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Experimental investigation of cable catcher systems for office building blast protection

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Abstract
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Keywords
cable, investigation, experimental, catcher, systems, blast, office, building, protection

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Experimental investigation of cable catcher systems for office building blast protection

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ABSTRACT
High performance cable catcher systems are an effective means of protecting office building windows and façades from effects of explosive blast. This paper presents experimental results for the response a simple cable catcher system subject to impact loads delivered using a drop-hammer testing facility. The objectives of this experimental programme were to investigate the load-deformation behaviour of steel strand cables and to evaluate the dynamic performance of cable catcher systems in reference to their ability to absorb blast energy. Two steel cable arrangements (compacted and normal spiral strand) have been tensile tested in order to provide load-deformation curves as well as experimental values for the breaking load and Modulus of Elasticity. The cable catcher systems with rigid attachments as well as using simple energy absorbing connections were tested under impact loading. It was found that different cable arrangements have different failure modes while properties such as the cable breaking load and Modulus of Elasticity are vital in determining the capacity and behaviour of cable catcher systems under loading. Through impact testing, it was found that simple energy absorbing devices are highly effective in reducing the tensile force experienced by the cables. These devices limit the force in the cables to below breaking load and also provide a longer impact time which reduces the likelihood of the cables failing, but also slicing the failed glass panel upon impact.

KEYWORDS
Blast resistance; Blast retrofit; Catcher systems.

INTRODUCTION
In the past few decades, especially in recent years, there has been a significant increase in the number of terrorist attacks on an international level. As a result of these attacks, there has been a significant shift to increase the blast resistance of now vulnerable office buildings. There is a strong desire for planners, architects and engineers to develop and implement cost-effective techniques which can be fitted to both new and existing buildings without eliminating their appealing aesthetic features.

Smith (2001) states that around 80% of casualties in blast explosions are a direct result of flying glass debris. Therefore, glass façades and windows are the elements of an office building structure which present the greatest risk to occupants in the event of a blast. It was also recorded that in 1995 bombing of the A.P. Murrah Federal Building in Oklahoma City façade damage was observed on buildings 1.6 km away from the detonation point and hence it is not only the target building which is at risk of damage.

Due to the weak nature of glass in resisting blast loading and its growing use in modern commercial office building designs, there is a strong need to provide measures of high performance protective blast design. High performance protective design utilises the ductile, plastic behaviour of 'non standard' construction materials or the use of 'standard' materials in unconventional ways which are
not obtrusive to the design of modern office buildings (Crawford et al., 2006). High performance cable catcher systems are simple debris containment devices which utilise steel, nylon or high density polyethylene (HDPE) cables to absorb energy presented by the impact of a failed glass surface. The cables used are typically around 8 - 10 mm in diameter but can be as large as 16mm and are fastened either horizontally or vertically behind the glass surface. Cables are spaced according to the specific geometry of a glass panel with a minimum of 2 cables being used per panel. In an explosive event, the glass section is likely to fail and break free from its frame impacting on the cables which consequently deflect, transferring loads to the supporting structure while preventing the glass panel from entering the building. Energy absorbing anchorages can also be used to absorb impact load, prevent cable overload and reduce the shear force applied to the projected glass panel. Reducing the shear force directly reduces the risk that the cables will slice the glass panel, which if occurred, could result glass debris entering the building. Cable catcher systems need to be used in conjunction with anti-shatter films or laminated glass which will keep fractured glass together allowing it to make contact with the cables as a single unit.

The experimental programme described in this paper aimed to investigate the effectiveness and energy absorption capabilities of cable catcher systems when used as a method of protecting occupants against the effects of external explosive blasts on glass façades in office buildings. The experimental investigation intended to increase understanding and the performance of these systems through two stages of experiments. The first stage consisted of obtaining load-deformation curves and stress-strain properties of different steel strand cables and the second stage utilised impact testing of a simple cable catcher system with both rigid and energy absorbing connections.

CHARACTERISATION OF CABLE PROPERTIES

These tests aimed to identify the load-deformation relationship for steel strand cables through a tensile load test. Knowing the load-deformation relationship will provide a better understanding of the tensile load response of steel strand cables as well as providing an experimental value of the Modulus of Elasticity (E) and breaking loads.

