A New Design Model Based on Actual Behaviour of Glass Panels Subjected to Wind Load

Dr. Leon Jacob
Jacob & Associates Pty Ltd
Dr. Ignatius Calderone
Connell Mott MacDonald

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Abstract

All existing models for predicting the behaviour of glass subjected to wind pressure involve simplifications using an assumed duration for the design wind pressure. Recent research has shown that the cumulative effect of the wind pressure fluctuations over the entire duration of a windstorm needs to be computed and that the previous simplifications were not appropriate for the correct use of Brown's integral. The new research has shown that the effective wind load can be determined by utilising a modified form of Brown's Integral together with the maximum principal tensile stress. The maximum tensile principal stress on a glass panel is a function of the glass geometry (i.e., size, shape and thickness). This now justifies fracture mechanics techniques to be used for glass design based on glass strength. Nevertheless, irrespective of glass panel strength, the glass deflection must be utilised in any design model.

Introduction

The evolution of the design techniques used for building glass panels has under gone significant development and transformation in recent years. From relatively humble beginnings in the early forty's to the reasonably complex finite element and finite difference techniques of today.

The deflection in laterally loaded glass panels is non-linear. Consequently, conventional analytical techniques for plates are inadequate. Numerical analytical techniques with the assistance of high-speed computers required to solve the 4th order differential equation for thin plate behaviour have made the onerous task of the non-linear analysis now feasible. The use of finite element techniques has enhanced our appreciation for the interaction of the various parameters that influence thin glass panel behaviour.

This paper reviews the various issues and complexities that exist in the current design procedure and determination of the fundamental characterisation of glass strength.

Current Position

Because of the variability in the strength of glass, industry has adopted a probabilistic approach to defining glass strength. Griffith was the first to explain the observed variability in glass strength. The use of the Weibull distribution to quantify a design stress for glass has apparently been found to be the most convenient. However, its use and understanding has been limited to a few researchers. Jacob [1] identified numerous limitations in the use of the Weibull distribution for determining a suitable design stress in glass. Calderone [2] has shown that a Log Normal distribution can also be more easily and accurately used to define glass strength.

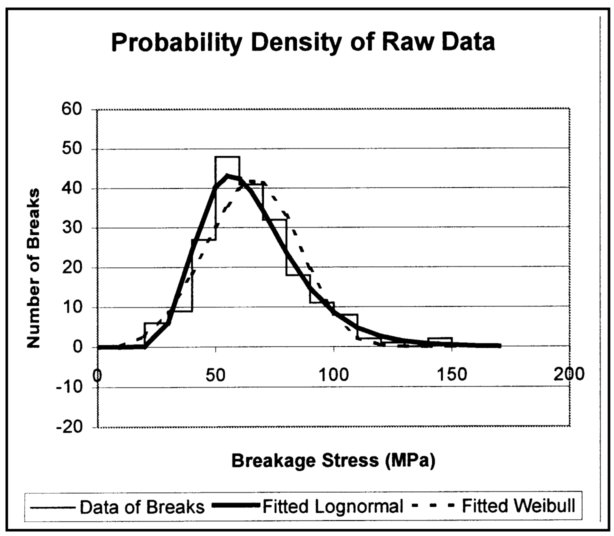

Figure 1. Comparison between the Weibull & Log normal distributions.

Figure 1 Illustrates the difference in the Weibull and the log normal distributions for a particular set of fracture data. It can be readily seen that at the lower stress levels the log Normal gives a better fit to the raw data in comparison with the Weibull distribution.

