Diagnostic Interpretation of Glass Failure

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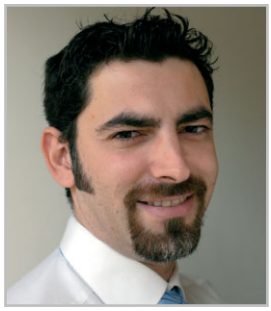

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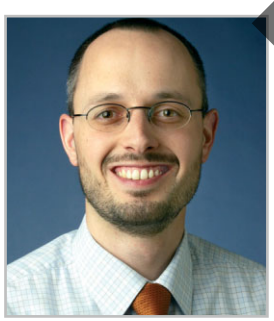

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Summary

The prevalent use of large glass panels and the increasing use of glass in areas traditionally reserved for other materials, such as floors, roofs and staircases, is imposing unprecedented loads on glass. The fracture of glass caused by these onerous service loads and by the increasingly severe threats could result in human injury or death and often triggers claims and litigation. However, despite the widespread and documented cases of glass failure, there is a paucity of quantitative techniques for interpreting the causes of failure in glass.

This paper attempts to redress the issue by providing a historical compilation of the existing knowledge on quantitative and qualitative techniques that explain glass failure. The static and dynamic fracture mechanics from this review form the basis of an empirical method, presented in this paper, that relates the fragment size to the fracture stress. This paper also describes a glass failure case study that illustrates some of the practical difficulties of carrying out a forensic analysis of glass failure.

Keyword: crack branching and architectural glass failure; architectural glass element failure; quantitative and qualitative techniques explaining glass failure; glass forensics and glass breakage; quasi-static and dynamic fracture mechanics; loaded glass element and subcritical crack growth; fragment size and fracture stress quantitative relationship.

Introduction

The failure of architectural glass elements in buildings often impairs the safety and security of a building and its occupants. The failure of glass also has a strong psychological effect on people as broken glass is perceived as a major hazard and such an occurrence triggers a sense of alarm, particularly when the cause of failure is not immediately apparent or when the failure seems to be disproportionate to the action that caused the failure.

Consulting engineers carry out a substantial number of forensic investigations on glass failures; however, there is a general lack of information available on this subject and the information that exists ranges from very basic and scattered qualitative techniques to complex fracture mechanics formulations reported in material science literature, principally in the field of ceramics research.

The single most direct and useful advice for glass forensics is the technical note on glass breakage produced by the Centre for Window and Cladding Technology [1]. This brief document provides a series of images of the most common glass failure patterns and includes accompanying descriptions. However, this technical note does not include any quantitative techniques for diagnosing glass failure.

One very useful quantitative technique in this regard would be the ability to determine the fracture stress from some easily determined physical characteristic of the fractured glass such as the fragment size.

The aim of this paper is therefore to compile and review the scattered and diverse information on glass fracture and present it in a format that can be used by consulting engineers for the diagnostic interpretation of glass failure. In doing so, the paper commences with a succinct review of principal theoretical developments in quasi-static and dynamic fracture mechanics. These relatively complex fracture mechanics formulations underpin glass failure and are used to derive the simplified quantitative techniques in the subsequent sections of the paper. The theoretical section is followed by practical advice on the quantitative and qualitative techniques for interpreting glass failure, including a relationship between fragment size and fracture stress. The final section provides a brief account of a glass failure case study illustrating the difficulties encountered in practice and methods for overcoming them.

Quasi-Static Fracture Mechanics

In contrast to most other materials, the molecular structure of glasses does not consist of a geometrically regular network of crystals, but of an irregular network of silicon and oxygen atoms with alkaline parts in between. In architectural soda lime silica glass (which is henceforth simply referred to as glass), the alkaline parts consist of oxides of sodium and calcium. The random molecular structure has no slip planes or dislocations to allow macroscopic plastic flow before fracture; consequently, glass is perfectly elastic at normal temperature and exhibits brittle fracture. The theoretical strength of a material is determined by the forces of the inter-atomic bonds. Orowan proposed that the stress necessary to break a bond, known as Orowan stress, is given by:

$$\sigma_m = \sqrt{E\gamma / r_0} \quad (1)$$

where γ is the fracture surface energy, r_0 is the equilibrium spacing of the atoms and E is Young's modulus. With E = 70 GPa, r_0 = 0,2 nm and γ = 3 J m^{-2}, we obtain a theoretical strength of 32 GPa for a typical glass [2].

In practice the tensile strength of annealed glass is much lower. Furthermore, the tensile strength is not a material constant, but depends on many aspects, in particular, on the condition of the surface, the size of the glass element, the duration of loading and the environmental conditions. The allowable stress proposed by the draft European Standard prEN 13474 [3] for an annealed glass element with a surface area of 1 m^2 and subjected to permanent loads is 6,75 MPa. The Institution of Structural Engineers [4] proposed a comparable value of 8 MPa for the design strength of annealed glass subjected to long-term loading.

