Vulnerability of Reinforced Concrete Structural Elements to Internal Explosions

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Introduction

International terrorism has made the civil environment a battleground not bound by international treaties. Explosions are the most widely used method to inflict terror to the masses and terrorists have refined their tactics and perfected their methods over the years. Shaped charges have already been used successfully by insurgents in Iraq proving that attacks using explosives are indeed sophisticated and the know-how to inflict maximum damage exists. A terrorist attack where the damage inflicted upon a structure is disproportionate, compared to the size of the explosion, is not something new. There are examples where the disproportionate collapse of the structure may have caused more loss of life than the explosion itself. As buildings become icons, the danger of an attack targeting the building itself is ever greater. Modern building designers are now forced to consider the effects of intended explosions and how the risk of a catastrophic collapse can be mitigated.

In the event of an attack that jeopardises structural integrity, the damage must be rapidly evaluated in order for the safety of responding rescue personnel to be ensured. This must be carried out quickly but effectively as minutes lost could amount to great loss of life. If vital infrastructure is attacked, disruption to key services must be kept to a minimum, requiring rapid assessment of the damaged structure in order for repairs to be carried out.

In order to comprehend the mechanism of collapse one must first understand the behaviour of individual structural elements under explosive loading as their combined failure initiates and sustains the collapse process. In addition to this, several key elements may also be targeted individually in order to trigger an "Implosion" type of collapse.

Scope

While there are several publications discussing the response of structures to explosions taking place both outside as well as inside, the response of individual elements to explosive loading is seldom investigated from the protective point of view. On the other hand there are studies and publications dealing with the demolition of reinforced concrete members. Therefore in order to get better insight into the mechanics causing damage to individual members, the subject is better approached from a demolition point of view.

Military manuals and civilian publications take into account the physical characteristics of an element in order to calculate the mass of explosive that will cause an explosion large enough to destroy it. They range from simple methods considering only the physical size and the general material class, U.S. Department of the Military [1] to more specialised and systematic approaches that takes into account individual explosive characteristics, the explosive element interaction (coupling), and the specific physical properties of the materials being exploded, Berta [2].

It is recognised that in the case of reinforced concrete, elements might have the same detailing and dimensions but the one factor that is almost always different, is the level of load imposed upon them prior to the explosion. This article is intended to illustrate how different load conditions affect the post-blast residual strength of reinforced concrete elements under static loads.

Explosive tests were carried out on small scale reinforced concrete columns. These where blasted internally using SEMTEX H plastic explosive. The charge was placed in the centre of the column in contrast to the outside for various reasons. A charge in the centre of an element will produce a shockwave propagating spherically from the centre to the outside. As the charge is at the centreline of the element and the column is axisymmetric, it does not cause any macroscopic effects associated with non-axisymmetrically placed charges that will induce bending of the element. Most of the explosive energy is expended in causing damage to the surrounding concrete (good coupling). In contrast, the damage levels induced by an external charge are greatly influenced by the method of attachment as well as the density of air. And not insignificantly for the present study, the axisymmetry simplifies the subsequent theoretical analysis.

Description of tests

Small scale reinforced concrete columns of 150 mm diameter have been tested. Tests were carried out on unloaded specimens as well as specimens statically loaded in uniform axial compression up to the level of 200 kN. This particular load was chosen as it is around 20% of the anticipated undamaged strength of the elements. For the initial test programme circular cross-sections were chosen because the shape favours simple propagation and reflection patterns which will be more amenable to ongoing theoretical work. The length of the test columns was 580 mm, which is short enough for the elements to be easily manageable in a laboratory environment, but long enough to show the full extent of any post blast damage patterns free from any effects of end support conditions. The strength of the concrete used was somewhat variable but was intended to be 70 N/mm^2. It is recognised that this strength is higher than that recommended in most codes of practice, but initial trials showed that for weaker strength concrete the columns were almost completely destroyed, with even very small amounts of explosive; the test on lower strength concrete for this reason did not yield any useful spread of data. For longitudinal reinforcement, six equally spaced, 5 mm diameter bars were used and 2 mm diameter hoops were placed at 30 mm centres along the column.

Semtex plastic explosive was used as a blasting agent, detonated with standard No. 8 electric detonators. A hole was drilled at mid-length of the column with a 20 mm diameter diamond rotation drill, taking care that reinforcement was not pierced or that vibrations did not cause micro-cracking. The explosive charge was placed at the bottom of the hole corresponding with the centreline of the column. When the experiment required load to be applied to the columns, a purpose built frame was utilised. The load was applied with a displacement controlled hydraulic jack and was monitored with a load cell. Two metal plates were used to install the column into the frame as well as ensure that it remained centred during the experiments.

