

# Construction the Specifier

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## Anchoring Blast-resistant Windows

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**M**odern building materials provide many different anchoring conditions—there are few into which a fastening cannot be made. However, the properties of a base material significantly affect the selection of a suitable anchor and the loads it can carry. Architects and engineers (A/Es) and specifiers must understand the three main principles of anchoring in order to appreciate the ways in which anchors can fail, and eliminate potential failures at both the design and installation stages. Anchors hold in one of three ways:

1. Friction. To generate sufficient friction to resist the applied load, it is necessary to apply an expansion force to the substrate.
2. Bearing and bonding. The force can be resisted by a bearing force generated on the opposite side of the base material to produce a state of equilibrium.
3. Adhesion. An adhesive bond can be created between the anchor body and the substrate.

### *Holding power*

These three principles can also determine holding power. When the anchor moves in a sleeve, an expansion force can act on the wall of the hole, permitting tensile load to be resisted. However, friction-force can locally deform the base material, requiring an undercut. This allows the load to be resisted by a combination of friction and keying action (the method by which a dovetail joint remains locked together, as in the sides of a drawer).

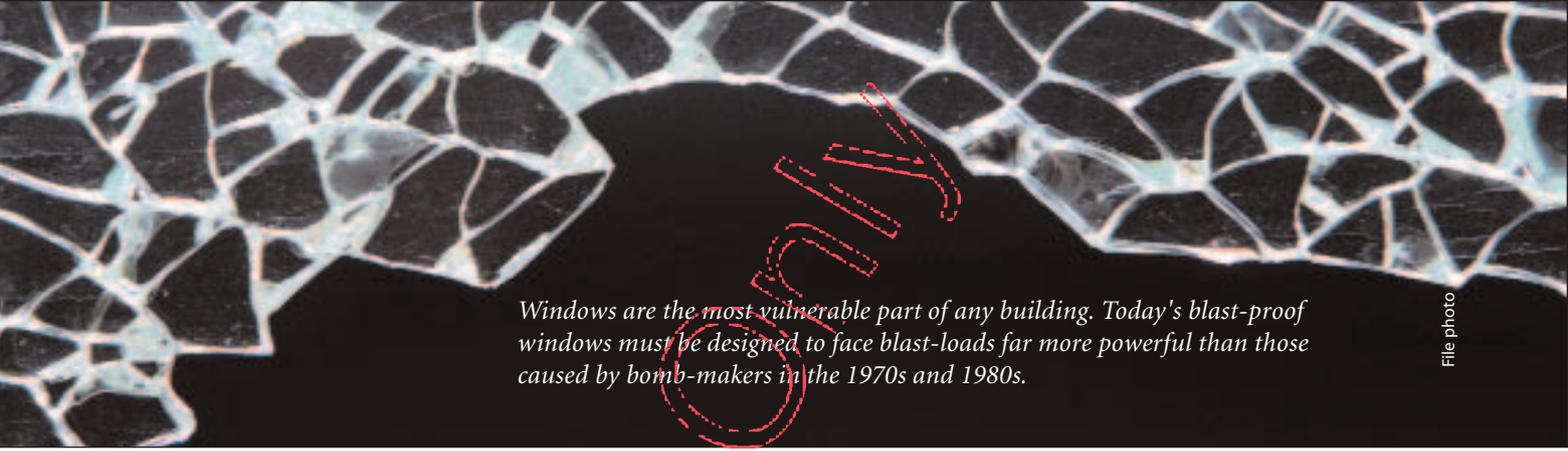
### *Expansion*

Anchors can be expanded either by controlled force or controlled movement. With the former, expansion force is dependent on the tensile force in the anchor body. With the latter, the amount of expansion is controlled by the geometry of the expanded condition (that is, by the anchor's shape when constrained by the sides of the hole into which it is put). For an adhesive anchor, some chemical reaction must take place between the bond material and the substrate, aided by additional local keying in the pores and voids within the base material.

