

Increasing the design strength of glass – fractography and stress testing

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Abstract

Brittleness is the unintended, but inevitable consequence of producing a transparent ceramic for architectural applications such as the soda-lime glass. Its tensile strength is particularly sensitive to surface imperfections, such as that from natural weathering and malicious damage. Although a significant amount of testing of new glass has been carried out, there has been surprisingly little testing on weathered glass. Due to the variable nature of the causes of surface damage, the lack of data on weathered glass leads to a considerable degree of uncertainty in the long-term strength of exposed glass.

This paper presents the results of recent tests on weathered annealed glass which has been exposed to natural weathering for more than 20 years. The tests include experimental investigations using the co-axial ring setup as well as optical and atomic force microscopy of the glass surfaces.

The experimental data from these tests is subsequently used to extend existing fracture mechanics-based models to predict the strength of weathered glass. It is shown that using an automated approach based directly on finite element analysis results can give an increase in effective design strength in the order of 70 to 100% when compared to maximum stress methods. It is also shown that by combining microscopy and strength test results, it is possible to quantitatively characterise the damage on glass surfaces.

Keywords: glass strength, weathered glass, fractography

1. Introduction

The strength of annealed soda-lime glass has been the subject of research since the invention of the float process in the 1950s. A substantial amount of testing has been carried out on new glass and standards now dictate the minimum strength of glass at the point of manufacture. This measured strength of new glass needs to be converted to a design strength that accounts for the in-service conditions of the end-application. This process has been codified into various design standards around the world, however most standards are limited to very basic common applications, based on experience in use and application specific testing.

Despite the well controlled material composition, the strength of glass is not a universal constant. It is very sensitive to stress distribution, surface area, load duration, surface

condition, residual surface stresses and environmental conditions. Due to this variability, one design method intended for a particular application cannot always be directly transferred to different design situations.

The inherently brittle nature of glass means that its tensile strength is very sensitive to surface defects, such as those resulting from natural weathering and malicious damage over the course of its service life. The result is that weathered glass is substantially weaker than new glass, but there is a considerable degree of uncertainty on the magnitude of strength reduction. This uncertainty arises from two factors. The first is the variable nature of the causes of surface damage and the second is the relatively small number of carefully controlled tests that have been performed on naturally weathered glass. These factors lead to the application of large safety factors in the design of annealed glass.

Current practice is often based on allowable stress design methods, with global factors of safety which attempt to account for numerous phenomena. This often leads to very conservative designs due to over-simplification of the design strength. Different factors of safety should also be selected depending on consequence of failure, which can be guided by the results of post-breakage tests.

When designing novel glass installations, such as in geometrically complex space structures, more accurate design methods are required. This can only be achieved by understanding the strength of weathered glass in different service conditions and considering the affects of complex loading scenarios that glass is expected to withstand. These can include transient and location-specific combinations of dead loads, snow loads, cold bending stresses and turbulent wind pressures arising from complex geometry.

2. Glass surface damage

2.1. Surface damage and stress amplification

The theoretical tensile strength of soda-lime glass, as derived from molecular bond strength, can be as high as 32GPa. However, the amorphous nature of its molecular structure does not allow glass to yield plastically since its glass transition temperature is over 500°C. At normal working temperatures its unordered molecular structure is interlocked, leaving no room for plastic deformations, thereby giving glass its brittle properties. This amorphous structure, which also gives glass its transparency, makes it sensitive to stress concentrations resulting from surface damage. As a consequence, structural failure is the result of tensile principal surface stresses.