The 'Instron' tensile load machine (Model 8033) located in the High Bay Laboratory at the University of Wollongong was used to complete this testing. Two different cable types (arrangements), Spiral and Compacted (see Figure 1) were tested until failure. Each cable type had a different Modulus of Elasticity and breaking load value and the experimental values achieved for these properties were compared to manufacture's values and also used in the analysis of results for the impact testing of a cable catcher system which is presented later in the paper.

![Figure 1. Cable arrangements: (a) spiral; (b) compacted; (c) cable failure mode.](image-url)
The two different cables that were tested were a 10mm Compacted strand 1x 19 arrangement Grade 316 steel cable and a 10mm Spiral strand 1x 19 arrangement Grade 316 steel cable. The Compacted strand cable is essentially prestressed however, the conventional Spiral strand requires pre-stretching before use and therefore to obtain the most accurate experimental value for $E$, the test specimens were loaded from 0 to 75% breaking load three times before loading until failure.

**Cable properties results**
Experimental results were compared to manufactures values for the Modulus of Elasticity and breaking load of the each cable type as seen in Table 1. The differences obtained in the breaking load are most likely due to a manufactures factor of safety. The ultimate load has been determined in these tests whereas, the factored breaking load is the value specified by the manufacturer and therefore higher loads have been obtained.

Table 1. Summary of tensile testing results

<table>
<thead>
<tr>
<th>Test</th>
<th>Cable Property</th>
<th>Modulus of Elasticity (GPa)</th>
<th>Breaking Load (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Theoretical</td>
<td>Experimental</td>
</tr>
<tr>
<td><strong>Spiral 1</strong></td>
<td></td>
<td>107.5</td>
<td>90.6</td>
</tr>
<tr>
<td><strong>Spiral 2</strong></td>
<td></td>
<td>107.5</td>
<td>90.2</td>
</tr>
<tr>
<td><strong>Compacted 1</strong></td>
<td></td>
<td>133.7</td>
<td>97.1</td>
</tr>
<tr>
<td><strong>Compacted 2</strong></td>
<td></td>
<td>133.7</td>
<td>98.2</td>
</tr>
</tbody>
</table>

The results obtained during experimental stage 1 clearly show the behaviour of different steel cables under tensile load. The different cable behaviours are a result of different cable properties such as cable arrangement, Modulus of Elasticity and breaking load. A comparison of the two different cables types tested and their behaviour under tensile load can be seen in Figure 2.

![Figure 2. Experimental load-deformation curves for cables.](image-url)

It can be seen from Figure 2 that the two different cable types are easily distinguished. It is obvious that the compacted strand clearly possesses a higher breaking load but also has a significantly different failure mode. The spiral strand cable is able to support load during failure however, the compacted strand experiences a more sudden and consequently 'brittle' failure. It was observed that that the failed Spiral strand had a significant number of individual strands which had failed before the specimen failed entirely and could not support any additional load. This was compared to the
compacted strand which only one or two individual strands had failed causing immediate failure of the entire specimen.

The compacted strand is constructed from 19 different size individual strands whereas the spiral strand comprised of 19 equal individual strands. The outer strands in the compacted arrangement are considerably larger in diameter than individual strands in the spiral arrangement and it is these larger strands which have failed first leading to the sudden failure observed. These results highlight that different cable properties can result in different failure modes of steel strand cables. These failure modes need to be considered when designing cable catcher systems especially in reference to the energy absorbing device/anchorage. The compacted strand failure mode is not particularly favourable however, the cable can support a higher breaking load. This is compared to the spiral strand cable which has a more favourable failure mode but as a result has much larger cable deflections and an overall lower breaking load. It is these properties which influence the energy absorption ability of the cables and hence it is vital that the cable and energy absorbing device interaction under load is strongly considered in order to adapt the most efficient design.

