New Developments in Predicting the Strength of Glass after 20 or more Years of Use in Buildings

Dr Ignatius Calderone
Arup Facade Engineering

Keywords

1 = Glass strength 2 = Wind load 3 = Cumulative effect 4 = Non-linear stress

Session 13

Abstract

It is well known that the strength of the glass varies with load duration. Therefore existing models for predicting the behaviour of glass subjected to wind pressure involve simplifications using an assumed short duration for the design wind pressure and using the corresponding glass strength for this load duration. However, the wind pressures, which load the glass, are fluctuating during all windstorms and tests have shown that breakage frequently occurs at a "gust" pressure lower than was previously resisted during the test. Therefore, the cumulative effect needs to be computed over the entire load history.

This paper presents a new proposed method of determining the effective strength of glass that has previously been subjected (over many years) to the fluctuating wind loads. The method includes the effect of the non-linear relationship between applied pressure and stress for the application of Brown's Integral. Actual wind pressures versus time data were integrated together with the actual glass breakage data of 20-year-old glass taken from a building. Comparing the results with the equivalent 3-second breakage pressure for new glass breakage data indicated that the method could be used to predict the strength of even older glass.

Fig 1

Pressure versus time for a fluctuating pressure test

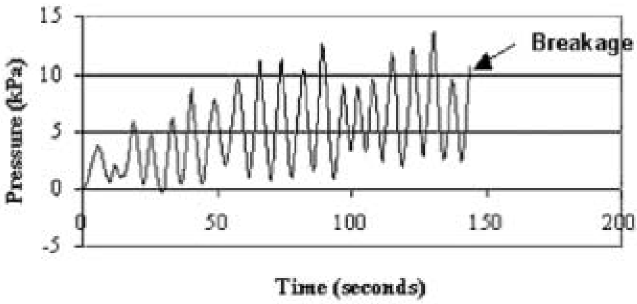
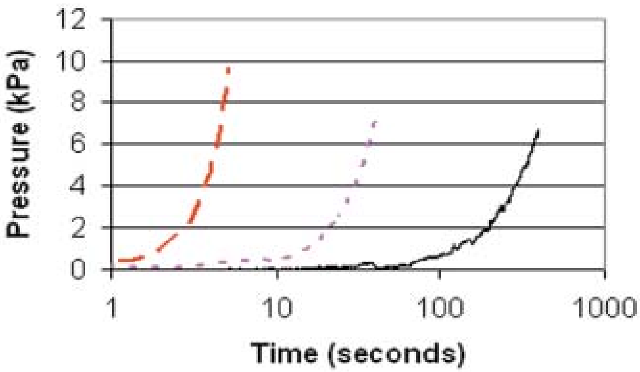


Fig 2

Pressure versus time for 3 ramp load tests.



Introduction

The phenomenon of static fatigue in glass is well known, yet it is not a simple matter to account for it properly in the design of window glass panels. The reasons for the complications have been described in a series of papers by the author and others in recent years [1], [2], [3] and [4]. It has been reported that these reasons include the following.

- The application of Brown's Integral [5], to account for the static fatigue phenomenon requires knowledge of the variation of stress with time. However, the relationship between the applied pressure and the resultant stress is non-linear and the same relationship is not applicable at all points on a glass panel.
- As the nature of the wind pressure fluctuations varies with location on the building and wind direction, and internal pressure characteristics as well as the meteorological event causing the wind, the same pressure duration may not be appropriate for different windows in the same building.

As reported in the papers referred to above, recent research [6] 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. The experiments on full size glass panels showed 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 constant wind load, P_E for a given load duration, T_E, which is equivalent to the instantaneous pressure, P_i, varying continuously over time, t, from the starting time, t_0, to failure at time, t_f. The modified form of Brown's Integral, which can be evaluated numerically, is given by the following equation.

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

Hence, the above equation was used in this investigation to determine whether or not the strength of glass after 20 or more years of use in buildings could be predicted. For this purpose, the experimental data from tests on twenty to thirty-year-old sheet glass panels removed from a building in Melbourne were used [4], [6] together with data of the actual wind experienced by those panels over their 20 to 30 years in the building. The results are presented below.

Behaviour of Window Glass Panes

Glass breakage does not always occur at the highest wind gust experienced by the panel. This fact can be seen in Figure 1, which shows the result of a test on a 6mm Float glass panel of size 2000 x 670 mm, with fluctuating pressure being applied, to simulate wind gusts during a storm.[6] In this case, it can be seen that there were several "gusts" that did not result in breakage, which were higher than the one at the instant of breakage. This confirms that static fatigue is a real phenomenon that occurs with window glass panes, which needs to be taken into account in the design of window glass.

