ANCHORING BLAST RESISTANT WINDOWS

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1. INTRODUCTION

The wide variety of building materials used in construction today provides many different anchoring conditions. There is hardly a material used in building today into which a fastening cannot be made. On the other hand, the properties of a base material significantly affect the selection of a suitable anchor and the loads it can carry. The most important base materials or substrates are concrete, 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.

Properties of the various substrates vary from strong and homogeneous (concrete) to very weak and inhomogeneous (random rubble and some brickwork); others lie in between but all are suitable for strengthening and window anchoring with proper engineering design.

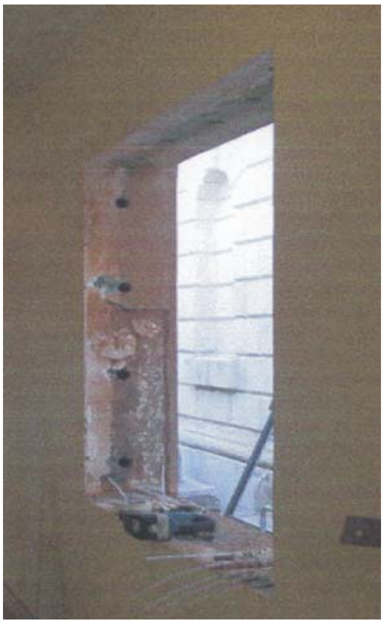


Figure 1: Typical retrofit project in brick masonry drilled and ready for blast proof window installation

2. HOW ANCHORS WORK

2.1. Principles

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.

2.2. The Load Path

Of all the construction elements present in a hardened building, the most vulnerable are surely 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 behaviour of window retention anchors above and beyond that normally associated with proving that they can accept the static load.
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 2 below:

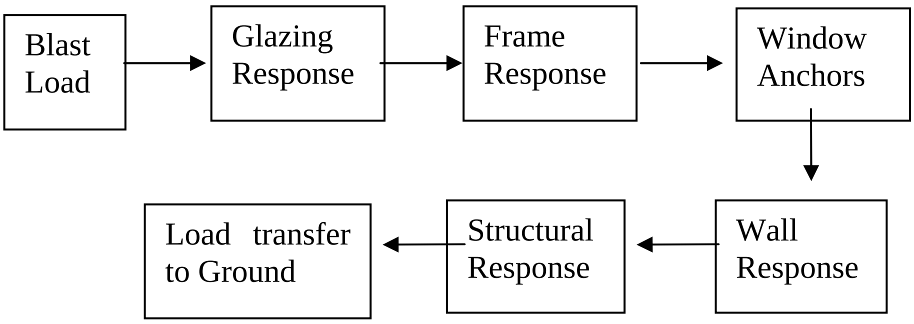


Figure 2: Simplified Blast Load Path

From the examination of previous incidents, it is clear that the most economic and effective blast resistant protection is provided when each element in the load path is in balance with its neighbour. If one component is either under or over designed with respect to the next, its performance and that of its neighbour will suffer adversely. This can lead to potential failures elsewhere in the load path and the possibility of disproportionate collapse – see Figure 3.

Figure 3: Disproportionate collapse — Oklahoma 1995

2.3. Modes of Failure

There are several potential modes of failure in the anchoring of blast resistant windows, some of which will be familiar to those experienced in anchor design. Before these failure modes are discussed in detail, it is worth noting that most failures will be based on shear failure, as tensile failure is unusual until the window frame has rotated sufficiently to cause tensile forces to develop in the anchor body.

The various modes of failure are described in Appendix A.

3. BLAST RESISTANT WINDOWS

This paper 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 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 systems such as those made by Arpal®, Thermolite® or Blast Blinds® and others 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 similar to those made by Frontline® in the UK, Salzter® in Europe and Masonry Arts® in USA 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 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 (300 to 400 mm 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 as well as being made operable but modern demands for increased performance have inevitably placed greater emphasis on anchorages particularly in weaker substrates.

Ballistic windows transfer huge 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 as such is almost totally inflexible. This means that almost all of the total 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 the window remains anchored in the structure. If this cannot be achieved satisfactorily, alternative support solutions will need to be employed.