The large variations between theoretical and practical strengths were explained by Griffith [5], whose experiments on glass form the basis of modern fracture mechanics. Griffith argued that fracture did not start from a pristine surface, but from pre-existing flaws, known as 'Griffith flaws', on that surface. Brittle solids such as glass are severely weakened by sharp notches or flaws in the surface because these imperfections (that are not necessarily visible to the naked eye) produce very high stress concentrations. Surface flaws in glass grow with time when loaded, the crack growth rate being a function of several parameters.

On the basis of previous work [6] and experiments on glass specimens, Griffith [5] modelled a static crack as a reversible thermodynamic system. In the configuration that minimises the total free energy of the system, the crack is in a state of equilibrium and therefore on the verge of extension. The total energy U in the system is:

$$U = U_M + U_S \quad (2)$$

where U_M is the mechanical energy (the sum of the strain potential energy stored in the elastic medium and the potential energy of the outer applied loading system) and U_S is the free energy expended in creating new crack surfaces. Therefore U_M favours crack extension, whereas U_S opposes it. The equilibrium requirement $dU / da = 0$ is known as the *Griffith energy-balance concept* (a is the crack length). From this, Griffith calculated the critical conditions at which instantaneous failure occurs as:

$$\sigma_f = \sqrt{2E\gamma / (\pi a_c)} \quad (3)$$

where σ_f is the failure stress and a_c is the critical crack length for crack growth.

Irwin [7] extended the original Griffith energy-balance concept to provide a means of characterising a material in terms of its brittleness or fracture toughness. He introduced the concept of the stress intensity factor K, which represents the elastic stress intensity near the crack tip. The stress intensity factor for mode I loading (opening mode, i.e. normal separation of the crack walls under the action of tensile stresses), K_I, is given by:

$$K_I = Y\sigma_n\sqrt{\pi a} \quad (4)$$

where σ_n is the nominal tensile stress normal to the crack's plane, Y is a correction factor and a represents the size of the crack (i.e. the crack depth or half of the crack length).

The correction factor Y, often called geometry factor, depends on the crack's depth and geometry, the specimen geometry, the stress field and the proximity of the crack to the specimen boundaries. A long, straight-fronted plane edge crack in a semi-infinite specimen has a geometry factor of Y = 1,12. For half-penny shaped cracks in a semi-infinite specimen, the geometry factor is in the range of 0,637 to 0,713, depending on the approach used [8].

Instantaneous failure occurs when the elastic stress intensity reaches or exceeds a material constant known as the plane strain fracture toughness or the critical stress intensity factor K_{Ic}. This condition is called *Irwin's fracture criterion* and is expressed as:

$$K_I \geq K_{Ic} \quad (5)$$

A typical value for K_{Ic} for soda lime silica glass is 0,75 MPa m$^{1/2}$.

Glass Tempering

The most common way of reducing the deleterious effect of the surface flaws is by thermally tempering the glass. In this process the glass is heated and then rapidly quenched, thus introducing a parabolic stress gradient within the thickness of the glass whereby the outside surface is stressed in compression (*Fig. 1*). Any externally applied force must overcome the residual surface compression before any surface tensile stress can be set up. In Europe, fully tempered glass with surface compressions ranging from about 90 MPa to 170 MPa is commercially available. Heat-strengthened glass has a lower surface pre-compression of approximately 40 MPa to 80 MPa. It should be noted, however, that the stress distribution induced by the thermal tempering may be distorted and reduced at plate edges, corners and holes. In North America, heat-strengthened glass is required to have a surface compression level between 24 MPa and 52 MPa, whereas fully tempered glass should have a minimum pre-compression of 69 MPa.

The fracture pattern is influenced by the magnitude of the surface stress induced by the heat treatment (*Fig. 2*). Annealed glass has no surface pre-compression and therefore fails at low levels of stress into large sharp shards which can cause serious injury. Fully tempered glass has the highest surface pre-compression and breaks at high levels of stress into small relatively harmless dice of about 1 cm^2. The fracture of heat-strengthened glass occurs somewhere between the former two and the fracture pattern is similar to that of annealed glass, i.e. relatively large sharp shards, albeit with a smaller fragment size.