The effect of static fatigue was also observed from the results of tests in which the load was applied as an increasing (ramp load) to breakage. Due to the limited number of samples available for the tests, only three different loading rates were used for each panel size. Examples of these loading rates in 3 tests on 6mm Float glass panels of size 2000 x 1600 mm, are shown in Figure 2.

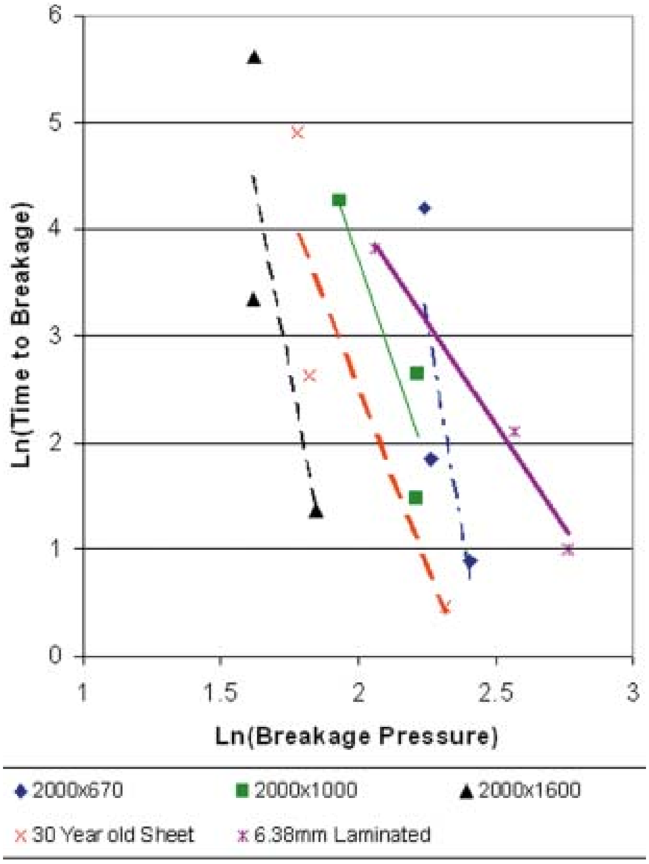
The ramp load tests confirmed that in general the faster loading rates resulted in higher breakage pressures. Logarithmic plots of the average breakage pressure versus average time to breakage for the ramp load tests on various samples are presented in figure 3.

The results shown in figure 3 suggest that the effective index (*S.n*) for evaluating Brown's integral varies with panel geometry. This effective index is the slope of the linear regression line (shown as broken lines) on the plotted data points. The details of the samples, whose results are plotted in figure 3, are given in Table 1. It is of interest to note that the effective index (S.n) may also vary with the glass type. That is, the slope of the line for the 6.38mm laminated glass sample is lower than for the other samples, which suggests that the long-term cumulative effect of wind loading might be more severe for laminated glass. However, more research work is required in order to determine the significance of this. That is, figure 3 indicates that the breakage pressure of the 6.38 mm laminated panels is greater than the corresponding size of 6mm Float glass at the shorter breakage times, but the lines cross over and at the longer breakage times, the 6.38 mm laminated panels have a lower breakage pressure than the corresponding size of 6mm Float Glass. Taking a 60 second ramp load to breakage, which is generally taken to be equivalent to a 3 second constant load, then the relative strength of the 6.38 mm laminated glass is 0.83 times the 6mm Float glass at this load duration. This is consistent with the relative resistance to the design wind load (0.8) used in the current Australian standard (AS1288) for glass design.

The results shown in figure 3 and Table 1 also indicate that the effective index for the 20-30 year old 6mm sheet glass samples (2045 x 968mm) is similar to the index for 6mm Float glass samples (2000 x 1000mm), which have a similar Aspect Ratio. Again, taking a 60 second ramp load to breakage, which is generally taken to be equivalent to a 3 second constant load, then the relative strength of the 20-30 year old 6mm sheet glass is 0.82 times the 6mm Float glass at this load duration.

Now, the20-30 year old 6mm sheet glass had already been subjected to many years of wind pressure. Thus, for the purpose of this investigation, the equivalent constant wind load, P_E was evaluated for the 2000 x 1000mm Float

Fig 3



Panel Description	Effective index (S.n) for evaluating Brown's Integral (Based on slope of linear regression lines in figure 3)
6mm Annealed Float Glass 2000 x 670 mm (Aspect Ratio = 3)	-15.74
6mm Annealed Float Glass 2000 x 1000 mm (Aspect Ratio = 2)	-7.78
6mm Annealed Float Glass 2000 x 1600 mm (Aspect Ratio = 1.25)	-13.74
6mm Annealed Bronze tinted sheet glass (20-30 years old) of size 2045 x 968mm (Aspect Ratio = 2.11)	-6.67
6.38mm Annealed Laminated Glass 2000 x 670 mm (Aspect Ratio = 3)	-3.86

Table 1

glass samples for comparison with the P_E evaluated for the 20-30 year old 6mm sheet glass samples together with 20-30 years of equivalent wind pressure data, as detailed below.

