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Experimental investigation of load-deformation response for blast-resistant facade glazing solutions

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Experimental Investigation of Load-Deformation Response for Blast-Resistant Façade Glazing Solutions

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Abstract
One of the major causes of injury and loss of lufe in structures subjected to blast loading is the glass windows. Common window glass is annealed glass. When annelaed glass is subjected to impulsive loads such as the one generated by a blast, it breaks into relatively large shards with sharp cutting edges. This is responsible for for most of the injuries incurred in explosions. In the bombing of the Alfred P. Murrah Federal Building in Oklahoma City in 1995, more than 75% of the injuries were due to flying shards of glass.

The current approach to testing blast-resistant glazing materials such as polycarbonates and laminated glass is to carry out tests in either a shock tube or an open-air arena. Limited access to such facilities is the main obstacle hampering the development of standardised tests for glazings under blast loading conditions.

This paper will present a simple and economical physical simulation technique for testing glass panels under impact and blast loading conditions. A technique that can generate pressure shocks simulating blasts of different magnitude and duration is based on a high-capacity drop hammer machine to produce impulsive loads which are distributed over the glass panel using the airtight chamber with a fluid medium. Experimental and numerical simulation results for the annealed glass panels with and without fragment retension films will demonstrate the effectiveness of the system to deliver a blast impulse with a given characteristic.

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1. Introduction

Modern building structures have traditionally been designed to perform under a wide range of foreseeable loading situations relating to their form of construction and intended purpose. In the past decade, an increased awareness of the threat of terrorism has forced the building industry to also give particular consideration to the performance of both new and old buildings, when subjected to loads arising from explosive blasts. This has resulted in a marked increase in research into the area of blast loadings which has set out to provide the building industry with tangible information for use in the analysis and design of building systems that provide a compromise between safety, cost and aesthetics.

In recent years, façade structures on new buildings have been designed using materials and glazing systems that perform much better under blast loading. The preferred glazing material for high risk areas has been laminated glass; glass comprised of two individual plies of glass that sandwich some form of polymer interlayer. Additionally, retrofitting solutions have been employed by building owners to improve the performance of existing annealed and heat-treated glass façades on older buildings. These retrofitting solutions include fragment retention films that act to retain broken glass shards, while offering little to no extra resistance to fracture. In the case of older buildings, it can often be the case that the increased threat of blasts requires a decision between replacing a façade system completely and applying a retrofit solution. The decision process needs to involve as much current information as possible in order for the most suitable option to be identified.

The information available to support glazing type selection and the relevant design codes has arisen through past research and experimental observations. The purpose of this study is to provide valid tangible information and experimental test data that can be used to advance the methods currently used in the blast-resistant design of glass façade structures. A validation of the methodology employed will ensure that data resulting from experimental observations adequately replicates real world situations.

2. Glazing solutions for new blast-resistant façades

Blast resistant façade systems for new buildings are generally very similar arrangements, with the main difference being the type of glazing material used. A number of important properties make laminated glass, polycarbonate and toughened glass the most commonly used glazing materials.

2.1 Laminated glass

The most effective glazing to provide protection against blast is laminated glass. Laminated glass is manufactured as two or more layers of glass with PVB (polyvinyl butyral) interlayers sandwiched between the glass layers. The quality of the bond between the PVB interlayer and the glass together effects the flexural capacity of the window. At cooler temperatures, the PVB bonds the glass panes together well so that the individual glass layers exhibit composite action and the window develops the same strength as a monolithic window of the same thickness. For higher temperatures, the PVB is weakened, the bond between panes is lessened, and the window response is something less than complete composite action. If laminated glass is cracked by blast pressures, the outer glass layer generally remains bonded to the inner plastic interlayer rather than forming flying shards. Maximum protective performance of laminated glass could be achieved by securely attaching the glass to a strong frame. This is often achieved by specifying deep rebates of about 25-30 mm and by using structural silicon sealant to anchor the glazing in the frame. This will enable the cracked laminated glass to resist the blast pressures through membrane action and bulge inward while remaining attached to the frame (see Figure 1).

