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DYNAMIC BEHAVIOUR OF CHEMICAL ADHESIVE ANCHORS IN MASONRY

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ABSTRACT

The Oklahoma City bombing and World Trade Centre attacks have alerted governments worldwide to the recurrent problems of terrorism. Research has shown that annealed glass breaks into high velocity shards (“knives and daggers”), which cause most of the injuries sustained during a blast explosion event.

Currently, building owners with property in high-risk areas upgrade exterior windows with an anti-shatter film. Anti-shatter films possess high strength and deformation capacities and prevent glass breakage into shards. When film is installed as a “daylight” application, glass breaks into one unit held together by the film while in the wet-glaze or mechanically anchored applications, where the film is anchored to the window frame, blast loads are transferred to the façade backup structure through the window frames.

In order to securely fasten window frames to the exterior façade, chemically bonded adhesive anchors are proposed. The behaviour of adhesive anchors in masonry is, however, not very well documented, while their dynamic behaviour to impulse type loading is totally lacking.

An experimental program designed to study the behaviour of adhesive anchors embedded in masonry has been completed. The adhesive anchors were exposed to impulse-type loading in a specially designed drop-mass loading frame. The anchors were tested in pure tension and combined tension – shear configurations in single masonry units.

The test results show that hollow clay brick is too brittle for use in blast-mitigation applications with a dynamic load factor of 0.6. Concrete masonry block showed a marginal increase in capacity under impulse type loading. Dynamic load factors of 1.0 and 1.1 are recommended for the design of adhesive anchors with normal and 45^{o} concrete block penetration, respectively.

KEYWORDS: Blast Mitigation, Explosion, Impulse Load, Anchors, Anti-shatter film.

INTRODUCTION

The Okalahoma City bombing and World Trade Centre attacks have alerted governments worldwide to the recurrent problems of terrorism. In past terrorist attacks, building structures proximate to the explosion events have been reported to suffer window glass breakage. The shattered glass is responsible for a large percentage of injuries to occupants in many explosion incidents [1]. In order to mitigate blast hazard effects on building occupants, property owners upgrade the exterior windows with an anti-shatter film. Anti-shatter films consist of a polyester-based material coated with adhesives. They have high strength and flexibility and their ease of installation, customization, and economy have contributed to their wide scale use in blast-mitigation applications. The reported minimum tensile strength and ultimate strain of anti-shatter film are 172 MPa and 120 %, respectively.

Three methods commonly used for application of anti-shatter film to windows are daylight, wet glaze, and mechanical anchorage. In the daylight application the film is bonded to the glass and terminated a few millimetres from the window frame. In the wet-glaze application the film is attached to the window frame with a high strength sealant (structural silicone) while in the mechanically attached application the film is mechanically fastened to the window frame with screws and/or battens.

The daylight application is usually not used in isolation as the glass breaks into a single massive unit with more potential for causing severe trauma to occupants. Daylight application can be coupled with catch cords or catch bars to mitigate the intrusion of the filmed glass into the building. With the wet-glaze and mechanically attached applications, the window frames are anchored to the façade backup structure in order to prevent the window, together with frame, from dislodging into the interior of the building and to transfer the blast loading from window frames to the façade backup structure.

Chemical adhesive anchors are proposed for fastening window frames to the façade backup structure because they are widely used in the construction industry and have become a much more economical substitute to cast-in-place anchors and through bolts. Until recently, the literature contained few references to the performance and behaviour of chemical adhesive anchors. The scant information available is provided by anchor manufacturers and generally comprises tests conducted under monotonous tension, with safety factors applied to the failure load to provide guidelines to designers. These tests are performed in concrete substrate materials. No information is available for adhesive anchor performance under dynamic loading or in masonry substrate materials.

This experimental program follows another initiated at Carleton University [2], to study the static behaviour of adhesive anchors embedded in masonry, and is designed to provide information about adhesive anchor performance in masonry under impulse-type loading. The results have been compared with the Carleton University study to establish dynamic load factors (DLF) that can be applied to the static capacity of adhesive anchors embedded in masonry to take advantage of the increase in strength of steel under impulse type loading and to provide safe and economical designs for blast mitigation applications. The DLF is defined as the ratio of the dynamic capacity to the static capacity of adhesive anchors.