Sub-critical Crack Growth

When $K_I < K_{Ic}$ failure may still occur. This is caused by stress corrosion

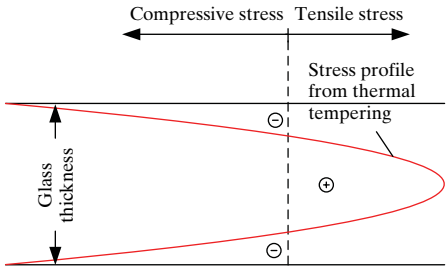


Fig. 1: Residual stress profiles produced by thermal tempering

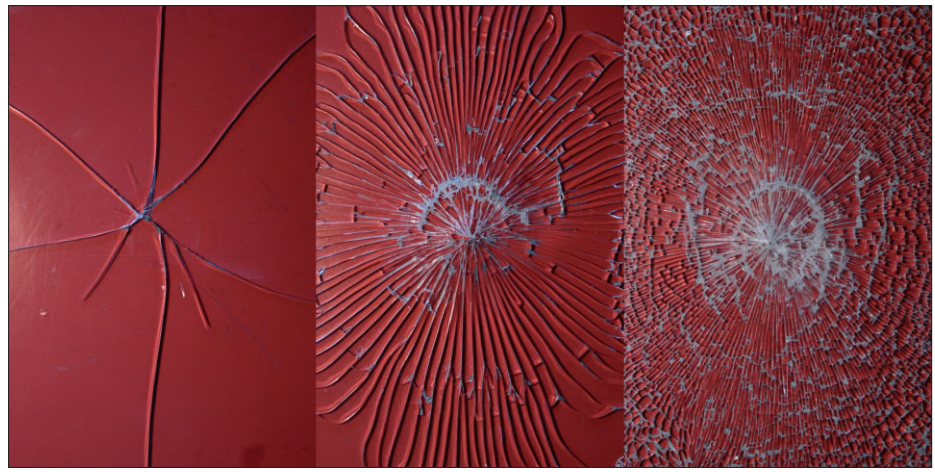


Fig. 2: Images of annealed glass failure (left), heat-strengthened glass failure (centre), and fully tempered glass failure (right) [8]

that causes flaws to grow sub-critically in the presence of humidity. The resistance of a loaded glass element therefore decreases with time, even if it is exposed to static loads only. The growth of a surface flaw depends on the properties of the flaw and the glass, the stress history that the flaw is exposed to and the relationship between crack velocity v and stress intensity factor K_I. The latter is usually modelled using the empirical relationship $v = S \cdot K_I^n$. The crack velocity parameters S and n have to be determined experimentally. To avoid the dependence of the dimension of S on n, the equivalent formulation:

$$v = \mathrm{d}a / \mathrm{d}t = v_0 \left(K_I / K_{Ic} \right)^n \qquad (6)$$

is more convenient $(S = v_0 \cdot K_{Ic}^{-n})$. The crack velocity parameter v_0 has the units of speed (length/time), and n is a dimensionless parameter. Below a certain threshold stress intensity of about $0{,}3K_{Ic}$, no crack growth occurs irrespective of load duration. The crack velocity parameters v_0 and n depend on the humidity, the temperature and the pH value of the environment, the chemical composition of the glass, the age of the flaws and even on the speed of loading [8]. Typical values for design purposes are $n = 16$ and $v_0 = 6$ mm/s.

Dynamic Fracture Mechanics

If an unbalanced force acts on the crack, i.e. $K_I \geq K_{Ic}$ there is excess energy to drive the crack and the fracture becomes unstable. This is known as dynamic fracture and the equilibrium conditions of Griffith and Irwin no longer apply. Under these conditions, the crack propagates and accelerates very rapidly, typically between 1,5 mm/µs to 2,5 mm/µs for soda lime silica glass. This phenomenon is therefore referred to as "instantaneous" or "catastrophic" failure. There are two ways in which a crack may become dynamic:

(a) The crack reaches a point of instability because the applied stress or the crack depth causes the stress intensity factor K_I to exceed the critical value K_{Ic}. Since cracks grow under static loads (cf. above), a dynamical state may arise even under constant loading conditions. A running crack accelerates rapidly towards a terminal velocity governed by the speed of elastic waves.

(b) The applied loading is subject to a rapid time variation, as in impact loading.

A general approach to the dynamic fracture problem was outlined by *Mott* [9] in an extension to the Griffith concept. He simply incorporated a term for the kinetic energy, U_K, into the expression for the total system energy (Eq. (2)):

$$U = U_M + U_S + U_K \qquad (7)$$

The kinetic energy term accounts for the kinetic energy of the advancing crack. Mott was able to quantify U_K for various (though rather simple) geometries and loading conditions, such that the behaviour of a running crack can be predicted in terms of kinetic energy and crack velocity as a function of the crack depth. He had, however, to make very restrictive simplifying assumptions. He assumed, for instance, that a crack does not bifurcate or branch. Further issues that are not taken into account include the influence of stress waves that are reflected at the specimen boundaries and the fact that the micro-structural processes in the crack tip area, which govern the crack growth behaviour, are not the same at high speeds as in quasi-static conditions.

Crack branching marks various stages of kinetic energy dissipation and is of major interest in the fracture of architectural glass. The initial acceleration of the flaw starts on a relatively smooth surface known as the "mirror zone". As the flaw continues to accelerate, the higher stresses and greater energy released produce some form of micro-mechanical activity close to the crack tip, producing severe surface roughening that finally causes the crack to bifurcate or branch along its front. This is observed as an abrupt branching when the glass is viewed laterally; however, an elevation of the crack surface will reveal a progressive increase in the roughness of the fracture surface from "mirror" to "mist" to "hackle" (*Fig. 3*).