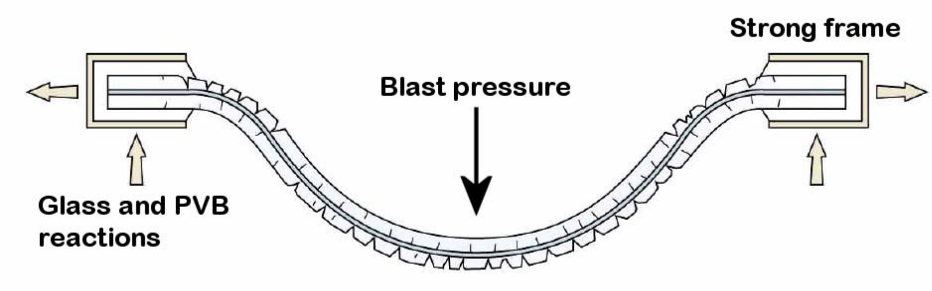

Figure 1 Laminated glass under blast loading (Sukhram, 2005)

2.2 Toughened (Fully Tempered) glass

Toughened glass or fully tempered glass is ordinary annealed glass that has undergone a controlled heating and cooling process in order to increase the capacity of the glass to resist imposed stresses. The process involves passing a ply of annealed glass that has been cut to the desired size on rollers through a tempering oven. The glass is heated to softening temperature of approximately 650°C before rapid quenching of the outer surface by jets of cool air (Norville & Conrath, 2001). This process induces a permanent compressive surface stress and an internal tensile stress in the glass as a result of the different rate of cooling between the inside and outside of the glass. This residual compressive surface stress is in excess of 69MPa (Ledbetter et al., 2006). As glass will almost always fail in tension under lateral loading, the advantage of carrying out this tempering is that the induced compressive surface stress must be overcome before the glass may fail. According to Ledbetter et al. (2006), fully tempered glass has approximately four times the nominal load resistance of ordinary annealed glass. When toughened glass breaks, it forms small rounded glass fragments commonly referred to as dice. These fragments do not have sharp edges and are much less likely to cause the laceration and contusion injuries associated with the breakage of ordinary annealed glass.

2.3 Polycarbonate glazing

Polycarbonate is a versatile thermoplastic material that has been effectively used as glazing material in many bullet and blast resistant applications. The material is often used in situations where risk of a blast is high and the need for the building envelope to remaining intact is crucial, as polycarbonate normally does not fail under blast loading (Norville & Conrath, 2001). Another advantage arising from the use of polycarbonate as a glazing material is that it does not suffer from the same spalling problem associated with laminated glass.

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While the tendency for polycarbonate to deform much more readily than other glazing materials and its significantly higher ultimate breaking stress can be advantageous, the characteristics also present a number of problems pertaining to the anchorage of the glazing. The capacity for the material to remain intact means that the force on the window framing and building structure is much greater than for other glazing. The anchorage must be designed with an adequately deep recess to support these forces and to minimise the potential for harm from a heavy sheet of polycarbonate moving or falling onto people (IWFA, 1999).

Polycarbonate and other plastic materials tend to have shorter life-spans and higher initial cost relative to other glass based systems (Ledbetter et al., 2006). The short life span is largely due to the tendency for polycarbonate to degrade under ultraviolet radiation, which results in a reduction in transparency, along with the ease with which the material can be scratched or vandalized. Another disadvantage of the material is its high purchase cost in comparison to other commonly used glazing materials (Norville & Conrath, 2001).

3. Experimental investigation of glazing solutions

The experimental program was devised in order to develop load-deformation relationships for glass panes that could be employed in Single-Degree-of-Freedom (SDOF) idealisation and dynamic analysis of window systems. Specifically, the experiments forming part of the investigation serve to provide qualitative and quantitative data on the performance of retrofit and new blast resistant façade glazing solutions, including laminated glass, through the implementation of a new and validated test method. The façade glazing solutions forming part of the experimental scheme are presented along with their identification (ID) code in Table 1. All specimens were of the same plan dimensions, 720x970mm, with only one glazing specimen tested in each experiment.