EXPERIMENTAL SETUP

The dynamic loading was designed to simulate blast loading on steel anchors embedded in concrete masonry blocks and hollow clay bricks. The steel anchors were bonded to the substrate by using a commercially available epoxy-based adhesive. The test parameters consisted of two anchor diameters (6.4 mm and 9.5 mm), two anchor penetration angles into the substrate (45^o and 90^o), and varying embedment depths. Table 1 presents the test matrix for the experimental program.

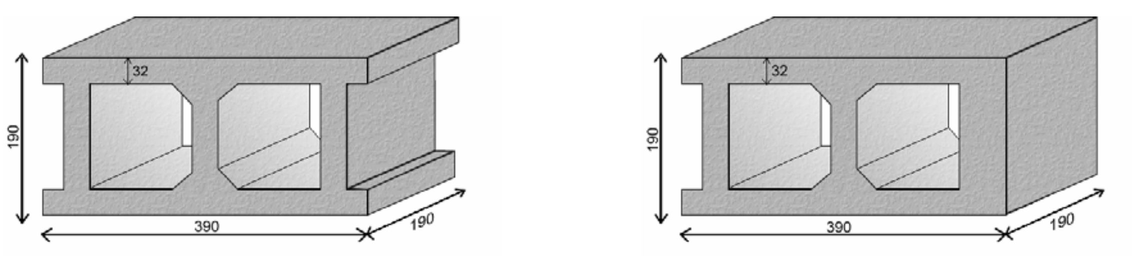
The test specimens were prepared in the laboratory and tested in a specially designed drop-mass test frame. The test frame generated impulse loads similar in duration to typical blast loads transferred to window frames [3].

Table 1 - Experimental Test Matrix

Substrate Material	Embedment Length (mm)	Number of Samples Tested			
		9.5ϕ Anchor		6.4ϕ Anchor	
		90^o Angle	45^oAngle	90^o Angle	45^o Angle
Hollow Brick	28	12		8	
	63	11		8	
	40		9		10
Concrete Masonry Units	35	9		9	
	55	7		8	
	49		8		6
	77		8		8

Material Properties

The epoxy-based adhesive (Epcon G5) is manufactured by ITW Ramset/Red Head. The adhesive is a two component structural epoxy, consisting of an epoxy resin and an amine-based hardener. The manufacturer reported properties of Epcon G5 are: tensile strength of 30 MPa, compressive strength of 71 MPa, and bond strength to concrete of 23 MPa.



(a) **(b)**

Figure 1 - Dimensions and geometry of concrete block
(a) standard two-core (b) standard bull-nose

Steel threaded rods meeting ASTM A-193 B7 specifications [4] were used for anchors. The threaded rods were installed in accordance with adhesive manufacturer's recommendations. The holes were drilled about 1.6 mm larger than the anchor diameter and blown free of dust with a compressed air gun. To contain the epoxy, a screen was inserted into the drilled holes and partially filled with adhesive. A nylon screen was used for test samples with the 9.5 mm anchors while a stainless steel screen was used for samples with the 6.4 mm anchors.

Two hollow concrete block types: standard two cell block (Figure 1a) and standard two cell block with a flat edge (Figure 1b), manufactured in accordance with Canadian Standards Association (CSA CAN3-A165) requirements [5], were used for concrete masonry block substrate. Auxiliary tests on concrete masonry blocks showed an average compressive strength of 10.5 MPa.

The geometry and dimensions of the hollow clay brick with 38 mm core diameter are shown in Figure 2. Auxiliary compression tests, in accordance with ASTM C67-89a [6] were performed to determine the compressive strength of the hollow clay brick. The average compressive strength of hollow clay brick was 38.5 MPa.