Surface scratches, or cracks, intensify the applied surface stresses. This can be modelled using quasi-static linear elastic fracture mechanics. The affect of cracks is described by a stress intensity factor K , which represents the elastic stress intensity near the crack tip, given in Equation 1, where σ_n is the nominal tensile stress normal to the crack's plane, Y is a geometry correction factor, and a represents the crack depth or half the crack length.

$$K_I = Y\sigma_n\sqrt{\pi a} \quad (1)$$

Instantaneous failure of a glass element occurs when the elastic stress intensity K_I due to tensile stress at the tip of one crack reaches or exceeds a critical value. This critical value is

a material constant known as the plane strain fracture toughness or the critical stress intensity factor K_{IC} which is normally taken as $0.75\text{MPa m}^{0.5}$ (Haldiman *et al.* [1])

The distribution and size of the resulting cracks is random and has been historically little understood. It is however clear that glass surface damage is unavoidable, and is the result of handling during production, transportation, environmental exposure, cleaning, accidental damage and vandalism. These effects of cumulative damage on glass are assessed through statistical analysis of experimental investigations on weathered glass, which enable structural design, as described in Section 5 of this paper.

2.2. Characterisation of weathered glass surfaces

In order to shed some light on naturally occurring surface cracks, 3mm glass which has been in service for over 20 years has been used for analysis. The building was poorly maintained and the glass had a considerable amount of organic and inorganic residue on the surface. This was cleaned prior to testing by softening the surface residue in water and subsequently removing the residue with non-abrasive fabrics and cleaning detergents normally used in glass cleaning, before any microscopic images could be taken.

New, as-received glass of the same thickness was used as a control for comparison. Some surface scratches on the weathered glass were visible with the naked eye; however the majority of the surfaces had no macroscopic scratches. Inspection under magnification using an optical microscope revealed very significant differences between the as-received and the weathered glass. Figures 1 and 2 show typical images of internal and external surfaces of the weathered glass. New glass was found to be very clear with no optically detectable surface damage over the examined surfaces. In contrast, surface damage was evident over the entire weathered glass surface even where no macroscopic scratches were observed.