A universally agreed explanation for the causes of crack branching is still elusive; however, a number of possible explanations have been put forward which are beyond the scope of this paper. Dynamic aspects of crack propagation are of formidable theoretical complexity and only the basic concepts

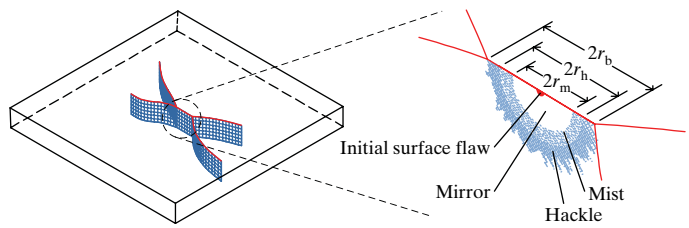


Fig. 3: Schematic representation of mirror, mist and hackle

have been discussed in this section. Interested readers may refer to specialised literature [10, 11]. However, some of the simplified empirical formulations of crack branching are useful in the diagnostic interpretation of glass failure and are presented here.

Relationship between the Failure Stress and the Fragmentation Pattern

From the early 1950s, experiments were performed to ascertain the role of crack velocity in branching. Researchers [12, 13, 14] found empirically that the fracture stress σ_f, i.e. the maximum principal tensile stress at the fracture origin, was approximately proportional to the reciprocal of the square root of the mirror radius (radius of the mirror/mist boundary) r_m:

$$\sigma_f = \alpha_m \cdot r_m^{-1/2} \tag{8}$$

On the basis of previous findings and further experimentation, it was concluded that crack branching is primarily controlled by a critical value of the strain energy release rate or stress intensity, rather than a crack speed criterion [15]. Though there is still much debate on the exact mechanism of crack branching, this interpretation is widely accepted today. Various experimental and theoretical efforts led to relationships of the same form as Eq. (8), and although its theoretical background is still in dispute, this relationship has found general acceptance since it is in reasonable agreement with experimental results. The relationship was found to be equally valid for the radius of the mist/hackle boundary r_h, and for one-half the crack length at macroscopic branching r_b (see [16] for a more detailed literature review), such that it can be rewritten in the more general form:

$$\sigma_f = \alpha \cdot r^{-1/2} \tag{9}$$

where r is either r_m, r_h or r_b with the corresponding branching constants α_m, α_h and α_b.

Researchers [17, 18] found that linear regression to experimental data always yielded finite intercepts and thus suggested a modification of Eq. (9) to:

$$\sigma_f - \sigma_{ar} = \alpha \cdot r^{-1/2} \tag{10}$$

where σ_{ar} was originally interpreted as being the residual compressive surface stress. An alternative explanation for σ_{ar} has since been put forward, and it is therefore pertinent to term this quantity *apparent* residual compressive surface stress. They furthermore concluded from their studies that the mirror constant is not influenced significantly by stress gradients in the specimen [17].

The mirror constant σ_m was determined by research reported in [19] that analysed published failure data of unweathered and weathered window glass panels using Eq. (9). The fact that the values obtained from this research (α_m = 1,92 MPa m$^{1/2}$ for unweathered and α_m = 2,18 MPa m$^{1/2}$ for weathered glass, assuming $\sigma_{ar} = 0$) were in close agreement to those determined in previous studies using small-scale laboratory testing showed that the relationship between the mirror radius and the failure stress may be extended to much larger structures such as windows panels.

The following relationship:

$$\sigma_{ar} r_m^{1/2} + \Psi_0 = \sigma_f r_m^{1/2} Y_F(\theta) \tag{11}$$

reported in [20] was used to predict the residual compressive surface stress σ_r from the failure stress σ_f. σ_r is assumed to be equal to the apparent residual surface compression stress σ_{ar}, Ψ_0 is a material constant, and $Y_F(\theta)$ is a crack-border correction factor. The angle θ indicates the point on the branching boundary ($\theta = 0°$: deepest point, $\theta = 90°$: point on the specimen surface). This means that while Eq. (10) is valid only on the specimen surface, Eq. (11) is in principle valid for all points along the branching boundary. This generalisation remained, however, of limited practical interest because no published mirror/mist boundary data at points other than the specimen surface was available. Conway and Mecholsky were able to show that the residual stress determined using Eq. (11) is indeed in relatively good agreement with direct residual stress measurements by optical techniques. The accuracy is, however, rather limited (tempered glass: 82 MPa from crack branching versus 96 MPa by birefringence measurement, annealed glass: 7 MPa versus 2 MPa), such that direct residual stress measurement remains preferable for diagnostic purposes.