4. 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 providing the substrate is sound, it remains an adequate technique. However, a rotary percussion drill action puts a considerable amount of energy into the material and can cause significant localised cracking and failure in weak or brittle substrates. In these situations a prudent approach is to use diamond drilling equipment which, whilst 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 drill bit: if it is too large, the benefit of an expanding mechanical anchor will be lost; if too small there is a risk of over-stressing 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 designed loads. Anchors that are 'torqued-up' must be allowed to 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.

It is clear that although the installation and setting of window anchors appears to be a trivial affair, there is much that can go wrong on site. Inevitably this will be the case if the installer is working under adverse conditions, under tight time constraints or is unfamiliar with either the anchor system or the masonry. Many of the problems can be addressed with proper site supervision and effective management, but commercial pressures often rule the day and the potential to 'cut corners' remains.

In the UK and USA an enormous amount of research and development over many years has gone into the design and manufacture of the blast resistant windows we see 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 his work is up to standard or lives will be put at

Figure 4: Rotary percussion drilled holes located too close to the masonry surface causing extensive spalling around perimeter of blast proof door.

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 ‘over-stress’ the parent material.
- Anchors must not ‘relax’ or creep.
- The anchor bond must not be affected by fire and vibration (including seismic).
- Installation is impossible in holes that are too large, too small and 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 will always produce a sound anchorage under all circumstances no matter what short cuts the installer takes, what conditions he is working under, and what supervision (or lack of it) is available.

Grouted cementitious anchors manufactured by Cintec International in the UK have been found to fulfil all these requirements.

5. BLAST RESISTANT WINDOW ANCHORS UNDER LOAD

Recent work in the UK* has demonstrated clearly what happens to the stresses in window retention anchors when a blast resistant window is loaded by a blast wave. For the analysis, an operable window was selected as being typical of its type and a finite element non-linear geometric model using Elfen† using elasto-plastic material properties incorporating frame hardening was made. For the purposes of establishing a base-line analysis, 28 window retention anchors were modelled as shown in Figure 5, the anchors being fitted at 200 mm centres, representing a standard installation fit. The window was loaded with a pressure and impulse

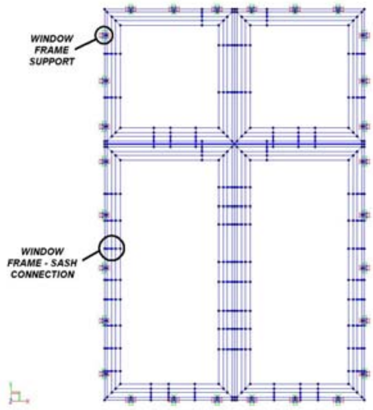


Figure 5: Location of Window Retention Anchors

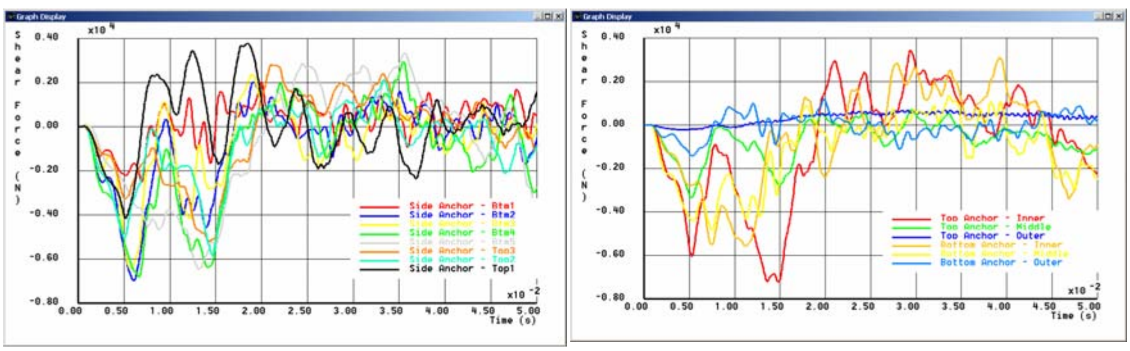


Figure 6: Variation in anchor loading around the perimeter of a blast proof window

