Glazing for Injury Alleviation Under Blast Loading – United Kingdom Practice

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1 = blast
2 = pulse
3 = hazard
4 = response
5 = P-I diagram

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Abstract

Over the last thirty years the United Kingdom has experienced numerous terrorist bombings. Historically, about 80% of casualties from bomb explosions have been caused by flying glass. The Government has therefore conducted a research programme into practical means of alleviating injuries from flying glass under blast loading. The approach to the problem and the various options which can be taken in specifying blast-resistant glazing are described.

Introduction

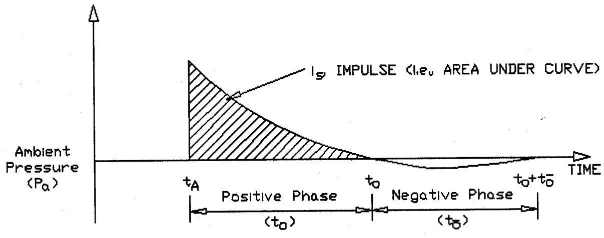
Shock loading from a blast wave presents the window designer with a special set of demands which require a different approach from normal. It is accepted in design for blast that after such a rare and extreme event there will be damage and distortion of the façade, but the over-riding requisite of a blast-loaded window is that injuries and loss of life shall be minimised. Secondary objectives are preservation of the contents of buildings sufficiently for the business or residential activities inside to resume fairly promptly after the event. These objectives will be met if the façade remains substantially sealed against the blast, even though it might be damaged.

All windows have some degree of resistance to blast, even though it may be small. The essential problems for the designer are to be able to quantify that resistance and the loading which might be applied. Assessment of the blast resistance of a window is a matter of scientific investigation, whereas assessment of the threat is a matter of judgement. In the case of hazards from an industrial plant or from an explosives storage site, the potential blast loading may be fairly confidently predicted, but in the case of a terrorist threat, the prediction of the loading is subjective.

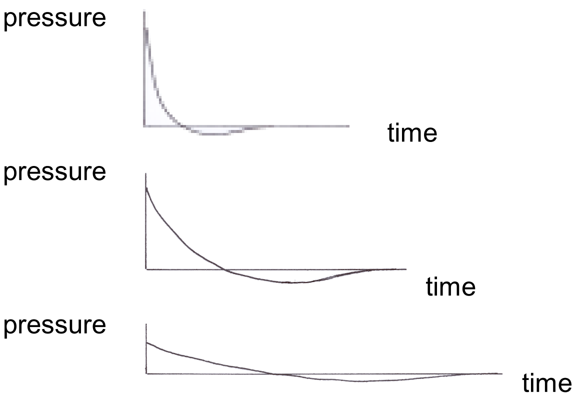
In the UK we have quantified the blast resistance capacities of different glazing types with sufficient accuracy for an effective type to be specified to meet a given threat. Our needs over the past twenty years have given rise to a programme of blast testing, augmented by theoretical studies, which has yielded an excellent basis for specifying alleviating measures. This paper describes the basic procedures we have followed.

Blast Loading

An air blast is a travelling pressure front of compressed air which is created by a massive and almost instantaneous release of energy following the decomposition (i.e. detonation) of a quantity of explosive material. The chemistry and physics of this reaction need not concern us here. The pressure front, or shock wave which is generated imposes a high-pressure, short-duration pulse on any object which it meets. The front leaves the explosive source at supersonic velocity due to the rapid speed at which the explosive destabilises during detonation. The pressure variation at a fixed point in space as the wave passes it, has the form;



As the shock front travels away from the source, the shape of the pulse remains the same, but the size of the initial peak pressure reduces, and the duration of the pulse increases.