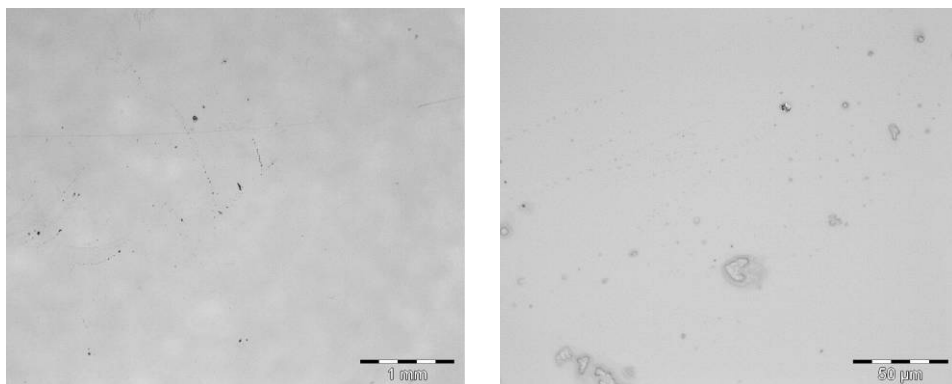


Figure 1: Optical microscope images of the internal surface of weathered glass

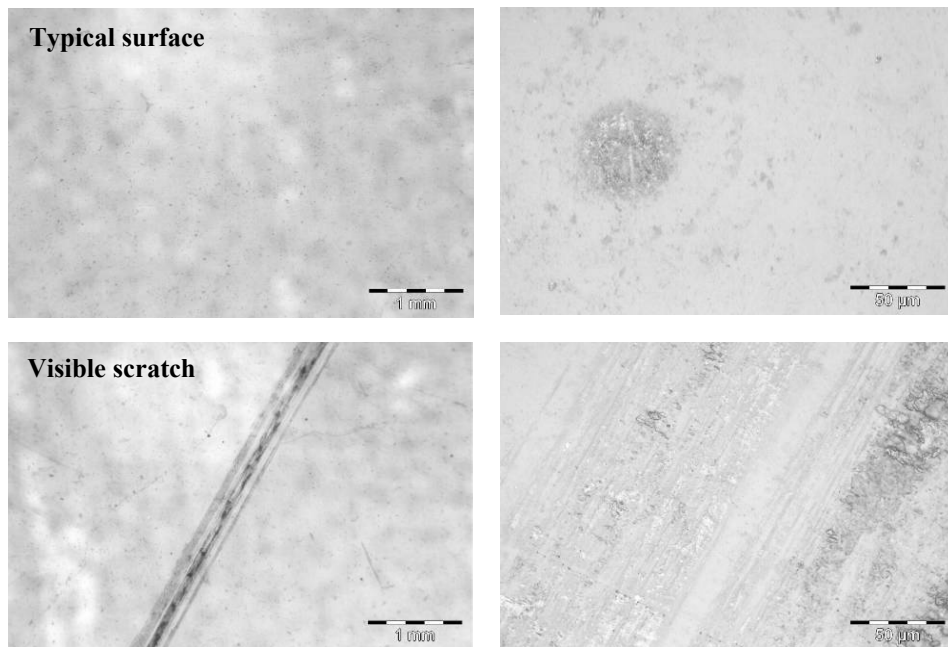


Figure 2: Optical microscope images of the external surface of weathered glass

Surface mapping of the weathered glass was carried out using an atomic force microscope. The results, shown in Figure 3, reveal the substantial difference observed between the internal and external surfaces. The measurements show valleys of up to $0.24\mu\text{m}$ in depth on the external surface. This surface damage would cause a significant reduction in tensile strength. The shape of these flaws affect the value Y in Equation 1, whereas the depth determines the value a , although Figure 3 may only represent part of a crack tip.

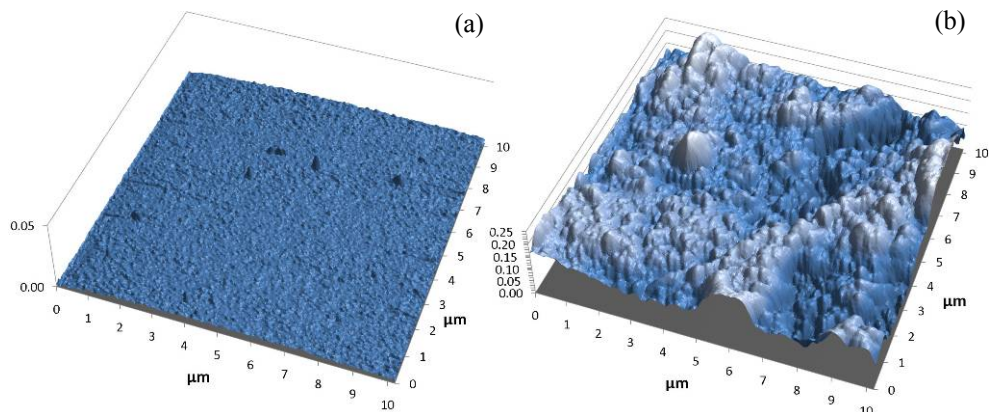


Figure 3: 3D surface maps of weathered glass (a) Internal surface (b) External Surface

2.3. Stress corrosion and crack healing

On exposure to humidity, surface cracks in glass will grow when subject to an opening stress. This is a chemical process which makes the strength of glass dependent on load duration. The phenomenon is known as stress corrosion or sub-critical crack growth, where the strength decreases with increased load duration.

A lower limit of stress exists below which no sub-critical crack growth occurs thereby defining a strength for permanent loads. This is shown graphically in Figure 4, from Haldimann [2], where convergence of strength curves can be seen for increasing load duration.

