July 2012 Test Report

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Executive Summary

The Explora Foundation is committed to supporting research in the field of physical protection in order to help develop the knowledge to protect those who risk their lives in the service of their country. This explosive test series is focused on understanding the performance of structural and architectural systems under blast loading conditions. The increased knowledge gained from these tests will be applied to improve structural codes currently used by the engineering community.

The tests were conducted at the Rafael Shdema Firing Range located south of Mitzpe Ramon, Israel. Members from academia, industry and military organisations were present for the explosive tests. There were four targets in this test series, each investigating the response of a different element to blast loading. The first target was testing rectangular hollow structural sections (RHS) as part of on-going research at the University of Toronto into their dynamic properties. The second test was investigating the applicability of the Glass Failure Prediction Model (GFPM) under blast loading conditions. The third test was part of research into the development and characterisation of an energy dissipating system for blast protection in structures. The fourth test was investigating the effect of blasts on industrial equipment, in this case a generator. A high-speed data acquisition system with 29 channels of instrumentation was used in this test series.

Two explosive tests were performed over the course of four days. The GFPM target only had one out of three windows break in the first test. Therefore, it was moved 10m closer to the charge for the second test. Despite the closer distance, no windows broke in the second test. The results obtained from this test will be useful in validating numerical models of glass performance under blast loading. In the first test, the bottom connection of the HSS beams rolled inwards about the inner line of anchor bolts instead of staying rigid and allowing the HSS beams to deflect. The top and bottom connections were repaired and strengthened over the course of one day to be ready for the second test. This allowed for a more successful second test since the supports did not move during the positive phase and the HSS members received the full blast load and reached their yield point. The results obtained from this test will be compared to numerical and single degree of freedom models to improve understanding of how these members perform under blast conditions. The energy dissipating system target behaved as expected in the first test and agreed with predictions. The target was moved much closer for the second test to evaluate its performance at the design limits. Following the second test, large movements were observed in all panels as expected. Some connections to the test structure failed, as did two elements of the steel frame where holes had been drilled for reflected pressure gauges.

The Explora Foundation demonstrated its ability to plan, coordinate, oversee, and instrument a test of this scale and complexity. Carrying out two successful tests in just four days was an immense achievement with direct benefits to all stakeholders.

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1. Objectives

Large investments in research for the protection of buildings from external explosive events, like a Vehicle Borne Improvised Explosive Device (VBIED), have produced innovative technologies capable of mitigating structural damage.

The Explora Foundation is committed to supporting research in the field of physical protection in order to help develop the knowledge to protect those who risk their lives in the service of their country. This explosive test series was focused on understanding the performance of structural and architectural systems under blast loading conditions. The increased knowledge gained from these tests will help to improve structural codes currently used by the engineering community as well as contribute to the development of innovative new protective designs.

2. Background

Explora Research is a limited liability not-for-profit company that is wholly owned by the Explora Foundation. The sole object of the company is to carry out primary research dedicated to resilience and whole physical protection systems and any related matters. The company will obtain and provide funds for this research, promote and encourage its development, and disseminate information on the same.

The primary vehicle for this research is the 'Explora Programme into Protection against the Effects of Energetic Events' at the University of Toronto Centre for the Resilience of Critical Infrastructure (CRCI). This programme is valued at Canadian $250,000 per year for a rolling five-year term, renewable every year. This funding is not exclusive and requests for research funds for investigations in the general area of physical protection will be considered up to a maximum total of US$500,000 over five years. In addition to this funding a further US $200,000 was contributed by the Explora Foundation to cover the costs of conducting this test series.

Explora Research Limited has brought together an industry consortium that provides, at no cost to the user, an instrumented arena blast test facility including up to three 500kg to 1,000kg of TNT equivalent detonations. Through the CRCI, this provides academic research projects cost-effective access to arena testing with only the cost of the targets and any supplementary instrumentation provided by the researchers with all other test overheads covered by the Explora Foundation. Intended for academic benefit, target arcs are open to any academic institution and should be booked with the CRCI by 15 January of the test year. Tests will ordinarily be conducted in the window May - July. The CRCI will be able to provide further information and specifications for each test series.

Explora Research is led by a Chief Scientist, who advises the Board of Directors and a team of corresponding associates, each a respected expert in his/her field. The company will, from time to time, compete for research funds to conduct in-house and collaborative projects. All proceeds from such projects are used as further research funding. The Explora Foundation also maintains close working relationships with academic institutions in the UK, USA, Canada, and Israel.

3. Roles and Responsibilities

Explora Foundation: Performing agency. Responsible for test planning, coordination and oversight, construction management, design assistance, test design, data reduction and analysis, and test documentation. Also responsible for instrumentation of all targets, determining the best way to record data of critical test elements, and retrieving this data following the test.

University of Toronto: Host of the Centre for Resilience of Critical Infrastructure. The University of Toronto is a world leading institution for engineering research. Through the Explora Programme into Protection against the Effects of Energetic Events, the University of Toronto is committed to advancing the study protective structures.

Rafael Israel: Provides test site supervision and management. Rafael is the owner of the test site and provides security and safety measures.

4. Technical Approach

The tests were conducted at the Rafael Shdema Firing Range located south of Mitzpe Ramon, Israel. Members from academia, industry, and military organisations were present for the test series. The following sections provide a description of the targets, the instrumentation used to record the event, and predictions of the response for each target that were used to select appropriate gauges.

4.1 Hollow Structural Section (HSS) Target

Hollow structural sections are being tested as part of on-going research at the University of Toronto into the dynamic properties of rectangular hollow structural sections (RHS). In order to determine the performance of cold formed RHS under blast loading conditions, beams of nominal external dimensions of 150mm x 150mm with various wall thicknesses were subjected to a blast load. The results of the test will be compared to SDOF analyses and finite element models. The goal of this research is to develop a better understanding of how cold formed RHS behave under blast conditions and enable better and more efficient designs.

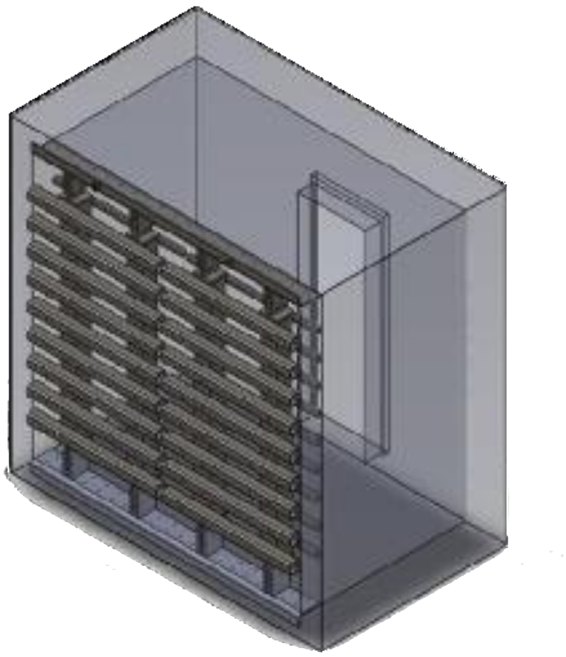

Figure 1 Hollow Structural Section Target

The test target consists of four rectangular beams, positioned vertically, spaced evenly across the open side of a 3m x 3m x 2m concrete cubicle. The beams are supported with a pin connection at the bottom and a roller (slotted hole) connection at the top. A cladding system consisting of smaller horizontal HSS elements reinforcing a steel deck spans between pairs of the main beams. This cladding is designed to transfer the blast loads without significantly affecting the flexural behaviour of the beams. The top and bottom connections are secured to the concrete floor and roof using anchor bolts. A rendering of the target is shown in Figure 1

4.2 Glass Failure Prediction Model (GFPM) Validation Target

The Glass Failure Prediction Model (GFPM) has been used to develop glass design standards such as ASTM E 1300. Recently, there has been increasing interest in utilising the GFPM in blast applications. However, the applicability of the GFPM in blast situations has never been tested. This test will attempt to derive the GFPM parameters under blast loading conditions in order for a comparison to be made to established values in the literature. The data acquired from the test will also be used to validate a new glass curtain wall analysis software package for blast loading being developed at the University of Toronto in collaboration with the Explora Foundation.

