Introduction

The threat to buildings and the public from blasts and other violent attacks is of natural concern to the fenestration industry. This threat is more visible today in the form of the London bombings of 1992, 1993 and 1996 and the Manchester bombing of 1996. Present bombings are not necessarily more severe than in the past but industry is having to develop strategies and materials to deal with these concerns and mitigate the effects.

This technical note introduces some of the concepts of protection of the buildings and occupants from damage as a result of internal or external explosions. For the purpose of this technical note internal explosions are considered to be gas explosions, and the principal aim of the building design is to vent the internal pressure either through the windows, cladding or roof to minimise damage to the building structure. For external explosions in the form of explosive devices being placed close to the building, the cladding and windows have to resist the external blast pressure, which may include significant positive and negative pressure loads.

Threats

Threats to buildings and their occupants can come from a variety of sources. This technical note looks at the potential threats and the role of windows and facades in protecting the occupants from injury. The potential threat mechanisms include bomb blasts and gas explosions.

The exact magnitude and location of the threat depends on the circumstance of the threat. These can be directed from either inside the building, in the case of gas explosions or small portable bombs, or outside the building, in the case of large bombs.

There are two broad groups of explosive, categorised as either high or low explosives. In low explosives the propagation of the reaction is primarily thermal in nature, whereas with high explosives energy is transferred from the exploded to the unexploded material in the form of a pressure shock.

Gas explosions are generally a result of gas build up and are usually internal in nature. These range from small localised explosions (most domestic gas explosions) to major internal explosions causing subsequent collapse, for example, the partial collapse of Ronan Point in 1968. In this incident, the windows and light cladding acted as vents, but a defect in the continuity of the structure lead to a disproportionate collapse of the building.

Threat assessment

Terrorist threats to the building and its occupants vary according to the following factors:

- The value of the target to the objectives of the terrorist;
- The vulnerability of the area;
- The accessibility of the area;
- The security measures present on the site.

These factors will vary with time and circumstance; when the threat is low the cost of adequate protection will appear high but where the perceived threat is high the building occupants may feel isolated and exposed to risk. The challenge for the building designer is to provide the client with informed advice on the appropriate level of protection without being over cautious.
External and internal explosions

Blast waves
The pressures involved and the speed at which the blast wave moves depend primarily on the size of the device producing the explosion and the distance from the centre of the blast (stand-off distance). The major damage caused by any explosion is the result of either the primary blast wave, which will create a significant and rapid over-pressure moving outward from the point of detonation, or the under pressure wave that follows it.

External explosion
In the case of an external explosion the blast front will disperse rapidly and be followed by an under-pressure wave of lower intensity but normally of longer duration. The idealised curve for a free-air blast wave is shown in Figure 1. The amount of damage caused is dependent on the over-pressure specific impulse, and the under-pressure impulse which may be greater (indicated by the area beneath the ambient pressure).

Blast waves do not behave in the same manner as the forces generated by the wind, where the flow of air travels around the buildings, forming a unique flow pattern dependent on the shape and location of the building relative to its surroundings. For a free air-blast, the peak over-pressure falls rapidly with increasing distance from the point of detonation. However, the action of resonance can amplify the effects of the blast which can also be reflected, diffracted and concentrated in local areas depending on the location of the blast and surrounding buildings. The combination of diffraction and reflection also means that surfaces not directly facing the blast centre can be significantly affected and may suffer severe cladding damage.

Internal explosion
Gas explosions are almost always of an internal nature when directly affecting a building and the idealised pressure-time graph for an unconfined gas cloud explosion follows a pattern typically like that shown in Figure 2. This pattern is significantly altered by internal reflections of the blast wave and the venting effects of windows or panels if blown out during the initial explosion.

Internal bomb blasts are generally smaller but the interactions are more complex. The venting of the building is critical to damage limitation and reflected shock waves will reverberate around the structure until sufficient venting has occurred to reduce the pressure.

Damage and injury criteria
Having established the threat it is important to determine the damage levels that are permissible. Avoidance of injury to people, or loss of life, will be the primary consideration, followed by damage to equipment and the building.

Human casualties
External explosions will have the greatest effect on personnel located close to the point of detonation (ear-drum rupture and lung over-pressure), with significant casualties occurring up to 200m away due to the presence of flying glass or other material fragments. Reduction of these is critical in reducing personal injuries during a blast.