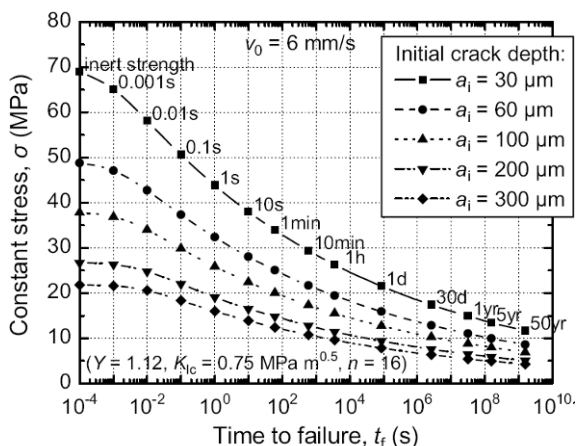


Figure 4: Strength of a crack vs. time [2]

In addition, an aged crack will not re-propagate immediately upon repeated loading, resulting in a form of crack healing [2]. These effects can be significant when considering fluctuating and repeated loading such as wind loading.

3. Coaxial double ring testing

3.1. Test Setup

The random nature of the surface cracks described in Section 2 means that material strength is affected by the stressed surface area. The larger the stressed surface area, the higher the probability of the occurrence of a deeper crack. This effect can be taken in to consideration using Equation 2. θ and m are statistical surface condition parameters used to calculate probability of failure P_f in Equation 3 using a two-parameter Weibull distribution.

$$\frac{\theta_{A_1}}{\theta_{A_2}} = \left(\frac{A_2}{A_1} \right)^{1/m} \quad (2)$$

$$P_f(\sigma) = 1 - \exp \left\{ - \left(\frac{\sigma}{\theta} \right)^m \right\} \quad (3)$$

In order to subject surface cracks to a uniform opening force, the stress field which is applied to the surface needs to be constant with equal maximum and minimum principle tensile stresses. To achieve this, tests were carried out using coaxial double rings (CDR)

as seen in Figure 5, which also have the advantage of being independent of edge conditions, since stresses outside the reaction rings are negligible.

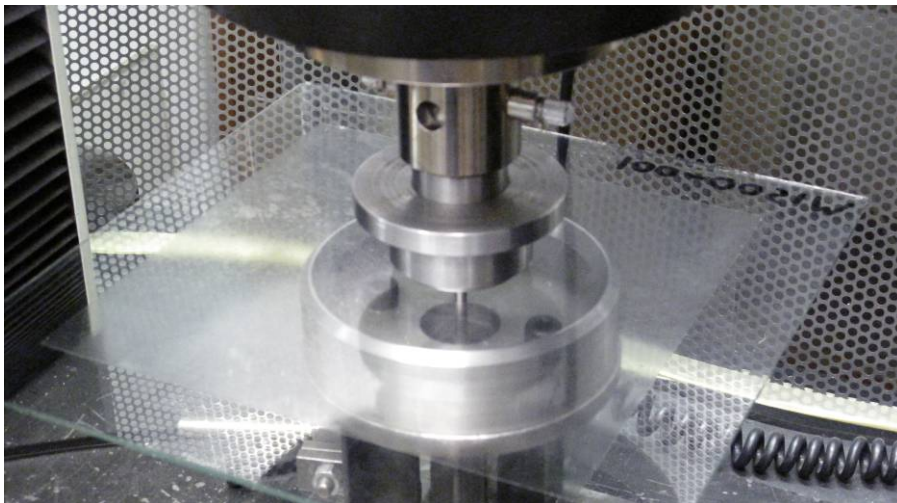


Figure 5: Test setup using 51 and 127mm rings

3.2. Finite Element Analysis

The CDR setup creates a roughly uniform stress within the area of the upper loading ring. A geometrically non-linear finite element analysis, was performed in Lusas to calculate the non-linear relationship between load to stress caused by large deformations. This was subsequently used to define the ramp load rate giving an average effective stress rate.

Frictional forces between the glass and steel ring surfaces distort the central stress distribution as seen in Figure 6. This results in tensile stresses below the loading ring that are 4.3% larger than the stress in the central regions of the plate for the load ranges tested.