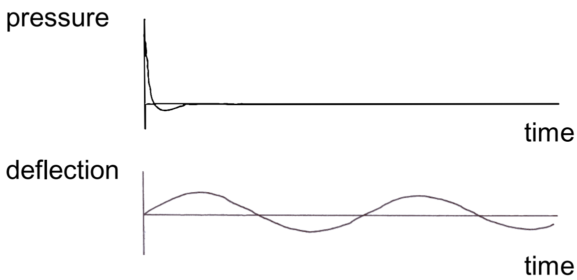
The numerical values of the pulse parameters at any given point in space depend mainly on the quantity of explosive and the distance of the point of measurement from the source. The type of high explosive makes a lesser difference to the pulse values. Pulses from improvised (or home-made) explosives may depart significantly from the pressure-time distribution pattern for pulses from high explosive. Typical pressures from high explosive blast are orders-of-magnitude greater than from wind loading, but durations are very short and measured in milliseconds. Note that the positive phase of the pulse, in which pressures are above atmospheric is followed by a negative phase in which they fall below atmospheric pressure. This can be important in its effect on window response, when the elastic rebound of an unbroken pane may coincide with the negative phase. Breakage might then occur during the rebound rather than during the inward motion. This effect is commonly observed.

A basic parameter of a pulse is the integral of the pressure-time function (for both the positive and negative phases). This is called the Impulse. In conjunction with the initial pressure, its value is significant in determining what the dynamic response of a flexible target will be.

The numerical values of the blast pulse parameters from high explosive have been evaluated from many test measurements (ref. 2). It has been found that whatever the weight of explosive, the initial peak pressure, when plotted against scaled range, is the same. Scaled range is the actual range divided by the cube root of charge weight. Also, impulse divided by the cube root of charge weight plots against scaled range as a single curve. Similarly, all the remaining parameters describing any blast pulse produced from high explosive can be normalised to produce single relationships which can all be expressed as polynomial functions. These curves facilitate the rapid evaluation of blast parameters for any charge weight and range. Fig 2–15 of Reference 4 presents these curves.

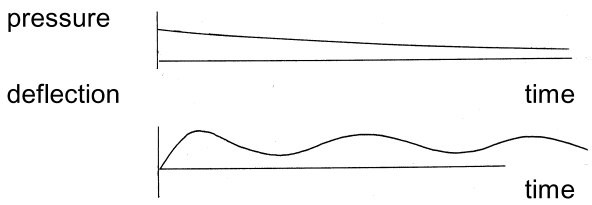
The response motion of any unbroken structural member (of which an uncracked window pane is an example) under high intensity, short duration loading is oscillatory, following closely simple harmonic motion after the forcing phase of the pulse has finished. While the pulse is still forcing, the simple harmonic response is modified. Damping will cause this motion to decay rapidly.

Short Duration Pulse



If the pulse is very long compared with the natural period of vibration of the member, the pulse will approximate to a static load and the member will oscillate about a mean deflection while the pulse is still acting (provided it doesn't reach its failure stress first). If the pulse duration is of similar order to the natural period of vibration, more complex interaction, involving a mixture of these two responses will occur.

