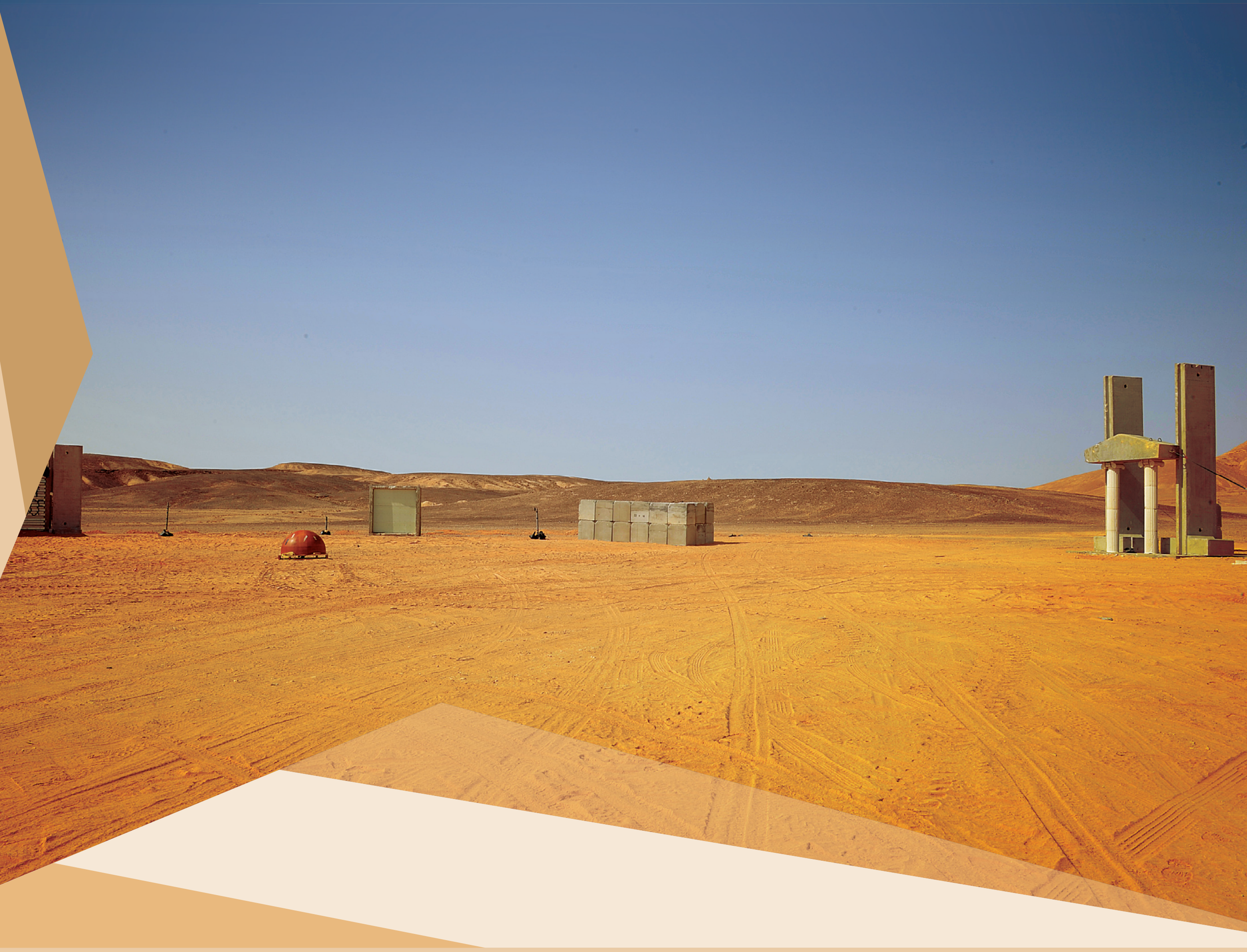
EXPLORA FOUNDATION

2013 TEST SERIES REPORT



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2013 Test Series

Report

Explora Foundation 2013 Test Series Report

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2013 Test Series

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 tests were conducted at the Rafael Shdema Firing Range located south of Mitzpe Ramon, Israel. Members from academia, industry and military organisations were present.

There were six targets in this test series, each investigating the response of a different element to blast loading. The first set of targets tested was an arena of three glass targets. Seven panes of glass were tested in each of four blast tests over the course of one day. The results obtained from these tests will be used in validating numerical models of glass performance under blast loading. The second target was concrete barriers arranged to form a traffic lane. The purpose of this test was to observe the response of concrete vehicle barriers to a blast.

The remaining targets were tested in a separate, larger, arena from the glass targets. The first test in this main arena included a full-scale historic masonry wall, neoclassical multi-drum columns, and an industrial generator inside an enclosure. The inner wythe of the historic masonry wall collapsed in the first test, while the outer wythe remained intact. The neoclassical multi-drum columns also collapsed in the first test. However, this appears to be due to the failure of one of the pediment restraints. Finally, the generator enclosure was severely damaged in the first test; however, the generator itself suffered only minor damage and was repaired in a short time.