### *Proper preparation*

Years of research and development have gone into the design and manufacture of today's blast-proof windows. These windows cannot reach their full potential without similar consideration given to the anchor system. The successful anchor system should exhibit the following properties:

- can be installed in all substrates;
- substrate remains sound after the hole is drilled;
- anchor performance is not adversely affected by the presence of dust and debris in the hole;
- securing the anchor does not 'over-stress' the parent material;
- anchors do not 'relax' or creep;



*Windows are the most vulnerable part of any building. Today's blast-proof windows must be designed to face blast-loads far more powerful than those caused by bomb-makers in the 1970s and 1980s.*

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- anchor bond is not affected by fire and vibration (including seismic);
- installation is impossible in holes that are too large, small, or short;
- it is impossible to use grout that is improperly mixed; and
- the anchor 'fails to safe.'

#### *Relevant standards*

There are a number of standards produced by ASTM International, the U.S. Department of Defense (DoD), the U.S. General Services Administration (GSA), and other federal agencies that address a window system's performance against a particular combination of blast-load and distance. However, there is rarely any guidance given beyond the general statement that window fixings should be able to resist an equivalent static load. No matter how well specified, tested, and approved a window system is, the onus is on the installer to fix it. Notable references include:

- ASTM F 1642-04, *Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings*;
- ASTM F 2248-03, *Standard Practice for Specifying an Equivalent Three-second Duration Design Loading for Blast-resistant Glazing Fabricated with Laminated Glass*;
- DoD 6055.9-STD, *DoD Ammunition and Explosive Safety Standards*; and
- DoD UFC 4-010-01, *DoD Minimum Antiterrorism Standards for Buildings*.

#### **Blast-load considerations**

In a hardened building, the most vulnerable construction element is the blast-proof windows. Considerable time, effort, and money have been spent in determining the response of glazing systems to a much wider range of blast-loads (measured in pounds per square-inch [psi]) than in the past. There are two main reasons for this. First, the size of terrorist bombs has increased dramatically—a typical Irish Republican Army (IRA) bomb of the 1970s weighed 45 to 227 kg (100 to 500 lb), while the bomb used against the Khobar Towers in Saudi Arabia in 1996 weighed 9072 kg (20,000 lb). Second, blast engineers have been successful in producing window systems that defeat past threats, and today's building owners expect more.

There are two parts to a blast wave. The first is pressure—a measure of the force the wave exerts on the structure. The second—and perhaps the most important part—is 'impulse.' This represents the dynamic force a blast-load exerts on the structure (also called 'momentum transfer'), measured in psi-milliseconds (psi-ms). To quote blast-loads as simply 'pressures' is incorrect; the proper procedure is to quote both pressure and impulse. Unlike

static loads, blast-loads exhibit high pressures over very short durations, often decreasing to zero before the structure has fully responded. In addition to momentum transfer, several factors need to be considered if one is to achieve a successful design.

#### *Natural period of vibration*

This is the frequency at which a building vibrates. Good seismic design requires an understanding of the primary, secondary, and tertiary modes of vibration—tall buildings have long periods of vibration, while short, squat buildings have swifter periods. If the length of the blast pulse (*i.e.* how long the blast wave takes to load the structure) is similar to the natural period of vibration, the building will suffer greater damage.

#### *Dynamic increase in material strength*

When materials such as steel or concrete are subjected to dynamic loads, they can have greater resistance than if the loading was purely static. This is because many materials are 'strain-rate dependent,' meaning the stress they can resist depends on the rate of loading. For blast design, where the rate of loading is high, steel is generally assumed to have a dynamic increase factor (DIF) of 1.25—a very conservative assessment. At very high strain rates (*e.g.* collisions in space), material properties change and one must consider hydrodynamic flow.

#### *Load path*

Load path is the route force must follow through the structure to get from the point of loading to the ground (a simplified load path is shown in Figure 1, page 48). Economic and effective blast-resistance is possible when each element in the load path is in balance with its neighbor. Should one component be under- or over-designed compared to the next, the performance of both will suffer. This can lead to failures elsewhere in the load path, and possibly to disproportionate collapse.<sup>1</sup>

#### *Aspect ratio*

When designing for blast-loads, one should also consider aspect ratio, defined as the ratio of a window's height to its width.

#### **Modes of failure**

There are several potential modes of failure when anchoring blast-resistant windows—shear failure occurs most often, since tensile failure is rare before the window frame has rotated sufficiently to cause development of tensile forces in the anchor body.