Blast Resistant Facade System	**ID Code**
6.0mm Annealed Glass	6.0AG
6.38mm laminated glass - 2 x 3mm annealed glass plies, 0.38mm PVB interlayer	6.38LG
6.76mm laminated glass - 2 x 3mm annealed glass plies, 0.76mm PVB interlayer	6.76LG
8.38mm laminated glass - 2 x 4mm annealed glass plies, 0.38mm PVB interlayer	8.38LG
6.0mm Annealed Glass with 0.175mm Fragment retention Film - daylight application	6.0FRF-D
6.0mm Annealed Glass with 0.175mm Fragment retention Film - wet glazed	6.0FRF-W
6.0mm Annealed Glass with 0.175mm Fragment retention Film - mechanically attached	6.0FRF-M

Table 1 Blast-resistant glazing test specimens

The experimental investigations of glass specimens were performed at the University of Wollongong High-bay Laboratory. Experiments involved the determination of the structural resistance of each glazing system when subjected to a monotonically increasing uniform pressure. Results of the experiments provided important parameters required in the verification of dynamic response of the blast-resistant glazing solutions.

3.1 Test arrangement and instrumentation

This section presents the instrumentation and test apparatus used within the three tests forming the experimental investigation. Where calibration of the instrumentation or test apparatus was required, a brief description of the process has been provided.

3.1.1 Airbags

The experimental testing regime used two different sized airbags, of un-inflated dimensions 850x600x100mm and 850x1100x150mm. The airbags consisted of a polymeric bladder contained within a tough PVC outer layer. The role of the PVC outer layer was to protect the more vulnerable bladder from puncture when inflated at high pressures and confined against broken glass shards. Two inlet/outlet valves were located on one of the shorter sides of the airbags, with one attached to the air compressor outlet hose for inflation and the other to the pressure sensor for airbag pressure recording. Thin steel tube 5mm in diameter was inserted into these valves to keep the one-way mechanism open, with flexible 5mm plastic hose connecting these tubes to the pressure sensor and compressed air hose respectively. Plastic cable ties were used to prevent air leaks from the valve connections. A picture of the two bags used and a detail photograph of the inlet/outlet valves are included as Figure 2.