In the second main arena test, the historic masonry wall was not tested. However, a hollow structural section target as well as a fibre reinforced plastic wall target was added. The generator and multi-drum columns were also included again in the second test. The hollow structural section target deformed plastically in this test, as was intended. The fibre reinforced plastic wall was severely damaged, with both shear and flexural failures observed. The multi-drum columns did not collapse in this test. This is likely because the pediment restraint did not fail. The generator was not damaged severely in this test but did not continue running, however, it was able to be repaired in a short time. The third and final test had much the same results, with the hollow structural section target experiencing larger plastic deformations. Since the fibre reinforced plastic wall was destroyed in the second test, it was not re-tested. The multi-drum columns did not collapse, also due to the fact that the pediment restraint remained intact. Finally, the generator only suffered minor damage and was repaired quickly.

The Explora Foundation demonstrated its ability to plan, coordinate, oversee, and instrument a test of this scale and complexity. Carrying out three successful tests in just four days in addition to performing four glass arena tests in one day was an immense achievement with direct benefits to all stakeholders. All participants deemed the test series a success.

Table of Contents

1. Objectives

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 several different 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

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.

The Explora Foundation 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.

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 Glass Failure Prediction Model (GFPM) Validation Target

The University of Toronto CRCI, Explora Research

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. A series of tests was performed to 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.

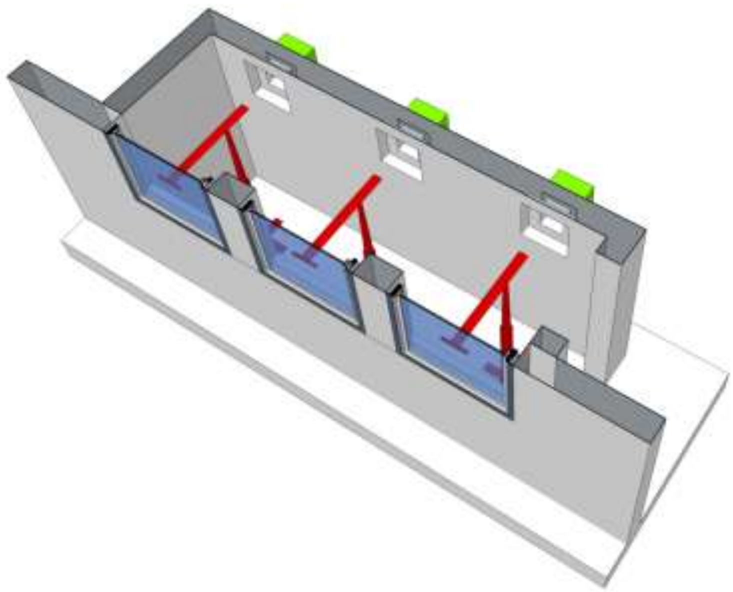

Figure 1 GFPM validation target

The target consisted 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 installed in standard aluminium window frames and then installed into target. 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 1.

4.2 Concrete Barriers Target

Explora Research

In order to observe the effect of a blast on concrete barriers, a mock traffic lane bordered by two rows of concrete barriers was constructed. One row of barriers was connected together using steel channel elements bolted into the concrete. The other row was not connected in any way.

4.3 Hollow Structural Section (HSS) Target

The University of Toronto CRCI

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 120mm x 120mm with wall thicknesses of 5mm and 8mm were subjected to a blast load. Both hollow and concrete filled elements were tested. 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.

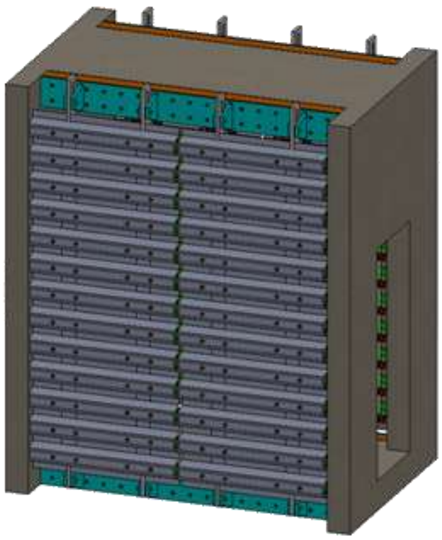

Figure 2 Hollow structural section target

The target was double sided, with four beams, positioned vertically and spaced evenly across each open side. 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. A rendering of the target is shown in Figure 2

4.4 Generator Target

Explora Research

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 3 Generator target

A typical industrial generator (Figure 3) was used and installed within a replica generator room. 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 Masonry Wall Target

The University of Toronto CRCI

The response of historic masonry walls to blast loading is poorly understood. Due to differences in construction methods and materials these walls may respond differently from modern masonry block walls. In order to better understand the response of such historic structures, a sandstone-rubble-limestone masonry wall constructed using period appropriate materials and techniques will be subjected to an explosive load. Extensive instrumentation and video will allow an in-depth analysis of the wall response to be undertaken.