#### *Masonry shear failure*

This is a most common mode of failure and can occur in both horizontal and vertical planes of the wall. The shear forces in the anchor body generate tensile resistance in the bricks—if force exceeds resistance, the anchor body bursts out from the back of the wall. Placing the anchors deeper (farther away) from the rear face of the masonry can help alleviate the problem.

## A Substrate Summary

### *Concrete*

Concrete is a well-documented material, with a relatively short history in the construction industry. As a substrate, it is both strong and uniform and lends itself well to all three methods of anchor installation, giving predictable performance.

### *Masonry*

Masonry (both solid and hollow, including fired clay and sand-lime bricks) is not a homogeneous material, due to the presence of mortar joints, cavities, and pores. Compared to concrete, it has relatively low strength.

### *Terra cotta*

While terra cotta blocks are similar to masonry bricks, they are very brittle and should not be drilled percussively.

### *Aerated blocks*

Aerated concrete blocks, both solid and hollow, are non-homogeneous, possessing very high void ratios and relatively low strength.

### *Lightweight blocks*

Lightweight concrete blocks are used mainly for thermal insulation and load bearing, and have strength similar to masonry bricks.

### *Cement-bonded wood fiber*

Cement-bonded wood fiber is primarily an insulation material; it is suitable for carrying light loads only, and cannot be relied upon under blast loadings.

### *Ashlar masonry*

Natural ashlar masonry varies considerably in strength, from weak sandstone to very strong limestone. Found mainly in older structures, it still finds application in modern façades.

### *Random rubble*

Random rubble substrate is usually found in historical structures, comprising two wythes of rubble masonry bonded to lime mortar, with an internal void filled with an assortment of non-structural material. Although the individual stones may be hard, the overall strength is generally very weak. ♥

### *Perimeter shear failure*

This is normally associated with relatively shallow (short) anchors, equally placed around the perimeter of the window within a relatively thin wall section. The normal failure plane moves outward from the edge of the window-reveal to a line common with the ends of the anchors. Increasing the anchor length simply increases the loaded area—the solution is to vary anchor length from one to the next.

### *Anchor body shear failure*

This is another common type of failure, particularly where low-quality anchors are placed within a strong substrate, causing them to shear while the bricks remain intact. It also occurs when little blast-wave energy is absorbed by the flexing of glass and frame (e.g. when ballistic glass is subjected to a blast-load).

### *Mortar joint failure*

Generally, mortar joint failures occur either through slippage of the bed joint, or a vertical delamination of the masonry wall. Both depend on the amount of vertical load, with single-story construction being the most vulnerable. (The greater the vertical load in a wall—proportional to the number of stories in a building—the more blast-resistant the building is.) These failures can be combated by artificially increasing the amount of vertical load using post-tensioned masonry anchors inserted vertically in the plane of the wall, or by stitching the wall

together transversely. Post-tensioned masonry anchors increase the amount of vertical load, creating the positive condition described above. Stitching the wall together transversely improves the composite action of the wall and mobilizes greater mass. Post-tensioned anchors are preferable if the structure is able to accept the increased level of vertical loading, while stitching is effective when the wall section is made of multiple wythes of brickwork (e.g. a cavity wall). Lightweight structures (such as guardhouses and caravans) require additional anti-blast panels.

### *Bearing failure*

This is a potential failure for weak or friable substrates in the horizontal or vertical planes, where shear load in the anchor body is too great for the bearing capacity of the masonry and the anchor is ripped out of the wall. Increasing the embedment depth (the distance between the center of the anchor and the rear face of the brickwork) effectively increases the volume of masonry available to resist the load. Increasing the anchor length increases the surface area over which the load is spread, reducing the stress level in the masonry.

### *Tensile failure*

Tensile failure is not as serious a concern as one might think. Significant tensile loads in anchors develop only when the window frame is so deformed that rotation occurs about the toe of the frame, creating a 'moment arm' (the distance from the line of load application to the point of rotation). However, most



*A building is likely to suffer heavier damage if the lengths of both blast-pulse and vibration period are similar. A design that maintains balance between the different construction elements usually offers the best performance.*

anchor specifications call for field tests to demonstrate the maximum pullout value of the anchor. This erroneously assumes that an anchor satisfying tensile requirements will also satisfy shear capacity requirements.

### Blast-resistant windows

There are four main techniques for treating windows to resist blast waves.