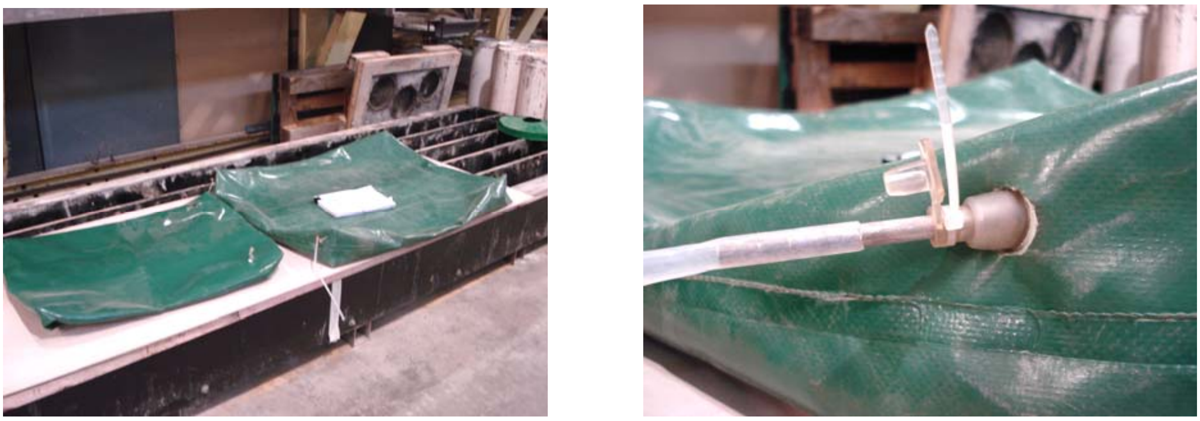

Figure 2 Airbags used for testing and detail of inlet/outlet valve arrangement

3.1.2 Pressure sensor

The pressure sensor used throughout the experimental testing was model SCX150DNC manufactured by SenSym ICT. This internally calibrated and temperature compensated sensor has an operating temperature range of 0-70°C. The operating pressure of the instrument is 0-1034 kPa with a typical sensitivity of 0.6 mV/kPa. A calibration procedure undertaken for the pressure sensor revealed that the instrument sensitivity was approximately equal to this value. The pressure sensor was connected to the airbag via a 5mm flexible plastic tube that was secured to the sensor via small cable ties to ensure no air was lost from the system. The pressure sensor was mounted on a circuit board, with a series of insulated copper wires connected from the data acquisition system to the sensor via a screw clamping connection terminal.

3.1.3 Laser optical displacement transducer

The laser optical displacement transducer model optoNCDT LD1627-100 manufactured by Micro-Epsilon was used for non-contact displacement measurements. The system has a working range of measurement of 100 mm. The laser displacement sensor system uses the principle of optical triangulation to determine the distance to a measured surface. It consists of two main components; the sensor and the controller. The role of the sensor is to produce an output signal based on the light reflected from the measured surface with the controller then interpreting this signal to produce a linear value of displacement. In order to ensure light was reflected from the surface of the tested glazing specimens, the glazing was painted white at the locations where deflection was to be measured.

3.1.4 Data acquisition system

The data acquisition system used for the testing regime was the NI PXI-1050 unit manufactured by National Instruments Corporation. This data acquisition unit served to convert the analog signal received from the various sensors and convert it to digital as well as condition the data before sending it through to the connected PC. The LabVIEW version 8.0 software, by National Instruments Corporation, on the connected PC then processed and saved the data.

3.2 Testing of glass under monotonically increasing pressure

The static tests involved the use of a pressurised airbag to provide a monotonically increasing static pressure to a test glazing system. Recording of the pressure in the airbag and the corresponding centre deflection allowed determination of the structural resistance function (load-displacement curve) of the glazing system. The glazing resistance functions are a crucial component of SDoF modelling to predict the dynamic response of window systems.\

The set-up consisted of a framed blast resistant glazing solution firmly held in place by a hold-down structure incorporating steel sections, blocks and hold down bolts. The smaller of the two airbags was located between the floor and the underside of the framed glazing system. The nozzle at the end of an air compressor hose was connected to one of the airbag valves by way of flexible plastic tubing. The pressure sensor was connected to the other airbag valve in the same way. A laser sensor was used for centre deflection measurement on the first tested specimen (6.76LG), but due to its limited range, was replaced by the draw-wire displacement sensor for the remaining tests. The draw-wire displacement sensor was secured above the sample and connected to a small piece of crafted tin that was adhered to the center of the upper side of the glazing specimen.

This arrangement is illustrated in Figure 3, as is the strain gauge located at the center of the glazing specimen and the steel mesh cage and heavy canvas placed over the test set-up to contain any flying glass shards. The draw-wire displacement sensor, pressure sensor and a strain gauge were all connected to the data acquisition system which recorded at a frequency of 5Hz.