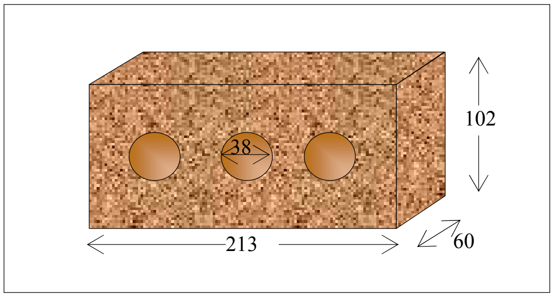


Figure 2 - Dimensions and Geometry of Hollow Clay Brick

TESTING

The drop mass test frame, shown in Figure 3, consisted of four W150x22 steel columns supported on W530x92 steel beams and attached to a 25 mm thick steel plate (PL 25x700x550) at the top. A 50 mm diameter hollow steel rod served as a guide for a falling mass. At the bottom of the guide rod, a preloaded force ring (compression cell) with a 25 mm thick neoprene pad formed an anvil assembly for the falling mass. The force ring recorded the impact load from the drop mass, while the neoprene pad dampened the load to achieve a load profile that closely relates to blast loads on window frames [7].

The guide rod was suspended from a tension force link transducer (tension cell), which was connected to the test sample through an adaptor. The force link recorded the load applied to the anchor from the drop mass striking the anvil assembly.

The test procedure consisted of loading a test sample onto 50 mm x 50 mm steel bar supports on top of the test frame structure. The steel anchor rod was attached to the guide rod through a steel coupler. A Linear Variable Differential Transformer (LVDT) was incorporated to measure displacements. The LVDT measured the combined slip and elongation of the steel anchor rod. If the anchor system failed, the guide rod and drop mass were designed to free-fall over a predetermined distance onto a catcher system.

The load registered at the compression cell represents the input load while the load recorded at the tension cell represents the input load to the adhesive anchor – substrate system. Test samples surviving the drop test were tested statically in a universal loading machine to determine their residual static capacity. The residual static capacity was compared to the static strength of virgin samples to establish the level of damage on the samples. The compression load, tension load, and displacements were recorded with a Yokogawa digital storage oscilloscope.