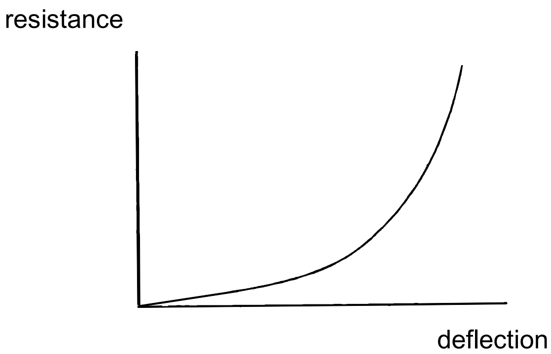
Long Duration Pulse



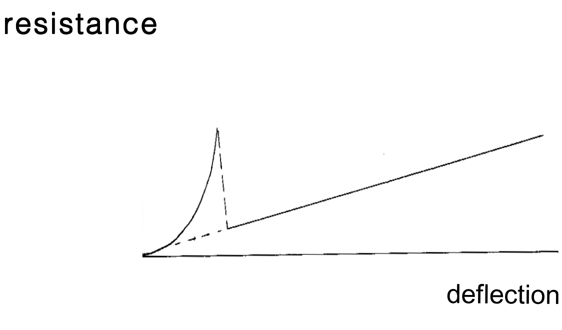
In general terms, the magnitude of the deflection (and the associated material stresses) during the motion determines whether the member fails or not. More correctly for glass, the criterion for failure depends upon whether the stress at the root of any surface fissure in the glass reaches a critical value, which then leads to propagation of that fissure. The critical fissure need not be at the point in the pane of greatest surface stress, when considered as a homogeneous member. This is because propagation of a crack from a flaw depends on the microscopic geometry of the random flaw, as well as on the stress in the homogeneous plate. Calculation based on this fracture phenomenon (see Ref. 6) is more difficult than calculation of stresses in a homogeneous plate, and the latter model is therefore commonly used as the failure criterion. Both failure criteria models represent the same random phenomenon, and therefore it is to be expected that the plate stress criterion should also have an associated confidence level.

An analytical approach to the dynamic response involving complex dynamic computer analysis of sandwich plates in three dimensions has been intentionally avoided, since the main areas of uncertainty lie in the material properties of glass and pvb under high speed loading, and in the evaluation of the pulse felt by the pane itself. For practical purposes, dynamic analysis can be carried out with sufficient accuracy by assuming that the member in question, whether it be beam or plate, can be represented by an equivalent single degree of freedom model. This comprises a discrete mass reacting against a varying resistance. The resistance need not represent a purely elastic spring; it may represent an elastic-plastic reaction, or even a stepped resistance function. The single-degree-of freedom analysis then follows a time-stepping procedure based on Newton's laws of motion. In this analysis the actual mass of the pane is factored to allow for the distribution of the actual mass over the whole extent of the actual member. (The procedure is laid out in Reference 1, chapter 1).

To perform a time-stepping analysis on a window pane, the resistance function of the pane must be derived. The resistance function relates the instantaneous resistance to the instantaneous deflection during the course of an excursion. For a solid, plane pane in an elastic material with negligible creep properties, this takes the following form, which can be evaluated by well-known plate analysis procedures. The relationship is linear initially, becoming non-linear for large deflections. Glass panes are capable of deflecting well into the large deflection condition.



For a laminated pane under high speed loading, the resistance initially follows that of a homogeneous pane and then drops after the glass fractures. Thereafter, if the pane is held securely in the frame rebates, the resistance will increase again as the resistance of the pvb interlayers, acting as a membrane, comes into effect. The general form of the complete resistance function will then be;



Such a curve is used in carrying out the time-stepping analysis of response for laminated glass.

In evaluating these resistance functions, representative values of the failure stress of glass, of the stiffness of the pvb membrane under high speed loading and of the deflection of the pvb membrane at the point of rupture, all need to be assessed. This paper does not discuss the background work involved. It is sufficient to say here that the values adopted have been derived from a study and back-calculation from test results and the literature. The problem of breakage stresses of glass under relatively long duration loading has been well discussed by Colvin (Ref. 5), and these principles are embodied in the draft code prEN 13474. However it is less certain whether the breakage stress – load duration relationship extends into the very short duration (a few milliseconds) area. This is a subject of further investigation.

The current values of glass breakage tensile stresses under high speed loading which are used by PSDB are 80 N/mm^2 for annealed glass and 200 N/ mm^2 for toughened glass. Recent testing has suggested that 200 N/mm^2 for UK toughened glass is much too low. Tests have also indicated that US tempered glass is considerably weaker than UK toughened glass. In the case of laminated glass, the stress at which the glass layers first crack has a secondary effect on the calculated ultimate protective capacity of the pane, since the protection depends on the continued bonding of the glass to the pvb after it has crazed, and on the ductile nature of pvb. These enable the pane to continue to absorb energy and keep the room sealed. Eventual loss of window integrity occurs when the pvb tears. The design problem for laminated glass thus reverts to predicting whether a given applied pulse will bring a particular laminated pane to the condition of pvb tearing.

