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Challenges and Outcome of Full-Scale Blast Experimentation on Structural Steel Members and Glass Elements

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ABSTRACT

Protective structures are an increasingly common design requirement for various stakeholders that perceive themselves to be at risk from explosion events. A variety of methods comprising complex theoretical tools for analysis, sophisticated numerical methods, and testing of protective structures and structural elements can be employed to ascertain their behaviour under blast loading. Research into the response of structures and structural elements to blast loading has been undertaken at the University of Toronto over the past six years. More recently, the establishment of the "Explora Programme into Protection against the Effects of Energetic Events" within the University's "Centre for Resilience of Critical Infrastructure" (CRCI) has contributed further to the scope and scale of this research. Specifically, the research efforts presented herein comprise two long-running projects investigating the response of building components to air blast loading.

Blast arena tests were conducted in June 2013 as part of two ongoing research projects investigating the response of building elements to blast loading. The first project consists of an investigation into the behaviour of hollow structural section (HSS) elements subjected to blast loading. The behaviour of HSS flexural elements, both hollow and concrete-filled, was investigated through two full-scale blast experiments. The second research project being undertaken involves the investigation of the effects of blast loading on curtain wall systems. A field-testing programme was undertaken to provide specific experimental data, given that the availability of published information in this area is limited or non-existent.

The field-testing programme was undertaken to provide specific experimental data with which the accuracy of various predictive models will be assessed. The overall experimental approach employed for the two field test programmes is detailed herein. Focus is on the design of test structures and experimental specimens, and results stemming from the large-scale blast experiments, for the two projects undertaken, are presented. Consequently, the lessons learnt from the testing programme will contribute to the improvement of the plans for future experimentation.

INTRODUCTION

Requirements for protective design are increasingly a prevalent concern. In order to better understand the behaviour of structural members during an explosive event, and thus provide optimal design solutions, full-scale field tests are necessary. Two ongoing research projects being conducted at the University of Toronto aim to improve the understanding of steel hollow structural sections (HSS) and non-laminated glass under blast loads. The tests described herein build upon previous blast testing conducted through the Explora Foundation in 2012 [1].

For the first research project, hollow structural sections (HSS) elements were tested to better understand the dynamic behaviour of square hollow structural sections (SHS). Cold-formed HSS elements with external dimensions of 120 mm by 120 mm and various wall thicknesses were subjected to blast loading. The results of the blast arena testing will be compared to predictions using single degree of freedom (SDOF) models and finite element analysis. The goal of this research is to develop a better understanding of how cold-formed HSS elements behave under blast conditions and thus improve on existing design practices.

The second project involved the testing of a series of regular annealed glass panes to produce experimental data on the behaviour of glass under blast loading. The tests are intended to address the current lack of publically available experimental data on the blast loading of glass. Additionally, the data collected from this series of tests will be compared to various predictive models, including a dynamic, explicit finite element analysis fast-run model developed at the University of Toronto. The results of these tests will be used to verify and improve upon existing predictive models and extend the knowledge base on the behaviour of non-laminated glass under blast loads.

METHODOLOGY

June 2013 Blast Test Series

The Explora Foundation 2013 test series extended the full-scale blast arena research that began with the 2012 test series [1]. Unlike the 2012 test series, the 2013 test series included multiple blast arenas set up on different areas of the test site. The HSS targets were part of the main blast arena and the glass targets had their own dedicated arena. Figure 1 shows the configuration of the glass testing arena prior to glass test 1. While other targets were a part of the 2013 test series, only the two aforementioned targets are discussed herein.