Recent research has shown that the cumulative effect of the wind pressure fluctuations over the entire duration of a windstorm needs to be computed and that the previous simplifications were not appropriate for the correct use of Brown's integral. The research has shown that the effective wind load can be determined by utilising a modified form of Brown's Integral, which uses lateral pressure instead of stress, since the stress in window panels varies in position and magnitude across the glass surface as the wind load increases. The experiments on full size glass panels showed that the fracture origins were generally located in the areas of maximum principal tensile stress. Hence, it was found that the exponent, S, which defines the power law relationship between the applied wind load and the maximum principal tensile stress at any point in the panel can be used with reasonable accuracy to determine the equivalent wind load, P_E for a given load duration, T_E. [2]

$$K = \int_0^T [\ p(t)\ ]^{S.n}\ dt$$

$$P_E = \left(\frac{1}{T_E} \int_0^f P_i^{S.n}\, dt \right)^{\frac{1}{S.n}}$$

There are significant differences in the interpretation and assessment of the correct design strength of glass. The value attributed to the so-called "m" & "k" for the Weibull distribution varies as a function of the test program and the subsequent analysis undertaken. For example, figure 2 clearly illustrates differences in the Weibull distribution for two typical data sets of full size panels. The value of the fracture stress for a probability of 8 lites in a thousand is 23.45 MPa for 1 set and using this stress on the other set gives a probability of failure of only 4 in a thousand.

Testing

Full scale testing of 180 panels of 6 mm thick annealed glass undertaken by the authors has shown that for new undamaged glass there is a minimum value of fracture stress for all the samples irrespective of thickness, panel geometry and lateral pressure. This was found to be 42.8 MPa. Furthermore, it was also observed that the

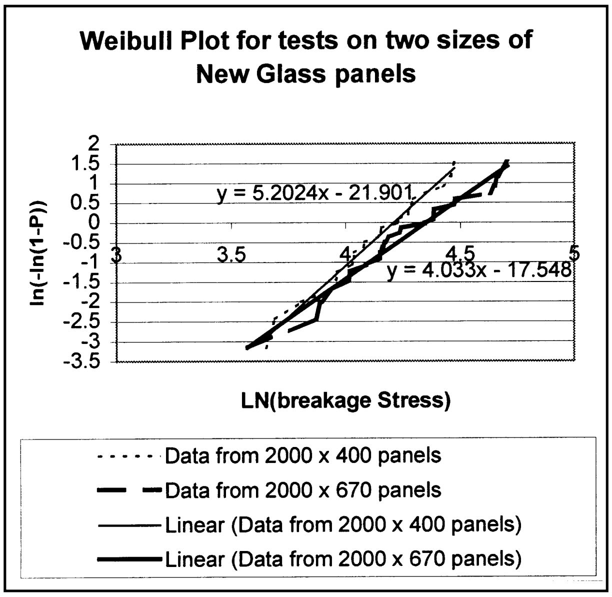

Figure 2. Weibull Plot for new Glass.

average fracture stress was found to be 60.7 MPa.

The results of 15 sets of ring on ring testing undertaken in Europe also showed a minimum fracture stress of about 48 MPa and the average of minimum values from 15 sets of data was computed to be 56 MPa.

Calderone [2] tested 17 panels of 6 mm thick thirty-year-old sheet glass and found that the distribution was significantly different. Even though there was a significant reduction in average value of the fracture stress, there was no reduction in the minimum value of the fracture stress obtained. This is illustrated in figure 3.

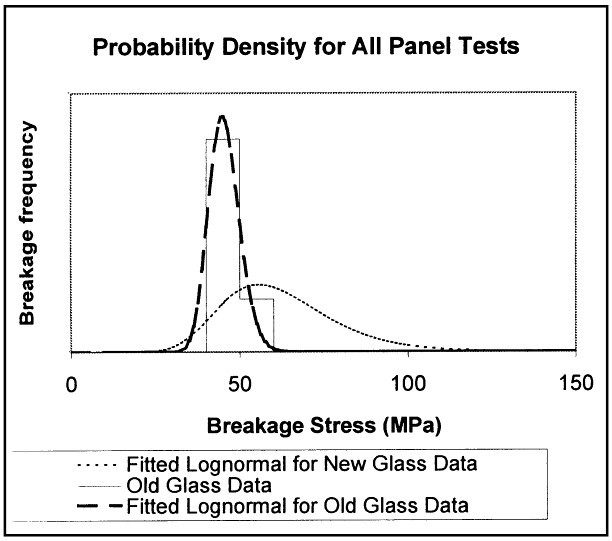

Figure 3. Breakage Data for 30 Year Old Glass.

