Anchoring Blast-Resistant Windows

By Stephen P. Ward, Eur Ing, CEng, MICE, MIExpE

The wide variety of building materials used in construction today provides many different anchoring conditions. The most important base materials or substrates are concrete and masonry – both solid and hollow, including fired clay and sand-lime bricks, terracotta blocks, aerated concrete blocks, lightweight concrete blocks, cement bonded wood fibre, ashlar stone blocks and random rubble.

- Concrete is both strong and uniform, and lends itself well to predictable anchor performance.
- Masonry, unlike concrete, is not a homogeneous material due to the presence of mortar joints, cavities and pores; and, compared to concrete, it has relatively low strength.
- Terracotta blocks are similar to masonry bricks; however, they are very brittle and should not be drilled percussively.
- Aerated concrete blocks, both solid and hollow, are also non-homogeneous, possessing very high void ratios and relatively low strength.
- Lightweight concrete blocks, used mainly for thermal insulation and load bearing, have strengths similar to masonry bricks.
- Cement bonded wood fibre is primarily an insulation material carrying light loads, and is very weak.
- Natural ashlar masonry varies considerably in strength from weak sandstone to the strongest limestone; it is found mainly in historical or older structures, as well as in some modern facades.
- Random rubble substrate is found usually in the oldest historical structures, consisting of two wythes of rubble masonry bonded with lime mortar, with the internal void filled with an assortment of non-structural material; although the individual stones may be hard, the overall strength is generally very weak.

How Anchors Work

It is necessary to 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 a base material due to one of the following principles: friction, bearing, and bonding or adhesion. In order to generate sufficient friction to resist the applied load, it is necessary to apply an expansion force to the substrate. Alternatively, the force can be resisted by a bearing force generated on the opposite side of the base material to produce a state of equilibrium. Finally, an adhesive bond can be created between the anchor body and the substrate.

Many anchors derive their holding power from a combination of the three working principles. By causing an anchor to move in a sleeve, an expansion force can be made to act on the wall of the hole permitting a tensile load to be resisted by the friction force acting against substrate. However, this friction force can locally deform the base material and it may be necessary to produce some form of undercut so that the load is resisted by a combination of friction and keying action. A further distinction is made between anchors that are expanded by controlled force and controlled movement. In the case of the former, the expansion force is dependent on the tensile force in the anchor body. In the latter, the amount of expansion is controlled by the geometry of the expanded condition. For an adhesive anchor, some form of 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.

The Load Path

Of all the construction elements present in a hardened building, the most vulnerable are usually the blast-resistant windows. Considerable time, effort and money have been spent in recent years around the world in determining the response of different glazing systems to an increasing variety of blast loads. However, with all this research and development, there has been surprisingly little investigation into the behavior of window retention anchors above and beyond that normally associated with resisting static loads.

Blast loads are unlike static loads in that they exhibit high pressures over very short durations, often decreasing to zero before the structure has time to respond fully. Momentum transfer, natural periods of vibration, dynamic increases in material strength, aspect ratios, energy absorption and load paths all need to be carefully considered if a balanced design is to be successful. A simplified load path is shown in *Figure 1* below:

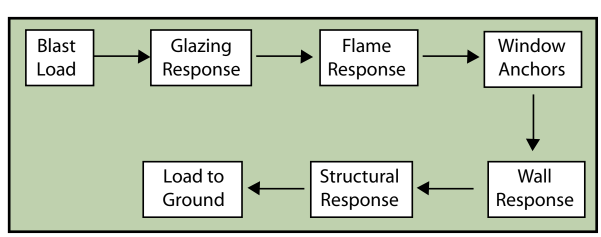

Figure 1: Simplified Blast Load Path.

From the examination of previous incidents, it is clear that the most economic and effective blast protection is provided when each element in the load path is in balance with its neighbor. If one component is either under- or overdesigned with respect to the next, its performance and that of its neighbor will suffer adversely. This can lead to potential failures elsewhere in the load path and the possibility of disproportionate collapse. (*Figure 2*)

Modes of Failure

As far as anchoring blast resistant windows are concerned, there are several potential modes of failure, some of which will be familiar to those experienced in anchor design.