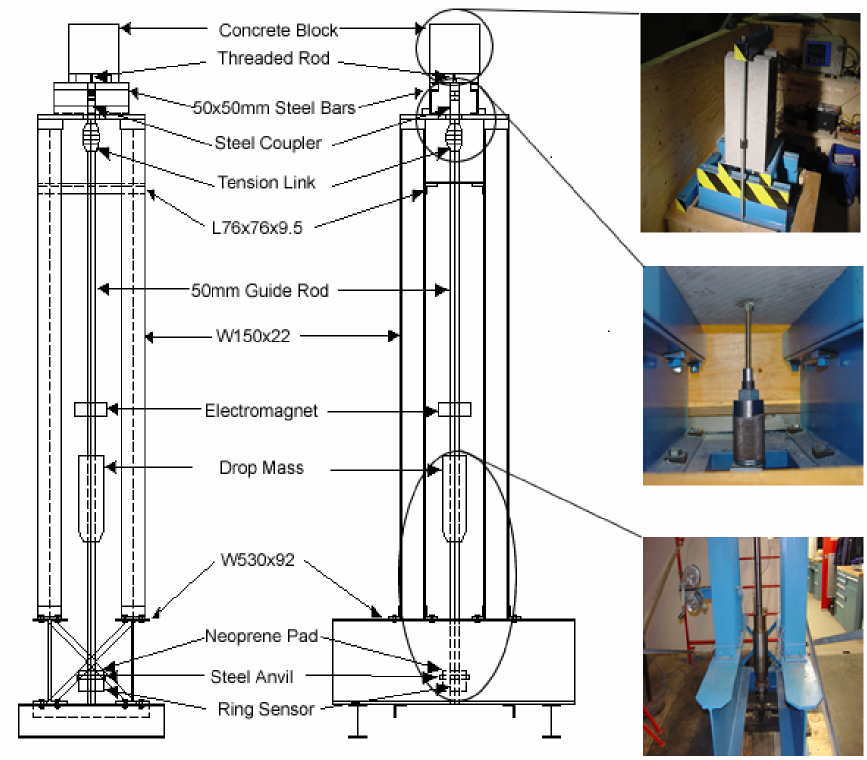


Figure 3 - Drop Mass Test Frame

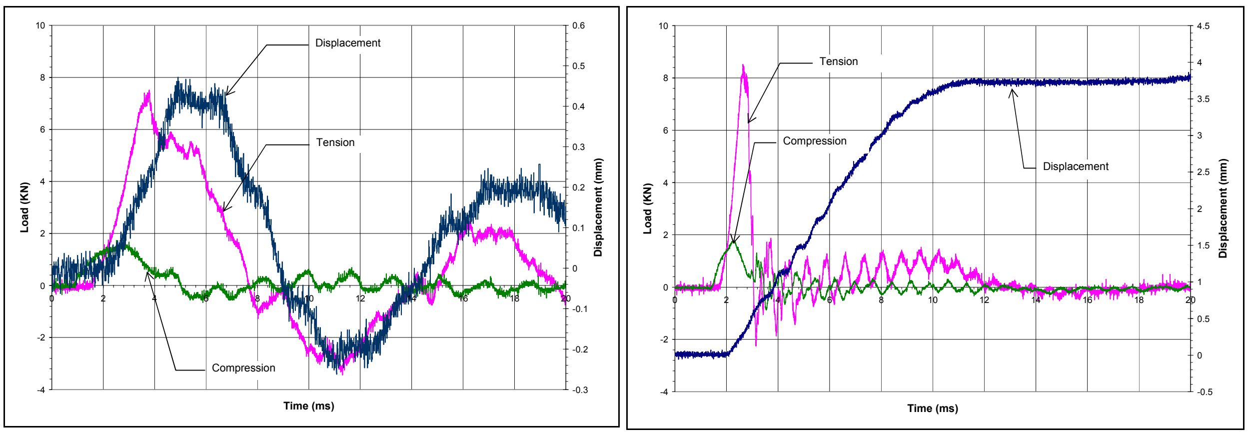
RESULTS AND DISCUSSION

Exposure to the impulse-type loading resulted in two main failure modes: steel anchor pullout, and substrate fracture. The test specimens that did not fail exhibited a level of damage dependant on the applied load level. This damage was either partial pullout of the steel anchor from the substrate material or cracking/spalling of the substrate material around the steel anchor. Residual static tests were performed to quantify this amount of damage.

Figure 4 presents typical load and displacement profiles for the adhesive anchor – substrate system. Figure 4(a) indicates that when the system sustained no visible damage, load and displacement profiles oscillate about, and return to, the original position. When the adhesive anchor – substrate system failed by cracking or splitting, however, a progressive linearly increasing displacement is observed (Figure 4(b)) until the guide rod/mass comes to rest on the catcher system.

The peak loads from the tests were determined from the load profiles of the tension cell while the impulse was found as the area under the tension load profile, up to the point of failure. This imposed peak load was compared to the static failure loads to establish a dynamic load ratio (ratio of applied dynamic peak load (tension load) to the static failure load). The dynamic load ratios (DLR) were subsequently used to establish DLF that could be applied to the static capacity to achieve a safe and economical design of anchor systems that could potentially be subjected to impulse-type loading.

Unlike the static strength of a structural element, the dynamic strength is dependent on the rate of loading. In the case of blast loads, the ratio of the positive phase duration (t_d) of the blast overpressure to the fundamental period (T) of the structure determines the load regime in which failure occurs. There are three possible load regimes, impulsive ($t_d/T<0.0637$), dynamic ($0.0637<t_d/T< 6.37$), and quasi-static ($t_d/T>6.37$) [8]. In the quasi-static regime, the failure is governed by the strength of the element while in the impulsive regime it is governed by the energy absorption capacity or ductility of the element. In the intermediate (dynamic) regime, a dynamic analysis is required to establish the behaviour of the system.



(a) (b)

Figure 4 - Typical Load and Displacement Profiles of Clay Brick Substrate (a) No Failure (b) Cracking Failure

In order to determine the regime of adhesive anchor – substrate system behaviour, the natural period of the system was estimated and compared with the duration of load. The comparison showed that the systems tested, in most cases, behaved in the dynamic or quasi-static regimes. Thus treatment of the problem with a DLF is appropriate.

