GLASS - THE NEW STRUCTURAL ENGINEERING MATERIAL

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ABSTRACT

The drama of designing from first principles in a material that has been used in buildings for at least one thousand years and has been manufactured since at least 50 B.C. is perhaps hard to impart. As engineers we are often comfortably and safely directed by ample research and codes of practice to tried and tested solutions.

Designing glass structures has been an exciting adventure in uncovering research that is relevant and being forced to make assumptions based more often on gut instinct than on scientific evidence. This paper will trace the gradual progress we have made over the past ten years summarising what we have learned and suggesting some immediate areas of research that might be useful to the practicing engineer.

INTRODUCTION

In 1986 we were approached by an architect to consider the design of a staircase with glass treads. This was our first encounter with the challenge of structurally designing a glass element.

In 1998 we had over one hundred enquiries from architects, clients and glass fabricators world-wide specifically relating to the structural design of glass assemblies ranging from facades to floor plates and framed structures to glass sculptures.

This rapid growth suggests that there are many challenges in the design of glass assemblies which can benefit from the special expertise of the consultant engineer.

This short paper will trace the milestones in the development of our role in glass engineering from the design of a single stair tread to the most recent projects which demonstrate the possibilities of creating free standing structures where all the principal loads are carried by glass elements.

GLASS AS A STRUCTURAL ELEMENT

In designing a glass element the following issues need to be addressed:

1. The degree and type of loading to which the element will be subjected.

2. The physical properties of the glass.

3. The ways in which the glass could fail.

Applied Loading

Codes of practice generally describe the range of static loading to be used in the design. Impact loading from falling objects or projectiles are of special interest in the design of glass structures as severe stresses can build up at the point of contact of the projectile causing failure which propagates through the element. A typical test for a stair tread is to drop a 4 kg steel sphere onto the surface from a height of 1m. Although the glass can crack under this load it should not cause complete failure of the assembly

Physical Properties

There are many different glasses produced using chemical compositions appropriate to their application. The vast majority of glass used in the construction industry is of one type namely soda lime glass. This glass has generally a blue-green tint due to the presence of iron in the mix which lowers its melt temperature thereby making a more economic product. This glass is produced in vast quantities in float plants world-wide and the designer can be confident that the physical properties of glass produced in Japan will approximate to those of glass produced in Finland.

Some well known properties of this glass are widely published such as:
Young's Modules of Elasticity: 70N/mm^2
Poisson's ratio : 0.22
Coefficient of thermal expansion : 85x10^{-7} / degree centigrade
Mass Density : 2500kg/m^3

The figures for ultimate tensile and compressive stresses are less readily published and this proved to be the most difficult subject to unravel in the early designs.

Possible Failure Modes

When a glass element fails it can lose all of its structural strength. Also pieces of glass can break away from the element causing injury or even loss of life.

The remainder of the discussion will show how we developed these initial principles into a workable design method for annealed and toughened glass elements.

GLASS STAIR TREADS

Our initial strategy in designing glass stair treads was to approach a well known major glass company to ask their advice. They helpfully suggested that a 25mm thick monolithic annealed glass tread spanning 300mm would, if continuously supported on its longer edges, safely support an imposed load of 4.0kN/m^2 and an imposed point load of 4.5kN.

The tread we had been asked to design however was to be supported at either end of its 900mm length and at third points in its length using circular pads of 50mm diameter. Unfortunately the glass company were unable to reveal the basis of their design so our only option was to back analyse their suggestion and assess the level of stress they had allowed in their design. From this analysis assuming the point load of 4.5kN activated an effective glass width of 300mm it was deduced that a working stress of at least 11N/mm^2 had been considered acceptable.

Using this stress we were able to suggest the use of a single sheet of 19mm thick annealed glass for the proposed design.

It became clear however that whereas the tread which was continuously supported an its long edges would be capable of sustaining a crack or even multiple cracks spreading across the short tread dimension the new design could result in structural collapse of the tread if the crack occurred on the end spans or if two such cracks developed in the middle span. This problem was overcome by introducing a sheet of clear acrylic below the glass tread.

The acrylic has a well documented ultimate tensile stress of 69N/mm^2 and although it would deflect significantly under a point load of 4.5kN a 15mm thick sheet would safely support this load until the glass tread was replaced.

We have successfully designed a significant number of staircases using this approach and to date we have heard of only one tread suffering a crack. In this case the broken tread was supported adequately by the acrylic until the glass was replaced.

GLASS FLOOR PLATES

In a similar way to glass tread design the Industry recommendation in 1989 for a glass floor panel was to use square sheets of 25mm thick annealed glass supported on all four sides with a maximum span of 750mm.

The glass floor panels for the Now and Zen restaurant in St Martins Lane London were required to span a clear space measuring 1m by 3.5m supporting a distributed load of 4kN/m^2 and a point load of 4.5kN. For this design we developed the idea of using two sheets of glass continuously supported on all four edges. For a point load of 4.5kN assumed to act over a width of 1m the bending stress in two sheets of annealed glass

19mm thick was calculated to be $9.3N/mm^2$. A 45kg steel ball was dropped from a metre height to prove the robustness of the panel.