After the blasts, the columns were removed from the compression rig, photographed, documented and were statically tested to failure under uniform axial compression. Total residual compressive strengths of the damaged elements were recorded.

Experimental Observations and Results

The columns were blasted under both loaded and unloaded conditions with explosive quantities ranging from only a detonator, to a detonator plus 5 g of Semtex. The data points on figure 1 represent averages of residual strengths of separate tests under nominally the same conditions. Residual strengths are represented as a percentage of the compressive strength of undamaged columns.

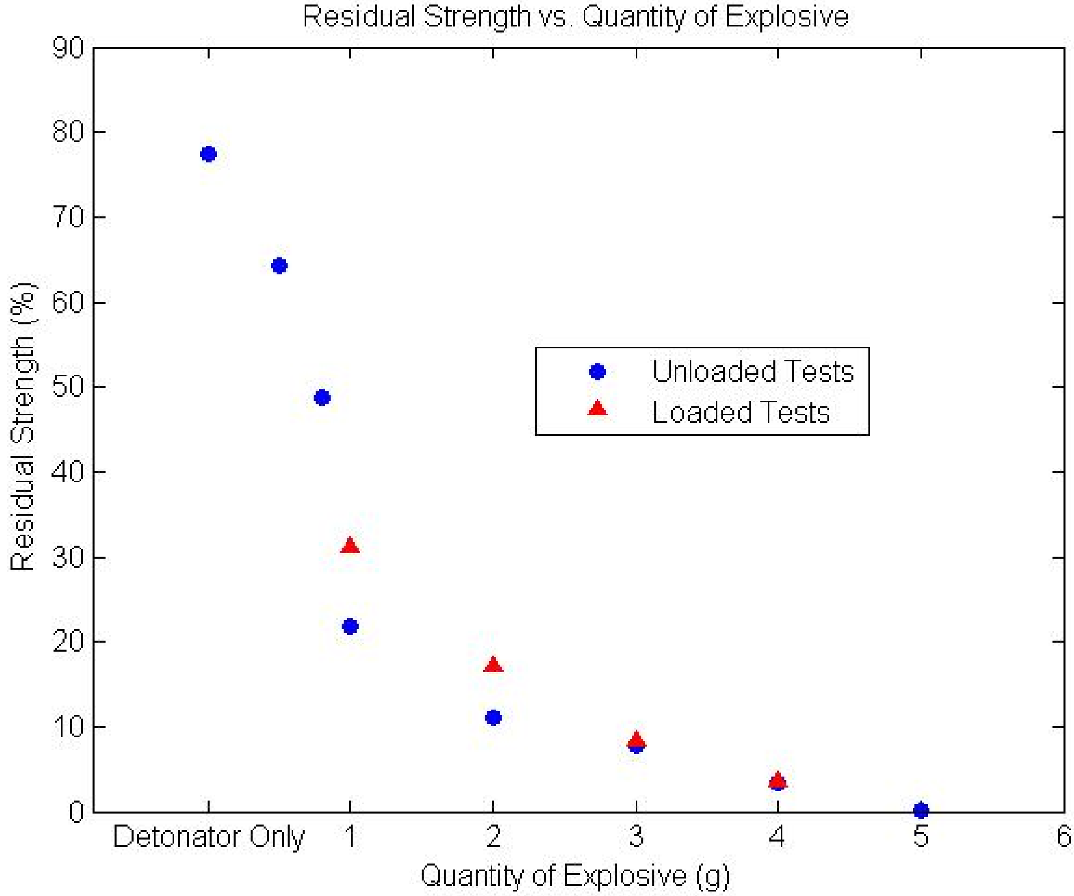

Figure 1: Residual Post-Blast Strength vs. Quantity of Explosive used. The data points represent mean values of experiments conducted under identical conditions.

From figure 1 it is clear that elements blasted under compression retain a greater percentage of their pre-blast strength. This can also be observed in the damage characteristics shown in figure 2 where the greater damage to the column under no load is clearly indicated by the much greater loss of effective concrete section and the blast related bowing out of the longitudinal reinforcement.