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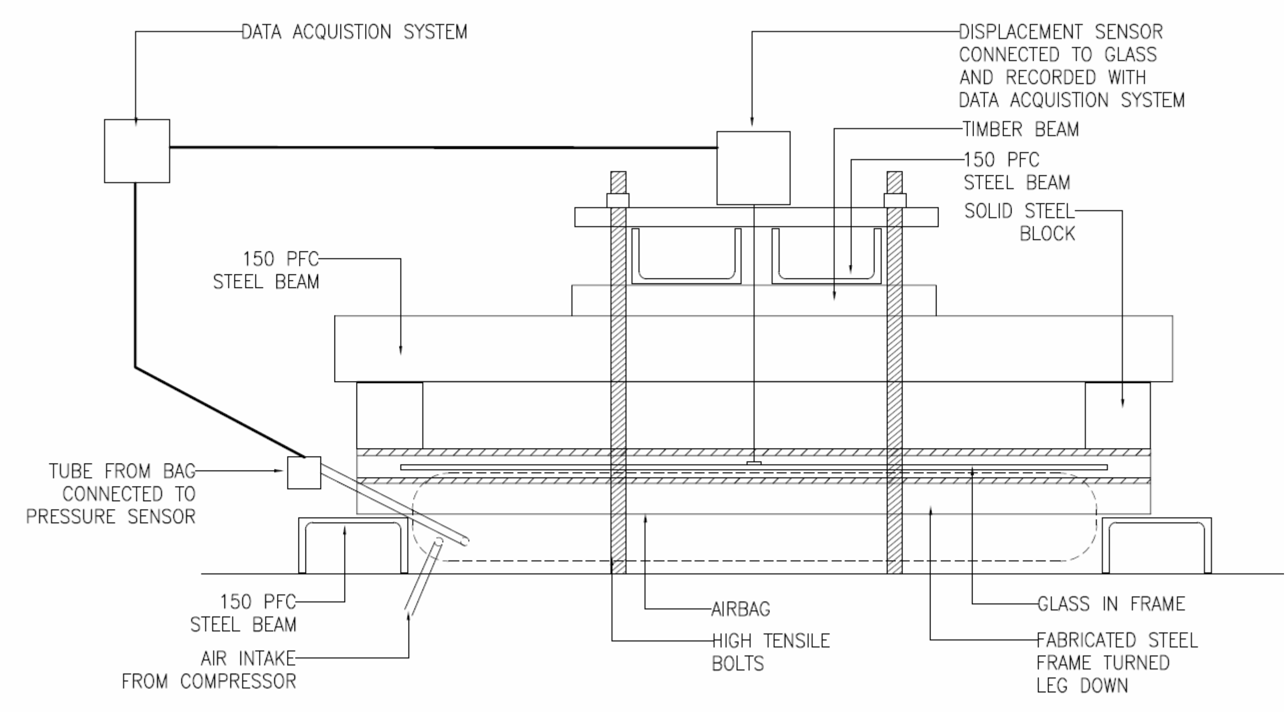

Figure 3 Experimental set-up for monotonically increased pressure on glass specimens

3.2.1 Summary of static test results

The results obtained from the static test are most suitably presented in the form of resistance function (load-deflection) curves, with the quantification of certain parameters of these functions also providing insight into blast performance. In addition to these resistance functions, the breaking stress (stress at fracture) of the specimens was determined from the measured strain by consideration of Hooke’s Law. The Young’s Modulus values used in this calculation were taken as 70 GPa for the annealed and FRF specimens and 72GPa for the laminated glass specimens. The behavior of the test façade glazing systems under the static test conditions provided both qualitative and quantitative information allowing prediction of in-service behavior in the event of an explosive blast. This information is summarised here in the form of Figure 4 and Table 2.