**EXPERIMENTAL INVESTIGATION OF CABLE CATCHER SYSTEM**

This phase of the experimental programme involved impact testing a simple cable catcher system in order to investigate the response of the system and its ability to absorb blast energy. The test setup comprised of three 10 mm Grade 316 compacted steel cables spaced 150 mm apart suspended between two anchorages 1910 mm apart. The cables were fitted with an AM adjustor with toggle and swage at one end and an AM toggle swage terminal at the other. The AM toggle terminals at each end of the cables were attached to machined steel lugs with pin connections. These lugs were then bolted to custom designed rigid brackets made from 16 mm think steel. The brackets were then bolted to large steel boxes constructed from 20 mm think steel which were secured to the floor in the high capacity impact machine. Impact tests were carried out using these rigid connections as well as a system incorporating an energy absorbing connection which replaced one of the rigid brackets. This energy absorbing connection consisted of a bent steel plate 10 mm in thickness which was designed to bend under impact and by doing so absorb a greater amount of impact energy. The energy absorbing cable catcher system used for impact testing can be seen in Figure 3.

![Figure 3. Experimental setup for impact testing of cable catcher system.](image)
Impact testing was completed using the high-capacity impact machine located in the University of Wollongong's High Bay Laboratory. The machine consists of a 600 kg hammer which can be dropped from any height up to 3m to deliver a known impact load. The hammer also has a load cell attached which can measure the force that is applied to the test specimen. As the drop hammer passes a laser gate on its descent, the load cell is triggered and impact data is recorded by a data acquisition system which is then transferred to a computer (PC). A spreader bar was used to ensure that the load applied by the impact hammer was evenly distributed to all three cables. Cable deflection was measured using a dynamic wire potential meter while cable force was measured through a force sensing bolt that was used to attach the middle cable to either the rigid or energy absorbing connection.

The rigid connection system and energy absorbing system were both dynamically tested using two different drop heights. These drop heights of 62 mm and 85 mm resulted in impact velocities of 1.10 m/s and 1.29 m/s respectively. The impact velocities were selected based on the maximum deflection range of the deflection gauges used in this study.

The expected experimental results for the rigid connection system were derived using a number of different techniques. The impact velocity of the hammer connecting with the cable assembly will be estimated using the principle of conservation of energy. Cable deflection was approximated using adapted equations from Rogers (2004) for the analysis of cables in the design of prestressed cable barrier systems. Cable force was estimated using the energy balance approach outlined by Crawford and Lan (2009) for the analysis of cables under blast loads. Equations have been developed to consider the energy of impact rather than energy of blast load and therefore are valid for the elastic response of the cables with rigid connections.

**Impact response of cable catcher system**

Table 2 displays results obtaining during impact testing conducted on both rigid and energy absorbing test configurations.

<table>
<thead>
<tr>
<th>Test</th>
<th>Impact Force (kN)</th>
<th>Cable Deflection (mm)</th>
<th>Cable Force (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rigid</strong></td>
<td><strong>Theoretical</strong></td>
<td><strong>Experimental</strong></td>
<td><strong>Theoretical</strong></td>
</tr>
<tr>
<td>v=1.10m/s</td>
<td>33.0</td>
<td>27.0</td>
<td>97.0</td>
</tr>
<tr>
<td>v=1.29m/s</td>
<td>38.7</td>
<td>31.0</td>
<td>102.3</td>
</tr>
<tr>
<td><strong>Energy Absorbing</strong></td>
<td><strong>Theoretical</strong></td>
<td><strong>Experimental</strong></td>
<td><strong>Theoretical</strong></td>
</tr>
<tr>
<td>v=1.10m/s</td>
<td>N/A</td>
<td>21.0</td>
<td>N/A</td>
</tr>
<tr>
<td>v=1.29m/s</td>
<td>N/A</td>
<td>22.5</td>
<td>N/A</td>
</tr>
</tbody>
</table>

In order to validate the experimental values achieved in the tensile testing and also attempt to improve the expected outcomes for impact tests, the equations adapted from Rogers (2004) have been recalculated using a Modulus of Elasticity ($E$) of 97.65 GPa which was the average value achieved for compacted strand cable. Table 3 presents the new calculated theoretical values compared to both the experimental results and original predictions which used the manufacturer's value for $E$. 