An internal explosion results in the blowing out of windows or panels to dissipate the build up of over-pressure. This process of rapid venting does not, however, prevent human causalities as injuries will have been sustained in the initial blast wave before the windows or panels have responded to the blast. This is outlined in the report *Protection of buildings against terrorism* (Elliott, 1992).

The building
The extent of building damage depends largely on its form of construction. For modern steel frame buildings a large bomb placed close to the structure will result in severe facade damage but collapse is unlikely. As the stand-off distance increases the possibility of damage to the structure rapidly diminishes,
although facade damage can remain significant. For older load-bearing masonry buildings a large bomb placed close to the structure may cause total collapse, and even at large stand-off distances there can still be significant structural damage requiring major repairs.

**General damage limitation measures**

**Building design**

Building design is critical to mitigating the structural damage caused by a gas explosion or bomb blast. For older buildings the major structural damage is caused by the initial blast and subsequent fire, whereas newer buildings generally possess good resistance to the initial blast, with the subsequent fire causing the major damage. New buildings (generally of steel frame construction) can, however, suffer substantial superficial damage to the large glazed and clad areas.

There are many good practice points for detailed design improvements and these are covered by *Protection of buildings against terrorism* (Elliott, 1992) and *Protecting buildings from bomb blasts* (James & Partners, 1993). The major design objectives for hardening a building against blasts are summarised as follows:

- Reduce the effects of primary over-pressure and secondary under-pressure so the building should not collapse;
- The building should not catch fire, or if it does so, should burn in such a manner as to leave adequate time for the evacuation of personnel;
- The interior of the building should be protected from flying glass or other materials;
- The building should be capable of rapid repair and re-occupancy;
- The building design should provide bomb shelter areas for the occupants.

**Building arrangement**

Buildings likely to be subjected to bomb threat can be improved by arranging the building elements to reduce the effects of a bomb blast. Certain measures that can be taken are:

- Increasing the stand-off distance from a potential bomb blast by physical barriers such as walls, bollards or other means;
- Moving critical areas further into the bulk of the building and using the building bulk as a protective barrier;
- Modifying the physical layout of the building to direct the blast wave away from the building; this may include tapering the building back on the upper floors and ensuring that there are no re-entrant angles on the face of the building to concentrate the blast;
- Improving facade design to block flying glass fragments;
- Improving fenestration to reduce the number or size of fragments.

These measures may considerably improve the resilience of the building and the safety of occupants in the event of a bomb blast.

**Fenestration damage limitation measures**

The decision regarding the level of fenestration protection to be provided is based on a risk assessment of the likely threat. For higher risk areas the glazing material may be augmented by the use of ASF (Anti-Shatter Film) to act as a sacrificial layer and to reduce the possibility of flying shrapnel penetrating the glass. Alternatively, Bomb Blast Net Curtains (BBNC) may be specified to reduce the possibility of flying glass. BBNC must be installed correctly so that the characteristic bursting strength is not reduced. However better performance will be achieved if the fenestration is replaced.
Glazing materials

In order to design effective explosion resistant glazing, the following information should be requested:

- Stand-off distances and sources
- Expected blast over-pressure and under-pressure (usually in kN/m²),
- Duration of blast, usually given in milliseconds (10 to 100 being the range of common values).

NB In some cases an equivalent static load may be stated.

Design principles

In the event of an external explosion the majority of injuries distant from the explosion are caused by flying glass - the choice of glazing material is therefore critical to reduce casualties. The failure mode of the glass to resist explosions follows two alternatives: either the glass is designed to remain unbroken (no-fail) or the glass is designed to remain in position if broken (fail-safe).

Designing the glass to remain unbroken

If detailed information about blast pressures is available it is possible to design windows where the glass will not break in an explosion. Due to the pressure involved, this will usually result in toughened glass being required. Although it is possible to design a single pane of glass to resist the blast over-pressure, explosions often result in debris being carried by the pressure wave. If the debris should hit the toughened glass the impact may penetrate the compressive surface layer of the glass causing fracture to occur. The toughened glass can be protected by laminating it to the back of another piece of glass, which acts as a sacrificial layer - it must still be assumed that the rear toughened pane is carrying all of the blast load.