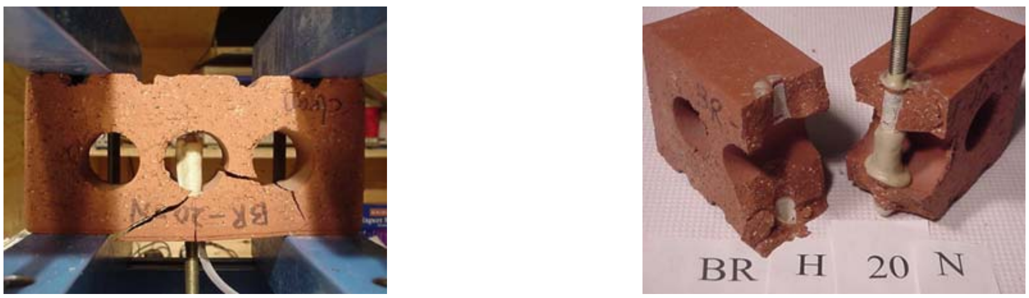
Adhesive Anchors in Hollow Clay Brick Substrate

An 8 kg drop mass was used to impart impulse-type loading to the adhesive anchor – brick substrate assembly. The three embedment depths studied were anchor embedment in one face shell (Figure 5(a)) of brick (28 mm), two brick face shells (63 mm), and embedment in one face shell at 45^o (Figure 5(b)) substrate penetration angle (40 mm).

The observed failure modes of the adhesive anchor – brick substrate system were predominantly by splitting or cracking of the clay brick. Test samples that failed by cracking of the substrate developed cracks around the supports and these cracks progressed toward the anchor location, breaking out a pyramidal piece of substrate from the face shell (Figure 6(a)). With failure by splitting of the clay brick substrate, however, the cracks formed across the face of the brick at the location of the steel anchor, splitting the substrate in two halves (Figure 6(b)).

(a) (b)

Figure 5 - Anchor Placements in Hollow Clay Brick
(a) Normal substrate penetration (b) 45^{o} substrate penetration



(a) (b)

Figure 6 - Failure Modes of Hollow Clay Brick

Table 2 presents a summary of the test results for the adhesive anchor – clay brick substrate system. The ratio of load duration to natural period of the system was, mostly, in the dynamic regime range [3]. The maximum dynamic load recorded during the drop test was compared with the static failure load of companion virgin test samples to establish the DLR. The peak load that caused failure of the anchor-substrate system varied with the DLR ranging from 0.8 to 1.9.

Adhesive anchor – brick substrate system with 6.4 mm anchor, 28 mm embedment and 90^{o} substrate penetration exhibited a minimum DLR of 1.0. Increasing the embedment depth to 63 mm resulted in a reduction of the DLR to 0.8. Systems with 9.5 mm anchor and normal substrate penetration angle exhibited a minimum DLR of 0.9 at 28 mm embedment depth which reduced to 0.6 with an increase in embedment depth to 63 mm. Changing the substrate penetration angle from 90^{o} to 45^{o} resulted in a marginal effect on the DLR.

Table 2 - Minimum Dynamic Load Ratios of Anchor in Hollow Clay Brick Substrate

Anchor Diameter (mm)	Embedment Length (mm)	Penetration Angle (degrees)	Minimum DLR
6.4	28	90	1.0
6.4	63	90	0.8
6.4	40	45	0.9
9.5	28	90	0.9
9.5	63	90	0.6
9.5	40	45	0.9

Adhesive Anchors in Concrete Masonry Substrate

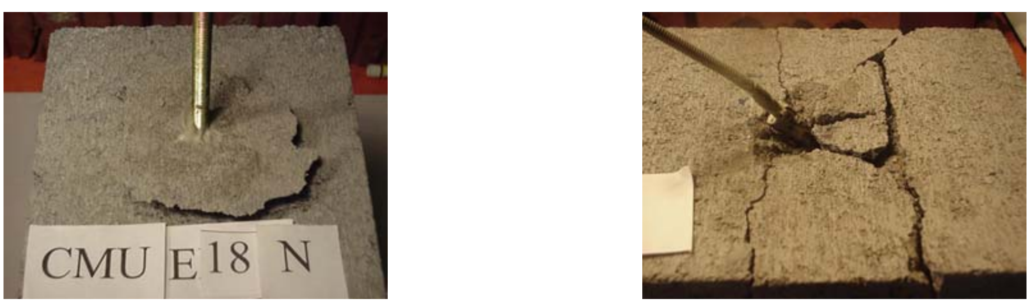
The standard two-cell 190 mm concrete block had the anchor embedded into the side, through the face shell (Figure 7(a)), with 35 mm embedment, while in the 190 mm standard two-cell concrete block with flat end the anchor was embedded into the end (Figure 7(b)), with 55 mm embedment. For 45^{o} substrate penetration angle, the embedment depths were 49 mm and 77 mm for the standard two-cell block and standard two-cell concrete block with flat end, respectively.