Figure 1. Glass Testing Arena

Hollow Structural Section Targets

For the 2013 test series, 16 cold-formed HSS elements with external dimensions of 120 mm by 120 mm and various wall thicknesses were subjected to blast loading. The HSS elements were tested in two blast arena tests. To facilitate testing, a concrete test structure was designed to support the HSS and allow the members to behave like simply supported flexural elements. Pinned and slotted connections were located at the centerline of the bottom and top slabs respectively. The effective span of the HSS elements was 3.26 m. The 2013 test series added concrete filling to half (8) of the HSS elements; these members were filled with 30 MPa non-shrink grout. The HSS elements were clad with steel decking covering the clear opening of each concrete target. The steel decking was split vertically down the middle allowing the two panels to move independently of each other. The targets were created with two open faces, so they could be quickly reset between firings by lifting and rotating the test structures. Figure 2 illustrates a design rendering of an HSS target.

Two test structures were constructed such that hollow and concrete-filled HSS elements could be tested simultaneously. One target contained hollow HSS members and the other one held concrete-filled HSS members. Each face of the targets held four HSS elements, two 5 mm wall thickness and two 8 mm wall thickness. The member sizes were selected to ensure significant plastic deformation would be achieved during the tests. Once the HSS targets were placed in the blast arena, 1x1x1 m concrete blocks were placed on the roof of the targets as near the front face as possible. Concrete T-barriers were also placed on either side. These elements were used to minimise clearing effects. Figure 3 shows the completed test setup, for two targets, prior to HSS Test 1 (in which a total of four unfilled and four concrete-filled HSS were tested).

Figure 2. Rendering of an HSS Target

Figure 3. HSS Targets Prior to HSS Test 1

In each test, the two HSS targets were placed beside each other to facilitate a comparison between the hollow and concrete-filled elements. Hemispherical TNT charges were used for both tests. For the first test the scaled distance was 2.7 m/kg$^{1/3}$. In the second test, an increased level of plastic deformation was desired; therefore, the scaled distance was reduced to 1.9 m/kg$^{1/3}$.

Glass Targets

Building upon glass tests done in the 2012 test series, a series of annealed glass panes were subjected to blast loading. Three reinforced concrete reaction structures were used as targets for the glass tests. Openings provided in each target were framed with steel HSS members to facilitate the placement of 1 m square glass panes. Target 1 was designed to accommodate three glass panes and Targets 2 and 3 held two panes each. The distance from the target edge to the edge of the glass panes was at least 1 m in order to minimise clearing effects. All of the glass panes were 12 mm thick and each pane was set in a standard aluminum window frame, which was mounted in the target openings. This enabled the rapid replacement of the glass panes between tests.

Figure 4. Glass Target 1

Figure 5. Glass Targets 2 and 3

A break circuit system was pre-installed on each pane using conductive paint. The circuit was connected to the data acquisition system in order to get an approximate measure of the time of the glass fracture, which could then be matched up to the displacement-time measurements to determine the maximum deflection of the pane at failure. The break circuit can be seen in Figure 6.

Figure 6 Mounted Glass Panes

Four firings were conducted on seven glass panes, each. To achieve a statistically significant set of data the charge weight and standoff were kept the same for the first three tests, with Target 1 placed at a scaled distance of 5.4 $m/kg^{1/3}$ and Targets 2 and 3 placed at a scaled distance of 4.7 $m/kg^{1/3}$. For the fourth test the scaled distances were increased to 5.8 $m/kg^{1/3}$ for Target 1 and 5.0$m/kg^{1/3}$ for Targets 2 and 3. The scaled distances were selected such that the glass would fail under the predicted blast load.

Instrumentation

For the HSS tests, instrumentation was used to measure four parameters: free field pressure, reflected pressure, displacement, and strain. A Hi-Techniques meDAQ data acquisition system was used with a sampling rate of 2000 kHz for 1000 ms. Each of the two blast tests on HSS used 29 channels of instrumentation in total. There were eight channels for displacement (one per HSS member), 16 channels for strain (two per HSS member), and five channels for reflected pressure gauges. In addition, free-field pressure gauges were included at the same standoff distance as the concrete targets (one for the first test and two for the second test). The displacement gauges and strain gauges were mounted at the midspan on the HSS elements, on the inbound tension face of the members. Pressure gauges were mounted at the mid-height on the outer edge of both concrete targets. Three additional pressure gauges were mounted between of the two targets, one at mid-height and as well as at 1.3 m towards the top and bottom. This arrangement of gauges gave both the horizontal and vertical profile of the blast wave. The free-field pressure gauges were mounted on 1.5 m tall stands and placed at the same standoff distance as the targets.