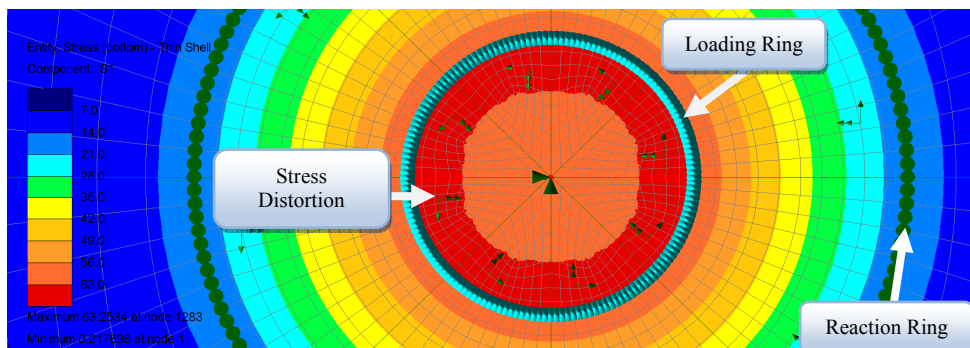


Figure 6: Maximum principle tensile stresses at 1kN Load

3.3. Results

Fifty glass specimens were tested to failure using different loading rates giving failure stresses ranging from 21.3 to 348.9MPa, as shown in Table 1. The origin of failure was ascertained visually and recorded using polar co-ordinates, for assessment during statistical analysis and crack branching assessments. The majority of failures occurred within the loading ring, with a greater concentration closer to the ring, reflecting the stress distribution in Figure 6. A number of new glass specimens fractured in locations between the two rings, where stresses are significantly lower. Consequently, such failures gave failure loads in the higher end of the range. Such a phenomenon was not observed in the weathered glass specimens.

	SAMPLE 1	SAMPLE 2	SAMPLE 3	SAMPLE 4	SAMPLE 5
Code	N1F00	N1S00	W1F00	W1S00	W1P00
Number of specimens	10	10	10	10	10
Size [mm]	300	300	300	300	300
Surface condition	New	New	Weathered	Weathered	Weathered
Stress rate [MPa/s]	21	0.21	21	0.21	0.11
θ [MPa]	214.32	164.62	83.36	56.25	57.81
m	2.76	2.25	3.02	3.91	3.89

Table 1: Sample details and test results

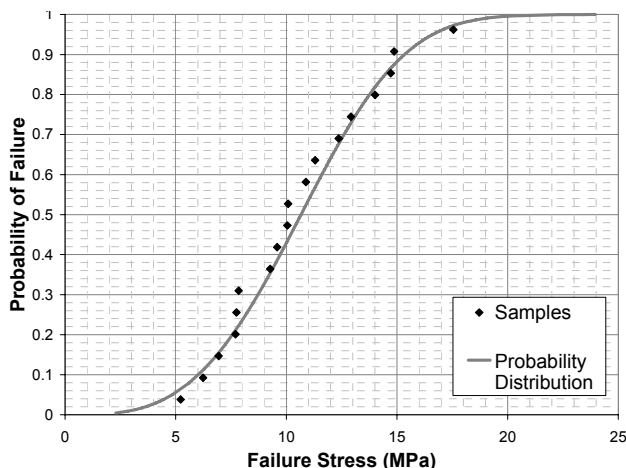


Figure 7: Cumulative distribution curve of test results for weathered glass

The combined probability distribution curve of all test results for the weathered glass, converted to the standardised parameters as described in Section 5.2. This gives the values θ and m in Equation 3, which were used to derive the results of Section 5.3. A high value of m indicates small scatter of strength (and hence crack depths) whereas a high value of θ indicates a high mean strength and wide scatter of strength.

The results were checked for goodness-of-fit to a 2-parameter Weibull distribution, with all but one sample giving a good fit using the Anderson-Darling goodness of fit test with a 5% rejection error. The sample giving a bad fit was for new glass loaded at a high stress rate. This included one specimen which failed at an unusually high load, almost 100% higher than the second highest load, distorting results.