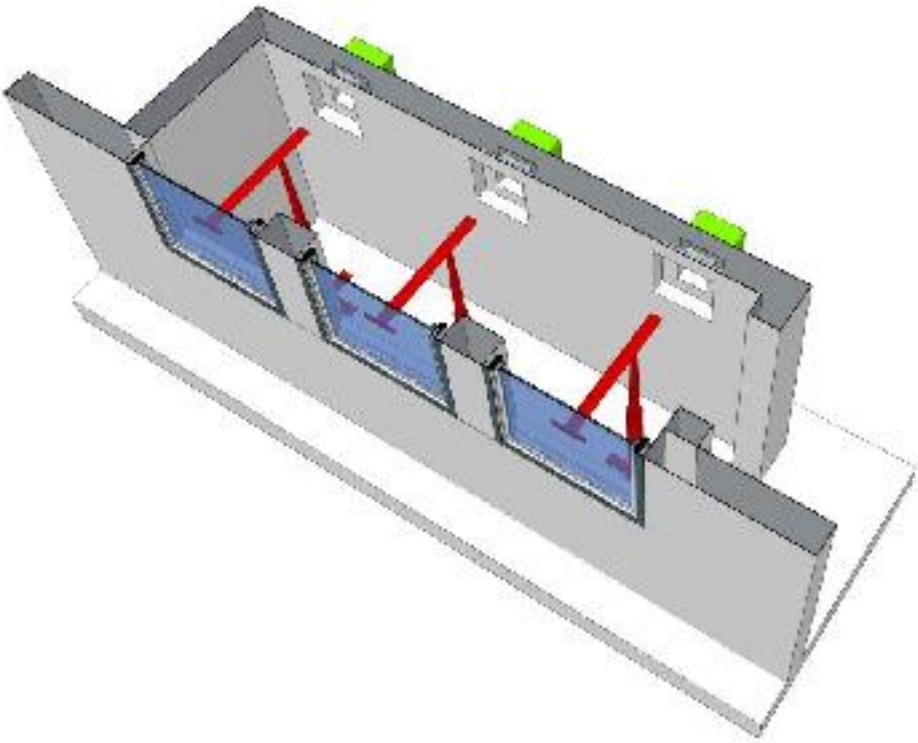

Figure 2 GFPM Validation Target

The target consists of a reinforced concrete frame with a large opening in the front. This opening was divided into three windows using steel hollow sections. Panes of 12mm thick annealed glass were fixed into the frames with a clamped boundary condition. Protected mounts for high-speed cameras were cast into the back of the target directly behind each window. A rendering of the target is shown in Figure 2

4.3 Energy Dissipating Component (EDC) Validation Target

Research is underway at the University of Toronto to develop and characterise Energy Dissipating Components which can be used for blast protection in structures. These tests will validate the prediction model for this system, developed using static and dynamic laboratory testing as well as finite element modelling. In addition, these tests will investigate the influence of supported mass on performance. This system provides an efficient and versatile method of absorbing a blast load and protecting the main structure from damage.

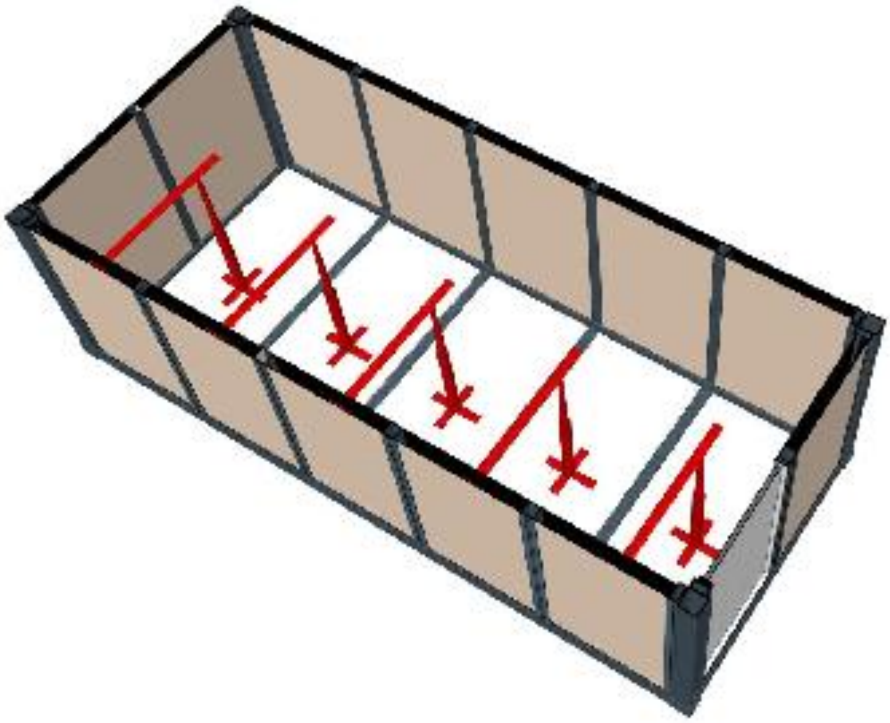

Figure 3 EDC Target

The test structure is a welded steel frame constructed using steel hollow sections. Within each bay on the long sides, rigid panels were installed using energy dissipating components to connect them to the test frame. The side and roof of the frame were covered using steel sheets welded to the underlying frame. A rendering of the target is shown in Figure 3.

4.4 Generator Target

While much research and experimentation has been conducted on blast effects and mitigation for buildings and personnel, the same cannot always be said for equipment that is used in these facilities. Vital equipment can be just as important to the continuity of operations following a blast event. For this reason, an industrial sized generator was set up in the arena and left running during both tests to gain an understanding of how it performs under blast conditions.

Figure 4 Generator Target

A typical industrial generator was purchased and the outer shell was removed which exposed all the internal components to the full effects of the blast as shown in Figure 4. The goal of this test is to see not only how equipment performs under blast conditions, but also to determine what type of damage occurs and possible retrofit strategies.

4.5 Test Field

The test site was approximately 1000m long by 750m wide and bounded by hills to the North, South and East as shown in Figure 5. The terrain was rocky, flat desert pavement.

Figure 5 Test Site

The targets were arranged in an arena configuration to minimise interaction between structures. The arena layout for test 1 and 2 is shown in Figure 6 and Figure 7 respectively. The arena was covered in a layer of clean sand in order to minimise rocks and debris being thrown against the targets.

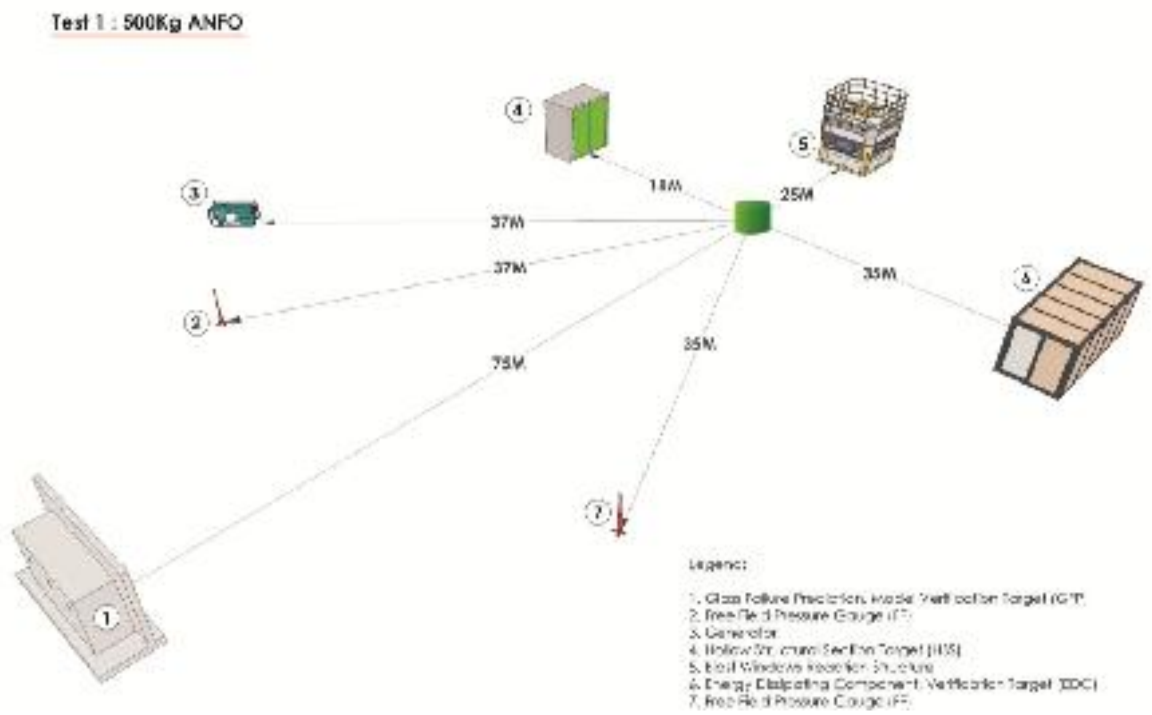

Figure 6 Test 1: Layout of Targets in Arena

For the second test, two new targets were added. These were a typical site office as well as a steel sea container that was adapted into an office (items 5 and 6 respectively in Figure 7). The purpose of including these additional targets was to demonstrate the effect of this explosive size and standoff distance on typical temporary structures.