Consideration of the likely failure pattern led us to conclude that if one sheet cracked it would retain some residual strength due to the four sided support condition and that even if no residual capacity remained the unbroken sheet would be subject to a maximum stress of $18.6N/mm^2$. In addition the two sheets were laminated together using a 2mm thick acrylic resin which gave the following benefits:

1. Broken shards of glass would not fall from the panel in the case of breakage.
2. For short term loading and in temperatures less than 60 degrees centigrade the panel works as a monolithic slab reducing the maximum stress in the glass from 9.3 to $2.1N/mm^2$
3. For longer term loading the resin ensures equal and well distributed load sharing between the sheets of glass and also prevents dirt or condensation forming in the gap.

We have completed numerous designs based on these simple principles and we understand that the industry standard has been changed to recommending laminated glass for floor panels rather than monolithic sheets.

GLASS BEAMS AND COLUMNS

The proposal to built a small glazed extension to a private house in North London gave us our first opportunity to consider the use of glass beams and columns. The architect was interested in designing a structure using the smallest possible steel sections.

Having by this time gained some understanding of workable stress levels in glass and an approach to fail-safe design we proposed the use of a lean-to glass portal frame. The frames were spaced at 800mm centres with rafters spanning 3.8m onto 1.6m high columns at one end and supported in a metal bracket fixed to the rear wall of the building at the other bearing.

The roof imposed load was $0.75\ kN/m^2$ and the wind uplift was shown to be less than the dead weight of the glass roof panels at $0.55kN/m^2$. The rafters were fabricated from three plies of glass. Each ply measured 10mm thick by a maximum depth of 250mm. at the centre curving to a dimension of 150mm at the support. The stress in the glass due to the dead load of the roof was calculated as $3.0N/mm^2$ and due to the live load $4N/mm^2$. A total deflection of 1mm was predicted at the centre of the beam.
The columns were also fabricated from three plies of glass measuring 10mm by 100mm.

Due to a wind loading of 0.5kN/m^2 a bending stress of 2.56N/mm^2 was calculated for the columns together with a compressive stress of 0.7N/mm^2 from the rafter reaction. Buckling of the beam and the column was considered and it was shown that the structural silicone joint connecting the glass roof and wall panels to the beam and column could comfortably deal with the buckling forces.

The fail safe aspect of the design considered the loss of two of the three plies in the beam resulting in a stress of 21N/mm^2 in the remaining element. Also the laminating material ensures broken sections of glass do not fall to the ground on cracking and as with the floor plates dirt cannot accumulate in the gap.

This simple design procedure has led to a proliferation of this type of structure.

TOUGHENED GLASS BEAMS

The Yurakucho glass canopy project in Tokyo Japan presented us with our first opportunity to consider the special qualities of toughened soda lime glass. Annealed glass can be toughened by re-heating the glass and then cooling the outside surface in a carefully controlled manner. The subsequent cooling of the inner core of the glass prestresses the outside skin and greatly enhances the capacity of the extreme fibres to resist tensile stress. Different degrees of tempering can be achieved using this basic method.

In the design of the canopy we used fully toughened glass. The architectural ambition was to create a structure using as far as possible only glass. The plan area of the canopy was 5m by 10m. The roof of the canopy was to be covered with 10 glass sheets measuring 2.5m by an average of 2.2m supported on three 10m long glass cantilever beams spaced at 1.67m. The cantilever beams were connected to a stainless steel torsion bar close to the ground level springing point and soared 4.5m into the air at the leading edge of the canopy.

The loading criteria which had been established from a wind tunnel study was quite severe with anticipated upward and downward pressures at the tip of the canopy reaching figures as high as 5kN/m.^{2} In addition the earthquake design criteria were as severe as anywhere in the world. As the maximum length of toughened sheets of glass available at that time in England was 5m, we decided to fabricate the ten metre long beams from four overlapping elements or 'blades' to minimise the force at the connection points, as we suspected that this might be the critical feature of the design. The blade nearest the support was 5m long and the blade nearest the tip was just under 4m long with the blades reducing in length in accordance with the Fibonacci series and each blade overlapped its neighbour by an average of 2m.

For the initial proposal we were able to determine a geometry for the blades based on our knowledge of the stress used in designing cantilevered toughened glass balustrades which we had deduced from back analysing recommendations from well established glass companies. This was a stress of $50N/mm^2$.

The bolted connections were, however, a different scale of problem as we had no precedent to refer to other than bolts used to attach planar glass assemblies to buildings and the scale of loading in those fixing was much less. We therefore set up a simple test with the help of a friendly glass fabricator to get a feel for the magnitude of loading that could be transferred through a 22mm diameter hole in a 19mm thick glass beam. We were surprised to find that an applied load of 67kN, which was the limit of our testing equipment, could be sustained by the glass without failure.