Actual Wind Pressure History

The 20-30 years old 6mm Annealed Bronze tinted sheet glass was taken from the west elevation of a building in Melbourne, Australia. Also, this glass was tested with the interior installed surface in tension. Therefore, the wind speed data was analysed for the windward wall with this wind direction in Melbourne. Figure 4 shows the results of the analysis, together with the frequency distribution of the highest wind speeds that actually occurred during the time that the glass was installed in the building.

From this data, the actual wind pressure history for the glass was determined (taking into account the city terrain roughness and pressure coefficient applicable for the wall). The pressure history was calculated using wind speed intervals of 0.2 ms^{-1} until the highest pressure (having duration of 0.2s) was reached. These highest pressures were 1.05, 1.09 and 1.14 kPa for 20, 30 and 50 years of history respectively. The resulting cumulative pressure history experienced by the glass over 20, 30 and 50 years is shown in figure 5.

Fig 4

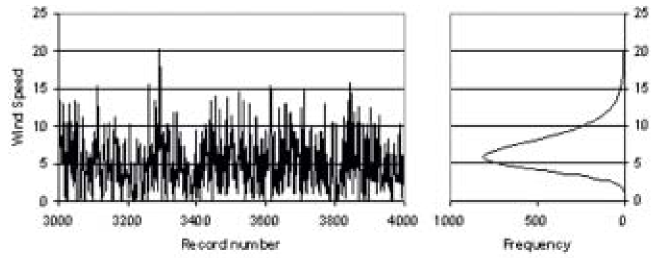


Fig 5

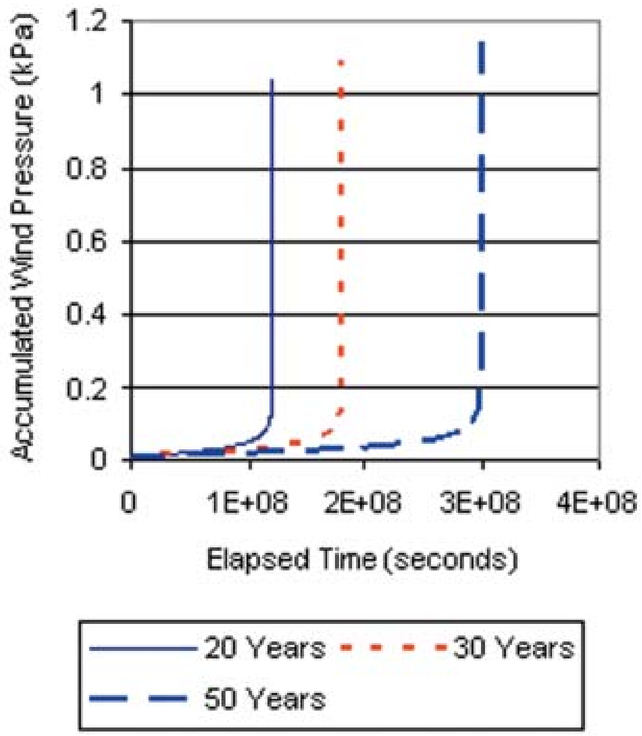


Table 2

Effective index (*S.n*)	Equivalent 3 second constant pressure, P_{E3} (kPa) to cause breakage, for the noted years of pressure history		
	20 years	30 years	50 years
16 (*S*=1)	1.09	1.12	1.15
14.4 (*S*=0.9)	1.07	1.12	1.18
12.8 (*S*=0.8)	1.10	1.15	1.21
11.2 (*S*=0.7)	1.15	1.20	1.27
9.6 (*S*=0.6)	1.23	1.29	1.37
8.0 (*S*=0.5)	1.40	1.48	1.58
6.67 (*S*=0.417)*	1.72	1.83	1.98
6.4 (*S*=0.4)	1.82	1.94	2.11

* index for the 20-30 year old glass

Integration of Pressure Histories

The equivalent 3 second constant breakage pressures (P_E) were calculated using the modified Browns integral on the breakage pressure histories of both the old and new glass. The average was 7.32 kPa for the new glass and 6.29 kPa for the 20-30 year old glass with the test pressure alone. When the integration was repeated for the 20-30 year old glass, together with the accumulated wind load, the new P_E was found to be only marginally greater than for the test pressure alone.

This indicates that, as the wind load actually experienced by the glass during 20-30 years in the building (which is only up to 1.09 kPa, as seen in figure 5), was much lower than the average breakage pressure (6.29 kPa), then the strength of old glass is not significantly affected by the wind pressure history of the glass. In view of this finding, it may be concluded that the observed reduction in mean breakage pressure of the old glass, is due mainly to the treatment received by the glass surfaces during the installed life of the glass.