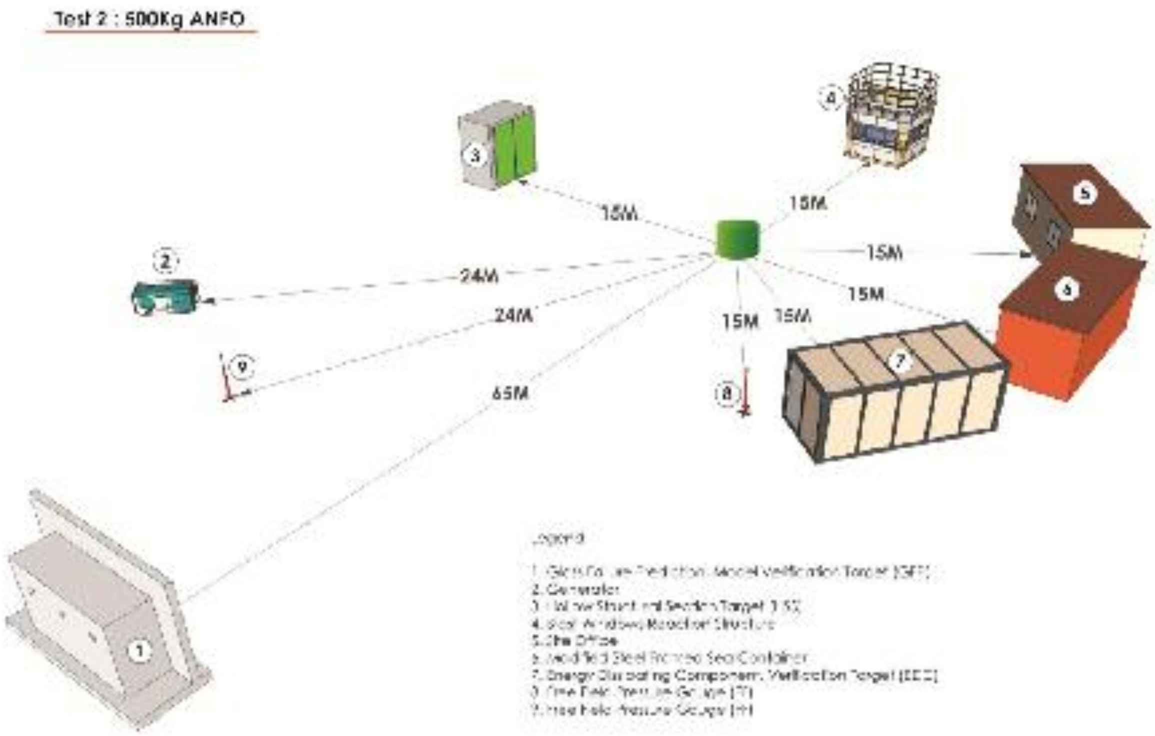

Figure 7 Test 2: Layout of Targets in Arena

4.6 Explosive Device

The explosive charge consisted of 495kg of commercial Ammonium Nitrate and Fuel Oil (ANFO) poured into a cylindrical cloth barrel as shown in Figure 8. The final charge had an aspect ratio of 1:1, with a height and diameter of 0.93m. The ANFO main charge was boosted by a 5 kg C4 charge placed at the centre of the cylinder.

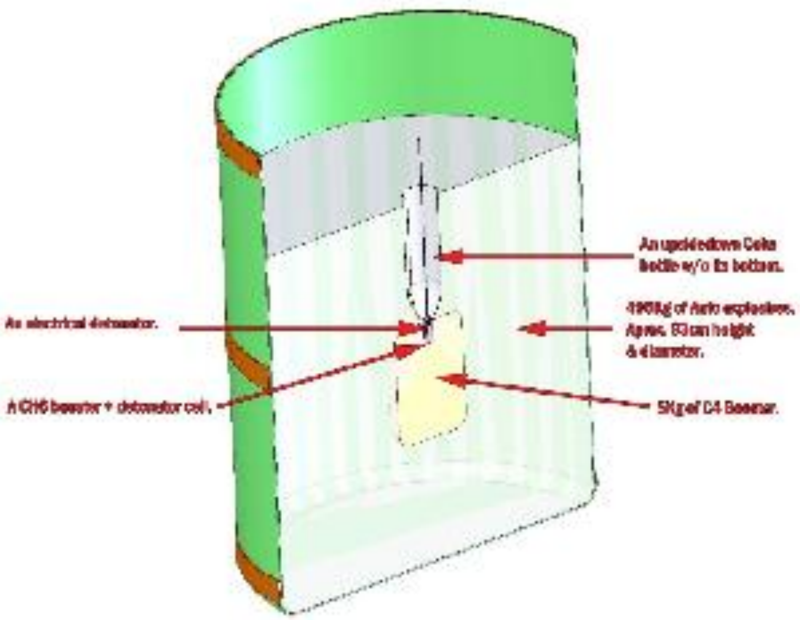

Figure 8 Charge Configuration

An electric detonator was used to initiate the booster charge. A break-wire was taped around the main charge so that the expansion of the charge case broke the wire and closed a circuit to trigger the data recorders and high speed digital cameras.

4.7 Instrumentation

Pressure, strain, and deflection data was recorded using a Hi-Techniques, Inc. meDAQ data acquisition system with on-board signal conditioning. The data was recorded at 2×10^6 samples per second for 500 msec. Calibration factors to convert voltage readings into engineering units were entered directly into the meDAQ with the exception of the strain gauges, since they have a nonlinear equation to convert voltage to strain. The recording equipment was housed in the protective firing bunker situated 250m from the charge. The data acquisition system (including the high-speed cameras) was triggered with an opto-isolated circuit with a break-wire wrapped around the explosive charge.

The Hollow Structural Section (HSS) target had 14 channels of instrumentation installed. This included four displacement gauges, two reflected pressure gauges, and eight strain gauges as shown in Figure 9.

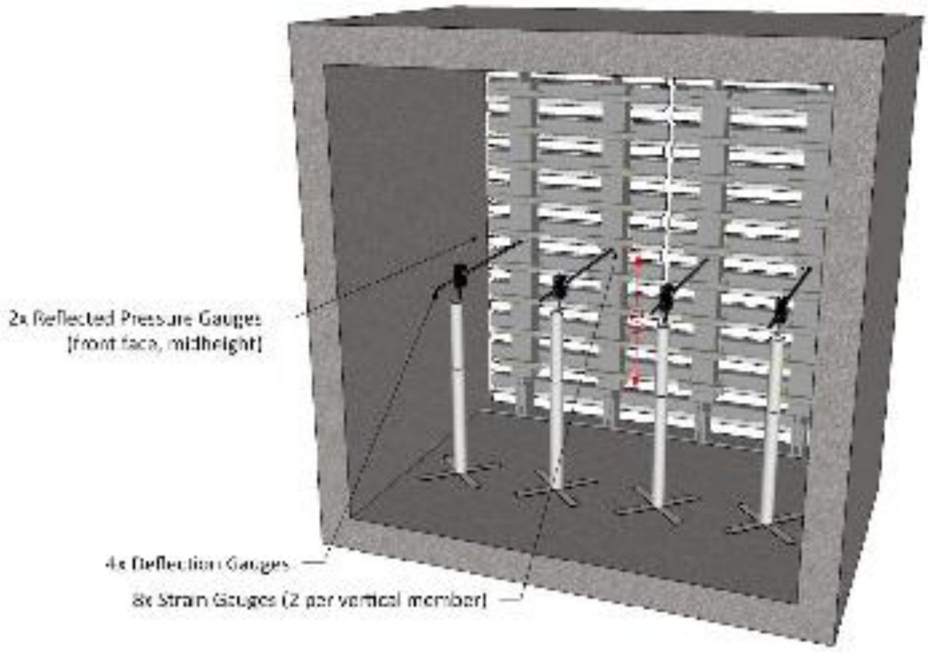

Figure 9 HSS Target Gauge Locations

The Energy Dissipating Component (EDC) target had eight channels of instrumentation installed. This included one free-field pressure gauge, five displacement gauges, and two reflected pressure gauges as shown in Figure 10.