Another series of three point bend tests on small samples of glass also shows that the variability in the fracture stress in glass is similar to that of full-scale tests. The only difference being that the magnitude of the fracture stress is marginally lower due to edge defects in the three point samples.

Fracture Mechanics Approach

The fracture behaviour of glass is ideally suited to the study of fracture mechanics. Failure in glass panels generally emanates from the surface or edge depending on the loading conditions. Most of the research work undertaken relates to new glass panels. In reality installed glass is subjected to surface degradation due to cleaning and the development of surface scratches is a natural occurrence. Therefore surface scratches must be considered in the determination of a suitable design stress for the glass panel.

A simple relationship between fracture stress [3] and flaw depth is:

$$\sigma_f = K_{IC} / 1.12 (\pi c)^{1/2}$$

Here 'K_{IC}' is the critical stress intensity factor and 'c' the flaw depth.

Consequently, for a particular fracture stress the critical flaw depth can be calculated. As an example, for a fracture stress of say 42.8 MPa, the critical flaw depth will be 0.009 mm. A scratch with this depth is barely visible to the naked eye. On the other hand for a stress of 15.7 MPa (Australian Standard) the limiting flaw will be 0.745 mm deep. This is a deep scratch. Here the word scratch is used interchangeably with the word flaw. Obviously the flaw geometry at the crack tip will influence the stress generated.

Edge damage can also induce fracture in glass panels. Again the stress for glass failure from edge damage can be computed using the following equation.

$$\sigma_f = K_{IC} B / a^{1/2}$$

Here 'a' is the flaw depth and B a constant for corner flaw geometry.

Using a limiting -(ultimate) fracture stress for glass of 42.8 MPa based on measured data and a factor of safety of say 2.5 the permissible design stress will be 17.12 MPa. This provides an adequate safety margin, which can be considered to accommodate issues like area effects, load duration effects and crack growth during sustained loading from windstorms. Using a conversion factor of 1.5 and a material factor of 0.9 the ultimate limit state design stress for glass computes to 23.15 MPa.

The lowest stress at fracture of all the 30 year old glass tested was also about 40.0 MPa. Therefore the ultimate limit state design stress of 23.15 MPa would also be acceptable for old glass.

Stress Analysis

Glass panel behaviour becomes non-linear once the panel deflection exceeds about 75% of its thickness. This non-linearity makes the stress analysis in the glass panel difficult; requiring sophisticated finite element analysis. The availability of high-speed computers has made this analysis possible. All the attributes that influence the development of stress and deflection in a laterally loaded glass panel can now be represented in the analysis.

Commercially available software can be readily used to determine both the stress and the deflection in laterally loaded glass panel. Once the boundary conditions are correctly described then most commercially available finite element software programs may be used effectively.

It is essential that all the stresses in the panel be computed. Also, the relationship between the applied load and the maximum principal tensile stress in the panel should be determined in order to determine the effective wind load for a given panel geometry. It should also be remembered that any fixity along the edges, would induce tensile stresses on the top surface and enhance the edge stresses.

A comparison between various glass codes shows that for the same panel geometry and lateral pressures the required glass thickness will be different [4]. For instance a 6.0 mm thick glass panel with an aspect ratio of 3.0 subjected to a lateral pressure of 1.0 kPa will be 4.7 m^2, 3.0 m^2 and 6.5 m^2 using the Australian, ASTM and the British Standard glass standards respectively. The reason for this difference can be attributed to:

- the different approach to stress analysis in glass panels
- the influence of aspect ratio (length / width) and
- slenderness ratio (width / thickness) in the glass panel are critical
- the load duration and hence the permissible design stress used.