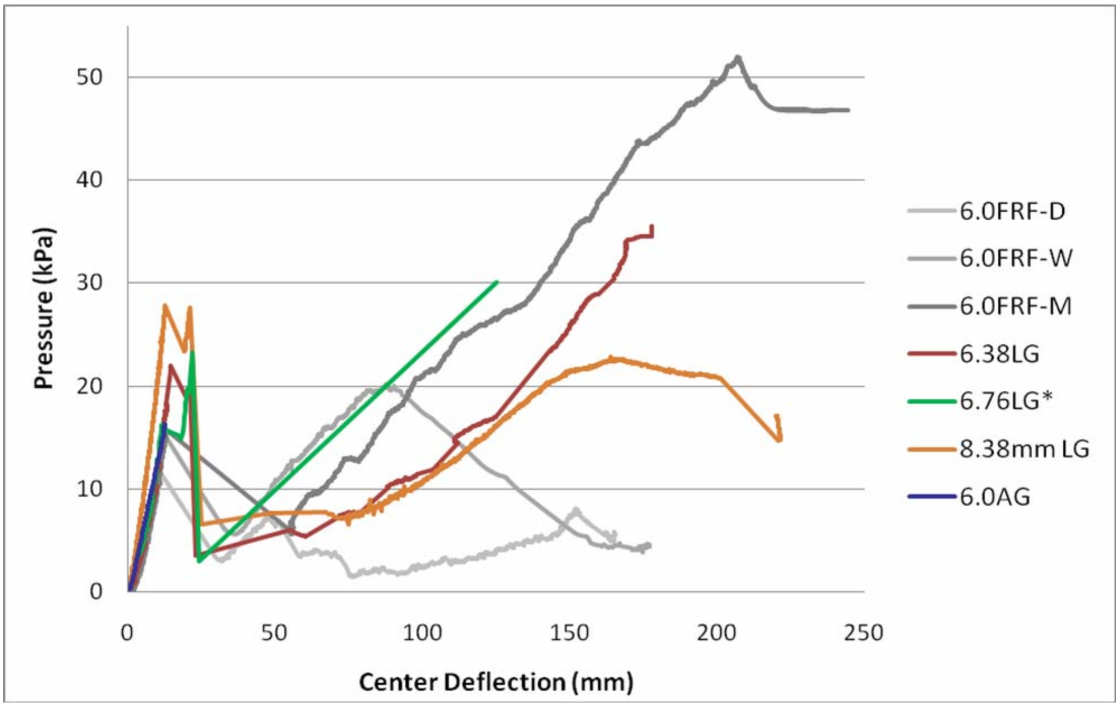

Figure 4 Comparison of resistance functions of statically tested façade systems

Table 2 Key parameters defining resistance functions

Blast Resistant Facade System	Pre-fracture		Fracture	Post-fracture		
	Peak Resistance (kPa)	Peak Deflection (mm)	Breaking Stress (MPa)	Peak Resistance (kPa)	Ultimate Deflection (mm)	Post Fracture Energy Absorption (Nm)
6.0AG	16.3	12.4	-	0	N/A	0
6.38LG	22.0	14.4	38.6	35.5	178.0	1620
6.76LG	22.6	20.6	25.0	30.0	-	-
8.38LG	27.0	20.8	21.9	22.8	200.2	1831
6.0FRF-D	11.4	11.2	28.0	8.1	161.7	418
6.0FRF-W	15.6	11.9	17.9	20.0	176.4	1137
6.0FRF-M	15.6	13.2	36.4	51.8	239.5	3317

The testing showed that laminated glass of comparable thickness to the monolithic annealed glass and FRF glazing systems demonstrated considerably higher peak resistance and deflection pre-fracture. The observed breaking stresses were of comparable value for the FRF and laminated glass specimens, and generally within the 25-60 MPa range expected for annealed glass. Post-fracture behaviour was generally more favorable for the laminated glass systems, with the exception of the 6.0FRF-M specimen which had the highest post-fracture peak resistance, peak deflection and energy absorption.

4. Validation of glazing resistance functions

In order to establish the validity of the resistance functions provided by the monotonic tests, the experimental functions were compared to those obtained from a specialised blast resistant façade design computer program WinGARD (GSA, 2004). This program was used to produce standard response functions for each of one each of the laminated glass and FRF façade systems (6.38LG and 6.0FRF-D). These "standard" response functions provided by WinGARD have been established by analysing a large set of experimental data. For each façade system, experimental and standard response functions were plotted on the same graph and compared, before an overall appraisal of the results obtained in the static test. Examples of resistance function validation for the 6.38mm laminated glass and the 6mm annealed glass with fragment retention film are given below.

6.38mm Laminated Glass (6.38LG)

The resistance function obtained for the 6.38LG façade system by the static test is presented on the same graph as the standard resistance function provided by WinGARD (Figure 5).

Figure 5 shows that the resistance functions have very similar stiffness within the elastic range, with the tested 6.38LG system fracturing at a considerably lower pressure. This behaviour is not considered unusual due to the inherent variability in material properties of glass arising from the presence of impurities. A notable aspect of the standard resistance function is that failure of the two separate plies observed in practice is approximated by one combined failure. Post-fracture, the standard resistance function drops in pressure instantaneously to around one third of the peak pre-fracture resistance before increasing at a constant rate. This behaviour is contrary to the results obtained experimentally, which imply that the pressure drop is not instantaneous. Resistance provided in the experimental response function in the post-fracture region is observed to be somewhat lower than that of the standard response function.