Figure 8 shows photographs of the failure modes of adhesive anchor – concrete masonry block substrate. The observed failure modes were either combined cone-bond pullout failure (Figure 8(a)) or cracking and splitting of the concrete block (Figure 8(b)). Combined cone-bond pullout failure consisted of cracking and formation of a shallow concrete cone on the surface and pullout of the anchor from the substrate. Cracking and splitting on the other hand began with a crack at the anchor location, which progressed and penetrated the full depth of the concrete block face shell.

(a) **(b)**

Figure 7- Anchor Placement in Standard Hollow Concrete Block

Another mode of failure observed with the concrete masonry block was bond failure between the adhesive and substrate. This bond failure however, never produced complete pullout of the anchor as the chemical adhesive in the screen formed an adhesive bulb below the face shell that prevented progressive pullout of the steel anchor.



(a) **(b)**

Figure 8 - Failure Modes of Concrete Masonry Block

Impulse-type loads were also generated with an 8 kg drop mass in this test series. Table 3 presents the DLR of adhesive anchor – concrete masonry block substrate tests. The ratio of load duration to natural period of the adhesive anchor – concrete masonry substrate system was within either the dynamic or the quasi-static regime range [3]. Thus, the peak load was compared with the static capacity to establish the minimum DLR that caused failure of the system.

The DLR for the 6.4 mm anchor in concrete masonry block substrates was 1.0 at 35 mm embedment (standard two-cell block) and reduced to 0.8 for 55 mm embedment (standard two-cell block with flat edge). The DLR for the 9.5 mm anchors was 1.2 and for the increased embedment depth of 55 mm increased to 1.6. In general the DLR increased with an increase in the adhesive anchor diameter. Changing the substrate penetration angle from 90^o to 45^o resulted in marginal effect on the DLR.

Table 3 - Minimum Dynamic Load Ratios of Anchor in Concrete Masonry Block Substrate

Anchor Diameter (mm)	Embedment Length (mm)	Penetration Angle (deg.)	Minimum DLR
6.4	35	90	1.0
6.4	55	90	0.8
6.4	49	45	1.3
6.4	77	45	1.5
9.5	35	90	1.2
9.5	55	90	1.6
9.5	49	45	1.1
9.5	77	45	1.4

CONCLUSIONS AND RECOMMENDATIONS

The experimental program was designed to investigate the effect of impulse-type loading on adhesive anchors embedded in masonry substrate materials. A drop mass test frame was developed to simulate dynamic loads generally associated with blast loading on film-retrofitted windows. The tests reported in this paper considered anchors embedded into single masonry units. Future testing will look at the effects of masonry assemblages on the dynamic behaviour of the adhesive anchors. Using single masonry units limited the edge distances to about half the masonry widths. In tests with anchors embedded in masonry assemblages, the edge distances will be increased and the effect of edge distance on adhesive anchor performance will be evaluated.

DLR was defined, as ratio of applied dynamic peak load to the static failure load, to determine a safety factor (DLF) that can be applied to the static capacity of adhesive anchors in masonry substrate materials to provide safe and economical designs.

Although the performance of only one adhesive was evaluated, and it is strongly recommended that the behaviour of other adhesive types under impulse loading be investigated, the following principal conclusions can still be made:

1. The DLR changes marginally with a change of substrate penetration from 90^o to 45^o
2. Clay brick substrates are very brittle and lead to lower DLR
3. The adhesive bulb below the concrete block masonry face shell enhances the dynamic capacity of the anchors after bond failure
4. Increasing the adhesive anchor diameter from 6.4 mm to 9.5 mm resulted in increased DLR

In addition, the following DLF are recommended for design of adhesive anchors in masonry substrates:

1. DLF for adhesive anchors in clay brick substrate is 0.6
2. DLF adhesive anchors in concrete block masonry substrate with normal substrate penetration is 0.8
3. DLF for adhesive anchors in concrete block masonry substrate with 45^{o} substrate penetration is 1.1

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