Designing the glass to remain in position if broken

This option usually results in a more economic solution, since the glass is no longer required to remain unbroken. The principle of this design is to use a laminated glass with a highly plastic interlayer, such as polyvinyl butyral (PVB), which can absorb considerable quantities of energy. The deformation of the interlayer can be designed to absorb the explosive energy and thus provide resistance to the explosion while still remaining in place in the frame. The broken pieces of glass adhere to the interlayer and are prevented from creating dangerous shrapnel.

Where laminated glass fractures the resulting material becomes very flexible because the plastic interlayer has no inherent bending strength. This bending can only occur where the broken laminate can flex, which will not occur in the rebate of the frame, only across the unsupported span. If the interlayer is within a rebate on all four edges, the broken glass will jam in the rebate stopping the interlayer from pulling out of the corners. This design approach requires a deep rebate, possibly augmented by adhesives or clamping.

As an alternative to laminated glass, an applied film in the form of Anti-Shatter Film (ASF) may provide significant resistance to blast pressure, but it has to be applied to the full surface of the glass, including that part within the rebate of the frame. If film application is a retrospective measure, the glass will have to be deglazed to enable satisfactory application. Laminated glass is generally preferable to ASF, since the plastic component is protected from atmospheric degradation, which may require the ASF to be replaced after 5 to 10 years. It is generally recommended that applied films are not attached to toughened glass for blast resistance. The breakage pattern of toughened glass makes it less likely that the glass will remain in the frame and if it falls it will fall as a single blanket of glass.
The rankings provided in Table 1 give a basic means of assessment of blast resistance. However, the final risk/cost ratio must be assessed for each building on the basis of the likely threat.

**Framing materials**

The immediate framing to the glazing transmits the blast loads to the cladding framework, and from there to the main structure of the building. To enable the blast energy to be dissipated, the key property of the framing is ductility, making full use of the plastic deformation of the framing elements.

Improvements which stiffen the glazing alone with no consideration of the dynamic effect of the frame may actually worsen the situation. Rigid panels will have a stiffening effect on the framework so that it cannot easily deflect and absorb the blast, increasing the load on fixings. Alternatively, stiff framing members restrain glass/panels at the edges, inducing large stresses that increase the likelihood of breakage.

Hence there is a need to provide frame materials and designs that allow appropriate movement in the glazing material, whilst providing damping to dissipate some of the blast load, and adequate frame cover to prevent dislodgement before failure occurs. Cladding components must not be designed for blast resistance in isolation, but as part of the complete system in terms of how the components affect the behaviour of others and how loads are transferred.

Note that frame cover to glazing (edge cover) of less than 25mm is unlikely to be effective in retaining glazing in the event of a significant blast wave - 35-50mm may be required depending on the type of glazing and magnitude of blast. It should also be taken into account during the risk assessment that a blast over-pressure from a bomb is accompanied immediately by a suction pressure, typically two-thirds of the over-pressure but of longer duration, and the support system should be designed with this in mind.

**Internal explosions**

In the case of internal explosions the desired effect is to achieve rapid blowing out of panels or glazing to vent the blast pressure. However, venting must be achieved without providing shrapnel or large flying objects that could increase the risk of injury to persons outside the building. In buildings where the risk of a high pressure blast is great, design features include the direction of blast waves upwards and the use of roofing elements that blow open.

Attempting to design a building to resist both internal and external explosions is difficult, and emphasises the need to assess risk properly.

**Fixings**

Fixing of the cladding framework to the building must be such that complete frame dislodgement is not possible but should allow flexing of the cladding system where this is a design feature. One way of reducing possible damage to the primary structure is by making the main fixings energy absorbing, so minimising loads that are transmitted back to the main structure. In this way, the amount of repair work following a bomb blast is confined to the cladding system, although fixings will still need to be checked for integrity.

An important requirement of the building and cladding design is that all fixings are located in such a way that they can be inspected reasonably easily after a blast event. This is to prevent unnecessary disturbance/damage to the cladding system, and particularly to internal finishes, when carrying out inspections and subsequent repairs.

**Current Standards**

**British Standards**

Few British Standards exist on the subject of threat resistant glazing although currently
there are standards for anti-shatter films (BS 5350), bullet resistant glazing (BS 5051: Part 2) and anti-bandit glazing (BS 5544).