For the glass tests, four parameters were measured: free-field pressure, reflected pressure, displacement and voltage readings from the break circuits. The same data acquisition system and sampling rate as for the HSS tests were used. A total of 19 channels were used in each of the targets. Target 1 used eight channels consisting of three LVDT displacement gauges, two reflected pressure gauges, and three break circuits. Both Targets 2 and 3 used five channels each, consisting of two LVDT displacement gauges, one reflected pressure gauge, and two break circuits. The LVDT displacement gauges were attached to the centre of each glass pane on the inside face. The reflected pressure gauges were located at mid-height on each target. The free field pressure gauge was mounted on a 1.5 m tall support.

High-Speed Video Recording

In addition to the instrumentation mentioned above, high-speed video cameras were used to film the blast tests. During the first HSS test, two high-speed video cameras and one normal speed video camera were used. Each camera was located in a bunker with a different angle of the blast test arena. The high-speed cameras were more critical during the glass tests.

For the glass tests, three Phantom high-speed cameras were mounted in cases attached to the back of Target 1. Halogen lights were placed inside the target to provide additional lighting. The cameras were intended to capture the time and pattern of glass fracturing for the three panes installed in Target 1. Previous tests have shown that a minimum frame rate of 30,000 frames per second is recommended to adequately capture the glass fracture pattern. At this frame rate a large amount of light is required (which is why the additional halogen lights were used) and only a relatively low resolution would be achieved.

Data Processing

The raw data obtained during testing required processing to produce interpret the results. The data processing, done using DPlot, was kept to a minimum to preserve the key features of the curves. Firstly, any baseline shift was removed from the results. Secondly, the pressure-time curves were smoothed to reduce any high-frequency spurious noise. The smoothing window was kept to a minimum to ensure that the extremities of the curve were not eroded significantly. Once a satisfactory pressure curve was reached the curves were integrated to produce the impulse-time curves. These displacement-time curves were filtered using a band-pass filter. Through the proper selection of the upper and lower limits, this filter maintained the periodic shape of the curves while eliminating the majority of the noise inherent in the raw data.

RESULTS

Hollow Structural Section Results

The results provided significant insight into the behaviour of HSS elements subjected to blast loading. As shown in Figure 7, the free field pressure-time and impulse-time curves from HSS Test 1 are close to predictions using the UFC 3-340-02 values for hemispherical TNT explosions [2]. A sample of the reflected pressure-time and impulse-time curves shown in Figure 8 illustrates that these curves also closely correspond with the UFC 3-340-02 values. The most significant difference as seen in both figures is that the blast value arrived at the free field gauge and targets slightly earlier then expected.

All eight of the HSS elements tested deformed plastically and the displacement of the elements was differed based on their flexural strength as predicted. The hollow, 5 mm thick HSS elements displaced the most while the concrete-filled, 8 mm thick HSS elements displaced the least. Figure 9 illustrates the displacement-time curves for the various 5 mm thick elements. The displacement gauge for T1-5CF-2 failed near its maximum displacement and it corresponding curve was truncated at this location. Manual displacement measurements were taken before and after the tests to obtain information for each HSS element in order to provide some redundancy in case of equipment failure as well as to provide a check of the displacement time history.