Figure 7 shows the

4. Fracture Patterns

4.1. Crack branching theory

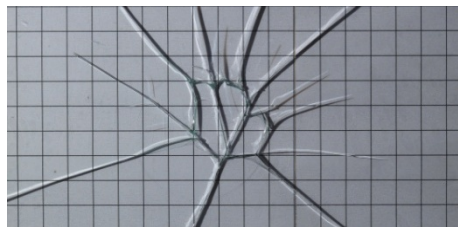
Substantial research has been undertaken on the relationship between the speed of the crack branching and the fracture stress. However, a direct relationship between crack velocity and crack branching was not proven experimentally. A more recent hypothesis is that the branching stress is controlled by the strain energy release rate.

On close inspection, it is possible to recognize three different zones around a crack: the mirror, the mist, the hackle. The mirror is a smooth region around the origin of the crack. The mist is a region that surrounds the mirror and is characterized by edges of increasing roughness. The hackle is a region that surrounds the mist, characterized by multiple fracture planes. These features can be related to the fracture stress σ_f by:

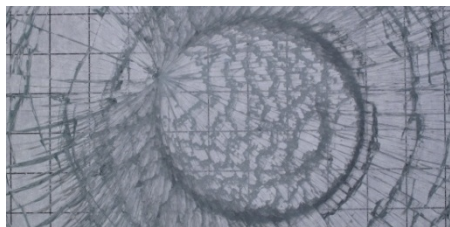
$$\sigma_f = \alpha \cdot r^{1/2} \quad (4)$$

Here, r is either half of the mirror radius, half of the hackle radius, or half of the branch radius and α is the corresponding branching constant, which is reported to be $2.1 \text{ MPa m}^{1/2}$ [5]. This equation, also referred to as the branching equation, is of practical interest, because it is simple and could be used to predict the failure stress knowing the fractured surface features or to predict the branch length from the failure stress.

4.2. Crack patterns from CDR tests



Weathered glass failure at 0.66kN



New glass failure at 7.2kN

Figure 8: Fracture patterns from CDR tests

Equation 4 has been validated by several tests, but the mirror, mist and hackle zones require optical magnification techniques and are notoriously difficult to identify. The branch length is therefore the preferred physical phenomenon to measure as this is visible with the naked eye. However, the CDR specimens tested by the authors have shown that the true branch length is sometimes masked by secondary cracking (Figure 8).

For use in engineering practice, it is necessary to distinguish between primary and secondary cracking. Figure 8 shows, the qualitative difference that can be seen between failures at different stress levels. Quantitative correlation of such fracture patterns to failure stress is being investigated by the authors as a diagnostic tool for glass failure.

5. Application to Design

5.1. Background

The test results described in Section 3 can be used to estimate the probability of failure of glass in various applications. This is illustrated by example for a triangular glass plate forming part of a grid-shell roof.

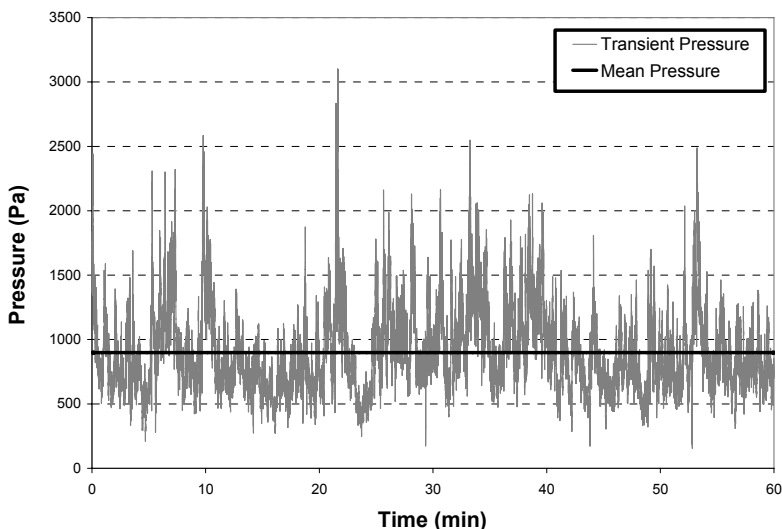


Figure 9: Wind Loading History

For simplicity, the calculations described in this Section assume that wind loads alone are acting upon the glass plate. Since load duration significantly affects the strength of glass, a dynamic wind loading history was used, shown in Figure 9. These pressures were taken from full scale roof pressure measurements in naturally occurring wind [3]. In design practice, such pressures could be taken from wind tunnel tests, which could be either project specific or standardised for common building shapes.

