Glass Engineering without the Concept of Stress

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Keywords
1 = stress 2 = static fatigue
3 = proof test 4 = art

Abstract

The thirty-four panels of an art glass chandelier at Pariser Platz 3 in Berlin were formed from fused, distorted bundles of sandblasted borosilicate glass tube. They were suspended from a glass ceiling above a dining area by thin stainless steel cables. Each panel was unique and of unpredictable form unsuited to stress analysis. Therefore it was impractical to calculate the applied stress in the glass at the highly loaded connection points. The design of connections was developed experimentally and the structural integrity of the panels was tested by a long-term proof test. The proof test was formulated to establish that the stress intensity in each panel was below the static fatigue limit.

Background

The concepts of stress and strain are so fundamental to modern engineering that it is easy to forget that they are not much more than 200 years old, having first been explained by Thomas Young (1773–1829). The teaching of mechanics of materials, and all the branches of engineering built upon it, generally starts with the concepts of stress, strain, strength and stiffness [1]. At first the cross sectional areas of simple tension and compression members are easy to calculate and then the problems become more difficult. The concepts of bending, second moment of area, elasticity, plasticity and fracture are added. Progress into more realistic problems is a journey into stress systems that are increasingly difficult to analyse. It has become expected that to engineer the physical realm is to manipulate stress. This paper presents an example of how other engineering methods can be applied when it is not appropriate to use mathematical stress analysis.

Great things were achieved before the invention of stress, when engineers worked in terms of the strength of objects rather than the strength of materials. Common objects like ropes and wooden beams were tested under typical kinds of loading so that their capacity would be known. Rope has the advantages of only one real mode of loading (tension) and being made in standard sizes, has always been characterised by breaking load or safe working load not stress. Proof testing was the most scientific way to assure the strength of something and it is still in widespread use, particularly for pressure vessels, lifting gear and glassware.

When grey cast iron was a popular structural material, beams were routinely proof tested.The principal reason was that, although the bulk of the iron had a reasonably consistent structure of flakes of graphite in a crystalline iron matrix, large bubbles could occur. These bubbles were impossible to detect before the advent of modern non-destructive testing and could reduce the strength of a beam by a factor of 3 or 4. Grey iron also has rather non-linear stress-strain behaviour. Glass, in contrast, has a homogenous, amorphous molecular structure and such predictable elasticity that it was the ideal experimental subject for much of the classical work on stress analysis and fracture mechanics by Griffith and Irwin [2][3]. It also has the advantage that internal defects are less common and are visible.

Some complex objects used to make the calculation of stress, and hence quantitative prediction of performance, impossible. Take for example a vehicle body subject to dynamic loads from the road or a sudden impact. For much of the history of the motor car, little useful stress analysis could be done on the body-shell and development proceeded by rule of thumb, prototyping and testing. In aerospace, where the strength to weight imperative was stronger, lengthy calculations were done by hundreds of engineers and finite element computational analysis (FEA) was developed to reduce this labour. Now FEA is in routine use for all sorts of complex structural analysis including vehicle bodies, windscreens and architectural components. However, despite the increasing capability to analyse the most complex forms and stress systems, there are still occasional situations where it is impractical.

Introduction to the project

The design of an art glass chandelier by Nikolas Weinstein for Pariser Platz 3, Berlin, posed a combination of factors that made engineering by stress analysis impractical. Each of the 34 panels of the chandelier would be unique, made by a process with very loose control of shape, from a new form of glass composed of thin-walled tubes fused together into a mass.

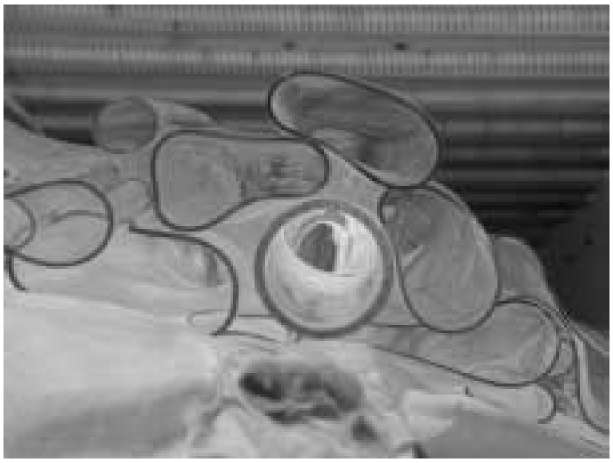

Figure 1 End view of glass tube bundle in kiln

The panels were roughly tear-drop or leaf shaped and ranged in size from 1m long by 0.6m wide up to 3m by 1.5m. Each panel was curved in two directions reflecting a three-dimensional sculpted surface. The designer wanted to use glass with significant volume but had found that solid glass of suitable thickness would be very heavy and visually rather uninteresting. He had experimented with bundles of glass tubes slumped together in a kiln and found that the tubes would fuse together where they touched. The resulting mass had a fragile appearance and was much less dense than solid glass with numerous surfaces to reflect and refract the light. The slumping process distorted each tube by differing amounts and the width of the fused areas, which came to be known as welds, varied according to the pressure between the tubes and the time and temperature in the kiln.