Thus, the minute surface flaws and scratches, which weaken the glass, are generated in handling and cleaning the glass. While the surface flaws are only microscopic and the surface scratches are only small, the number of such flaws and scratches increases during the installed life of the glass. Consequently, due to the reduced variability as there are many more flaws, the average breakage pressure is reduced, even though the deepest critical flaw, which results in breakage, may not be significantly deeper than the deepest flaw in relatively new glass.

Notional Integration of Pressure Histories

Nevertheless, if the critical flaw is deep enough, or the wind pressure high enough, then breakage can occur due to the accumulation of the effect of the pressure history of the glass. Therefore, the wind pressure history alone, for 20 years, 30 years and 50 years of wind were notionally integrated to evaluate the equivalent 3 second constant pressure, P_{E3} to cause breakage. These integrations were carried out for a range of values of the effective index (S.n) for evaluating Brown's integral, to enable the effect of panel geometry to be assessed. The results were as shown in table 2.

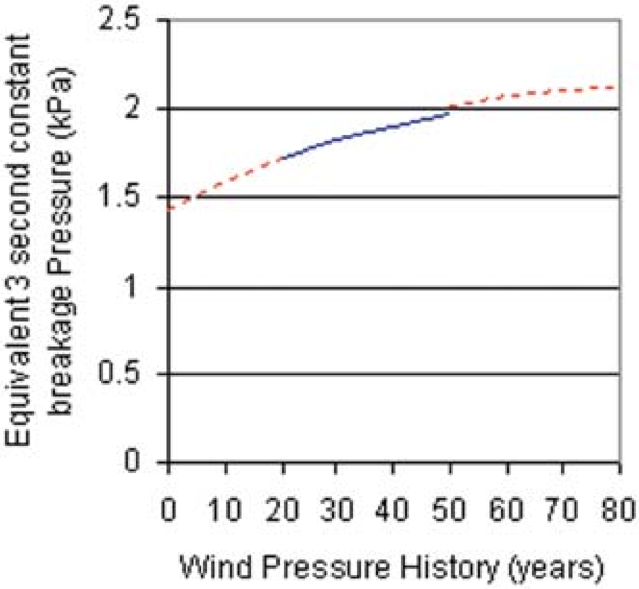
The notional P_{E3} versus the number of years of pressure history, as shown in table 2, was then plotted for the 20-30 year old glass (see figure 6) and extrapolated (both towards zero and for greater than 50 years) using a regression analysis for a polynomial curve. The extrapolation (see the broken lines on figure 6) gave an equivalent 3 second constant breakage pressure of 1.44 kPa at zero years of pressure history. The extrapolation also indicated that the highest notional P_{E3} was reached after 80 years. Based on these results, the effective strength of the glass may be inferred as detailed below.

Predicted Effective Strength of Glass

The results shown in table 2 and figure 6 indicate that the glass feels the effect of longer pressure histories as higher P_{E3}. Thus, for a given flaw depth, the higher effective pressure translates to a lower glass strength. Therefore, for the purpose of determining the relative strengths, the ratios of the notional P_{E3} for the various years of pressure history were taken relative to the extrapolated P_{E3} at zero years. The results, using the effective index for the 20-30 year old glass were as shown in Table 3.

The results shown in Table 3 indicate that the strength of 30 year old glass is 78.5% of the strength of new Glass. This prediction is remarkably similar to the strength of the 30 year old glass relative to the experimental strength of new glass (6mm Float Glass 2000 x 1000 mm) as noted previously in this paper (82%), although slightly more conservative. Hence, in the absence of actual breakage data for old glass, the notional P_{E3}, as shown in table 2, appears to give reasonable, although possibly conservative estimates of the strength of old glass relative to the strength of new glass.

Fig 6



Age (Years)	Relative Strength
0	1
5	0.946907
10	0.901992
20	0.833898
30	0.784716
50	0.726862
60	0.693006
70	0.681169
80	0.676037

Table 3

Conclusion

It has been shown that the strength of old glass is not significantly affected by the wind pressure history of the glass, due to the actual pressure history being much lower than the breakage strength of the glass. However, the method presented for predicting the effective strength of older glass, utilising the modified form of Brown's Integral, to evaluate the notional equivalent 3-second breakage pressure from the actual pressure history experienced by the glass, appears to give conservative estimates of the strength of old glass relative to the strength of new glass.

Therefore, in the absence of more accurate data on the strength of old glass the method could be used to predict the strength of 20 – 30 year old and even older glass. It is recommended that further research work be conducted to explore the significance of the proposed method and how it would affect the current glass design charts.

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