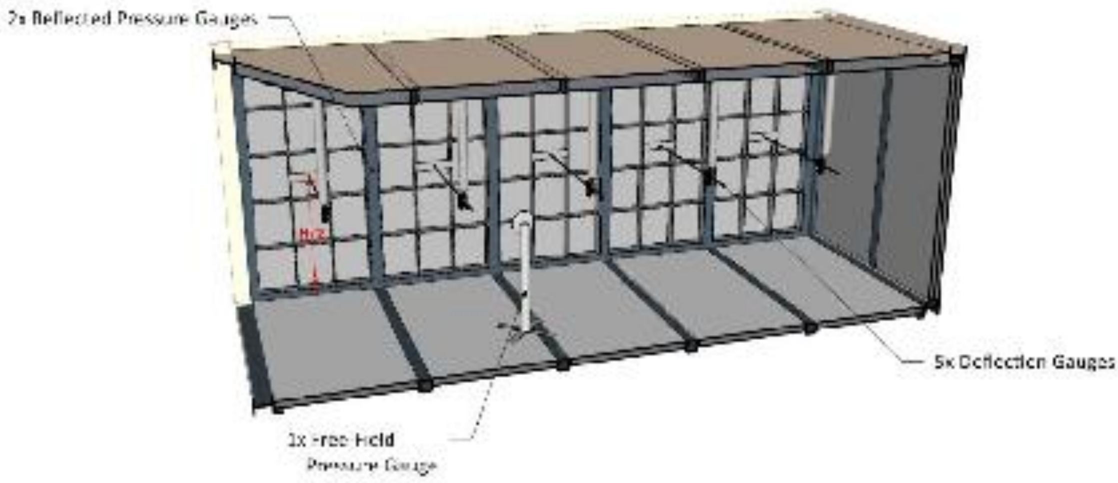

Figure 10 EDC Target Gauge Locations

The Glass Failure Prediction Model (GFPM) validation target had five channels of instrumentation installed as well as three Phantom high-speed cameras as shown in Figure 11.

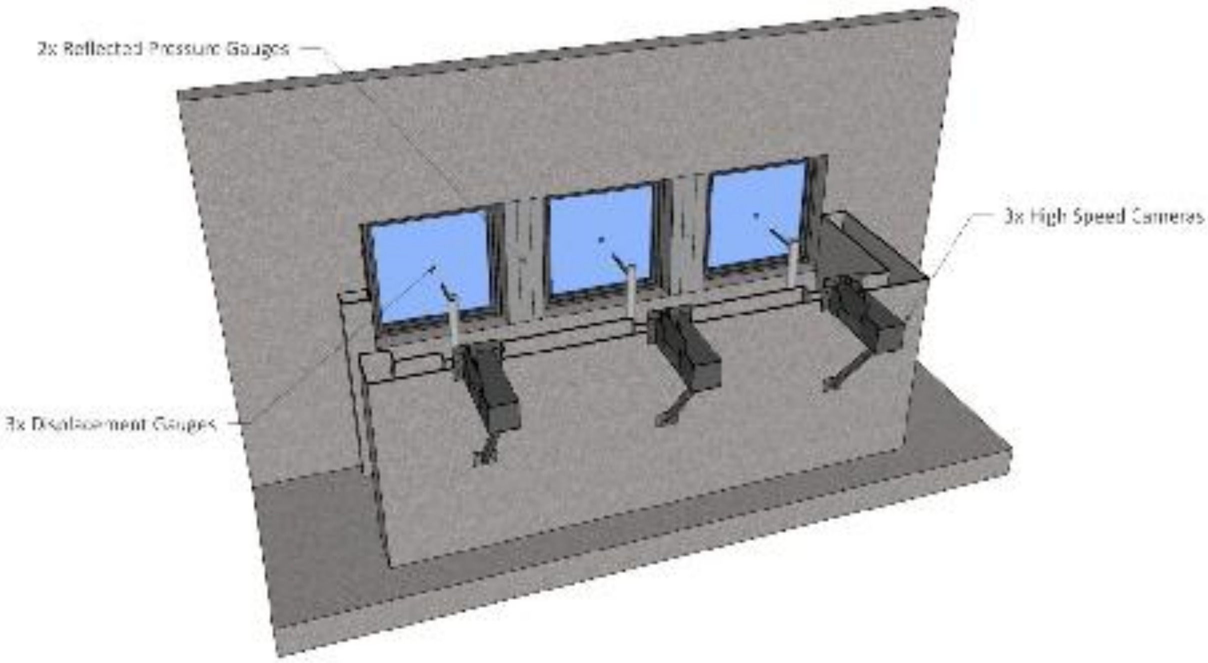

Figure 11 GFPM Target Gauge Locations

In addition to the targets, two free field pressure gauges were located within the arena. A summary of the gauges and expected peak measurements is provided in Table 1 for test 1 and Table 2 for test 2.

Table 1 Test 1: Gauge Measurement Predictions

Target	Gauge Name	Gauge Type	Peak Measurement	Peak Impulse (kPa-msec)
HSS	HSSRP-1	Reflected	593 kPa	2103
HSS	HSSRP-2	Reflected	593 kPa	2103
HSS	HSSDG-1	Displacement	28 mm	
HSS	HSSDG-2	Displacement	28 mm	
HSS	HSSDG-3	Displacement	34 mm	
HSS	HSSDG-4	Displacement	34 mm	
HSS	HSSSG-1	Strain	3% (gauge max)	
HSS	HSSSG-2	Strain	3% (gauge max)	
HSS	HSSSG-3	Strain	3% (gauge max)	
HSS	HSSSG-4	Strain	3% (gauge max)	
HSS	HSSSG-5	Strain	3% (gauge max)	
HSS	HSSSG-6	Strain	3% (gauge max)	
HSS	HSSSG-7	Strain	3% (gauge max)	
HSS	HSSSG-8	Strain	3% (gauge max)	
GFPM	GFTRP-1	Reflected	34 kPa	331
GFPM	GFTRP-2	Reflected	34 kPa	331
GFPM	GFTDG-1	LVDT	15.9mm	
GFPM	GFTDG-2	LVDT	15.9 mm	
GFPM	GFTDG-3	LVDT	15.9 mm	
EDC	EDCRP-1	Reflected	106.1 kPa	928.5
EDC	EDCRP-2	Reflected	106.1 kPa	928.5
EDC	EDCDG-1	Displacement	79 mm	
EDC	EDCDG-2	Displacement	79 mm	
EDC	EDCDG-3	Displacement	32 mm	
EDC	EDCDG-4	Displacement	99 mm	
EDC	EDCDG-5	Displacement	99 mm	
EDC	EDCFF-1	Free Field	< 35 kPa	