**German Standards**

There is currently a German Standard DIN 52 290 which defines categories of blast loading for the purpose of specifying different levels of blast performance of glass. German practise is to use ‘shock tube’ testing, i.e. simulated blast, and define three categories D1, D2 and D3 in terms of pressure pulse and duration.

**European Standards**

Considerable work is being carried out in Europe by the various CEN committees on aspects of threat resistant glazing described below.

**External explosions (bomb blasts)**

This work has been carried out mainly by CEN working groups and the programme of work is well advanced.

Glass components are dealt with by the draft European Standard prEN ISO 14440 Glass in building - specification for security glazing - explosion pressure resistant glazing - classification and test method. This standard applies a plane shock wave of defined maximum over-pressure to a glass sample and, depending on the results, assigns a classification to the glass product.

The total window, door or shutter performance is being dealt with by an ad-hoc group formed by CEN/TC33/WG1 & 2. This work has generated requirements and classification documents as well as test methods for both shock tube testing and range testing of complete products. The test methods do not require that the window, door or shutter remain operable after the testing but require that any opening sections remain closed (whether the opening mechanisms are still operable or not) and that it is not possible to gain unauthorised access to the inside of the building. There is no requirement for preservation of conventional window properties such as air or water tightness after the test. The assumption is that after an attack the window would need to be replaced under all circumstances.

**Internal explosions (gas explosion)**

To the best of the current knowledge there is no publicly available work being carried out in Europe (or anywhere else) on the design or standards for gas explosion resistance.

**Other sources of information**

Information on protection against terrorist threat is generally held by government departments, although such information is often classified or of limited access. In some industries (e.g. chemical, petrochemical and refining) the risk of process explosion is often high, and data may be available regarding the effects of blast on structures and buildings.

Manufacturers of cladding and fenestration systems may also have data from explosion testing of products, often from ‘range’ testing using real explosive devices.
Figure 1  Idealised pressure-time variation for a solid-explosive produced blast wave

Figure 2  Idealised pressure-time variation for a gas explosion
Summary

This technical note is intended to highlight that threats to buildings can come from a variety of locations. For simplicity the threats have been classified as either external or internal explosions. The very nature of an explosion is difficult to model because of the complexity and variability of the building arrangement and surrounding features. However, limited guidance is given on the difference between a gas explosion of internal nature and an external explosive device in the form of pressure-time variation graphs, for which specific information must be gathered in order to design effective explosive resistant glazing for a particular application. A list of available glazing materials are ranked to guide the specifier on the level of protection provided from various glazing products and treatments, and framing and fixing arrangements.

<table>
<thead>
<tr>
<th>Ranking of glazing materials for protection in the event of bomb blast</th>
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<tbody>
<tr>
<td>4 mm annealed + ASF</td>
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<tr>
<td>4 mm annealed + ASF + BBNC</td>
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<tr>
<td>6 mm toughened</td>
</tr>
<tr>
<td>6 mm toughened + ASF</td>
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<tr>
<td>8 mm toughened</td>
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<tr>
<td>6 mm toughened + 6 mm toughened</td>
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<tr>
<td>6.4 mm or 6.8 mm laminated</td>
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<tr>
<td>8 mm toughened + ASF</td>
</tr>
<tr>
<td>10 mm toughened</td>
</tr>
<tr>
<td>7.5 mm laminated</td>
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<tr>
<td>10 mm toughened + ASF</td>
</tr>
<tr>
<td>11.5 mm toughened</td>
</tr>
<tr>
<td>6 mm annealed + 7.5 mm laminated</td>
</tr>
<tr>
<td>6 mm toughened + 7.5 mm laminated</td>
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</table>

Note from Table 1 that:

1. Grouped glazing configurations have approximately equal properties.
2. Increasing performance is generally accompanied by increasing cost of installation.
3. Rankings are given for guidance only; the properties will vary with individual products.

ASF ages due to the effects of ultra-violet light and will need replacement at regular intervals.
References and bibliography

BS 5350 (C11) Adhesives (For ASF films and coatings), British Standards Institution.


BS 5544, 1978, Specification for anti-bandit glazing (glazing resistant to manual attack), British Standards Institution.


Colvin, J B, Explosion resistant glazing (guidance notes), Pilkington Glass Consultants.


James, R T, 1993, Protecting buildings from bomb blasts, CSW - The property week, 10 June 1993, p58.