From these initial ideas we were able to convince the client to fund further study. We were given a very generous sum of money which enabled us to carry out an intense programme of physical testing at a University laboratory and we undertook an extensive finite element analysis of the entire structure particularly to measure its response to earthquake loading. This research programme resulted in a clearer picture of the strength of toughened glass and provided us with sufficient data to design the bolted connections with confidence.

Of particular interest to all parties was the demonstration of a fail safe method in the development of the design. The roof sheets were designed as flat panels supported at four points using bolted connections to the top of the beams. Each panel was fabricated from two sheets of 15mm thick toughened glass laminated using a 1.6mm PVB film. The design was developed to ensure that even if both sheets in one panel failed the beams would not suffer from buckling failure and in addition the pvb film would hold the panel together until it was replaced.

The ten metre long cantilever beams were each constructed of 14 individual blades. The blade nearest the tip of the cantilever was fabricated from an identical pair of 19mm thick toughened glass elements and the remaining three blades were each structured from two pairs of 19mm thick elements laminated to provide two separate beams of approximately 40mm thickness with a maximum depth of 750mm. The blades were laminated using a UV cured acrylic resin. The beams were designed with a factor of safety of 8 on the basis that the critical blades at the root of the cantilever could lose three of the four glass elements and still support the most extreme loading condition with a factor of safety of 2. The lamination of the elements also ensured that complete failure of a laminated element would not result in heavy pieces of glass falling to the ground.

Each individual glass element and all of the laminated pairs were fully tested to three times working load before installation in the works . Strain gauges were installed to monitor the performance of the elements and all 21 laminated pairs passed this test successfully with stress levels close to those predicted by calculation.

The techniques developed in the canopy design have subsequently been used in the design of a 50m high by 50m wide glass facade in Seoul Korea. This wall has recently been completed and was apparently erected within schedule and budget

A project recently completed in Saudi Arabia combined the lessons learned in Tokyo with our earlier structural silicone assemblies to create an 8m by 8m by 8m glass cube. In this design we established a two-way structural grid of beams spaced at 2.67m centres. The beams were laminated from two toughened glass beams 15mm. thick and 450mm deep.

A special two way friction grip connection was developed for this design and a special procedure for laminating the beams was adopted incorporating a short aluminium plate within the laminate thickness to transfer the friction forces. The laminated glass wall and roof panels were simply structurally siliconed back to the glass frame.

THE FUTURE

As practising engineers with a large number of live projects to take care of we have not been able to afford the luxury of developing a well researched scientific approach to the structural design of glass assemblies. However we have had considerable opportunity to experience at first hand the particular nature of some glass problems which have led us to a number of conclusions which might be useful to an aspiring designer.

1. A fail-safe approach should always be taken. An individual glass element can break due to events beyond the control of the designer. The consequences of such a breakage should be considered.

2. Annealed soda lime glass has the following physical properties:

   Modules of Elasticity : 70N/mm^2
   Poisson's Ratio : 0.22
   Mass Density : 2500kg/m^3
   Coefficient of thermal expansion ; 85x10^{-7} / degree centigrade
   Ultimate tensile stress 30 - 100N/mm^2

   The ultimate tensile stress varies with the duration of loading and the condition of the glass surface or edge. We have assumed, for example, that normally handled glass subject to a wind load gust of 3 seconds duration will have an ultimate tensile strength of 70N/mm^2. For normally handled glass subject to long term loading we would use an ultimate tensile stress of 40 N/mm^2. For heavily scratched e.g. sandblasted glass we would use 60% of the above values.

3. Toughened glass has exactly the same physical properties as annealed glass except for its ultimate tensile strength which can apparently vary between 150-200N/mm^2.

This stress value is not significantly affected by load duration and minor surface scratching does not affect its performance.

4. A factor of safety of 3 is used in all our structural assemblies
5. Glass in normal usage has a zero fire rating.
6. When toughened glass fails it breaks into many small regular size pieces. Annealed glass tends to break into larger pieces and can often remain in place performing as required even after a crack has developed.
7. A method statement for maintaining the glass and for replacing broken elements should be prepared for every project.

These few principles have provided us with tools to design glass structures that have extended the palette of the architect and the fabrication techniques of the glass companies. Currently a European code is under preparation which will give clear guidelines on the design of glass structures.

There are however many areas where research and design development will still be required, for example:

1. A statistical approach to applying factors of safety in multi-ply construction.
2. An approach to designing glass edge bearings and guidance on pull out and shear values for fixings through glass holes.
3. A guide to the use of adhesives and laminating inter-layers.

The only drawback in having all the design information one needs codified, is the inevitable fixed thinking that can result. For our company it has been an exciting and challenging journey to date, perhaps because we have had to use our engineering judgement where no other guidance was available, although the expertise and practical experience of many talented people in the industry provided us with firm guidelines to grow from.

In particular I would like to thank John Colvin of Hansen Glass and John Hodgson of F.A. Firman & Co for their continuous intellectual and practical support over the last ten years and to the many enthusiastic staff at Dewhurst Macfarlane and Partners who have contributed to the development of a design method for structural glass.