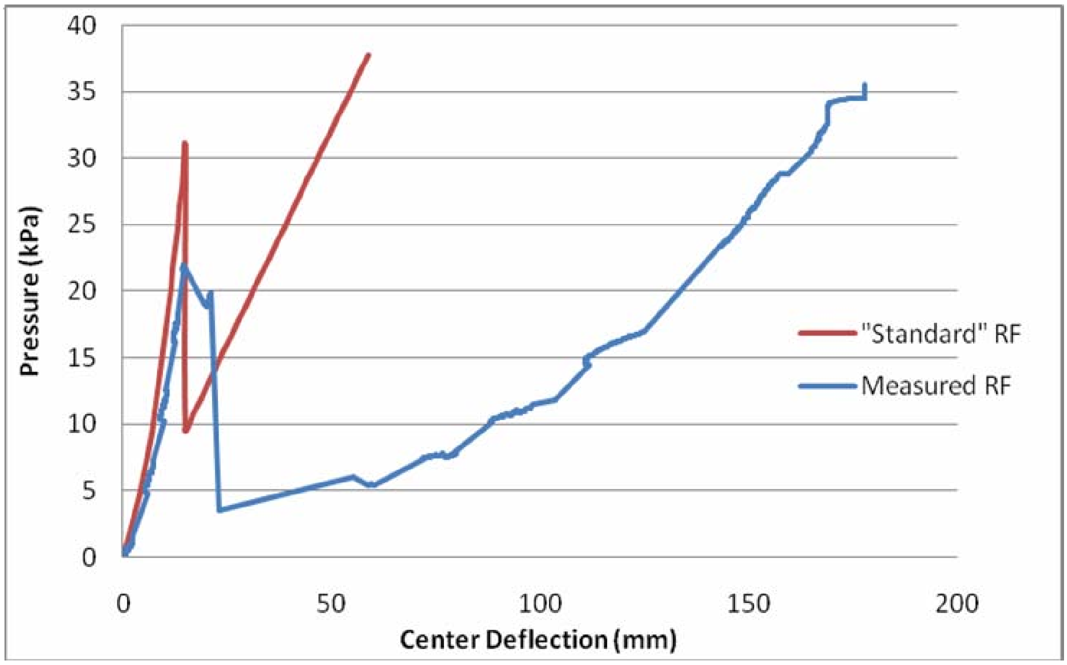

Figure 5 Comparison of experimental and analytical resistance functions for 6.38LG

6.0mm Fragment Retention film with daylight application (6.0FRF-D)

The resistance function obtained for the 6.0FRF-D façade system by the static test is presented on the same graph as the standard resistance function provided by WinGARD (see Figure 6).

Figure 6 demonstrates that the resistance functions have very similar stiffness within the elastic range, with the tested 6.0FRF-D system fracturing at a considerably lower pressure. As discussed previously, this behaviour is not considered unusual due to the inherent variability in material properties of glass arising from the presence of impurities. A notable aspect of the standard resistance function is that the computer program conservatively assumes that no structural resistance is provided by the film post-fracture. This assumption is somewhat supported by the experimental results in that only a minor amount resistance was experienced post-fracture, over large deflections.