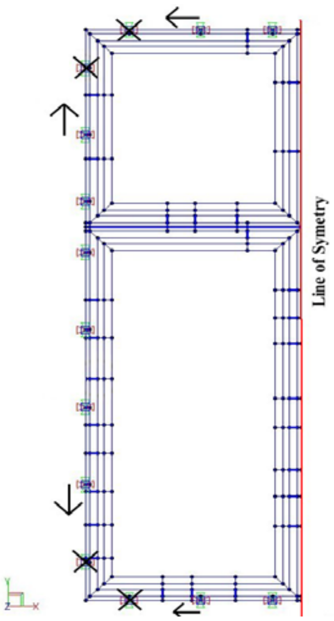
* Rockfield Software Ltd – Powerframe 2 Blast Loading Analysis – Jan 04.

† Written by Rockfield Software Ltd.

combination corresponding to 100 kg TNT at 21 m (P_r = 87 kPa, i_r = 537 kPa-ms), a load the window has successfully survived in a recent live arena test.

The shear stresses in each of the anchors were recorded and the results are shown in Figure 6. There is considerable variation in the level of shear load from one anchor to the next as might be expected. The loads in the top and bottom outer anchors tend towards zero, whilst those in the inner anchors, corresponding to the mullion location, are high. However, the interpretation is more complex for the side anchors, where the highest loads are not at the transom location, as might be expected, (side anchor top 3 and side anchor btm 5), but at the mid point of the longest side span (side anchor btm 2-4). Clearly, the forces in the anchors are significantly affected by frame geometry and aspect ratio.

As 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. These anchors were then repositioned as shown in Figure 9. Firstly it was necessary to ensure that the removal of the eight anchors did not adversely affect the performance of the frame. Analysis of the deflection at the intersection of the mullion and transom shows that both models have a similar response and the conclusion is that the modified model



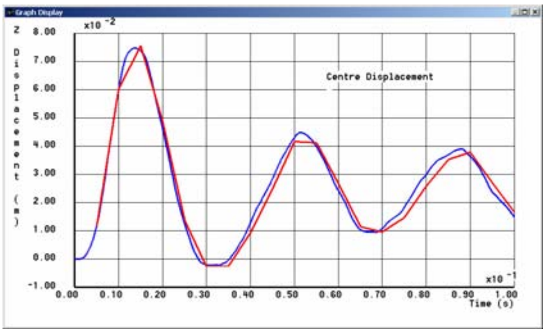


Figure 7. Repositioned anchors and centre displacement

with the reduced anchor positions does not produce adverse affects.

Comparing the output from both the original 28-anchor analysis and the modified 20-

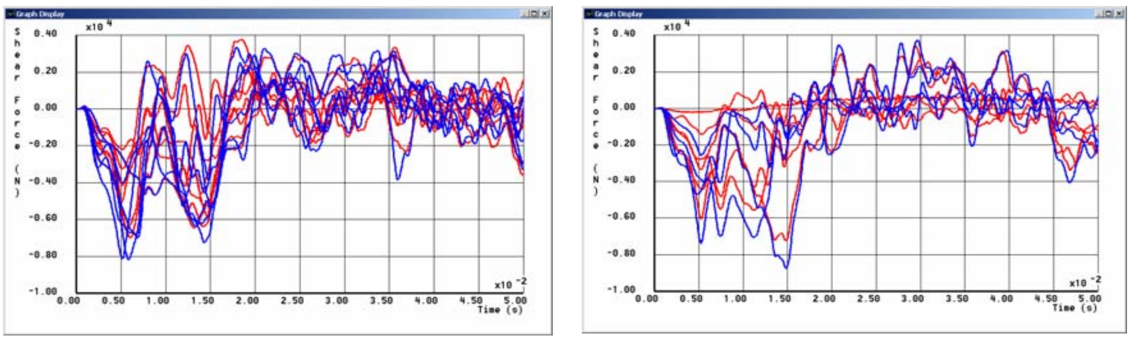


Figure 8: Comparison of shears forces in the top and bottom anchors (left) and the side anchors (right). Original 28 anchors in red; modified 20 anchors in blue.

anchor analysis, although the individual anchor loads have increased (by an average of 8%), the increase is hardly significant. As the frame performance (central deflection) remains the same, a useful conclusion is that the number of anchors could be reduced even further, providing the edge deflections remain within tolerance. This potential reduction in anchors could represent a significant saving in overall costs and the time taken to install the windows. The results of both analyses are shown in Figure 8.