Table 2 Test 2: Gauge Measurement Predictions

Target	Gauge Name	Gauge Type	Peak Measurement	Peak Impulse (kPa-msec)
HSS	HSSRP-1	Reflected	1020 kPa	2606
HSS	HSSRP-2	Reflected	1020 kPa	2606
HSS	HSSDG-1	Displacement	44 mm	
HSS	HSSDG-2	Displacement	44 mm	
HSS	HSSDG-3	Displacement	54 mm	
HSS	HSSDG-4	Displacement	54 mm	
HSS	HSSSG-1	Strain	3% (gauge max)	
HSS	HSSSG-2	Strain	3% (gauge max)	
HSS	HSSSG-3	Strain	3% (gauge max)	
HSS	HSSSG-4	Strain	3% (gauge max)	
HSS	HSSSG-5	Strain	3% (gauge max)	
HSS	HSSSG-6	Strain	3% (gauge max)	
HSS	HSSSG-7	Strain	3% (gauge max)	
HSS	HSSSG-8	Strain	3% (gauge max)	
GFPM	GFTRP-1	Reflected	34 kPa	386
GFPM	GFTRP-2	Reflected	34 kPa	386
GFPM	GFTDG-1	LVDT	15.0 mm	
GFPM	GFTDG-2	LVDT	15.0 mm	
GFPM	GFTDG-3	LVDT	15.0 mm	
EDC	EDCRP-1	Reflected	1021 kPa	2662
EDC	EDCRP-2	Reflected	1021 kPa	2662
EDC	EDCDG-1	Displacement	739 mm	
EDC	EDCDG-2	Displacement	739 mm	
EDC	EDCDG-3	Displacement	168 mm	
EDC	EDCDG-4	Displacement	509 mm	
EDC	EDCDG-5	Displacement	509 mm	
EDC	EDCFF-1	Free Field	< 35 kPa	

Digital high-speed cameras were used to attempt to identify the location of the first crack in sheets of annealed glass under blast conditions. Previous studies showed that a frame rate of over 30000 fps is required to capture crack formation in glass. This high frame rate is not necessary for most structural behaviour; therefore, a 600 fps camera was used to record the HSS behaviour. The cameras located in the GFPM target were protected by steel boxes placed within the test frame. Lighting inside the GFPM target consisted of halogen lamps placed along the back wall of the target and angled downwards to reduce glare. The camera recording the HSS behaviour was positioned behind the HSS target with a view through the open door, which allowed light into the interior of the target. The camera frame rates are shown in Table 3.

Table 3 High Speed Cameras

Target	Camera #	FPS
HSS	1	600
GFPM	2	7000+
GFPM	3	26000+
GFPM	4	30000+
Arena	5	3000
Arena	6	3000

All cameras except the 600fps camera were triggered using a trigger signal from the break-wire on the explosive charge. The 600fps camera was manually triggered before the arena was cleared of personnel for the test and left to record.

5. Logistics

All attendees to the tests had accommodation arranged by the Explora Foundation in the Israeli resort town of Eilat on the Red Sea. Transportation to and from the site was provided on the test days and was approximately an 80 minute drive. The test site itself was fitted with a large air-conditioned tent, power supply, toilets, and catering to make it as comfortable as possible. Figure 12 and Figure 13 show the tent being erected and in use.

Figure 12 Tent being erected on-site

Figure 13 Interior of the tent on the day of a test

For safety reasons, all guests were relocated to an observation point overlooking the test site over a kilometre away before each blast occurred. From there they had a view of the surrounding area and could see the entire test site as the charge was detonated. Figure 14 shows the view of the test site from the observation point.

Figure 14 View of test site from observation point

6. Test Results

The following section outlines the free-field and reflected pressure measurements for each test. Additional measurements on the individual member responses, such as deflection and strain, are provided to the experimenters and are not provided in this summary report.

6.1 Test Conditions

At the time of the first test, atmospheric conditions were 100.7 kPa and 37 C. Winds were 10.0km/h from the North.

At the time of the second test, atmospheric conditions were 101.0 kPa and 42.1 C. Winds were 19.2km/h from the North.

6.2 Recorded Pressures

For each of the three instrumented test structures, the reflected pressures on the front face were recorded. These are compared with theoretical predictions produced in Conwep for an infinite reflecting surface. Free-field pressures were recorded for both tests and are compared with predictions.

