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Mass Glass Structures

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Glass has a long tradition as a medium for art and sculptural design. Yet, with a few notable exceptions, these items remain small and studio based. Over the last six years, the author has developed a number of larger scale projects which bridge the gap between architecture and sculpture. These projects incorporate predominantly annealed glass and rely on gravity and mass for stability, yet their simplicity of form belies a complexity of construction. This paper explains the typologies of mass glass structures and explores the geometrical, engineering, manufacturing and installation challenges which have been encountered and overcome in their realization.

Keywords: Mass Glass Structure, Glass Sculpture, Layered Glass.

1. Introduction

Glass has a long tradition as a decorative material in both jewellery and artefacts. These items have exploited the colors, and more importantly, the light changing characteristics of the basic material. In the last fifty years the architectural use of glass has expanded rapidly with float glass becoming a regular construction material in the windows and curtain walling of our built environment. The mass production of glass has led to a common construction typology which utilizes glass to maximize daylight and control the internal environment in buildings, whilst minimizing material usage. This paper deals with a completely different form of glass construction which synthesizes modern day glass production, gravity based or mass structures, and sculptural or decorative forms to create mass glass structures.

2. What is a Mass Glass Structure?

For the purposes of this paper the author proposes that a mass glass structure is an arrangement of glass in which the forces are transferred through a solid mass of glass in compression and the stability of the structure is ensured through the interplay of gravity, the arrangement of the glass elements and any supporting structure. The differences between conventional glass structures and mass glass structures have been summarized in Table 1.

The recent experience of this form of construction derives from a series of projects undertaken by the author in his role at both Arup, and more recently at IPIG, in which collaboration with the artist Danny Lane has enabled larger and more challenging Mass Glass Structures to be developed and constructed.

Table 1: Characteristics of Mass Glass Structures

Typical Glass Applications	Mass Glass Structures
Panels are individually supported	Panels are stacked
Viewer sees the flat surface of the glass panels	Viewer sees the mass, which is a compound surface of many glass edges
Performance is governed by out of plane bending or deflection	Support can be derived from glass torsional stiffness
The glass panels function as thin plates with small contact areas	The individual plies function in either compression, or as thick plates in in-plane bending, with large surface contact areas
Connection detailing focuses on transfer of forces in/out of individual panels	Connection detailing focuses on transfer of loads into / out of the complete system

3. Six Case Studies

In reviewing the six individual case studies, attention should be paid to the typology of construction, orientation of the glass and the use of gravity or other form of restraint. With an understanding of the methods of construction the limitations of form or alternative future uses can be appreciated.

Table 2 : Comparison of Case Study Projects

Project	Location	Internal/ External	Typology	Size	Support Structure	Panels	Weight
National Police Memorial	London	External	Horizontal glass. Post tensioned vertical stack	7.2 x 3.1 x 0.5m	Stainless steel base. Tension rods	616	28.6t
'Borealis'	Detroit	Internal	Inclined glass stack	30 x 7.4 x 3.0m	Concrete base stainless steel posts	2307	45t
Staircase	Sweden	External	Vertical glass. Post tensioned horizontal stack	6.0 x 4.2 x 1.9m	Steel base and structural fin	c.2000	1.8t (glass)
'Veil'	London	Internal	Inclined glass stack	8.0 x 7.2 x 1.5m	Stainless steel end posts	560	15.1t
Glass Wall	Lugano	Internal	Inclined glass stack	4.8 x 3.7 x 1.0m	Laminated glass end post	204	2.9t
Passage of Light	Quinto do Lago	Internal	Inclined glass stack	7.0 x 2.9 x 2.3m	Stainless steel end post	603	6t

3.1. National Police Memorial, London. Completed December 2004. Figure 1.

The National Police Memorial comprises a stack of 611 individual plys of annealed glass and 5 plys of toughened glass. The glass elements were assembled onto a fabricated stainless steel base which incorporated fibre optic lighting to illuminate the structure at night. The entire stack is post tensioned using 5 tendons each with a working load of 213 kN and an ultimate load of 271 kN.

3.2. 'Borealis' for General Motors, Detroit. Completed May 2005. Figure 3.

'Borealis' is located in the North Lobby of General Motor's World Headquarters in Detroit, USA. At the time of construction it was one of the largest glass sculptures in the world, with the glass elements alone weighing approx 45,700 kg. Each wall was formed by installing a fabricated stainless steel post to form a book-end type support and then leaning more than 1100 pieces of annealed float glass, each 6400 x 100 x 12mm, against it. An aluminium retention band at approximately mid-height of the glazing provides a failsafe support to the glass panels and increases the perception of the undulation in the structure.