6. WALL STRENGTHENING

In most installations it will also be necessary to strengthen the surrounding wall. Techniques for so doing have been discussed extensively in a previous paper by the authors (Jordan and Ward, 2004) in which, also, the experience gained in Australia in recent years in strengthening masonry for earthquake resistance is highlighted; the techniques for masonry wall strengthening required for earthquake and blast resistance are similar. One design study done recently by one of the authors (Ward) for a hospital in Korea showed the seismic and blast anchoring requirement to be the same, using the assumption that the two events would not coincide.

7. 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. He 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.

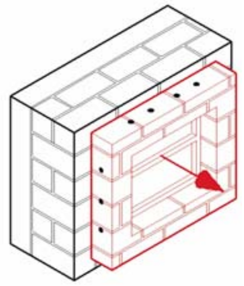
Many blast resistant anchor systems are generically over designed. Fixing at nominal 200 to 300 mm centres simply means there are too many anchors, many of which will never be loaded to their true capacity. Such a practice, whilst conservative is wasteful and uneconomic and will increase the possibility of key anchors being installed incorrectly as hard-pressed installers struggle to keep up with required rate of installation. Reducing the number of anchorages to a rigorously designed minimum will help to eliminate the possibility of error and reduce installation costs and times accordingly.

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 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.

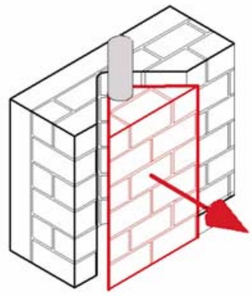
8. REFERENCES

Ward, S.P. and Jordan, J.W., Retrofitting existing masonry buildings to resist explosions, Australian Journal of Multi-Disciplinary Engineering, Special Edition “Engineering a Secure Australia”, Institution of Engineers Australia, 2004, pp. 81 – 87.

Appendix A – Modes of masonry anchor failure.

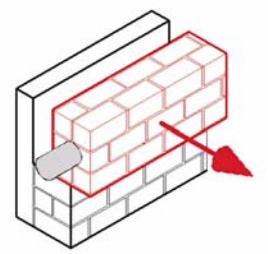


Perimeter Shear Failure – this mode of failure is normally associated with relatively shallow (short) anchors equally placed around the perimeter of the window within a relatively thin wall section. The normal failure plane moves outward from the edge of the window reveal to a line common with the ends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

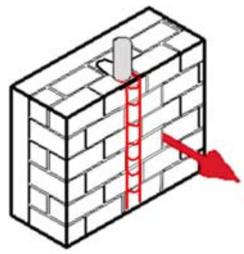


Masonry Shear Failure – this is a primary mode of failure and can occur in both the horizontal and vertical planes. The shear load in the anchor body exceeds the tensile capacity of the substrate retaining the anchor in the plane of the wall. Placing the anchors deeper (further away) from the rear face of the masonry can help alleviate the problem.

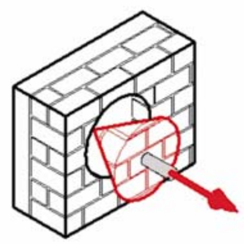
Anchor body shear failure – another common type of failure, particularly where inferior quality anchors are placed within a strong substrate or where very little of the blast wave energy is absorbed by the flexing of the glass and frame as can happen when ballistic glass is subjected to a blast load.



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 storey construction being the most vulnerable. The solution is either to artificially increase the amount of vertical load by use of post-tensioned masonry anchors inserted vertically in the plane of the wall or by stitching 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 as well as increasing the anchor length.



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 statement is obvious.