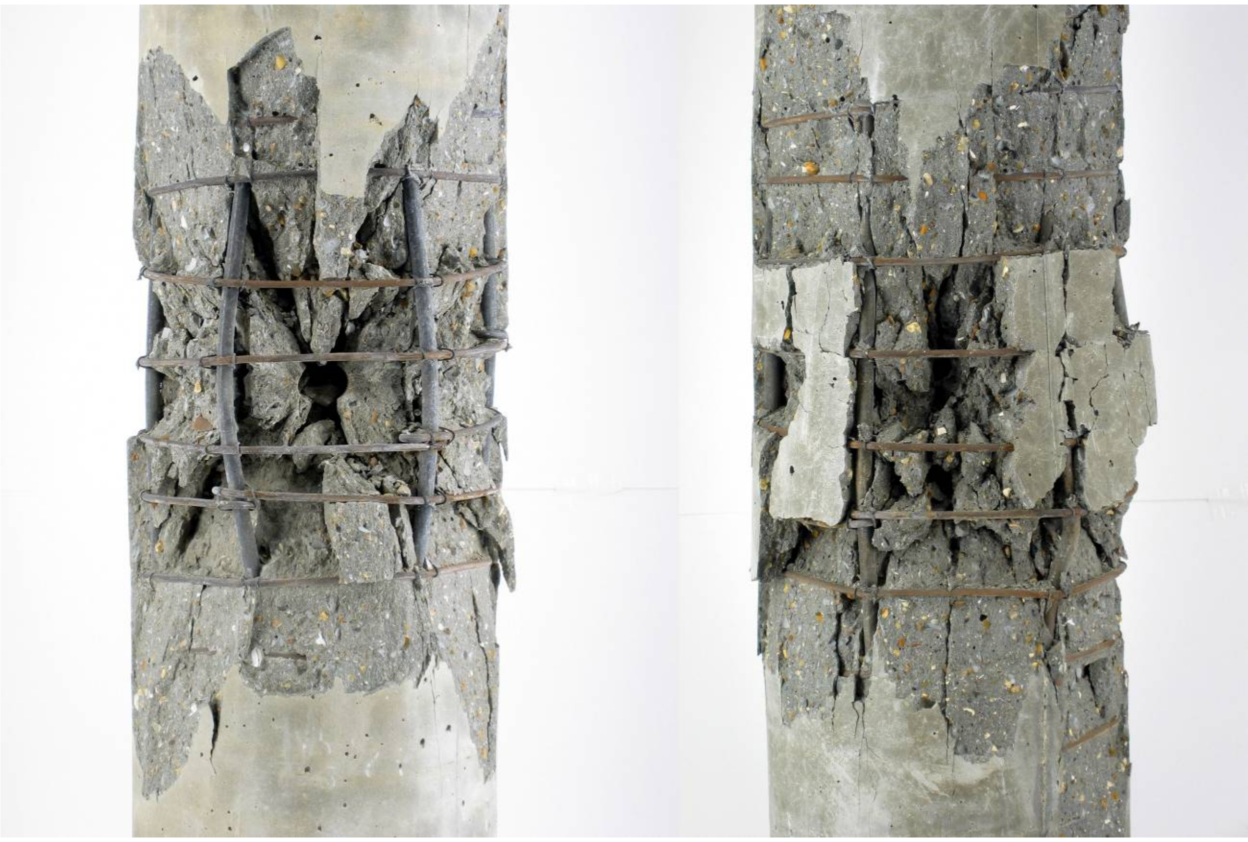

Figure 2: Comparison between two columns blasted with 2 g Semtex, under no load (left) and under 200 kN axial compression (right). Note that the column blasted under load is less damaged.

A single detonator blast, without any explosive, induced cracks and some cover damage on the side where the detonator was inserted (figure 3). This damage is sufficiently small for the column to retain 78% of its strength. In contrast, a 0.8 g explosive charge will reduce the residual strength to about 48%, a 1 g charge will reduce it to merely 22%. This rapid reduction in residual strength with just a slight increase in charge weight indicates that there is a threshold above which any increase in explosive charge weight would simply cause excessive damage to the column. Beyond this threshold any subsequent increase in charge weight can be seen in figure 1 one to induce a much more gradual reduction in residual strength. A column blasted unloaded with 2 g had a mean residual strength 11\% of the undamaged strength and at 3 g, 7.5% of the undamaged strength and finally 4 g retained just 3.5% of the undamaged strength.

Figure 3: Column blast with only a detonator. Some covered has spalled on the insertion side and some cracks have developed around the circumference

For this class of column a 5 g Semtex charge is enough to completely remove the concrete from the cross-section and induce heavier buckling of the reinforcement. For the column shown in figure 4 the element has almost no residual strength.