#### Window film

While film is cheap and proven, it has a limited lifespan, and must eventually be replaced. Anti-shatter film (ASF) was once thought the panacea for window-blast protection, but manufacturers will only guarantee the product for 10 years, as it degrades from exposure to ultraviolet (UV) light. Re-installation is difficult, since the original layer must be removed, the adhesive cleaned off, and a fresh layer of film applied. Once the two cycles of film application have been performed, it can be more cost effective to re-glaze the building with blast-proof windows.

Window film has an upper limit that many current threat scenarios exceed. Depending on how it is installed, the loads transferred to the window frame and anchors vary considerably:

1. Daylight Application involves simply sticking a sheet of film to a piece of glass. The film runs up to the edge of the frame, usually with a small gap between the edge of the film and the edge of the frame, depending on the skill of the installer. This gap is where the window/film combination usually fails.
2. Retained Film involves running the film over the junction between the glass and the frame, physically securing it to the frame. This allows the film to achieve better tensile membrane action.
3. Catcher Bars are vertical or horizontal steel bars running from one edge of the window to the other, parallel to the surface of the glass, and usually at the internal mid-point. The bar is firmly fixed to the frame or wall at either end. As the film fails and the glass is projected into the room, it wraps around the bar.

Since film cannot withstand high blast-loads, film and glass combinations (retrofits) are unlikely to place large loads on the frame anchors. However, film remains a good choice when budget is limited, blast-loads are low, and building occupation is unlikely to exceed one decade.

#### Reacting windows

Through momentum transfer, reacting windows use blast-wave

energy to move the window elements, with total movement limited by some physical means. Since the glass moves with the wave, loads transferred to the frame (and hence the anchors) are reduced considerably, enabling blast-resistant windows to be retained using relatively lightweight anchors, such as screws and bolts.

#### Flexible windows

Flexible windows are designed so frame and glass act in harmony—often featuring two layers of glass with a thermal break between them. The outer layer is usually toughened or tempered glass with a higher breaking resistance than float/annealed glass of similar thickness. (Float glass has a tensile capacity of 27,000 to 62,000 kPa [3900 to 9000 psi], and tempering can increase this strength by a factor of 10.) As the outer layer fractures, it absorbs some of the energy from the blast wave, reducing load on the inner layer. The inner layer is usually laminated glass selected for its ductility under adverse loads. Blast waves cause this glass to deflect considerably and fracture, but the internal polyvinyl butyral (PVB) membrane will stretch and absorb the remaining load. While loads passed into the frame are reduced, one must ensure laminated glass does not pull out from the rebates as the glass deflects (this could be prevented by increasing the rebate's depth or providing a structural silicone glazing sealant steel combination). The frame—made of aluminum, steel, or a combination of the two—also absorbs load through local deflections up to a specified limit. Flexible windows can be designed to resist considerable blast-loads while remaining operable (*i.e.* they can be open or shut) but demands for higher resistance place greater emphasis on anchors, particularly in weaker substrates.

#### Ballistic windows

Ballistic windows transfer huge loads to the frame and anchors due to the rigidity of the glass employed in their make-up. This glass is often multi-layered laminated glass—several inches thick, and almost totally inflexible—meaning nearly all the load is transferred to the anchors initially acting in shear. These anchors must be robust, and it can be necessary to reinforce the walls near the window to ensure full blast-load can be transmitted from anchors to the structure.

#### Installation of anchors

Anchor holes are often produced using a rotary hammer, fitted



*There are several means of treating windows for blast-resistance. While window film is the most cost-effective option, it cannot withstand high blast-loads. Although ballistic glass can be a tougher choice, its thickness and rigidity need strongly built anchors. It could also possibly require wall reinforcement.*

with a carbide-tipped drill bit. This allows many holes to be drilled in a short space of time, and is acceptable when the substrate is sound. However, the drill transfers considerable energy into the material, and can cause significant localized cracking and failure in brittle, soft, friable, inelastic, or hard substrates (Figures 2 and 3). In such cases, diamond drilling is recommended; while slower than a percussion drill, it transmits less energy to the substrate, producing sound, clean holes.