Initial estimates of the density of the fused bundle, combined with the desired area and thickness, indicated that the largest panels would weigh about 100kg and the chandelier would weigh a total of about 2500kg. All together the panels covered an area of 150m^2 and would be suspended over an area for dining and relaxation in new offices for DG Bank at Pariser Platz 3, Berlin, a building designed by American architect Frank O. Gehry.

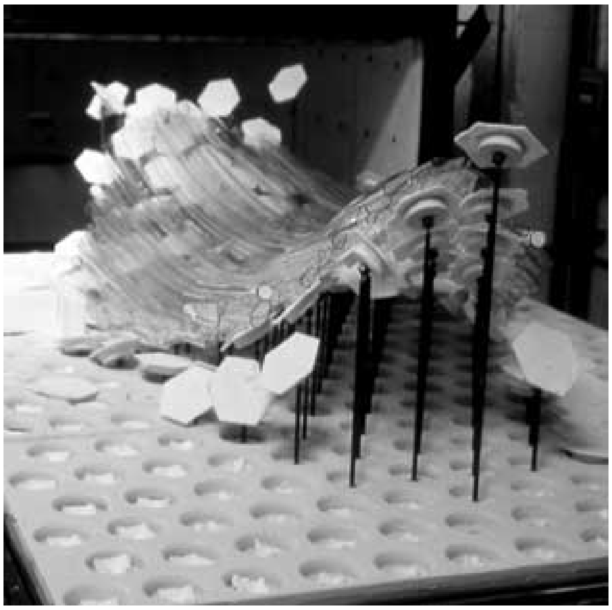

Figure 2 Slumped panel on moving bed of kiln

Exploration of the concept

The location defined several engineering parameters. Safety was paramount because the area below the glass would be populated regularly and at some times densely. The glass would not be subject to snow or wind loads other than air currents caused by the ventilation system and we could expect the chandelier to be carefully and diligently maintained as a work of art and not subjected to vandalism.

The novel form of glass had some attractive features; it was low in density, effectively a foam composite with elongated cells similar to plant structures and numerous changes of direction and thickness to impede the propagation of cracks. However, the wall thickness of the tubes was only around 2mm and the tubes would be of unknown section, the welds of unknown strength and one surface of each panel was to be sandblasted to improve light diffusion. Two key questions arose about whether and how we could use the material:

- how would it break if impacted or over-loaded and
- how could it be suspended on thin cables to give the impression of floating?

The artist's prototypes were subjected to a series of informal destructive tests involving impact, bending and crushing to gain a qualitative feeling for the properties of the glass tube bundle composite. It was found to sustain impact well by containing fracture to a region around the impact site. The number of tubes broken depended roughly on the force of the impact and cracks running around the tube wall tended to be diverted along the tube walls parallel to the welds. After some larger scale impact tests we concluded that the tube bundles would not have a catastrophic failure mode like that of toughened (tempered) glass and so would potentially be safe for use overhead.

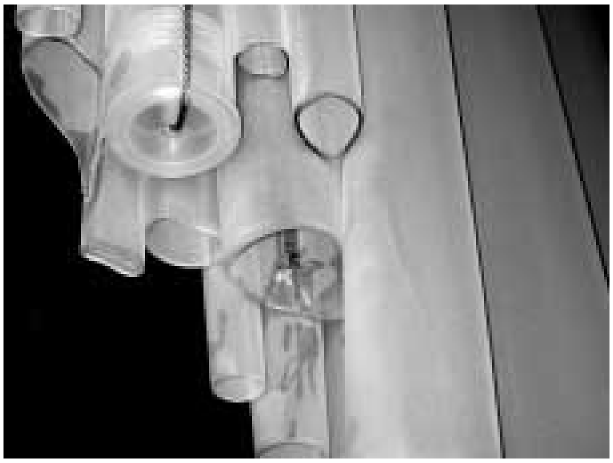

Figure 3 Impact damage site close to suspension plug

The question of attaching cables was more difficult and a number of concepts were generated initially for evaluation. These included;

- piercing through the bundle by drilling (terrible stress raiser) or
- hot working (laborious and a stress raiser),
- bonding by adhesive (reliant on the top section of a tube) or
- hot working (laborious and reliant on the top section of a tube),
- enveloping the panels in something like a fishing net (secure but visible and not in the artistic spirit of the piece),
- putting magnets inside the tubes and matching them with attracting magnets on the outside attached to cables (even rare earth magnets turned out to be too bulky and visible).