- *Perimeter Shear Failure* – this mode of failure is normally associated with relatively shallow (short) anchors equally spaced 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 the anchor length from one anchor to the next.
- *Masonry Shear Failure* – this is a primary mode of failure and can occur in both the horizontal and vertical planes. The shear load in the anchor body exceeds the tensile capacity of the substrate retaining the anchor in the plane of the wall. Placing the anchors deeper (further away) from the rear face of the masonry can help alleviate the problem.

Figure 2: Disproportionate collapse – Oklahoma 1995.

- *Anchor Body Shear Failure* – another common type of failure, particularly where inferior quality anchors are placed within a strong substrate, or where very little of the blast wave energy is absorbed by the flexing of the glass and frame. This sometimes happens when ballistic glass is subjected to a blast load.
- *Mortar Joint Failure* – this can occur in two main ways, either through a slippage of the bed joint or a vertical delamination of the masonry wall. Both forms of failure are dependent on the amount of vertical load, with single-story construction being the most vulnerable. The solution is either to increase the amount of vertical load artificially by use of post-tensioned masonry anchors inserted vertically in the plane of the wall, or to stitch the wall together transversely.
- *Bearing Failure* – this is a potential failure mode for weak or friable substrates in both the horizontal and vertical planes, where the 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 can reduce the potential for this to happen.
- *Tensile Failure* – this is not such a major issue as might be initially thought. Significant tensile loads in anchors only develop when the window frame deforms to such an extent that rotation occurs about the toe of the frame, creating a moment arm. However, it is interesting to note that most anchor specifications call for field tests to be conducted to demonstrate the maximum pullout value of the anchor. This assumes that if an anchor satisfies the tensile requirements, it will also satisfy the more likely shear capacity requirements. The erroneous logic of this philosophy is obvious.

Blast-Resistant Windows

This article would not be complete without a discussion of the various generic ways available today to treat windows to resist the effects of a blast wave. Generally speaking, there are four main approaches: film, reacting, energy absorbing, and ballistic. Film is a useful expedient method that was once very popular; however, it has a limited life, which means that it must be replaced at some stage. Depending on how film is installed (daylight application, retained or catcher bar), the loads transferred to the window frame and anchors vary considerably. Due to the relatively low magnitude of the blast loads that can be resisted effectively by film, it would be unusual to find that the anchorages require special treatment.

Reacting windows use the energy of the blast wave, through the principle of momentum transfer, to cause the elements of the window system to move, the total movement being limited by some physical means. Due to the fact that the glass moves with the blast wave, the loads transferred to the frame, and hence the anchors, are reduced considerably, enabling blast-resistant windows to be retained using relatively lightweight anchorages. However, the demand for larger windows and improved performance has inevitably created a situation where the loads transferred into the window retention anchors are no longer insignificant and must be dealt with in some way.

Flexible windows are designed around the theory that the frame and glass act in harmony with each other, and often there are two layers of glass with a thermal break in between. The outer layer is usually toughened or tempered glass that has a higher breaking resistance than normal or annealed glass for a similar thickness. As the outer layer fractures it absorbs some of the energy from the blast wave,

Substrate damage due to rotary percussion drilling.

reducing the load on the inner layer. The inner layer of glass is inevitably laminated glass selected for its ductility under adverse loadings. The blast wave will cause the laminated glass to deflect considerably (12-16 inches is not uncommon), and although the glass will be fractured, the internal polyvinyl butyral (PVB) membrane will stretch and absorb the remaining load. The loads passed into the frame are reduced, although considerable care must be taken to see that the laminated glass does not pull out from the rebates as the glass deflects. The frame itself is also designed to absorb load through local deflections up to a specified limit. Flexible windows can be designed to resist considerable blast loads, and can even be made operable, but modern demands for increased performance have inevitably placed greater emphasis on anchorages, particularly in weaker substrates.