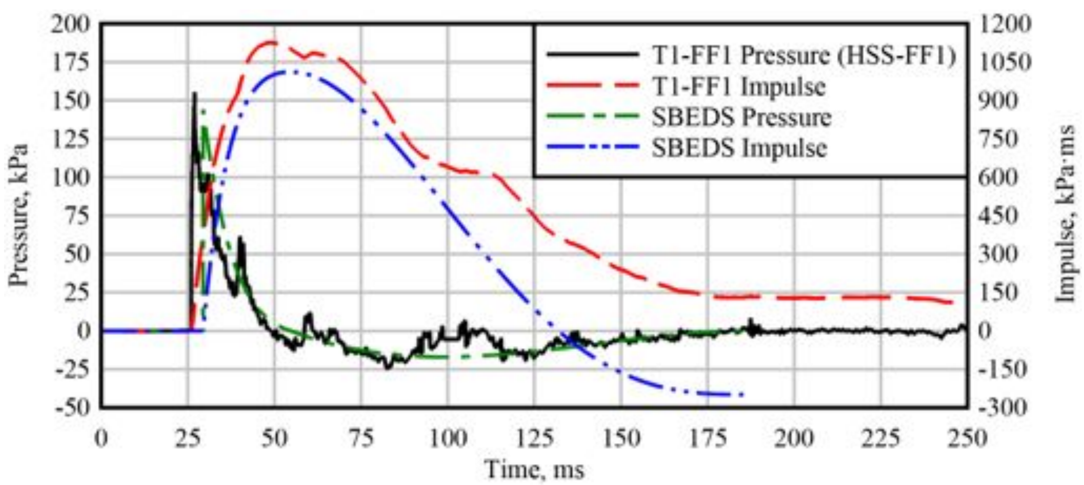

Figure 7. HSS Test 1 Free Field Pressure and Impulse

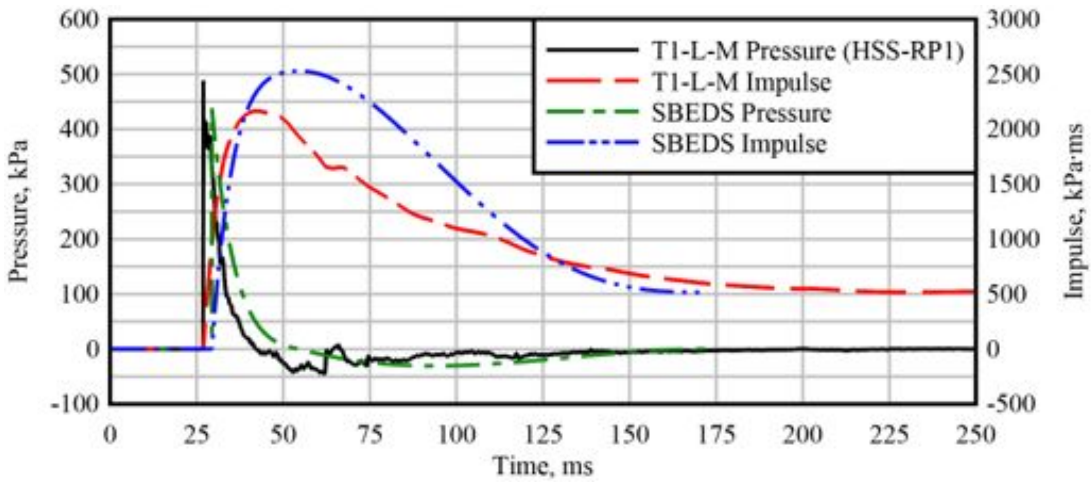

Figure 8. HSS Test 1 Reflected Pressure and Impulse

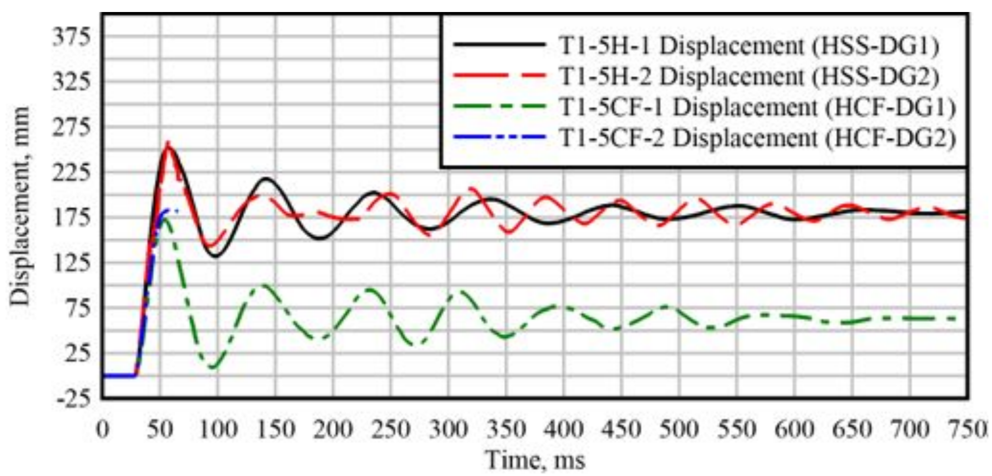

Figure 9. HSS Test 1 Displacement

The second HSS test successfully produced larger deformations in the HSS elements. The pressure and impulse-time curves were also very similar to the UFC 3-340-02 predicted curves. As shown in Figure 10 and Figure 11, the time of arrival is indistinguishable between the actual and predictive curves. In both the free-field and reflected pressure-time figures, the peak pressure is slightly higher than the predicted value. Figure 12 details the displacement-time curves for the 5 mm thick HSS elements.