The high creep rate of pvb under slow loading means that resistance functions for crazed laminated glass measured under slow loading do not represent behaviour under blast loading. We have derived the effective high speed relationship by back calculation from observations of blast-loaded laminated panes and on the assumption that the resistance-deflection relationship in the post-crack, membrane phase is linear. We have also found that the bonding of the glass plies to normal pvb is extremely effective, as only glass dust is sprayed off the inside face. Most of the glass of the inner ply remains bonded on. The dust can be reduced, if desired, by the addition of polyester film to the inside face. The recent availability of stiffer interlayer plastics in laminated glass offers few advantages under blast loading, when energy absorption is the prime requirement, although they give greater resistance to vandal attack. The tendency for glass to de-bond under blast loading is also greater.

The superior strength of plain toughened glass over plain annealed glass is a valuable property. However, when panes of toughened glass break under blast loading, the room is subjected to flying fragments which, whilst being of a less injurious shape than shards from annealed glass, fly at high velocities due to the bigger pulses needed to break them. Although there may be a design pulse (or a charge weight and range) specified for a particular project, there can be no certainty that this will be the size of an actual terrorist attack. The advantage of laminated glass over plain glass is that even after the pvb has begun to tear, the hazards are not immediately acute, and the residual pulse which enters through the tear will be small compared with the total pulse. There is thus a large degree of protection from laminated glass, even when the threat is under-estimated and the pvb tears.

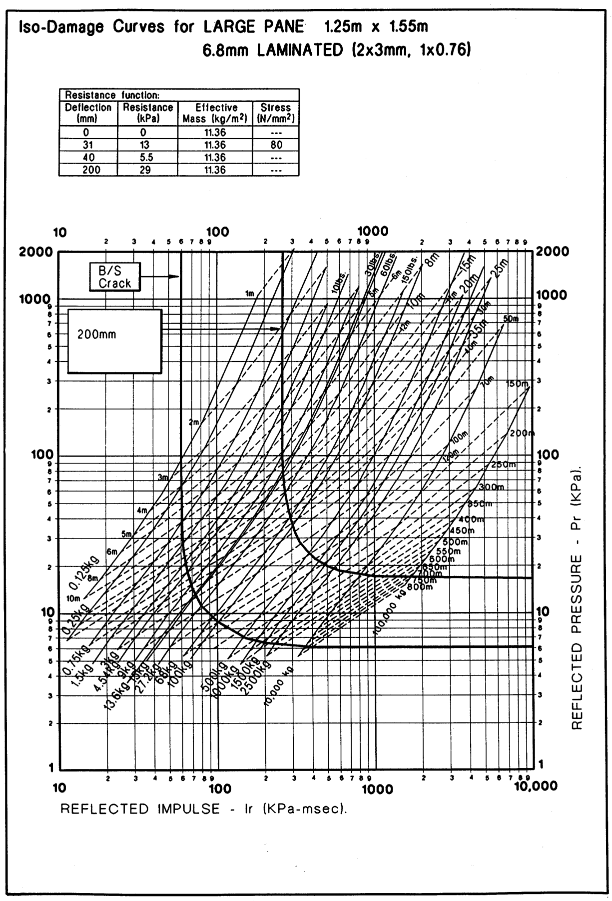
Presentation of Guidance Data

Design procedures for most live and environmental loads have factors built into loads and material stresses to provided margins against failure due to uncertainties. However, in reality, blast loading, if it occurs, may fall within a wide range of values. The design blast threat for a particular building, in terms of bomb size and stand-off always has to be assessed on a somewhat intuitive basis, based on the current and future expectations of terrorist activities, and taking into account the importance and vulnerability of the building. There are no codified factors of safety against breakage. If any margins are provided, they are allowed for in the threat parameters on a building-by-building basis, based on considerations of risk, threat level and the importance of the building, and on consideration of acceptable hazard levels inside. This differs from the normal building design approach of providing strength and a margin of safety so that failures do not occur. The provision of blast-resistant windows can be expensive and the funds available will also affect the measures adopted. Further discussion of such assessment is beyond the scope of this paper.