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Table 2. Summary of impact testing results
Table 3. Effect of using experimental Modulus of Elasticity

<table>
<thead>
<tr>
<th>Test</th>
<th>Result</th>
<th>Experimental</th>
<th>Rogers (2004), $E = 133.7$ GPa</th>
<th>Rogers (2004), $E = 97.65$ GPa</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cable</td>
<td>117.5 mm</td>
<td>97.0 mm</td>
<td>107.7 mm</td>
<td>9.1 %</td>
</tr>
<tr>
<td>Rigid $v=1.10$ m/s</td>
<td>Deflection</td>
<td>116.1 mm</td>
<td>102.3 mm</td>
<td>113.6 mm</td>
<td>9.7 %</td>
</tr>
<tr>
<td></td>
<td>Cable</td>
<td>31.5 kN</td>
<td>36.7 kN</td>
<td>31.42 kN</td>
<td>16.3 %</td>
</tr>
<tr>
<td></td>
<td>Force</td>
<td>35.8 kN</td>
<td>42.9 kN</td>
<td>36.8 kN</td>
<td>17.0 %</td>
</tr>
</tbody>
</table>

It can be seen in Table 3 that by using the experimental value for the Modulus of Elasticity ($E = 97.65$ GPa) the predictions for cable deflection and cable force for both impact velocities become considerably more accurate.

The results obtained during impact testing clearly show the behaviours of cable catcher systems under impact loads and the effects of different anchorage types. Using the results of rigid and energy absorbing test configurations, it is possible to directly compare the effect of the different connections under the same impact load. Figure 5 displays a time-history plot of cable deflection and cable force for the impact velocity of 1.10 m/s. Figure 6 presents the same plot of cable deflection and force for the impact velocity of 1.29 m/s. The prestressing force from each test has been eliminated to provide a better comparison between the results.

Using Figure 5 and 6 it is easy to compare the effect of the energy absorbing connection on the cable deflection under a set impact force. The peaks on the graph clearly show how the addition of an energy absorbing plate connection results in a greater cable deflection. This larger cable deflection arises through the formation of plastic hinges which allows the plate to rotate, resulting in significant lateral and vertical displacement of the connection.

Positive rebound of cables in rigid anchorage shows that all impact energy is absorbed through elastic deformation of the cables. No positive rebound is present in the bent plate connection since energy has been dissipated through the formation of plastic hinges. This results in less energy being transferred back into the impact hammer by cables and also a lower force experienced by the cables. It can also be concluded that it takes a longer time to reach maximum cable deflection with the addition of the energy absorbing connection. This effectively means that the impact has been slowed through the additional cable deflection supplied by the rotation of the bent plate and again reducing the force experienced by the cables.

It can be seen that through the addition of the energy absorbing anchorage the cable force is greatly reduced through increased time over which impact occurs. Energy is not only absorbed through the elastic deformation of the cables but also through the plastic deformation of the plate which effectively reduces the tensile force experienced by the cables. As a quantitative result, the cable force has been significantly lowered by approximately 35%.
The results which have been obtained during impact loading of cable catcher assemblies are very useful in demonstrating how different anchorages can effectively alter the behaviour of the system under blast loading. The use of energy absorbing anchorages effectively increases the time over which the initial impact occurs, resulting in lower tensile forces in the cables. Through effectively limiting the force experienced by the cables, energy absorbing devices increase the efficiency of the cable catcher system, allowing for smaller cable diameters to be used and hence providing unobtrusive blast protection which is well suited to the aesthetically pleasing architecture of modern office building design.

CONCLUSIONS
There is a strong need for high performance blast protection. This is due to increased terrorism worldwide and consequently suitable, non invasive blast protection which complements the aesthetically pleasing modern architecture seen in office buildings is highly ideal. High performance blast protection measures utilising high-strength and ductile behaviour of standard or non-standard construction materials can be used to provide effective blast protection.
Cable catcher systems are a highly favourable method of blast protection for glass façades due to their simplicity, adaptability, non invasive design and cost feasibility. These systems do not provide the highest level of protection as they are not overly effective in restraining blast born debris from entering occupied spaces of an office building.

Cable properties such as breaking load and Modulus of Elasticity ($E$) are vital in determining the capacity and behaviour of cable catcher systems under loading. Knowing the exact behaviour of a particular cable under loading can lead to a more efficient design of a cable catcher system.

Energy absorbing devices are highly effective in reducing the tensile force in the cables under loading. These devices limit the force experienced by the cables to below breaking load and also provide a longer impact time which reduces the likelihood of the cables slicing the failed glass panel upon impact.

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REFERENCES