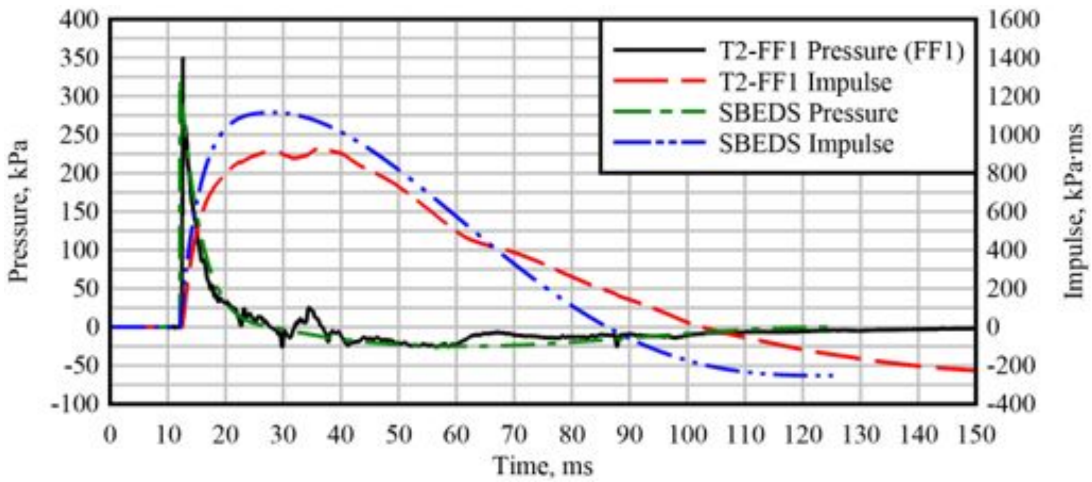

Figure 10. HSS Test 2 Free Field Pressure and Impulse

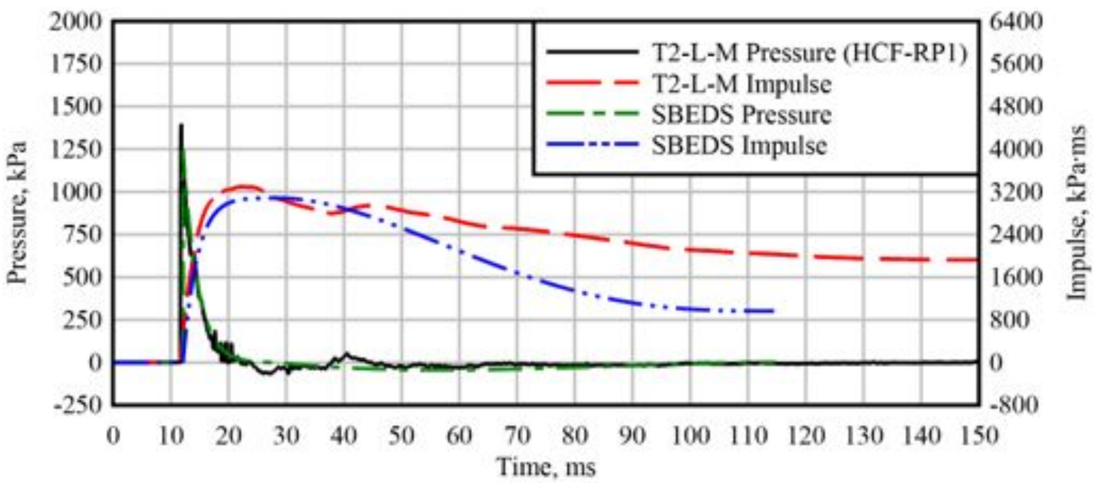

Figure 11. HSS Test 2 Reflected Pressure and Impulse

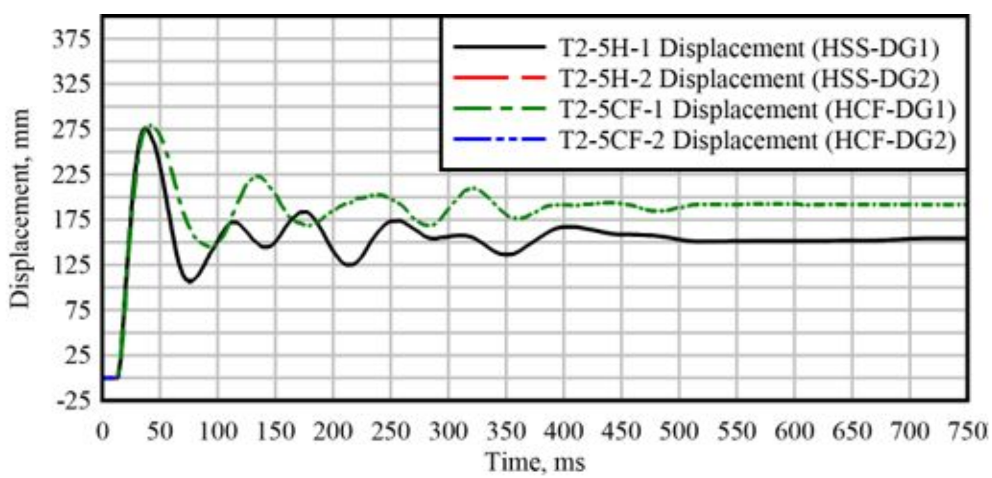

Figure 12. HSS Test 2 Displacement

In the case of the second HSS test, significant plastic deformation of the hollow 5 mm HSS elements was observed. As a result, the displacement was very large, causing the top bolt to reach the end of the slotted connection, preventing further axial movement and resulting in the HSS element experiencing tension membrane behaviour. This skewed the values of the displacement-time curve somewhat, even though the shape appears similar to the other elements (Figure 12).

Figure 13 shows the general deformation of the two HSS targets after the blast loading. Figure 14 shows the significant hinging and inelastic local buckling that occurred in the T2-5H-2 element that was a result of this large displacement. Local buckling also occurred in the hollow, 5 mm thick elements during HSS Test 1, but to a somewhat lesser degree.