6.2.1 Hollow Structural Section Target

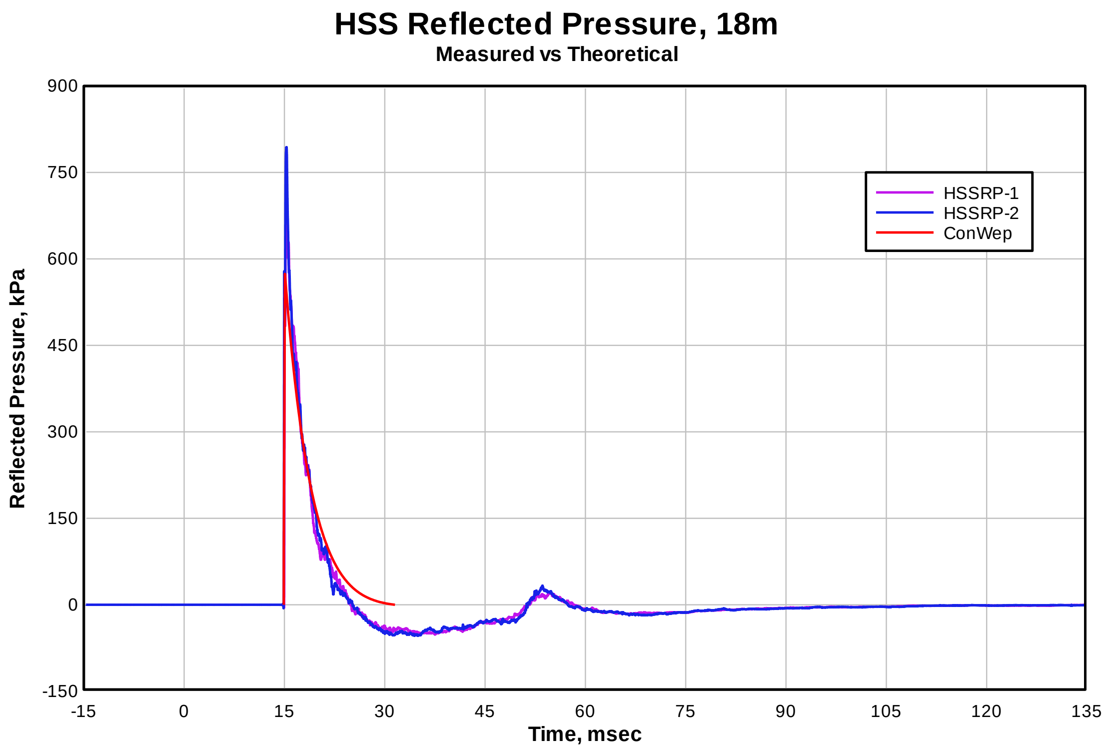

Figure 15 Test 1: HSS Target Reflected pressure-time History

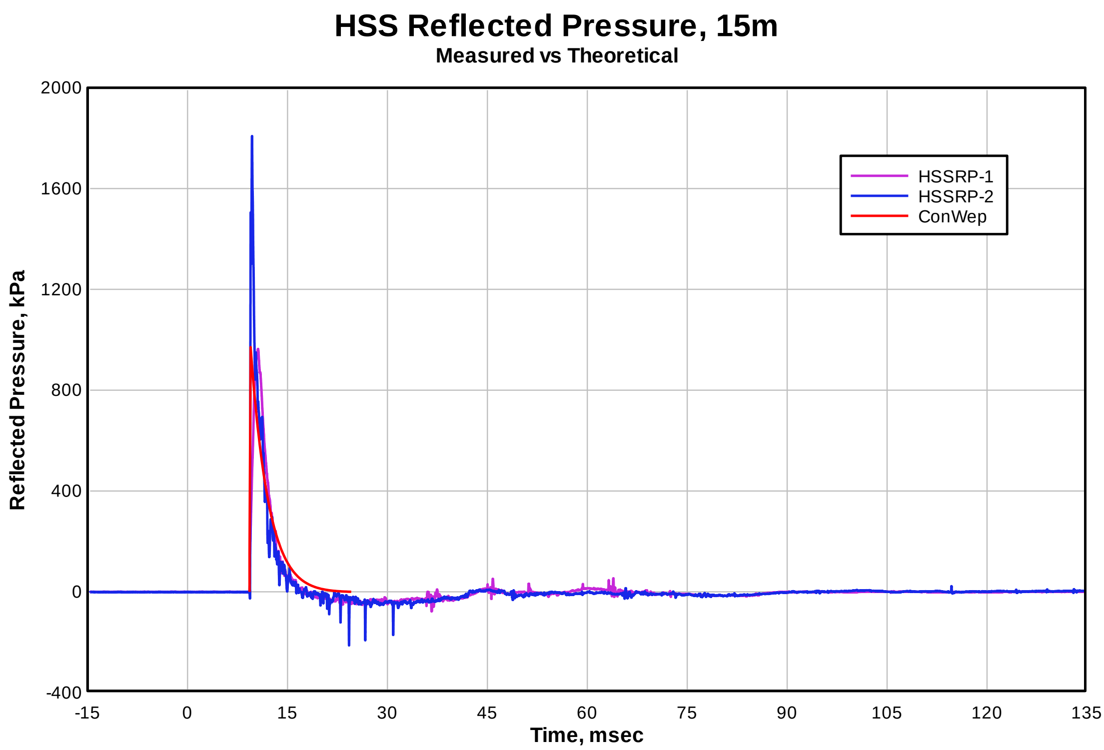

Figure 16 Test 2: HSS Target Reflected pressure-time History

6.2.2 Glass Failure Prediction Model Verification Target

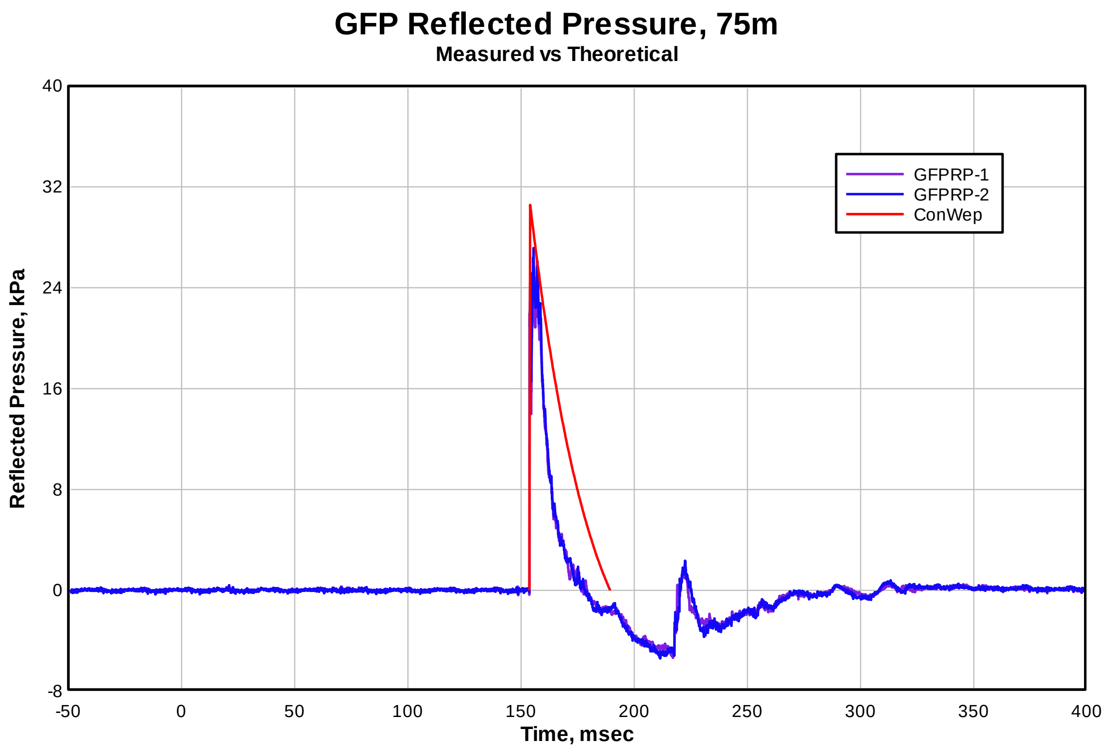

Figure 17 Test 1: GFPM Target Reflected Pressure-time History

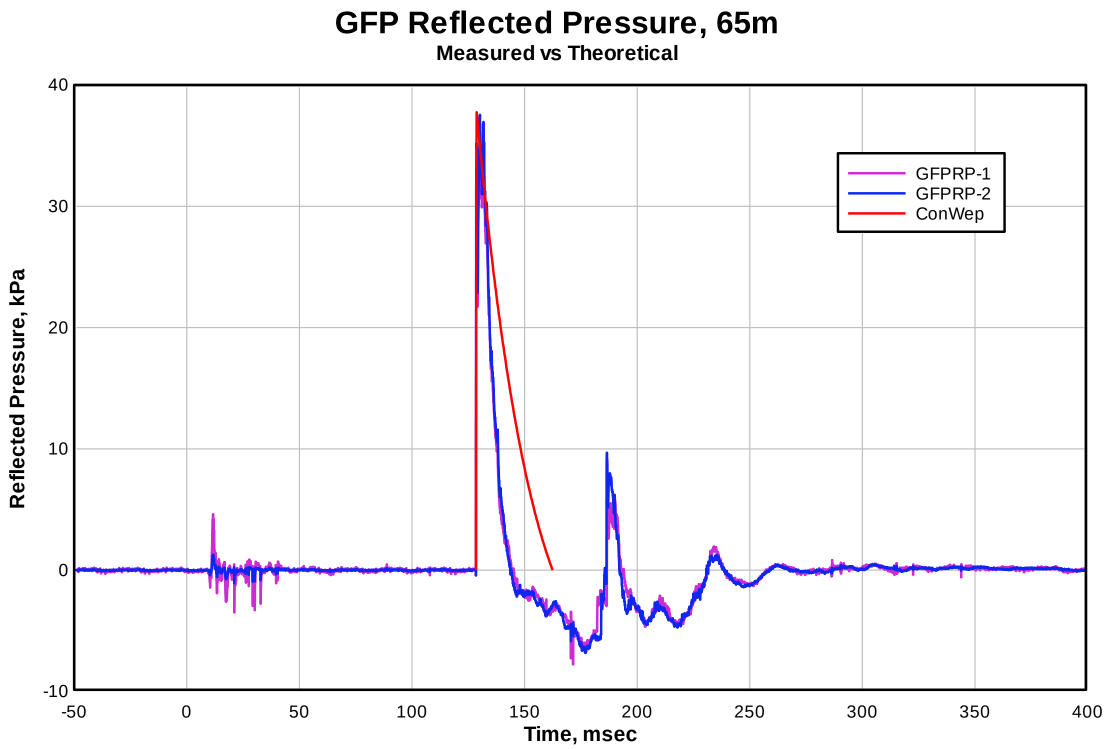

Figure 18 Test 2: GFPM Target Reflected Pressure-time History

6.2.3 Energy Dissipating Component Verification Target

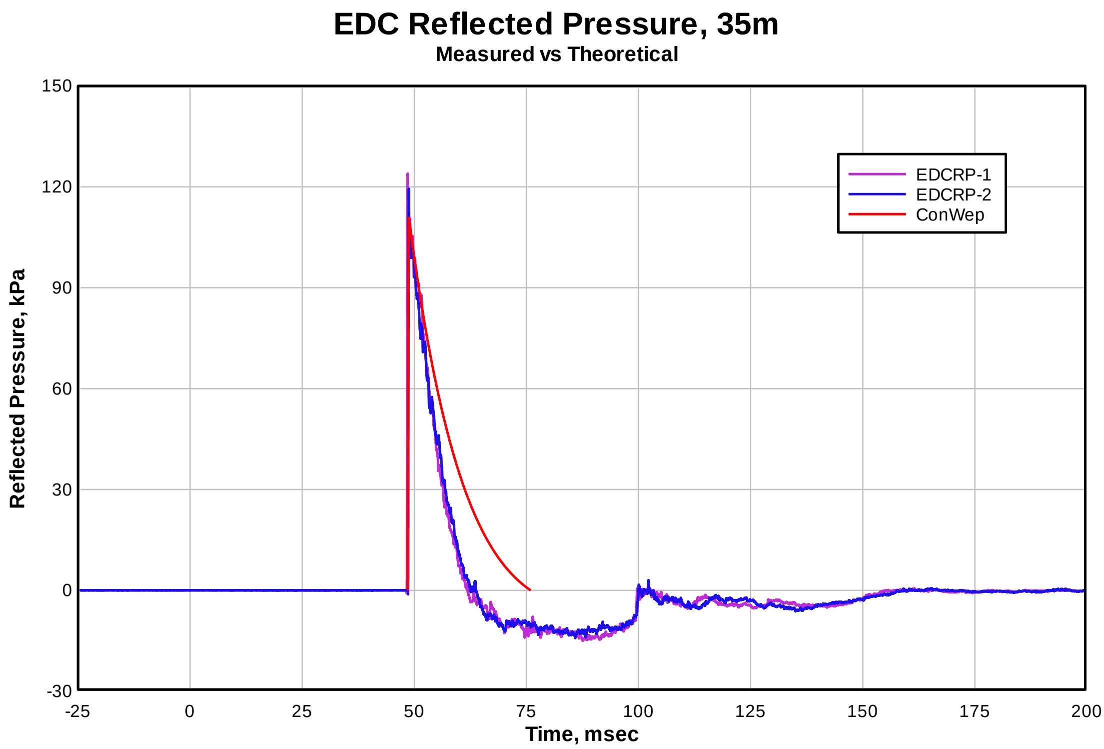

Figure 19 Test 1: EDC Target Reflected Pressure-time History

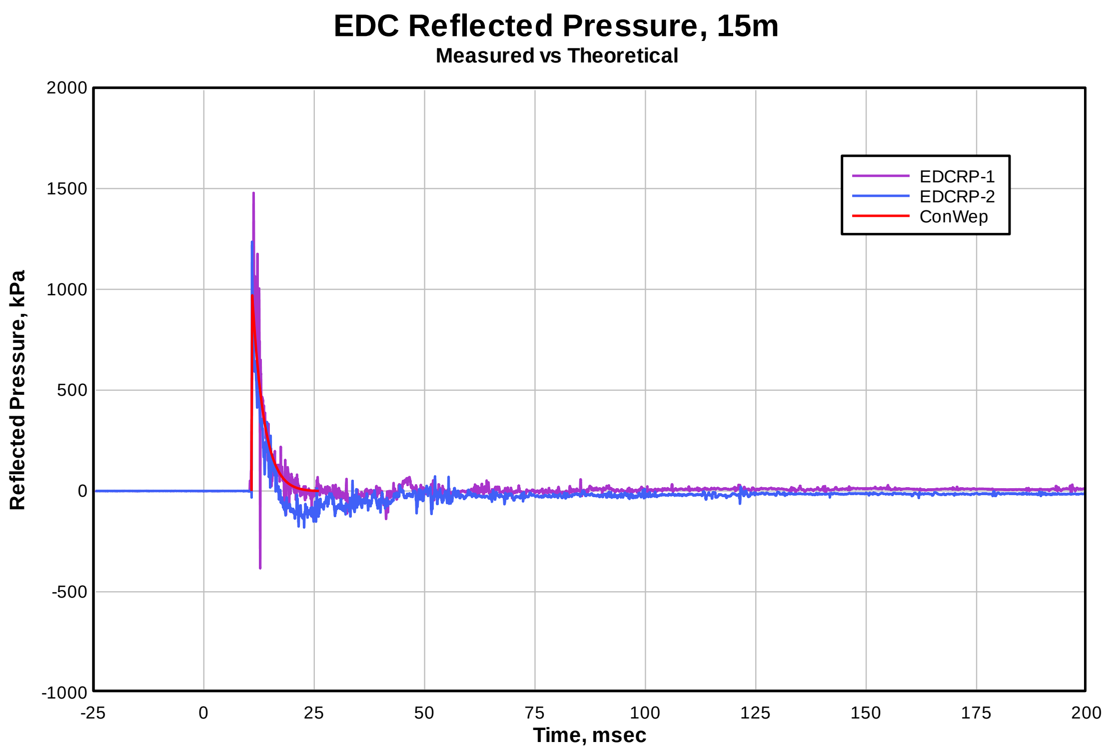

Figure 20 Test 2: EDC Target Reflected Pressure-time History

6.2.4 Arena Free-Field Gauges

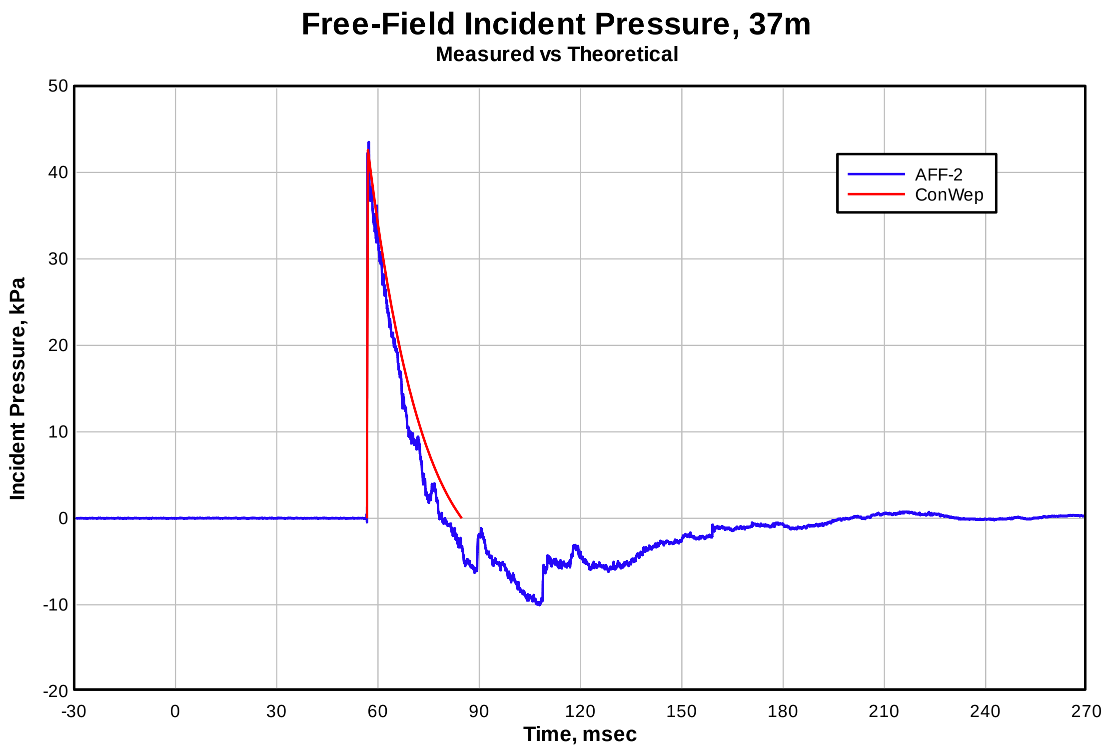

Figure 21 Test 1: Free-field Pressure-time History at 37m Standoff

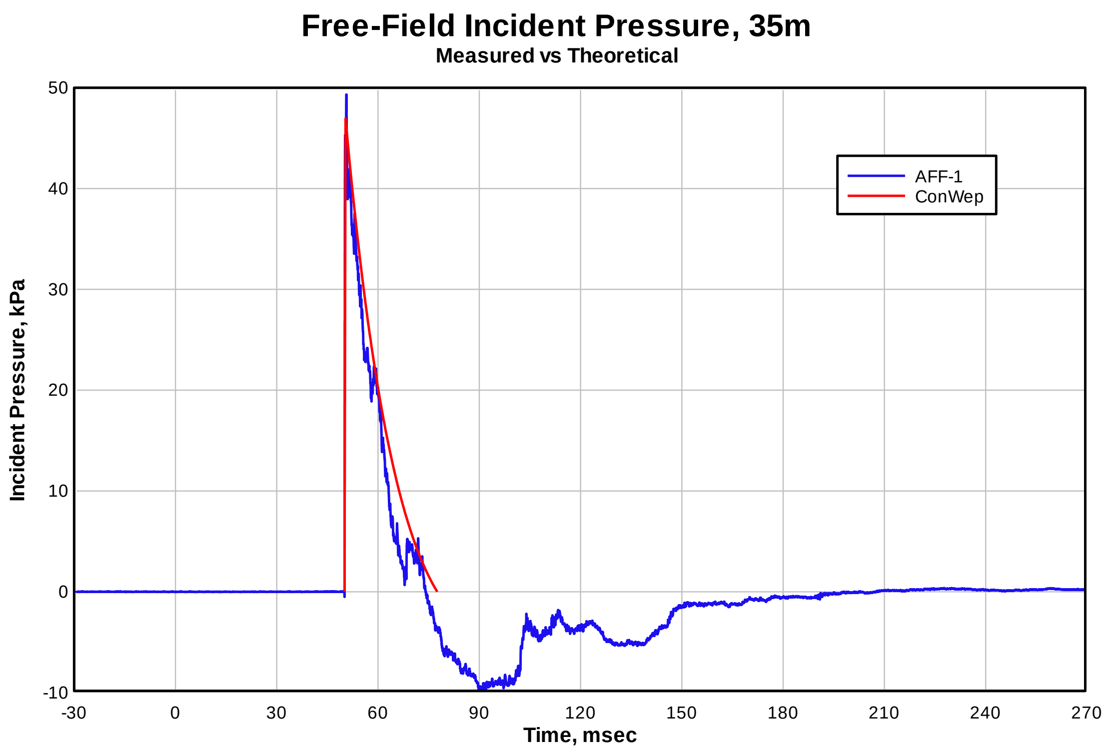

Figure 22 Test 1: Free-filed Pressure Time History at 35m Standoff

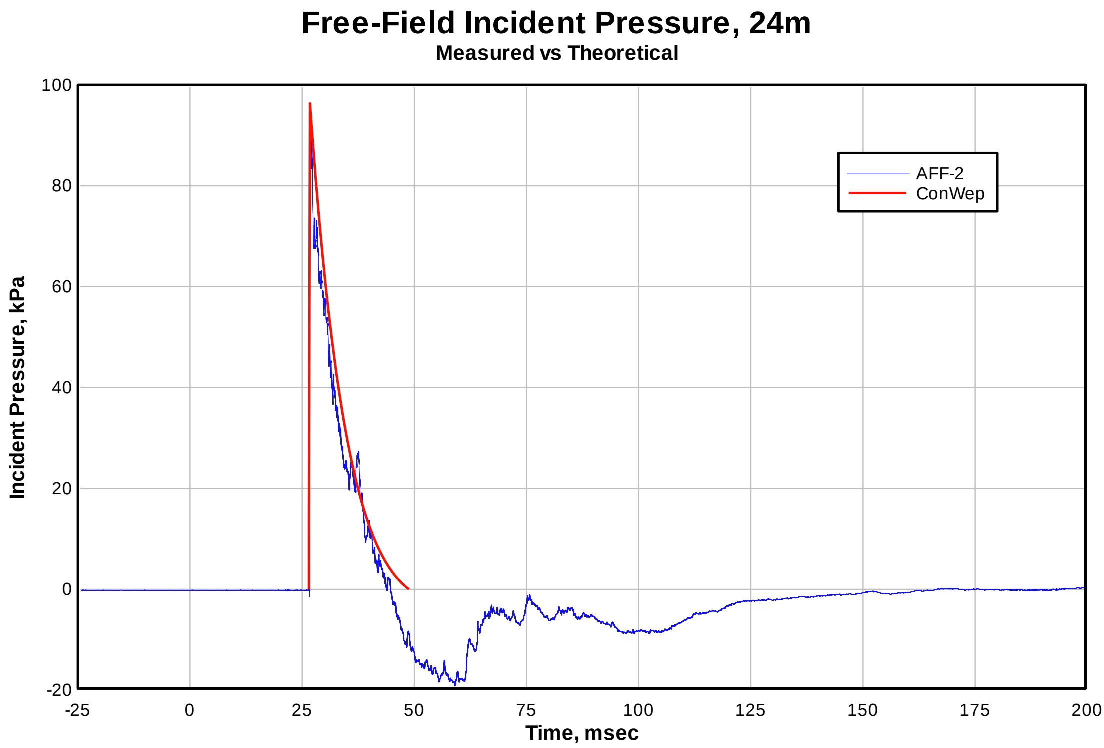

Figure 23 Test 2: Free-field Pressure Time History at 24m Standoff

7. OBSERVATIONS

It can be seen that the measured peak pressures matched predictions well. The only pressure gauge that did not work during the test was the free-field pressure gauge located at 15m standoff in the second test. Although the peak pressures observed matched the predictions quite nicely, the reflected impulses were lower than predicted due to clearing effects.

In the first test, the GFPM target only had one window break, which is why it was moved to a 65m standoff for the second test from 75m in the first test. Despite the closer distance, no windows broke in the second test. In the first test, the high-speed cameras did not trigger since they overheated due to the temperature. For the second test, a cooling system was deployed for the cameras to address the overheating issue. In the second test, all of the cameras triggered correctly.