Ballistic windows transfer huge blast loads to the frame and anchorages due to the nature of the glass employed in their make-up. Ballistic glass of often multi-layered laminated glass several inches thick, and thus is almost totally inflexible. This means that almost all of the blast load will be transferred to the window anchorages initially acting in shear. These anchorages will need to be very robust, and it may be necessary to reinforce the walls in the immediate vicinity of the ballistic window to ensure that it remains anchored to the structure. If this cannot be achieved satisfactorily, alternative support solutions will need to be employed.

Installation of Anchors

For the sake of on-site expediency, anchor holes are often produced using a rotary hammer fitted with a carbide-tipped drill bit. This technique allows many holes to be drilled in a short space of time, and as long as the substrate is sound, it is an adequate technique. However, a rotary percussion drill puts a considerable amount of energy into the material, and can cause significant localized cracking and failure in weak or brittle substrates. In these situations, a prudent approach is to use diamond drilling equipment which, while slower than a rotary percussion drill, is more sympathetic to the substrate, producing sound, clean holes.

Once drilled, the hole must be cleaned out and, particularly if resin grout is to be employed, blown clear of all dust. Failure to ensure that the hole is clean will significantly reduce anchor performance, as will inadequate mixing of the resin grout components. Similarly, anchor holes must be drilled using an appropriately sized bit - too large, and the benefit of an expanding mechanical anchor will be lost; too small, and there is a risk of overstressing the parent material.

Tightening anchors to achieve specified torque settings requires special attention, as these systems rely almost entirely on the internal force to achieve the required fixity to resist the design loads. Anchors that are 'torqued-up' must relax for 24 hours before being 're-torqued' again – only adequate site supervision and a rigorous system of testing will allow this to be managed effectively.

An enormous amount of research and development over many years has gone into the design and manufacture of the blast-resistant windows that are being installed today. It is ludicrous to expect such windows to perform to their full potential without similar considerations being given to the anchorage system. The onus is therefore on the blast window installer to ensure that the work is up to standard, or other people's lives will be put at risk; window installation has never been so critical.

Given that the successful performance of a blast-resistant window relies on the integrity of the anchorages, what is required is an anchor system that exhibits the following properties:

- Can be installed in all substrates.
- The 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 'overstress' the parent material.
- Anchors do not 'relax'or creep.
- The anchor bond is not affected by fire or vibration (including seismic).
- Installation is impossible in holes that are too large, too small or too short.
- It is impossible to use grout that is improperly mixed.
- The anchor 'fails to safe'.

In other words, the system by which the anchors are installed should always produce a sound anchorage under all circumstances, no matter what short cuts the installer takes, what conditions he or she is working under, and what supervision (or lack of it) is available.

Conclusions

The ideal anchor system for a blast-resistant window should be engineered such that the installer working in a hurry, with limited resources, trained personnel and supervision can achieve a high standard of window installation in accordance with the overall design. The installer must be able to do this repeatedly without having to consider the effects of weakened substrates, poorly mixed chemicals and the necessity to retighten anchors.

Installing blast-resistant window anchors is not unlike installing any other type of window anchorage, except that the consequences arising from faulty workmanship, inadequate supervision and poor selection of materials could be catastrophic. Blast windows offer building occupants the first line of protection against external attacks, and as they are often the most vulnerable parts of the structure, they must be installed correctly. Failure to achieve this relatively simple task puts human lives at risk and exposes clients and building owners to potential litigation. The term 'duty of care' should not be taken lightly. ▪

Rotary percussion drilled holes located too close to the masonry surface, causing extensive spalling around perimeter of blast-resistant door.

Stephen Ward, Eur Ing, CEng, MICE, MIExpE is a division manager at Cintec International Ltd. His division is responsible for research and development, marketing, and subsequent project management of contracts involving dynamic loads on masonry. He can be reached via email at **solutions@cintec.com**.

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