Figure 13. HSS Targets after HSS Test 2

Figure 14. Local Buckling of HSS Element after HSS Test 2

This local buckling feature is one of the most noticeable differences between the behaviour of the hollow and concrete-filled HSS elements. The plastic deformations seen in the concrete-filled elements were significantly lower. The deformed shape of the concrete filled elements was also different from the hollow elements. The hollow HSS elements had a sharper plastic hinge location and the members appeared to be nearly straight from the connections to the plastic hinge. The concrete-filled HSS elements had a gradual bend at the mid-span, indicating that plastic hinge deformation was spread out over a larger portion of the element than that observed in the hollow specimens.

Glass Test Results

Similar to the HSS experiments, the series of tests on glass proved to be a success, providing valuable experimental data. As was predicted, every pane of glass broke under the blast load. The primary results from the experimental data collected included pressure-time, impulse-time, and deflection-time curves. The recorded reflected pressure values and calculated impulse curves match closely to predictions using UFC 3-340-02. Figure 15 illustrates the recorded pressure and impulse values for one of the tests.

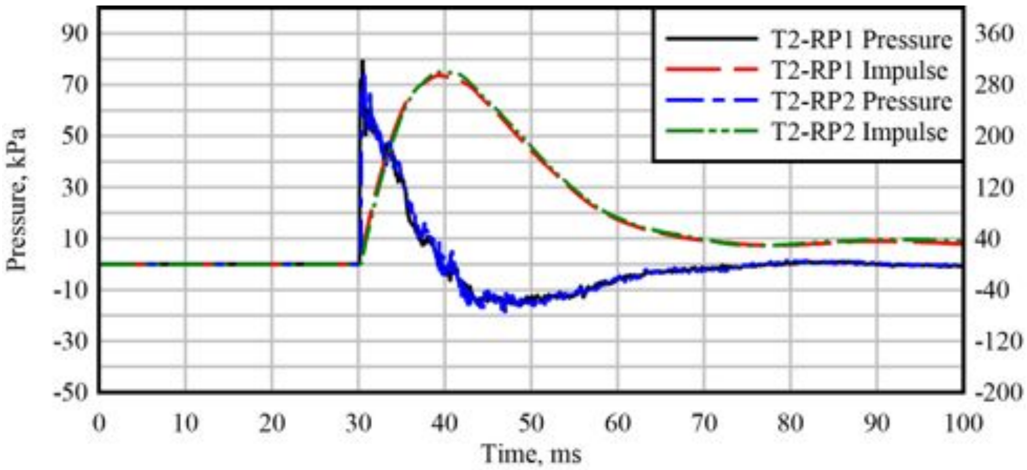

Figure 15. Glass Test 2 Reflected Pressure and Impulse

The displacement at the centre of each pane was recorded using a LVDT displacement gauge. An example of a displacement curve is shown in Figure 16. The displacement profiles show that all the panes broke during the initial positive displacement phase. The majority of the recordings show the gauge displacing until it reaches some peak value as limited by the maximum stroke of the gauge. By measuring the voltage drop along the break circuit the time of glass fracture is signalled by a sharp rise in the voltage reading. The time of fracture indicated by the break circuits was validated through comparison to the collected high-speed video. The difference in the time of glass fracture as indicated from the video footage and the break circuits was found to be negligibly small. Therefore, the break circuits can be used to determine the time of glass fracture for test specimens for which video was not collected. As Figure 16 shows, once the time of glass fracture is determined, the corresponding displacement of the glass pane can be found. Similarly, the values of the pressure and impulse at time of the glass breaking can be estimated.