Once drilled, the hole must be cleaned out and blown clear of all dust, especially if resin grout is to be used. Failure to clean the hole will significantly reduce anchor performance, as will inadequate mixing of the resin grout components. Anchor holes must be drilled using an appropriately sized drill bit. Too large a bit eliminates the benefit of an expanding mechanical anchor, since it will reach its limit of expansion before enough pressure has been exerted on the sides of the hole to generate the required friction force. Using too small a bit can over-stress the parent material, as the anchor may expand until the pressure on the sides of the hole causes the masonry to burst apart. An undersized bit could also prevent the anchor from properly 'engaging' with the sides of the hole.

Tightening anchors to achieve specified torque settings can be complex, as these systems rely almost entirely on internal force to resist loads. 'Torqued-up' anchors must be allowed to relax for 24 hours before being re-torqued—only adequate site supervision and testing with a torque wrench will allow this to be done effectively.

### Blast-resistant anchors under load

Research in the United Kingdom has demonstrated what happens to anchor stresses when a blast-resistant window is loaded by a blast wave. For test purposes, researchers selected a typical operable window, from which a finite element, non-linear geometric model was made, using elasto-plastic material properties incorporating frame hardening. As a base-line analysis, 28 window-retention anchors were modeled, the anchors being fitted at 203-mm (8-in.) centers, representing a standard installation fit. The window was loaded with a pressure and impulse combination

corresponding to 100 kg (221 lb) of trinitrotoluene (TNT) at 21 m (70 ft)—it had successfully survived this load in a recent live arena test.<sup>2</sup>

The shear stresses in each of the anchors were recorded and the results showed considerable variation in the level of shear load from one anchor to the next. The loads in the top and bottom outer anchors tended toward zero, while those in the inner anchors—corresponding to the mullion location—were high. However, interpretation was more complex for the side anchors, where the highest loads were not at the transom location, as might be expected, but at the mid-point of the longest side-span. Apparently, forces in the anchors were significantly affected by frame geometry and aspect ratio. Since the forces in the eight corner anchors were lower than the remainder, they were 'removed' to see what effect, if any, there would be on those that were left.<sup>3</sup>

The anchors were then repositioned. Researchers first verified that removing the eight anchors did not adversely affect the performance of the frame. After comparing the output from both the original 28-anchor analysis, and the modified 20-anchor analysis, it became clear that although the individual anchor loads increased by an average of eight percent, this number is not significant. As the frame performance (central deflection) remains the same, the number of anchors could be reduced even further, providing the edge deflections remain within tolerance. Such reduction could represent significant savings in costs and window installation time.

### Conclusion

Many blast-resistant anchor systems are generically overdesigned. Fixing at nominal 200- to 300-mm (8- to 12-in.) centers means there are too many anchors, many of which will never be loaded to their full capacity. Wasteful and time-consuming, this practice also increases the chance of key anchors being installed incorrectly. The ideal anchor system for a blast-resistant window should allow a hurried installer, with limited resources, to achieve a high standard of performance. He or she must be able to do this repeatedly, without having to consider the effects of weakened substrates, poorly mixed chemicals, or the need to retighten anchors. ♥

Figure 1 Simplified Blast-load Path

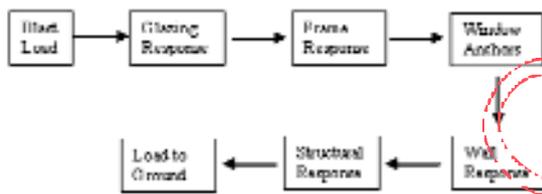


Figure 2 Substrate Drilling Damage



Figure 3 Door Perimeter Spalling



in London, England, in 1968, when a gas cooker exploded and blew out the wall of one apartment, leading to the collapse of the entire block.

<sup>2</sup> Initially, a real window was tested with all anchors present, then tested again on a computer simulation to check that results were the same. The anchors were then removed from the computer model to see what difference this made to the results.

<sup>3</sup> 'Removal' refers to points where the elements and nodes corresponding to the corner anchors were deleted from the computer model, contrary to the real test where all the anchors were retained.

Notes

<sup>1</sup> Disproportionate collapse is a structural response out of proportion to the load that causes failure. A classic case occurred

## Additional Information

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Abstract

Modern blast-resistant windows rely heavily on the anchor systems used to hold them into the wall. Should one element in the load path under-perform, then the

whole system can fail, sometimes catastrophically. The connection between window anchor and supporting substrate is particularly important, but many of today's windows are unnecessarily overdesigned.

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