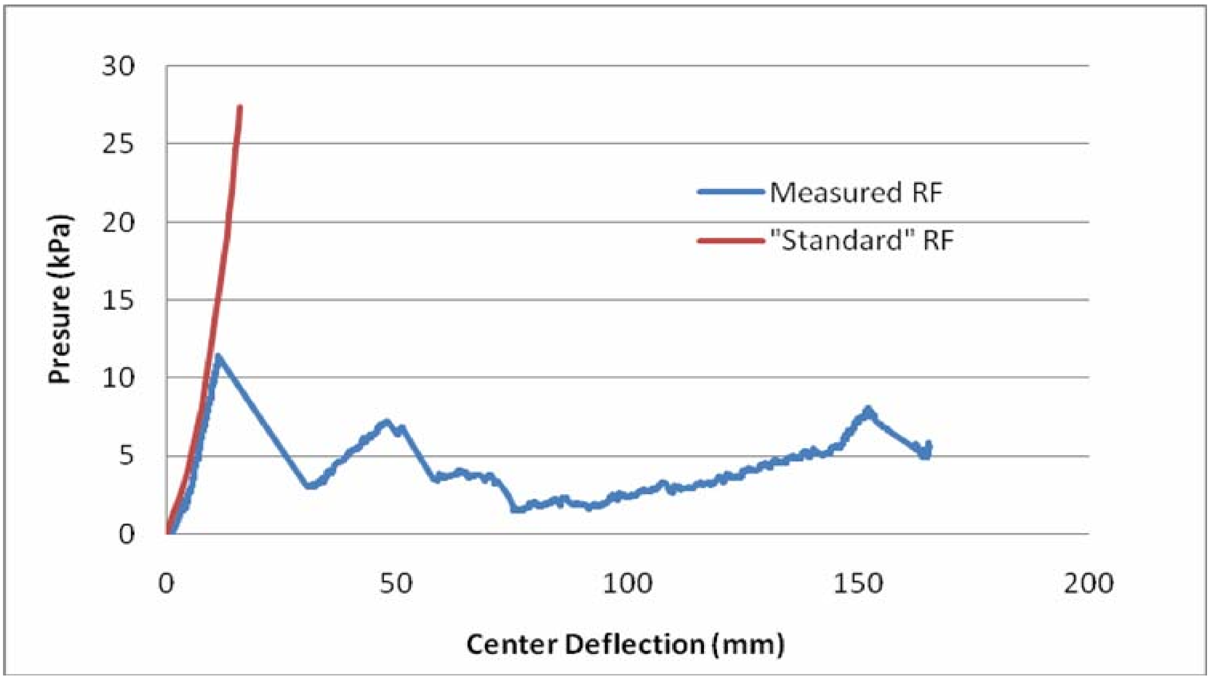

Figure 6 Comparison of experimental and analytical resistance functions for 6.0FRF-D

5. Conclusions

The purpose of this study was to investigate the performance of glazing solutions commonly used in building façade structures when subjected to explosive blasts. The investigation incorporated an experimental testing regime that required the development of a new test method based on the technique of using airbags to applying a uniform dynamic loading to test façade glazing systems. Specifically, the experimental investigations were performed on annealed glass, laminated glass and fragment retention film fitted annealed glass specimens as the three categories of glazing represented commonly used glazing with no blast protection, new glazing solutions and retrofitting solutions respectively.

Based on the findings of this research, the following conclusions are provided with regards to comparison of performance between new and retrofit glazing solutions:

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1. Dynamic stiffness and fundamental frequencies were slightly higher (17% and 7% respectively) for laminated glass over similarly thick annealed glass and annealed glass with FRF fitted. These parameters were found to be far more dependant on overall glazing thickness than on glazing type.
2. The key advantage of laminated glass in blast resistant façade glazing applications is the superior pre-fracture performance it exhibits, with considerably higher peak resistance (approx. +45%) and moderately higher deflection (approx. +20%) for comparable thickness FRF solutions. Laminated glass also typically has more favourable post-fracture behaviour, with the exception of mechanically attached FRF which had the highest post-fracture peak resistance, peak deflection and energy absorption.
3. Provided sufficient bite conditions are provided, failure of laminated glass specimens will result in tearing of the PVB interlayer rather than pull-out of the entire sheet, with the high likelihood that at least one edge will remain secured to the window. In contrast, daylight application FRF tends to fail as entire panel along the edge of the filmed portion and project in the direction of the force.

The conclusions above indicate that retrofitting of existing annealed glass windows can, in the case of mechanical attachment, ensure blast performance comparable or to that provided by a new blast resistant façade glazing solutions.

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