The bottom connection of the HSS beams rolled inwards pulling out some of the anchor bolts in the first test. The top and bottom connections were repaired and strengthened over the course of one day to be ready for the second test. This allowed for a more successful second test since the supports did not move during the positive phase and the HSS members received the full blast load and deformed as planned.

During the first test, the EDC target behaved as expected and the movement of the panels agreed with predictions. The middle, heavier panel had noticeably less deflection than the lighter outside panels. For the second test, the entire target was rotated so that the panels facing the outside of the arena during the first test were facing the charge. Following the second test, large movements were observed in all panels as expected. Some connections of the EDC's to the test structure failed, as did the steel frame of the target where holes drilled for the reflected pressure gauges had weakened the structure. The second test was intended to test the system to its limits, which explains the failure of some components of the target.

8. CONCLUSIONS

All participants deemed the test series a success. The scheduling of the test was quite ambitious in that only one day before each test was allotted for the team from the Explora Foundation to arrange the arena, install, set-up, and test all 29 channels of instrumentation for the targets, and install and test the high-speed cameras. This reduced the cost of the test as personnel, equipment, and the test site could be engaged for a shorter period. It also made it easier for guests to attend the test series as the tighter schedule meant they had to spend less time in the field. It can be seen that the quality of the test was in no way compromised by the scheduling.

