row, (4) the block to be bonded was carefully situated in position, thus splashing the glue, (5) any small overflow was cleaned, (6) the spacing between blocks was adjusted and (7) the bonded connection was UV-radiated for 4 minutes.

The bonding was carried out by eight specialists, divided in four groups of two people. Every group was assigned to one quadrant in order to minimise interferences. There was also a supervisor and two people in charge of supplies.

Two ten-hour shifts were established, with eleven workers per shift. An average of 500÷600 blocks per day were bonded, six days per week. Every three days, the working platform was lifted. All displacements of the platform were carried out by specialists during the time between two shifts.

Fig. 7 - Sealing the glass wall

5.1.4 External sealing

Both horizontal and vertical joints between glass blocks were sealed in order to guarantee water-tightness and to protect the adhesive from the adverse effects of weathering and pollution. An ultra-transparent acid silicone was chosen for its aesthetical appearance and its compatibility with the adhesive.

The sealing was carried out in parallel with the construction of the wall. A total joint length of approximately 5.000 m was sealed.

5.2 Fabrication and installation of the glass roof

The fabrication of the glass girders started with the production of the four-leaf and two-leaf laminates in Austria and their transport to Bellapart's facilities in the north-east of Spain. There, the beams were assembled in horizontal position on wooden templates. The stainless steel pins were installed in position and a two-component resin was injected in the gap between the pins and the glass so that loads were properly transmitted to all glass lites.

Once the resin was cured, the girders were resistant enough to be lifted by a crane and inserted in vertical position into wooden supports that would be later used as protection for transport. In the framework, the spaces between the central four-leaf laminates and the lateral two-leaf laminates were filled with a transparent polyester resin.

After three days of curing, the girders were completely cleaned and the a stainless steel T-shaped profile was fixed onto the top surface of the girders by means of a two-component structural silicone.

Fig. 8 - Fabrication of the glass girders

The finished girders were transported to the site and installed on top of the glass wall. The overhead travelling crane and the tent's roof had been previously dismantled to facilitate the operation. An accurate positioning of the girders was required due to the tight tolerances of the roof panels and their supports. Once in position, the space between the glass girders and their stainless steel supports was filled with a two-component resin to guarantee an even transmission of loads between the supports and the four glass lites.

The roof panes were simply installed on the girders' stainless steel T-shaped profiles, and the space between their webs and the edges of the roof glass panes was filled with structural silicone in order to obtain a stiff top plate structure that is able to transfer the bracing membrane forces. A 100 mm x 10 mm structural silicone seal was also installed along the perimeter of the monument, between the top surface of the glass wall and the roof panes.

The depth of the seals required to use a two-component structural silicone, which was the only connection between the roof panes and the structure in order to prevent uplift.

A solar protection foil was installed on the internal surface of the roof panes prior to installation in order to reduce climatic loads.

Fig. 9 - Glass girder on site

6.- The inner bubble and the meditation room

A pressure stabilized ETFE foil (t = 150 µm) constitutes the monument's inner structure. Expressions of condolence in many different languages, which were written down on sheets of paper in the Atocha Railway Station after the terrorist attacks, are printed on the amorphous form of the 186 m² large surface. Form finding resulted in an unusual form for a pneumatic structure, with concave and convex areas. The foil’s geometry was developed in accordance with the stabilizing pressure so that there would not be any wrinkles due to the different biaxial stresses.

Fig. 10 - Meditation room

The determination of the patterning of the foil segments takes into account the spiralling of the condolence messages, so that these could be read over the seams without interfering with their legibility.

Compressed air blowers produce the necessary pressure difference of 100 Pa. An air-gate at the entrance of the 500 m^2 meditation room reduces the pressure loss through air leakage.

Because of the high transparency of the ETFE foil, lighting in the cobalt blue-coloured public room is provided by sunlight. The visitor views a reflection of light and forms between the semi-transparent glass structure and the amorphous foil.

Fig. 11 - Interior view of the monument

With the interior illumination at night, the glass monument appears to be a twinkling crystal of light: the twinkling elements are the 15.100 light transferring glass blocks that also allow to see the free-form outline of the pressure stabilized ETFE foil.

Fig. 12 - Monument at night

Project Participants:

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Structural Engineering:	Schlaich Bergermann und Partner, Stuttgart
Project team:	Knut Göppert, Mike Schlaich, Christoph Paech, Markus Balz, Jens Schneider, Miguel Paredes
Main contractor:	Dragados S.A., Madrid
Executive company glass:	Bellapart S.A.U., Olot
Executive company ETFE:	Hightex International AG, Kriens
Glass manufacturer:	Schott AG, Grünenplan
Client:	City of Madrid, RENFE