Design Model

The international trend towards ultimate limit state design requires a revised look at current design methods. It is an opportunity for a fresh look at the performance of glass panels. Both stress and deflection must be considered. A limit of span / 60 for the centre deflection of glass panels is a reasonable starting point. The limiting stress based on a limit state design concept ought to be at least 23.15 MPa as discussed earlier. Using these two criteria the following graph has been developed as a design tool. All the critical factors that influence the behaviour of a laterally loaded glass panel are used in this design format. The stress analysis used assumed that the all panel edges were simply supported with no deformation in the supports. The lateral pressure used is the equivalent 3 second constant wind load.

It has been observed that toughened glass with high levels of surface compression is more susceptible to fracture as a result of surface scratches and edge damage. The reduction in glass strength due to surface scratching is significant [1 & 2]. As an example, using three point bend tests there was found to be a 100MPa reduction in the fracture stress between undamaged samples and samples with a scratch depth of only 0.2 mm.

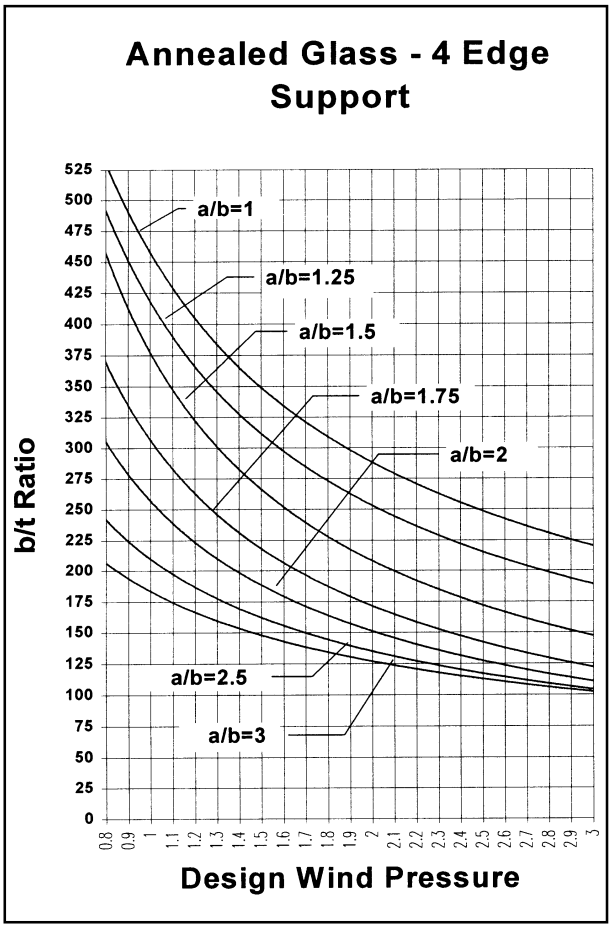

Figure 4. New Design Chart - UltimateLimit State Loading.

The perceived increased strength of toughened glass being 4 times that of equivalent thickness annealed glass is therefore erroneous. From a design aspect glass deflection is a critical factor for toughened glass. It is strongly recommended that serious consideration be given to limiting the upper level of surface compression in toughened glass to about 110 MPa, to minimise the risk of spontaneous breakage and that there be a deflection limit of Span / 60 for the central deflection in toughened glass.

Conclusions

The use of a fracture mechanics approach to glass panel design provides simplicity and a true picture of the fracture behaviour. Furthermore, it provides a means to evaluate the possibility of glass fracture as a function of surface damage.

Structural glazing in curtain wall construction has exposed glass edges. These edges are vulnerable to accidental damage through impact from the building maintenance units required for the purpose of cleaning the glass. A measure of the damage can and will help determine the possibility of glass fracture.

Glass design to withstand wind loading can now be a simple matter of stress analysis without any concern as to probabilities of likely failure. We should now establish a technique for the identification of those panels with defects such as scratches and shells that will require replacement.

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