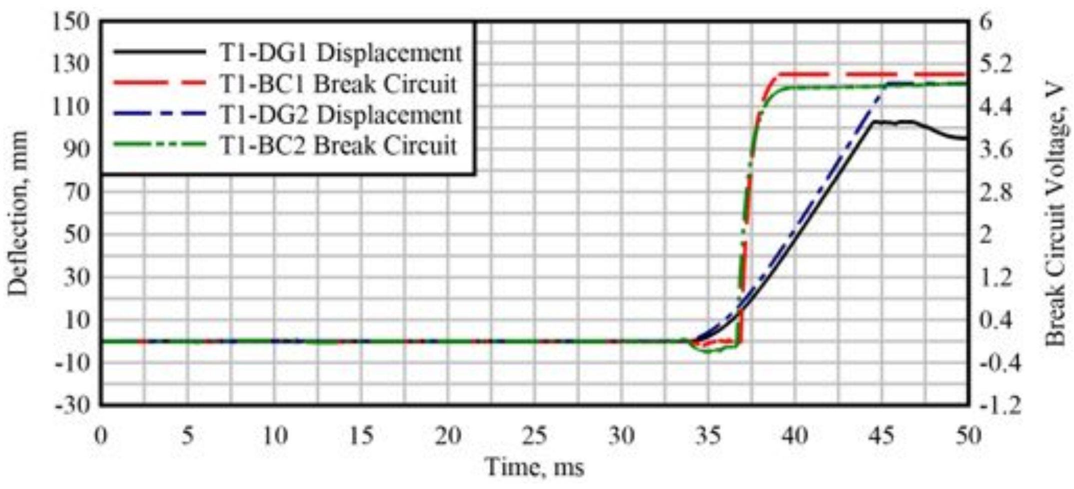

Figure 16. Glass Test 1 Displacement and Break Circuits

The results from these tests will be used to more in-depth calibrate a novel dynamic, explicit finite element analysis fast-running model for the evaluation of the behaviour of glass panes subjected to blast loading being developed at the University of Toronto [4] and validate dynamic behaviour prediction models for glass.

Challenges and Suggestions for Improvement

As can be expected with high-energy loads involved with blast testing, the instrumentation of the targets is typically under tremendous stress and, therefore, accurate recording of data can pose significant challenges. During both the HSS and glass tests a few instruments either failed to function correctly during the test or were damaged by the blast loading.

During the HSS tests, the higher loads in Test 2 caused additional problems due to equipment malfunction. Also, it is imperative that the procedure for attaching displacement gauges to the test specimens is perfected such that the instrumentation devices will not separate from the specimens during the test, as was observed in a couple of instances. Therefore, the instrumentation systems used in blast testing must be robust, reliable, properly installed and configured, and sufficiently redundant to ensure reliability and accurate recording of data.

Another challenge faced was related to the operation of the high-speed cameras. As previously experienced during the 2012 glass tests, the high-speed cameras sometimes failed to operate correctly due to being exposed to the increased air temperatures of the testing site, which can routinely reach over 40º C. Various heat relief measures were employed to provide shade on the cameras but technical difficulties were still encountered and some cameras failed to trigger during the testing. Therefore, additional cooling for the cameras should be considered, as well as additional testing of the camera setup should be performed prior to the tests to ensure full functionality.

CONCLUSIONS

The HSS tests performed successfully and produced a large quantity of information that will assist the understanding of HSS elements behaviour under blast loading. The differences between hollow and concrete-filled HSS element response were observed and measured. The compiled information will now be compared to analytical predictions, including SDOF and explicit finite element models. A laboratory-based blast simulator will be used to further expand the data set. The goal remains to develop an understanding of the behaviour of HSS elements under blast loading and to improve on current design practices, exemplified elsewhere [3].

The glass experimentation series has provided a substantial amount of information on the behaviour of annealed glass under blast loading. Through repeated tests, a statistically significant number of data points has been gathered. Using information from the break circuit system, relevant parameters including the displacement, pressure, and impulse at the exact point of failure can be determined. This will allow for the failure mechanisms of annealed glass under blast loading to be better understood.

As protective design requirements become more frequent, better design guidelines and predictive models will be required to provide optimal solutions. Both of these ongoing research programs have provided valuable data on the actual behaviour of structural components under blast loading through full-size field experiments.

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