The two parameters of the pulse which significantly affect a pane's response are the initial peak pressure and the positive impulse. In the theoretical time-stepping analysis, the shape of the positive phase of the pulse is usually simplified from an approximately exponential decay to a linear decay. The equivalent triangular pulse is given an initial peak value the same as the actual value, but its positive phase duration is adjusted from the actual value so that the positive impulse remains unchanged. In this way, the two most influential blast parameters for determining response are preserved. By making this idealisation it becomes possible to present the resulting responses to all pulses in terms of the initial pressure, P, and the positive impulse, I, on a plot of P against I. One diagram refers to one glass type, thickness and pane size. Contour lines on the diagram connect all values of P-I pairs which give rise to the same deflection (and therefore the same stress) and are called iso-damage lines. The iso-damage lines which correspond to the thresholds of Hazard Levels are of particular interest. For laminated glass, the line of greatest interest is that representing the limit of tearing of the pvb interlayer. Another significant line is that representing initial crack of the glass, although this condition is not of great importance in designating hazard. For plain glasses, the iso-damage lines of interest are those representing breakage with various residual velocities of fragments, which correspond to projection of fragments to the rear wall of the test cubicle at various heights.

An overlay grid can be added to a P-I diagram which relates weights of explosive (usually TNT as a standard). A complete pattern of response to all threats can therefore be contained on a single diagram. There is a unique P-I diagram for each pane size, pane thickness and glass type.

A typical P-I diagram is reproduced below. The



Resistance function:			
Deflection (mm)	Resistance (kPa)	Effective Mass (kg/m²)	Stress (N/mm²)
0	0	11.36	---
31	13	11.36	80
40	5.5	11.36	---
200	29	11.36	---

P-I DIGRAM FOR 6.8 mm LAMINATED GLASS
(Overlay grid refers to fully reflected pressures from hemispherical burst on large façade without clearing)

co-ordinates of the resistance function from which the iso-damage lines are derived are tabulated at the top. In the example diagram shown (for 6.8 mm laminated glass), the upper iso-damage line denotes all the combinations of P and I values which bring the pvb membrane to the point of tearing (at about 200 mm central deflection for this size of window). The lower line represents the combinations of P and I values at which the glass just cracks. The grid overlying the whole diagram relates the weight of explosive (TNT) to stand-off distance.

Further iso-damage lines could be added to represent cracking at different stresses and tearing for different values of tearing deflections. These would give an indication of the sensitivity of the line positions to the assumed cracking and tearing values. Sensitivity to the size of the threat can be seen at a glance from the overlay grid.

Comparison with Tests

In the UK, range tests have been carried out on a regular basis since 1982 in order to observe hazard levels behind windows of various types. Windows were mounted in the face of a closed cubicle, since free-standing rigs allow rear face blast loading to affect the test performance in a way which does not occur in a real building. An arbitrary scale of Hazard levels was set up, based on how far across the floor, or how high up the rear wall of the standard sized test cubicle fragments of plain glass were projected. When most fragments fell less than one metre beyond the window, the Hazard is now termed "Very Low" (previously "Break Safe"). When fragments hit the rear wall not higher than half a metre above the floor the Hazard is termed "Low", and when they hit higher than half a metre, it is termed "High". For laminated glasses, free-flying fragments do not occur (provided the edges of the pane are held), and major hazards only commence after the pvb has torn. Before tearing, the hazard is termed "Minimal". After the laminated glass has started to tear and before pieces have begun to be torn off, it still offers partial protection and the hazard is termed "Low". The single iso-damage line for commencement of tearing (the Low Hazard Threshold) is therefore the line of primary interest.