5.2. Analysis

A geometrically non-linear Finite Element Analysis (FEA) of a 2m side, 6mm thick equilateral triangle of glass was used to calculate the maximum principal tensile surface stresses, shown in Figure 10. Using the transient analysis method developed in earlier work by the authors [4], the cumulative effect of stresses at each 0.02s of wind load are integrated to give a 60 second equivalent uniform stress, σ_{eq} .

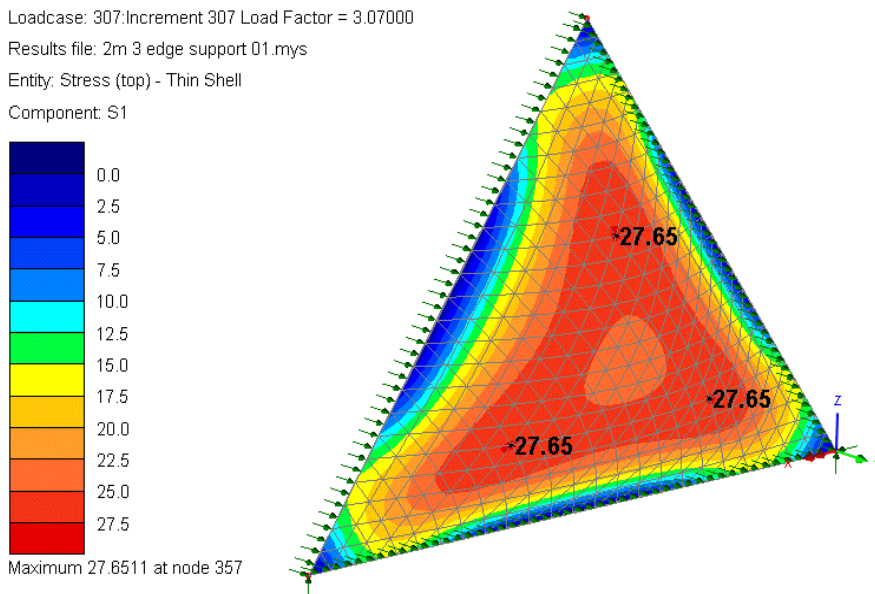


Figure 10: FEA principal tensile stresses at peak gust load

This is done directly from the FEA software using a script based on the work by Overend et al. [5]. The procedure accounts for the changing non-uniform stress distribution over the glass surface area, unequal maximum and minimum principal tensile stresses and the growth of surface cracks during a period of high wind load.

The CDR test failure stresses also need to be converted to an equivalent constant stress causing failure in t_{ref} seconds, chosen as 60s. The tests in Section 3 were carried out using a linearly increasing load until failure occurred. However, due to geometrically non-linear effects, stiffening of the glass plates occurs. This results in a non-linear load to stress relationship, which varies with glass thickness. This relation, taken from the FEA in Section 3.2 can be approximated by a polynomial, which is subsequently integrated to give an equivalent constant stress σ_e in Equation 5, where n (the exponential crack velocity parameter) is taken as 16.

$$\sigma_e = \left\{ \frac{\int_0^{t_f} [\sigma^n(t) dt]}{t_{ref}} \right\}^n \quad (5)$$

The CDR tests have an approximately uniform stress distribution within the loading ring. As long as failure occurs within the loading ring, σ_f can be approximated by Equation 6

which converts the stress in the 0.002m² loading ring to a stress which would cause failure on 1m² of glass surface area under the same conditions.