The concept that became established was to thread members through two tubes in each panel and suspend the ends from cables. Strong flexible steel rods (spars) were imagined with rubber buffers pushed down inside each end to the tube so that the contact force would be away from the vulnerable mouth section. The tubes selected would be deep within the section of each bundle so that reliance was not placed on a single wall thickness to stop the spar pulling out.

Design development

A full size prototype was made and loaded with sandbags to double its own weight. It was also impacted with a number of hard objects to verify the failure mode. The suspension concept was successful but it was realised that the steel spars would be difficult to bend within the confines of the most tightly curved panels.

The steel spars were replaced by threading the suspension cables right through what had become known as the spar tubes. Plastic plugs to prevent the cable bearing on the open end of the tube replaced the rubber buffers. Without these the cable would have acted like a cheese wire, raising an extremely high local stress and maintaining it if a fracture started to propagate. Bending around a tight radius would also have seriously weakened the cable.

Samples of the plastic plugs were tested in small bundles of tubes and the strength was at first disappointing because failure originated at the mouth of the tube. The design developed over several iterations with the plug becoming much longer to transfer load well inside the tube in a manner similar to the original steel spar. At one stage prototype plugs were made from steel pipe with turned rubber tyres.These were very successful in terms of strength but unacceptably ugly. The final version of the plug was made in clear acrylic plastic with clear silicone tyres at the contact points.The spar tube diameter was increased to accommodate the diameter of acrylic required to resist the bending moment on the plug but the increased diameter happened to be readily available with a thicker wall for use in laboratory waste piping.

Figure 4 Clear acrylic connection plug without tyres

Strength of the glass panels

The original strategy was to develop a standard spar tube connection and test enough samples to estimate the characteristic strength, having established that the body of the tube bundles was strong and robust. The samples tested would have to represent the typical variability of the glass fusing process and subsequent sand blasting. The statistical characteristic strength would have to be substantially greater than the worst load case for the largest panel. This would be half the factored dead weight (assuming weight supported on diagonally opposite corners) plus an accidental imposed load from maintenance.

A test was devised where a small panel was suspended from two diagonal corners and loaded with a water container from the other two. The water load was increased steadily until breakage occurred and the time and load recorded. Effectively four connections were being tested at one time although only one would break. Examination of the fragments indicated where fracture was originating and several improvements were made to the plug design as described above.

As the connection detail was developed, a point was reached where the sample panels were no longer strong enough to cause breakage at the connection and it was evident that we would not get a useful set of strength statistics at several times the required loading. Therefore a reliable characteristic strength for the connections could not be established for use in a calculation of loading against capacity following the usual limit state approach.

Proof testing

Techniques of proof testing were investigated in order to verify the strength of each completed panel once installed. Additional reliance was to be placed on this process since it was not possible to characterise the strength of the connections with all their inherent variability. Proof testing is common for engineering ceramics and also used for critical glass applications such as space craft windows [4]. A typical proof test involves applying a stress σ_p of R times the service stress σ_s for the minimum possible time period. The multiple R of service stress is often two or three times but has to be calculated according to the lifetime required and the service stress. The objective is to apply sufficient stress in the short term to make existing cracks, which could grow to critical length during the required life, critical instantaneously and cause breakage. The loading time is minimised to avoid weakening good parts by extending sub-critical cracks that would otherwise not cause failure. Unfortunately it is not possible to calculate the required proof test ratio R without knowledge of the service stress. Therefore it is not possible when working only in terms of load on a component to design a short-term proof test. However, it has been observed by Michalske [5] that it is possible to relate the static fatigue limit to a long time period and this suggested an alternative form of proof test for the chandelier.