In Ref. [21], the accuracy of Eq. (10) for the prediction of the macroscopic branch length $2r_b$ is verified by testing five-hundred and forty 4-mm thick annealed float glass specimens containing only natural flaws in biaxial loading. Eq. (10) fits well to his experimental results. Furthermore, the crack mirror constant α_b = 2,14 MPa m$^{1/2}$ and the apparent residual stress $\sigma_{ar,b}$ = 10,9 MPa determined from this data are similar to previously published results from both biaxial and uniaxial loading tests. This confirms the usefulness of the approach in diagnostic fracture analysis in which the exact nature of the loading is generally uncertain. However, the apparent residual stress σ_{ar}, although similar to previous measurements, is clearly higher than the actual residual compressive surface stress σ_r of the samples. This casts a doubt on whether σ_{ar} is an accurate measure of the residual stress. Oakley found from an analytical analysis that the slope of the curve (α_b) is insensitive to the plate thickness, but the intercept increases for thin plates. He therefore attributed the difference between apparent and actual residual stress to the effect of the finite plate thickness on the branching criterion when cracks are large.

Finally, all three branching constants α_m, α_h and α_b as well as the corresponding apparent residual stresses σ_{ar} were determined in a recent study [16]. The researcher [16] used experimental data from biaxial strength tests on annealed glass disks that were performed under a wide range of conditions, including different environments, stress rates, and both artificial and natural surface flaws. The following parameters were found: α_b = 2,28 MPa m$^{1/2}$, $\sigma_{ar,b}$ = 10,7 MPa; α_h = 2,11 MPa m$^{1/2}$, $\sigma_{ar,h}$ = 9,1 MPa and α_m = 1,98 MPa m$^{1/2}$, $\sigma_{ar,m}$ = 9,6 MPa. Although the BK7 (a high-quality optical bor-crown glass) used in these tests is not normally used in architectural applications, the study provides some additional insight. In particular, it is an experimental confirmation that the relationship between the fracture stress and the size of the measured fracture feature (r_m, r_h, or r_b) is constant over a wider range of conditions. This relationship is independent of the environment (dry nitrogen, air, water), the rate of applied stress, the surface condition and the fracture stress. The fact that the parameters found are in good agreement with the values determined by Oakley on soda lime silica glass (cf. above) suggests that these conclusions are equally valid for soda lime silica glass and that the glass composition has a minor influence on the crack branching behaviour. Furthermore, another alternative explanation has been suggested in Ref. [16] for the difference between the apparent and the actual residual stress. He interprets the apparent residual stress he

observed (about 10 MPa, cf. above) as a threshold stress below which crack branching does not occur.

Techniques for Interpreting Glass Failure

Glass failures may be generally classified under one of the following:

- Instability failure, i.e. the glass element lacks adequate lateral fixing or stability or is susceptible to elastic buckling instability such as flexural buckling in the case of compression members or lateral torsional buckling in the case of flexural members.
- Overstressing of the glass in direct or indirect tension. The overstressing may be caused by excessive uniform loads, blast, impact, thermal stresses or uneven/inappropriate supports.

It is important to note that any macroscopic flaws or inclusions in the glass will often cause premature failure of the glass at loads that are well within the load-bearing capacity expected for a sound glass element. These weaknesses in the glass may either be:

- In the glass surface (due to macroscopic scratches induced during manufacture or on-site surface damage).
- On glass edges (due to poor handling or excessively feathered edges resulting from poor cutting techniques).
- Solid inclusions within the thickness of the glass. (This includes nickel sulphide inclusions which are responsible for spontaneous breakage of tempered glass; however, it is important to note that both air bubbles and inclusions other than nickel sulphide often cause failure patterns similar to nickel sulphide failures [22]).

In the event of glass failure, it is often desirable to determine the cause so that liability may be established, and to ensure the reliability of the remaining sound glass elements in the building in question and elsewhere. To this end a failure analysis should be undertaken. This typically includes:

(a) The collection and review of the history of the use of the glass component (e.g. support conditions, environmental / loading conditions at instant of failure, opportunities for vandalism etc.);
(b) A stress analysis model;
(c) An evaluation of the extent to which the component was used in conformity with specifications;
(d) A detailed investigation of the failed glass component (e.g. fractograhpic and/or chemical analysis).

The first three points given above follow standard forensic engineering procedures adopted for most structures and materials [23, 24] and are therefore beyond the scope of this paper. On the other hand, the detailed investigation of the failed glass component (i.e. point (d) above) often requires the broad understanding of the factors that influence the fracture patterns of glass and the experience of interpreting these failures.

Fractography, which is the study of fracture surface topography and its relationship to crack propagation, may be very useful in the diagnostic interpretation of glass failure. Fractography techniques normally involve the observation, measurement and interpretation of fracture surfaces in order to determine the origin of failure and the path of the crack, thereby providing some insight into the cause of failure. Some of these techniques date back to the observations of Robert Hooke, who first reported on the fracture surface of limestone in his book 'Micrographia', published in 1665. An excellent review of the wider applications of fractography is given in [25]. Specific fractography applications on glass are discussed in [26].