Empirical test observations of hazards in cubicles, co-ordinated with measured values of pressure and impulse on the front face, enabled observations to be compared with calculated predictions.

The many different pane types tested, the variety in blast parameters and the difficulty of anticipating, when setting up a test, what the exact threshold range will be, has meant that even after 20 years of testing, information for many of the less-commonly used pane types is very deficient. The test charge sizes which were employed varied from 4.5 kg to 100 kg, whereas in reality, threats may vary from a few hundred grammes to a few thousand kilogrammes. The end positions of iso-damage lines (which are asymptotes of rectangular hyperbolae, and represent very short and very long duration pulses) can be easily calculated from theory by hand methods (Ref. 1, art. 5.5), but in practice, tests are needed to verify their accuracy and to identify whether any unforeseen effects are occurring.

Measures for Protection

Reference has been made to the merits of laminated glass. Great flexibility is possible in its make-up in respect of the number and thicknesses of glass plies and the number and thicknesses of pvb layers. This enables resistance to almost any pulse to be designed for. The mass of the pane provides inertia against acceleration from rest (which affects the eventual deflection as a solid plate), while the thickness of pvb determines the ultimate resistance to tearing after the glass has crazed. There is an important additional requirement that the pane edges must be securely held. Suitably-robust frames are needed, with rebate depths of the order of 35mm. Silicon sealant bedding is needed to hold the edges of the panes. The common detail of neoprene gaskets in shallow rebates with snap-in beading is not adequate for utilising the full tearing resistance of laminated glass, except for glass of 6.4 mm thickness or less.

The performance of glazed facades with unframed panes supported on bolts through holes in the edges of the panes, has not been quantified, since this has not been a common feature in UK Government buildings. Engineering instinct suggests that, thickness for thickness, the blast resistance will be substantially less than with full framing. This is explained by the fact that plates with unsupported edges cannot develop in-plane radial and circumferential stresses, which would contribute to lateral strength. These glazing systems are being used more frequently and their blast performance is a subject we intend to address in due course.

Treatment for Existing Windows

When a terrorist threat is recognised, the complete replacement of all windows over large facades with laminated panes in robust frames is often not economically viable. A second option, which is cheaper, easier and quicker to install is the addition of polyester film to the inside faces of the existing windows. UK practice has been to use it in conjunction with Bomb Blast Net Curtains. Tests have shown that this installation gives a significant reduction against a certain range of threats. However, its protection capacity is limited, and above certain threat levels, becomes negligible. Testing is necessary to establish these limits. The net curtains, woven from a high strength polyester filament in a strong weave, have weighted bottom hems and a generous surplus width and length. The film binds the fractured pane as one sheet which the curtain is then able to arrest in flight, whereas an unfilmed pane produces loose shards which cut through the curtain. For higher threat levels, the random motion of the flying pane also starts to tear the film, breaking it into pieces and tearing through the curtain. The scope for increasing the protection from this treatment does not match that from using laminated glass with a specially-selected make-up, but for buildings with large facades which are more distant from the seat of the explosion, film and curtains will improve the protection for a large number of people. On a statistical basis, this is therefore still very worthwhile.

A difficulty arises in attempting to quantify from theoretical calculation the hazards arising from filmed glass. At present, empirical full-scale range testing has been the only way forward. Test observations for filmed and curtained windows were plotted on P-I diagrams for the corresponding plain glasses. The iso-damage lines calculated for the same thickness of plain glass were then repositioned on the diagrams to match the test observations. However, uncertainties exist over the directions, relative to the two axes, in which this adjustment should be made, as the test observations only cover a small part of the diagram.

Summary

A bomb blast will always create shock and dismay to those caught up in it. The element of surprise, and the rarity and severity of the event all create an impression of irresistible power and confrontation with the unknown. However, it is possible to design blast-resisting windows on a rational basis. The single-degree-of-freedom model allows a simple, quick and accurate calculation procedure to be followed. This short paper has endeavoured to set out the principles involved.

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