3.3. Staircase. Exhibition at Borgholm Castle, Sweden. 2005. Figure 2.

The staircase exhibited at Borgholm Castle in 2005 was conceived as a piece of sculpture rather than a functioning staircase as it did not serve an upper floor and did not comply with any geometric regulations. However, during construction it was used to provide access to the upper treads and the structural principles of the treads functioned as intended, proving the principle of post tensioned glass stair treads to be predictable and serviceable.

3.4. 'Veil' for British Land, London. Completed May 2007. Figure 4.

'Veil' is located in the North Lobby of British Land's new Headquarters building in London. It was designed in direct response to the double height space in which it sits. The floor to ceiling height for this project was 6900mm and hence the 560 panels of annealed low iron glass were processed at 7400mm length. As in 'Borealis' a fabricated stainless steel post provides a rigid support to the glass panels, which span from a channel set into the floor to a fabricated cage set into the ceiling.

3.5. Glass Wall. Private. Completed Autumn 2009. Figure 5.

The concept for the glass wall recently installed in a private house in Switzerland takes the typology of the inclined glass stack but uses a laminated glass beam to provide the rigid initial support. This project represents one of the first uses of a laminated glass post in this manner and is discussed in more detail later.

3.6. 'Passage of Light'. Private. Completed Autumn 2009. Figure 6.

The installation known as 'Passage of Light' again uses the inclined stack of glass in conjunction with a fabricated stainless steel end support in a private residence in Portugal. The geometry of this project incorporates the largest lean and tilt of any of the case study projects, to produce a dramatic, undulating architectural feature.

4. Challenges

The projects described above present some incredible statistics. For example, all six projects together incorporate approximately 100 tons of glass. The working compressive force in the annealed glass of the Police Memorial is in excess of 1050 kN. 'Borealis' alone required 30.2 km of edge working and all six projects between them have over 50 km of polished edges.

The specification, manufacture and processing of the glass for these projects is far removed from the standard window glass processing carried out by so many large scale fabricators. It is testament to the parties involved in these projects, that as each project has presented challenges in their design or preparation, these have been overcome through the adoption of technologies old and new, a flexible approach to manufacture and a creative approach to material handling.

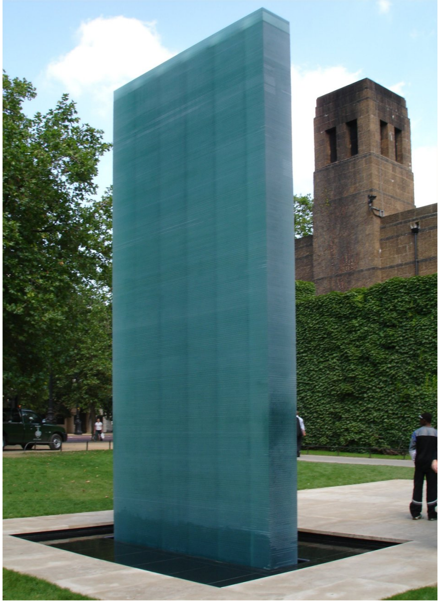

Figure 1: The National Police Memorial, London.

Figure 2: Staircase, Exhibited in Sweden.

Figure 3: ‘Borealis’, Detroit, USA.

Figure 4: ‘Veil’, London. (one of two similar walls)

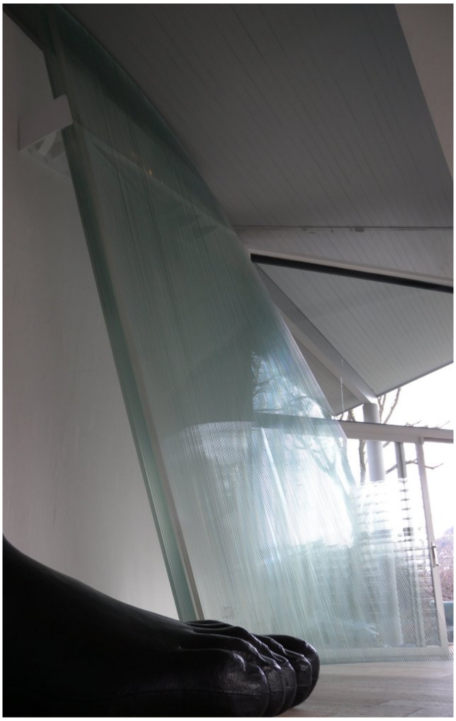

Figure 5: Glass Wall, Lugano, Switzerland.