Qualitative Analysis of Failed Architectural Glass

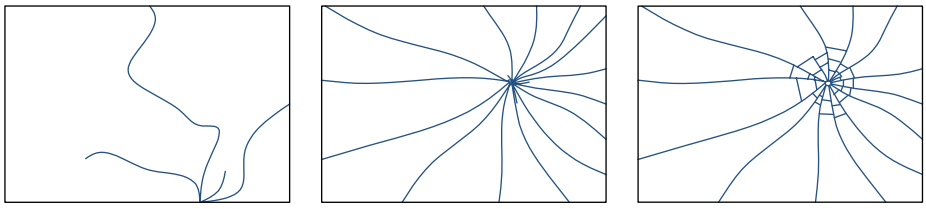
The first step in the investigation of the failed glass component is the on-site observation and the piecing together of the fragments. This may seem a trivial task; however, the broken glass is often disposed of by the building occupants or management and it is important to try and salvage as many of the glass fragments as possible for further analysis. As a minimum, it should be possible for the building management to take a picture of the glass before disposing of it.

From the failed specimen it is often possible to make some qualitative assessment of the cause of failure by determining the following:

(a) The failure origin which helps to identify the presence of large flaws or inclusions in the glass, regions of high stress concentration and evidence of bad detailing or possible deliberate damage;
(b) The failure pattern which gives an indication of the stresses at failure and the cause of failure. Cracks in annealed glass often nucleate roughly perpendicular to the major principal tensile stresses. The number of flaws or the extent of fragmentation is related to the type of glass used, the surface stress at the instant of fracture, or to the energy imparted to the glass by the action that caused failure (*Figs. 2* and *4*);
(c) Specific topographical features that may confirm or dismiss preliminary conclusions reached from the above, for example, the presence of localised crushing on the surface of the glass close to the failure origin indicates impact from a hard object.

Quantitative Analysis of Failed Architectural Glass

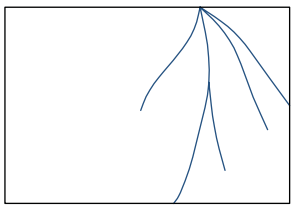
It is desirable to carry out some form of empirical numerical verification of the conclusions drawn from the qualitative analysis of glass failure; however, to date, the techniques available for glass forensic engineering have been either extremely complex or generally unknown. From the theoretical review of dynamic fracture presented in this paper, it is possible to obtain an approximation of the surface stress immediately prior to failure. This is determined by measuring the crack mirror radius r_m, the radius of the mist/hackle boundary r_h or the macroscopic branch length $2r_b$ from the failed glass component and using Eq. (10) to estimate the corresponding surface stress. From the three possible determining failure features, the crack branching length $2r_b$, i.e. the distance between the origin of failure and the next bifurcation or branching of the crack, is the simplest one to measure. From the experimental data discussed above, it may be concluded that a branching constant of α_b = 2,1 MPa $m^{1/2}$ and an apparent residual stress $\sigma_{ar,b}$ = 11 MPa (annealed glass) would provide good estimates for soda lime silica glass. In the absence of better scientific evidence on how to define the apparent residual stress $\sigma_{ar,b}$ in heat-treated glass, the actual residual surface compression stress, which is an approximation for $\sigma_{ar,b}$, should be used. The resulting relationship



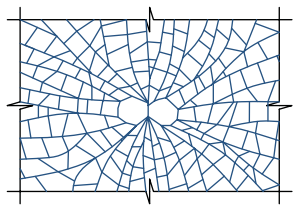
(a) Thermal failure

(b) Hard body impact

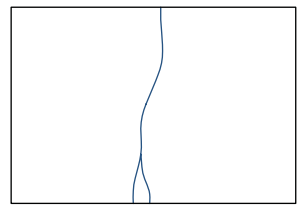
(c) Soft (spherical) body impact



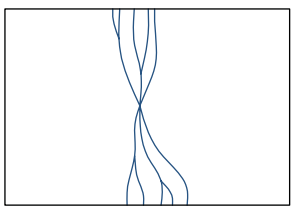
(d) Hard spot on the edge



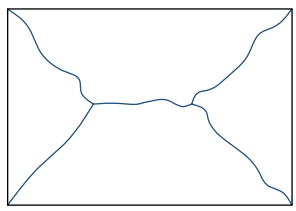
(e) Inclusion



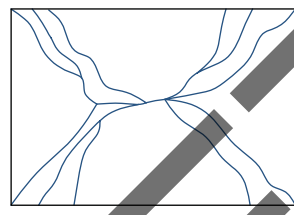
(f) Uniform lateral load, 2-edge support, low load intensity