The Explora Foundation demonstrated its ability to plan, coordinate, oversee, and instrument a test of this scale and complexity. Having carried out two successful tests in just four days was an immense achievement with direct benefits to all stakeholders.

Carrying out the tests in the short time provided required extensive planning and off-site preparation by the Explora Foundation and its partners. This type of collaboration and preparation will be replicated on future tests to ensure time on-site is minimised and overall costs are reduced while providing a test series of the highest quality.

Appendix A: Test Photos

Construction

Figure 24 Assembly of the Cladding for HSS Target

Figure 25 Installation of Cladding on HSS Target

Figure 26 Tightening of Cladding Supports for HSS Target

Figure 27 EDC Target after Assembly

Figure 28 Glass Panes and Supports Being Installed into GFPM Target

Figure 29 Lifting GFPM Target into Arena

Prior to test 1

Figure 30 GFPM Target Prior to First Test

Figure 31 EDC Target Interior Prior to First Test

Figure 32 EDC Target Prior to First Test

Figure 33 HSS Target Prior to First Test

Results of test 1

Figure 34 EDC Target Following Test 1

Figure 35 EDC Target Corner Detail Following Test 1

Figure 36 GFPM Target Following Test 1

Figure 37 GFPM Target Broken Window Following Test 1

Figure 38 HSS Target Following Test 1

Figure 39 HSS Target Following Test 1, Support Rotation

Prior to test 2

Figure 40 EDC Target Prior to Test 2

Figure 41 Site Office and Shipping Container Office Prior to Test 2

Figure 42 GFPM Target Prior to Test 2 with Broken Window Replaced

Figure 43 HSS Target Repaired Prior to Second Test

Results of test 2

Figure 44 EDC Target Following Test 2

Figure 45 EDC Target Panel Following Test 2

Figure 46 Modified Steel Framed Sea Container Office Following Test 2

Figure 47 Site Office Following Test 2

Figure 48 EDC Target, Shipping Container Office, and Site Office after Test 2

Figure 49 HSS Target Following Test 2

Figure 50 HSS Target Following test 2