Figure 6: ‘Passage of Light’, Quinto do Lago, Portugal.

4.1. Engineering and Design

The apparent simple form of construction conceals a number of non-typical engineering and design challenges which have been encountered during these projects.

Glass to Glass Friction

Projects like the Police Memorial, or the treads to the staircase, rely on glass to glass friction for shear transfer, yet in projects like 'Borealis' and 'Veil' the presence of friction introduces indeterminacy which must be considered in the design. A series of lab experiments established a static coefficient of friction for fresh float glass to fresh float glass of 0.23. Once moving, this drops to close to zero, and for long term exposed and wetted glasses, this value can exceed 1.0.

Tilt and Lean

The development of the more sculptural forms required the establishment of geometric definitions for tilt, lean and rotation, figure 7.

- *Axis* is used to define the overall or starting line of the structure.
- *Lean* is the constant angle which all of the glass panels exhibit along the axis of the structure.
- *Tilt* is the range of angles which the glass occupies in and out of the structure and perpendicular to the axis.
- *Rotation* is the angle through which the individual glass pieces have twisted, either through design or the accumulation of 2nd order effects.

Load Transfer

The requirement to transfer a load in excess of 1000 kN into the annealed glass layers of the police memorial required the design and testing of a bespoke fixing detail. A 200mm external diameter annular clamping plate, positioned concentrically over each set of holes and with a profiled, gently convex contact surface, was tested to the design ultimate load of 271 kN and then on to failure of the glass at 587 kN. See figure 8.

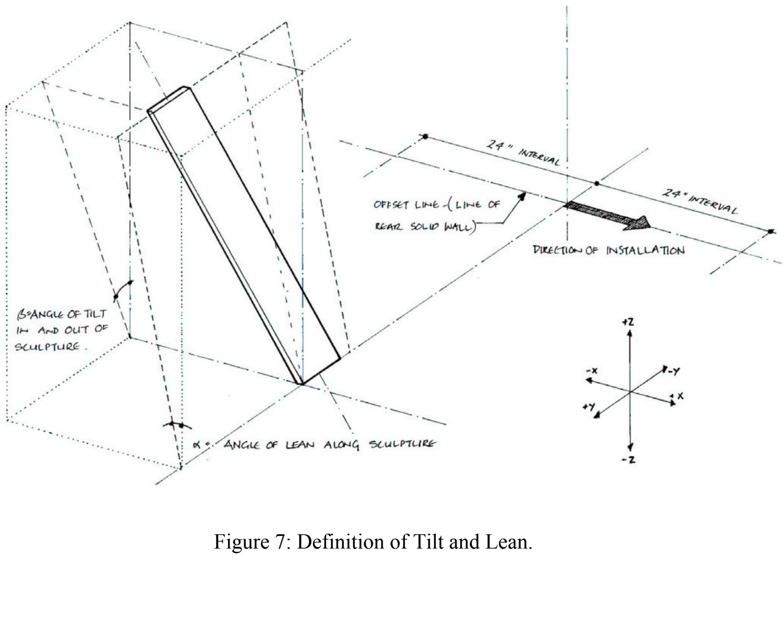

Figure 7: Definition of Tilt and Lean.

Rotational Stability and Torsional Restraint

The over-riding design challenge in many of these projects has not been the accommodation of very large forces due to the mass of material involved, but the provision of rotational stability to the glass panels. Due to the overlap required to achieve the intended forms, the longitudinal thrust along the structure is transferred eccentrically to each individual glass ply. If restraint is not provided then packs of glass will rotate to occupy a smaller space and the predictable close packed geometry will not be achieved, figure 9. A suitable method of restraint is shown in figure 10 in which the glass is clamped in packs of 12 – 20 panels as part of the base fixing detail.

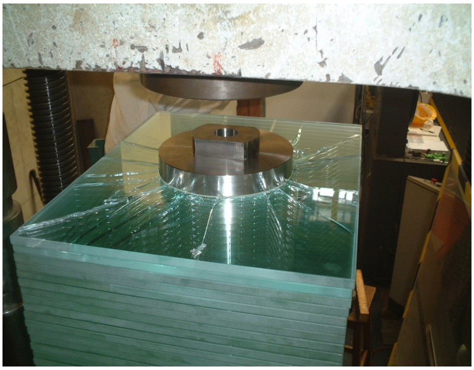

Figure 8: Compressive test of glass to 587kN.