Subcritical crack growth

The process of subcritical crack growth and delayed failure are described by the following equations:

Rate of subcritical crack growth in Region 1 [9];
$v = v_0 (K_1/K_{1c})^n$

Time to failure [7]; $t_f = 2/(n-2)v_0 \times (Y\sqrt{\pi}/K_{1c})^{-n} \times (a_0^{(2-n)/2} - (1/\pi \times (K_{1c}/Y\sigma)^2)^{(2-n)/2}) \times \sigma^{-n}$

Stress intensity [10];
$K_1 = Y \sigma \sqrt{\pi a}$

Where; K1c = critical stress intensity (fracture toughness), n = a material property dependant on the environment, Y = shape characteristic of initial flaw, a = half-length of initial flaw, σ = far field stress

Long-term proof test

What Michalske observed was that when he calculated the time to failure for soda-lime glass with a defined initial crack of 25microns, it was about 10^6 seconds. Furthermore a number of reported delayed fracture experiments on soda-lime glass in water did not indicate any failures at longer times. Theoretically there could be longer times to failure under constant load if the initial crack were longer but none were reported. The test devised for the chandelier panels was to suspend each one in a safe place for 10^6 seconds, about 11 days, and then closely inspect them for cracking. If a panel broke it would have to be replaced but if it survived then we would know that it was below the static fatigue limit stress intensity, or subcritical crack-growth threshold, K_{10} all over and that it should not crack simply with the passage of time.

There were several factors to consider within the long-term proof test:

1. the glass we were using was borosilicate and not soda-lime.
2. it would be impractical to proof test under water.
3. the panels were to be made in San Francisco and air-freighted to Berlin for installation so it would be very expensive to replace a cracked panel once installed.
4. swaying of the panels under the influence of air movements would cause very small changes in loading.
5. allowance had to be made for occasional imposed loads when cleaning or maintaining the chandelier.
6. a load factor was required over and above the

self weight, in order to have a safety margin.

Borosilicate glass has a higher value of 'n' than soda-lime glass, typically in the range 33–46 depending on environment and composition where 'n' for float glass is generally taken to be 16 in air. The higher value of 'n' indicates that the glass is less affected by stress corrosion cracking as indicated by the steeper gradient of region 1 of the v-K plot [6]. It also has a higher value of v_0, the crack velocity that a slowly growing crack would theoretically reach if it could grow steadily, getting faster as it extends, right up to the point where it is of critical length and $K_1 = K_{1c}$. These two properties strongly influence the time to failure [7] making it shorter in borosilicate than in soda lime glass for the same initial stress intensity. The times to failure from just above the fatigue limit of K_{10}=0.4 MPa√m of cracks of various lengths were calculated and fell within 10^6 seconds. Therefore, 11 days would allow sufficient time for even quite long and detectable cracks to grow slowly and then cause failure under test if they were above the fatigue threshold.

It has been shown that air with a range of humidity is effective in promoting stress corrosion cracking and data for borosilicates under various conditions have been reported [6,8]. Therefore it was not essential to proof test under water.

Figure 5 First panel installed in the building

Before freighting, each panel was subjected to a 'triage' test at the studio. For this it was loaded with 40kg of roofing lead, regardless of the size of the panel. After 3 days the panels were closely inspected under edge lighting for cracks or other defects before packing. Although this shorter test did not give the same security as the full long-term test, it gave sufficient confidence that it was worthwhile shipping, installing and proof testing the panels. One panel broke during the triage test, revealing a subtlety of the annealing process, which was subsequently improved. Photo-elastic strain analysis was used to investigate the residual strains in the panels and it qualitatively indicated that the stresses due to suspension were very low.

The full proof test was conducted with an imposed load of 40% of the self-weight of each panel applied with roofing lead to achieve an even distribution. This surcharge far exceeds any dynamic loads experienced as only very few of the panels sway just perceptibly. It also provides a margin for deterioration in service and accidental loading. A mechanical fatigue effect has been reported in borosilicate glass [8] but this is only very close to the subcritical crack-growth threshold and the proof load factor of 40% ensures that in service the panels are well below that.

Conclusions

The chandelier was installed during the summer and autumn of 2000 and none of the panels fractured under proof loading. However, subsequent construction work resulted in impact damage to a few panels, which remained safely in place until precautionary measures could be taken and the panels replaced. Although the design was unique and the techniques used were very specific, the experience did illustrate some interesting aspects of the long-term strength of glass.

It illustrated that the static fatigue limit can be related to a time period under constant load via the material and environment properties; n, K_{10}, K_{1c}, v_0 and the initial crack parameters; Y and a_0.

If a_0 is large enough to be visually detectable and the calculated time to failure is within an acceptable period for the project then a long-term proof test may be suitable for other unusual glass objects under constant load.

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