(g) Uniform lateral load, 2-edge support, high load intensity



(h) Uniform lateral load, 4-edge support, low load intensity



(i) Uniform lateral load, 4-edge support, high load intensity

Fig. 4: Schematic representation of typical glass failures

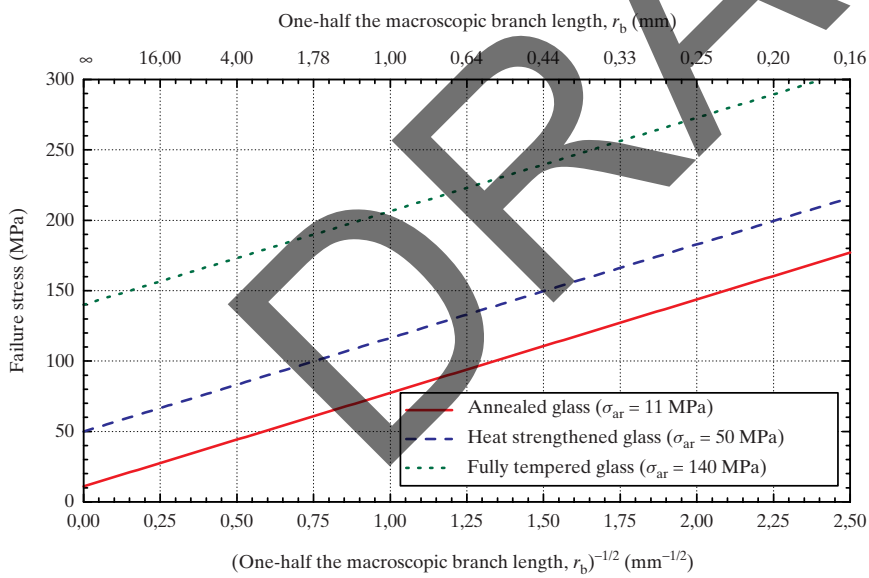


Fig. 5: Relationship between failure stress and macroscopic branch length

between failure stress and macroscopic branch length is plotted for all three glass types in *Fig. 5*. The figure is based on typical residual stress values for heat-treated and fully tempered glass. Since they are very variable, the actual residual stress in a broken heat-treated element should be measured for application.

This empirical calculation, combined with qualitative observations with the naked eye, often provides the information required to enable a thorough forensic investigation of the failed glass component. In some cases, however, it may be necessary to carry out a second stage of microscopy observations and/or chemical analysis. In glass these observations are carried out by means of an optical microscope or scanning electron microscope (SEM). These investigations provide crucial evidence of inclusions in the glass such as solid inclusions and air bubbles. Further investigations such as an energy dispersive X-ray (EDX) scan will provide an analysis of the chemical composition of the inclusion (e.g. to determine whether it is nickel sulphide or some other form of inclusion). Further details on these techniques are provided in [25, 22].

Case Study

The following example illustrates the importance of the diagnostic techniques to interpret glass failures and describes the typical difficulties encountered by building owners and consulting engineers. This case recounts the forensic investigations carried out by a firm of consulting engineers on the failure of glass balustrades that occurred at a building of a major financial company in the United Kingdom. The consulting engineers engaged on this forensic investigation were also responsible for carrying out analytical studies and model tests in order to fully understand the causes behind the failure and to advise on risk management issues.

Two of the panels forming the balustrade of a pedestrian bridge within a building had failed. The glass panels consisted of monolithic fully tempered glass and measured approximately 1665 mm (width) by 1524 mm (height). They were connected to the vertical stainless steel balusters by means of three 32-mm diameter bolted fixings on each side of the glass panel. The bolted fixings were located at 75 mm from the vertical edge of the glass.

On visiting the site, two major problems were apparent. First, there was no physical evidence (primary evidence) of the broken pieces of the tempered glass panes and therefore it was impossible to examine the origin of failure or the fracture pattern (*Fig. 6*). Secondly, as the balustrade contractor who designed, manufactured and installed the works had ceased trading, very little "secondary evidence" had survived and only a limited number of as-built drawings, method statements and operation and maintenance manuals were kept by the client. The case had, therefore, to be analysed on the basis of circumstantial evidence only and with the existing unbroken glass balustrades as a principal reference.

At the outset of the first site investigation, three possible scenarios were identified: breakage due to static or

Fig. 6: Status of the glass balustrade when the consulting engineers arrived on site

impact loads (overloading), spontaneous failure due to inclusions (possibly nickel sulphide, NiS) or excessive floor deflections. The first two possible causes represent common causes of failure in glass balustrades, particularly those built in the 1980s. The third cause is not a common cause of failure in balustrades; however, in this instance the relatively long span of the pedestrian bridge might have triggered this mode of failure.

All the necessary site observations and measurements including geometry, material, fixing details, loads and surface stress measurements of the remaining balustrades by using a grazing angle polarimeter were performed and the results were in line with the expected values. Subsequently a finite element analysis was performed using a software package that has been developed specifically for the analysis of glass elements. The results of this analysis indicated that the glass balustrades and associated fixings were effectively able to bear the working loads specified for balustrades by the British Standards (impact loads to BS 8200 and live loads to BS 6180).

Following these observations, a structural analysis of the primary structure was performed. This analysis showed that the failure of the glass panes was not the result of an excessive deflection of the cantilevered steel bridge.

The two remaining possibilities, overloading and NiS inclusion, could both have caused the failure. Failure induced by inclusions causes a characteristic fracture pattern (see *Fig. 4e*); however, the unavailability of glass fragments meant that the fracture pattern could not be analysed and the actual cause of failure could not be determined directly.