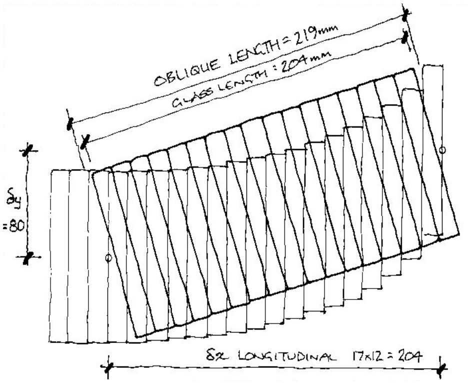

Figure 9: Rotational movement due to eccentric thrust.

Figure 10: Rotational restraint provided in base detail.

Figure 11: End support to glass beam.

4.2. Glass Processing

The requirements placed on the glass processors by these projects have been challenging and have led to a number of technical developments.

Glass Size and Cutting

Two of the projects incorporated over-length glass; 'Borealis' used strips of annealed float glass 6.55m long and 'Veil' used strips of annealed low iron glass 7.4m long. The glass panels were all cut by hand using a track slide cutter and then polished using edge working machinery with extended glass supports.

Edgework

The appearance of these installations is critically dependent on the quality of the edgework, as it is the edges which reflect and refract the incident light. All edgework was specified as ‘Polished Edge’ [EN 1863-1; 7(d)] and then subject to exacting quality control and sampling procedures. The presence of any defects, shells, blank spots etc., led to rejection. For ‘Borealis’ the glass processor provided in excess of 30,000m of polished edges without defects whilst achieving a tolerance on width of 100mm +/- 2mm.

Tolerances

A further consideration on tolerances is on thickness of glass. Though basic glass thickness tolerances are given for 12mm float glass as +/- 3mm in EN 572 – 2, experience has shown that the glass varies from approx 12.2mm at the edges of the ribbon to 11.7mm towards the centre. Consequently, to avoid the accumulation of several hundred gaps of approx 0.5mm, all glass should be cut along the ribbon.

Toughening and Laminating

All of the projects described in this paper feature annealed glass. In some cases, where projects have been installed in public spaces, anti-shatter film has been applied to the glass during production. For the project in Switzerland, a laminated glass end post was used for the first time. The post, of dimensions 4800 x 100 x c.100mm, comprises eight layers of 12mm toughened low iron glass and is laminated together using seven layers of Sentry Glass interlayer.

The beam was laminated using the vacuum bag and hot box process. The individual toughened glass pieces, at 4800 x 100mm, are the highest aspect ratio toughened glass panels known, figure 12. A fragmentation test was carried out to demonstrate the toughening quality and this is shown in figure 13.

Figure 12: ‘Veil’, London.

Figure 13: Glass Wall, Lugano, Switzerland.

4.3. Installation

In addition to the design and processing challenges, the handling and installation of the material for these projects required creativity and flexibility. The transportation of over-length glass, especially to the USA, required the fabrication of custom stillages which could hold 150 strips of glass and be stacked two-high in containers.

On site each panel required manual cleaning prior to installation and then manual handling into position. The use of automated handling was considered early on, but quickly discounted, due to the panel widths and site constraints. For both 'Borealis' and 'Veil', three tier scaffold towers were required to enable the safe and accurate manual positioning of the glass. This is shown in figure 14.

Figure 14: Installation of 'Veil', London.

5. Conclusions

Through this series of separate projects, a manufacturing technique and form of construction has been developed to effectively realize large mass glass structures. Though the origins of these projects lie in sculpture and decoration, they have extended the abilities and techniques of the architectural glass processors that have contributed to them. The understanding of methods for transferring large forces into and out of annealed glass has also been developed further.

Several of the technologies, particularly the efficient and predictable post tensioning of glass structural elements, and the toughening of very high aspect ratio panels, obviously have broader applications in glass structures and architecture, and the ability to toughen such panels makes their use in public spaces less challenging.

It is acknowledged that the forms of construction described herein have their drawbacks in terms of both weathering and resistance to potential damage, and that this could limit potential applications. However, each one of the projects succeeds in its goal of delighting the viewer and, in responding to their individual settings, each contains the vision and integrity of their unique design and construction processes.

6. Acknowledgements

The author wishes to acknowledge the boundless creativity, widespread experience and judicious wisdom of Danny Lane (www.dannylane.co.uk), the artist whose years of experimentation and working with glass and other materials have resulted in many of these, and other, beautiful glass sculptures, structures and artefacts. Additionally, Eckelt Glas in Austria (www.eckelt.at) should be acknowledged for their flexible yet diligent approach to the cutting, processing and handling of much of the glass used to realize these projects.