Columns blasted under 200 kN pre-load show significant increases in residual strength compared with their unloaded counterparts. For low levels of explosive the increase of residual strength in some tests reached 60%. On average the columns blasted with 1 g showed an increase in residual strength of 45% when a compressive load of 200 kN was applied. At 2 g the increase of residual strength was 55% when the column was blasted under load. At 3 g the increase in residual strength by the presence of compressive load was as much as 41% in some isolated tests but the average increase, in all tests conducted with the same explosive charge, was insignificant.

Figure 4: Column blasted with 5 g of Semtex, it is considered to have failed completely!

Figure 5: Close up on the cover spalling, this phenomenon was observed to different extents on all the experiments.

Around the circumference there was clear evidence of concrete having spalled off between the longitudinal reinforcement bars as well as between the hoop rings to create inwardly concave zones both circumferentially and axially (figure 5). This was a regular phenomenon which appeared in different degrees in all the columns that were tested. This damage pattern appears to be a consequence of the shadowing effects from the reinforcement and the greater-than-average reflection of the shock waves from the free concrete surface between reinforcing bars.

Note that even though the drilling of the explosive insertion holes were undertaken with care, any small shift in position would cause considerable change in the location of maximum damage from one side to the other. All the columns were more heavily damaged on the side the detonator insertion holes were drilled.

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Discussion

It has become clear from the above experimental data that there are certain trends in the way reinforced concrete columns behave when subject to internal explosions.

In the unloaded experiments, for elements that are blasted with small quantities of explosive (below 1 g) it can be seen that there is a threshold quantity of explosive above which the effects of the explosion on the residual strength of the element are devastating. From visual observation as well as experimental results this threshold for the present test samples can be placed between 0.8 g and 1 g of Semtex. Beyond this, the decay in residual strength is less extreme, leading to a state of total destruction of the concrete core of the element at about 5 g. The existence of this threshold is significant, since with just a small increase in explosive quantity the residual strength can greatly impaired. For example by doubling the quantity of Semtex, from 1 g to 2 g, the residual strength is only decreased by 10% and a further doubling to 4 g will only decrease by a further 7%. So by quadrupling the original charge of 1 g there is only a reduction of 17% this is in contrast to the original loss of 78% of undamaged strength achieved by just 1 g.

The effects of pre-existing stress conditions have also been made clear. Since structural elements will generally be under some form of load, the behaviour of elements subject to explosions cannot be adequately predicted by just taking into account the physical properties of the element. The difference between the two cases might not seem of great significance but it could make the difference between a full and a partial collapse. The increases in residual strength when members have pre-existing compressive loads, would appear to be sufficiently large that they should be taken into account. This implies that use of any empirical guideline to define the threshold level of charge, based upon the behaviour of columns not containing pre-existing stress could underestimate the charge level that an element can withstand when under axial compressive stress.

While increases in the residual strength of an element due to pre-compression has been made clear, there remains an additional issue as to the effects of tension on both the damage mechanism and the residual strength. If tension has the opposite effects to those displayed by compression, by reducing the residual strength, then this could be used to advantage in the dual stress condition case of bending. With the possibility that for a given charge level more damage would occur on the tension side. This may possibly be utilised in protective design to predict collapse mechanisms; by indicating locations of maximum damage and possibly controlling the direction of buckling of certain elements in order to disrupt and even avoid collapse.

Conclusion

Even though specific structural elements have not yet been targeted by terrorist, their behaviour during internal explosions may be an important aspect in the understanding the nature of failure during intentional explosive attack. Understanding the mechanics of failure should help to produce safer and more robust designs. In the case of evaluating structures after terrorist incidents this understanding could also make a difference between characterising a structure as safe or loosing valuable time for unneeded remedial measures and possibly delaying rescue.

Pre-existing compression loads during the blasting of column elements have been shown to increase the residual post-blast strengths, an effect that could be crucial to protective design and post-blast evaluation. In addition to this, the presence of an explosive level threshold above which the damage is detrimental to the element, suggests that the principle of prescribing a mass of explosive a structural element can withstand should be a product of scientific study and not an extrapolation of limited empirical data. Even though current protective design practice seems to be satisfactory, there is a strong need for better understanding of the phenomena involved.

It is clear that theoretical work on the physics of the damage mechanisms is the next logical step to this research. A successful analytical model, taking full account of column geometry, concrete properties, reinforcement configurations and load conditions, if properly calibrated by reference to these experimental results, will be of considerable benefit to both protective design and post-blast evaluation.

References

[1] U.S. Department of the Military. *Field Manual 5- 250, Explosives and Demolitions*.
United States Joint Operation Command.

[2] Berta Giorgio. *Explosives: An engineering tool*. Italesplosivi - Milan