A process of elimination was therefore undertaken to arrive at the plausible cause of failure. The relatively protected location of the bridge meant that deliberate damage was unlikely and that the possibility that two panels had been accidentally overloaded was improbable. In the absence of further evidence, it was therefore established that the most likely cause of failure was inclusions on the glass, specifically nickel sulphide. The client was also advised that in such a scenario there were no technical grounds to find the main contractor liable as the monolithic fully tempered glass procured in the 1980s was considered "safe" by contemporary standards and appropriate for a balustrade application at the time of the construction. Furthermore, the problems caused by nickel sulphide inclusions in tempered glass were not fully recognized by any standard at that time. The problems of spontaneous failure due to NiS inclusions was not properly addressed by the industry until recently with the introduction of heat soak testing to EN 14179:2005 [27, 28].

Two risks were also highlighted by this investigation:

(a) Monolithic fully tempered glass often fragments into harmless small particles. However, these particles are also known to clump together and not break apart until they hit another object. This is a particular hazard if people are likely to walk underneath such installations when they fail;
(b) If the monolithic fully tempered glass of a balustrade fails and falls away, the guarding function of the balustrade is lost, which results in a hazard for people working in the building.

The client was concerned that a building with a chronic risk of spontaneous glass failures would create serious problems in terms of the company's image and could be a source of concern for individual occupants, thereby affecting the value of the asset. In addition, the client anticipated several contractual difficulties in the event of the building being let to a third party. Furthermore, the presence of this risk may effectively deter a significant number of tenants (banks, solicitors, insurance companies and architects) who would not want to be associated with a building suffering glass failures.

The above risks persuaded the client to replace all the existing monolithic tempered glass panes with laminated glass (two sheets of heat-strengthened glass bonded by 1,52 mm of PVB) as well as the steel fixings and bolts. These works, including a series of impact tests to EN 12600 [29], were carried out at the client's expense and under supervision of the consulting engineers (*Fig. 7*).

Conclusion

The general principles of quasi-static and dynamic fracture mechanics have been reviewed and reproduced in a useable format. From these fundamental formulations a quantitative technique has been identified that enables engineers to estimate the fracture stress from the physical characteristics of the broken glass.

The existing knowledge on the qualitative techniques has also been compiled and updated. The diagrams representing typical glass failure and the advice presented on detailed qualitative investigations of failed glass components provide a useful broad understanding of the factors that influence the fracture patterns, which is required for interpreting these failures and which complements the quantitative method.

The case study highlights the fact that in practice diagnostic interpretation of glass failure may present difficulties that are beyond accurate analytical investigations. Nevertheless, good qualitative and quantitative techniques are powerful and useful tools for identifying the cause of failure or, alternatively, as in the case study, for eliminating causes of failure from an initial list of possibilities. The case study also shows the importance and urgency of appointing an expert engineer after glass failure has occurred.

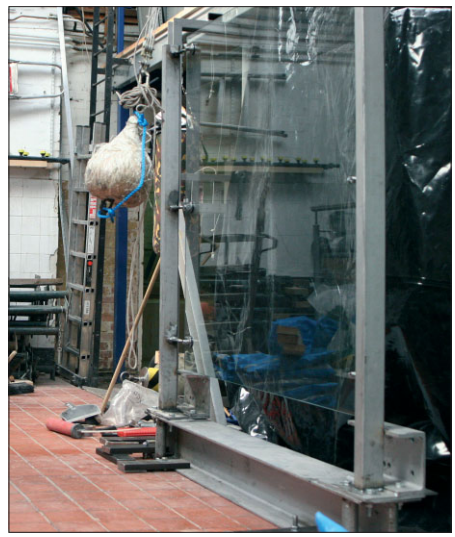


Fig. 7: Impact testing of a prototype of the new glass installation

In view of the present scientific evidence, the quantitative relationship between fragment size and fracture stress yields useful results for estimations. However, this should be used with caution, as significant gaps in the present knowledge have been identified and require further research:

- The existing experimental data on heat-strengthened and fully tempered glass has been obtained from small and thin specimens. Furthermore, some researchers have indicated that the thickness of the glass may affect the crack branching characteristics. Experimental investigations should, therefore, be performed on glass panels of all glass types with size and support conditions that are representative of the service conditions encountered in architectural applications. This would enable the failure stress prediction to be calibrated for such cases and to obtain information on the associated margin of error;
- The existing research reviewed in this paper focuses on surface flaws. Failures in architectural applications may however be caused by edge flaws. This case needs to be investigated both analytically and experimentally;
- The experimental investigations discussed in this paper were carried out on glass specimens that contained only small flaws. However, in practice, glass elements may contain several long surface scratches (e.g. vandalised glass). These surface scratches may produce distorted branching patterns and may influence the macroscopic branch length, thereby producing inaccurate failure stress predictions. Further research should therefore investigate the validity of the failure stress predictions presented in his paper when applied to weathered and surface scratched glass.

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