$$\sigma_f = \sigma_e A^{1/m} \quad (6)$$

Specimens with failures occurring outside the loading ring were excluded from statistical calculations. In this way, the results from tests of different loading rates and surface areas can be combined to give a single value for surface flaw parameters. The resulting combined data gave an excellent fit to the Weibull distribution, which was significantly better than the fit of individual data sets in Table 1. This can be explained by the fact that the varying effects of crack growth in each specimen are removed by discarding the failures originating outside the loading ring. The above allows direct use of the CDR test statistics to calculate the probability of failure of any glass geometry and loading scenario.

5.3. Results

The equivalent constant stress was calculated for both new and weathered glass and the results are summarized in Table 2. The average wind loads (W_{mean}) were shifted by a multiplier to give a constant probability of failure $P_f = 0.8\%$ for the calculated equivalent 60s equivalent uniform stress (σ_{eq}), to enable direct comparison. This value was chosen to be in line with P_f taken in ASTM E 1300. The value σ_{max} is the maximum principal tensile stress from the FEA when loaded with the maximum wind load W_{max} . The ratio $\sigma_{max} / \sigma_{eq}$ is a measure of the over design incurred if maximum stress were to be used as a failure criterion, as frequently done in routine design calculations. σ_{eq} is calculated using an automated script applied directly to FEA results. The greater value of 2.04 for weathered glass is a consequence of the larger scatter of strength data when compared to new glass.

	σ_{eq}	P_f	W_{mean}	W_{max}	σ_{max}	$\sigma_{max} / \sigma_{eq}$
	MPa	%	Pa	Pa	MPa	
New Glass (reported tests) [5]	16.16	0.8	889	3070	27.97	1.73
New Glass*	10.06	0.8	520	1795	18.41	1.83
Weathered Glass*	1.55	0.8	72	248	3.16	2.04

*based on statistical surface flaw parameters calculated from tests carried out by the authors

Table 2: Sample details

Quite surprisingly, the failure load for new glass is 7.2 times larger than that of weathered glass, indicating that the weathered glass is very significantly weaker than the new glass. If a 1 in 50 year hourly mean wind load of 520MPa were to be applied to the weathered glass, this would cause 96% of the glass panels exposed to this wind pressure to fail.

By comparison, EN 572-1 recommends the characteristic strength of new annealed glass to be taken as 45MPa based on coaxial double ring tests. TRLV [6] uses tests on artificially abraded glass specimens to recommend an allowable stress of 18MPa for weathered glass. Thereby implying that the strength reduction factor due to weathering is 2.5 – which is commonly used in practise. This clearly shows that the strength reduction observed in the heavily weathered glass used in this research is much larger than the values assumed by current codes of practice.

6. Conclusion

The strength of glass is highly variable and is affected by several parameters, which has led to the application of large factors of safety in codes of practice. It has been shown that a more accurate analysis of the stresses induced on glass surfaces can yield a relative increase in effective strength of between 1.7 and 2 when compared to maximum stresses simply derived from peak loads.

Very limited strength data exists for weathered glass which can yield very significantly lower design strengths in comparison to new, as-received glass. This difference can be observed through microscopy and measured by surface scanning. The latter could be used for preliminary assessment of glass on existing buildings to indicate the degree of weathering when considering refurbishment, glass re-use or the significance of glass failures and damage after a significant storm. The extent of surface damage resulting from weathering was also seen to affect the crack branching phenomena in glass. This has repercussions on the use of fractography in forensic glass engineering and will also affect the post-breakage characteristics of weathered laminated glass.

Co-axial double ring tests are especially well suited to characterise the strength of glass and testing has indicated that heavily weathered glass will fall well below the minimum strength assumed by current codes of practice. This work is part of an on-going programme of research at the University of Cambridge which aims to assess the effects of crack growth, crack branching and crack healing on new and weathered glass and how these phenomena affect real-world applications of glass.

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