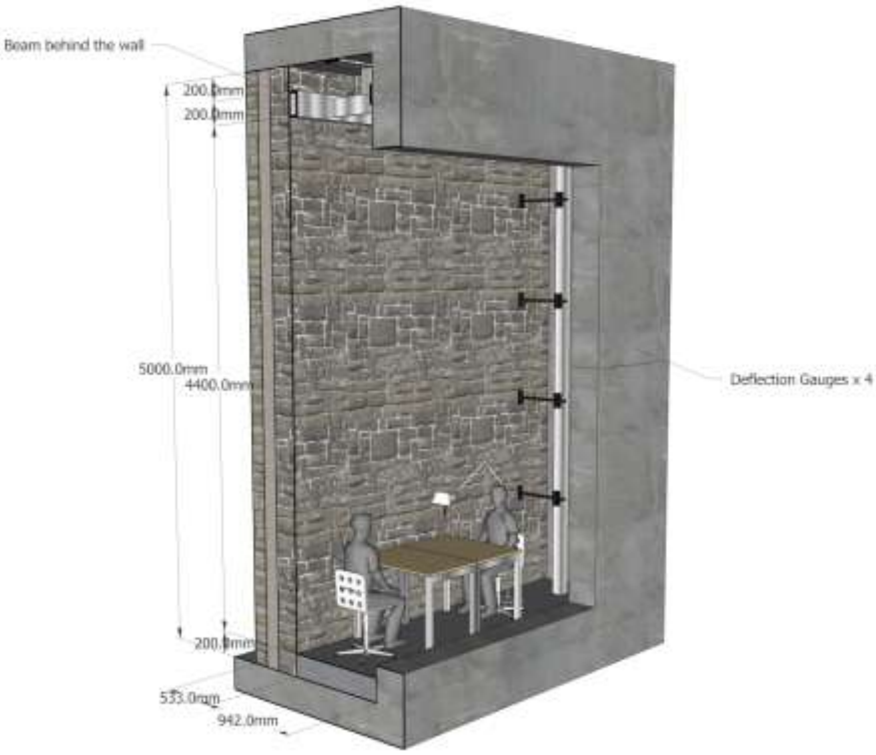

Figure 4 Masonry wall target

4.6 Fibre Reinforced Plastic Element Wall

Royal Military College of Canada (RMC), Explora Research

The purpose of this test is to investigate the feasibility of using pultruded fibre reinforced plastic structural members as primary elements in a blast loading application. These elements offer the advantage of a dramatic weight reduction over traditional steel or concrete construction which is ideal for expeditionary and temporary structures. However, disadvantages such as a relatively low shear resistance and brittle failure mode are a cause for concern in blast applications.

4.7 Neoclassical Multi-Drum Columns

Explora Research

This test attempts to understand the response of neoclassical multi-drum columns to blast loading, in order to provide a means of evaluating the vulnerability of structures constructed using these columns.

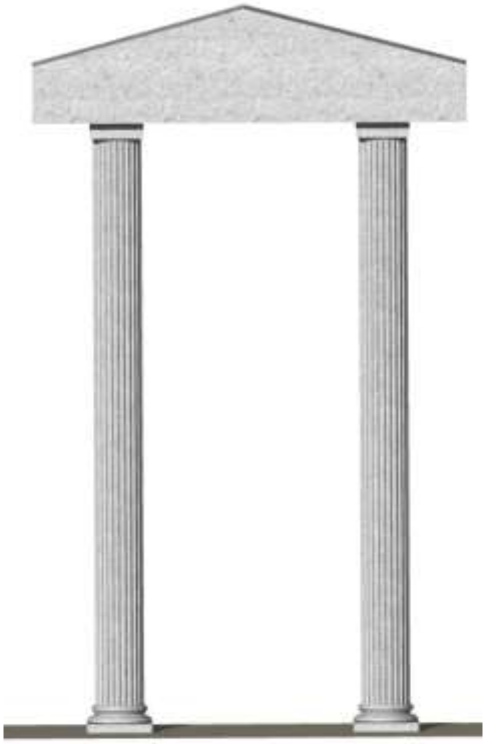

Figure 5 Multi-drum columns

The results of this test will be used to develop a model to evaluate of the vulnerability of neoclassical columns to blast loading.

4.8 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 6. The terrain was rocky, flat desert pavement.

Figure 6 Test Site

The targets were arranged in an arena configuration to minimise interaction between structures. Two different arenas were used in this test series, one for glass testing and another for main full-scale tests.

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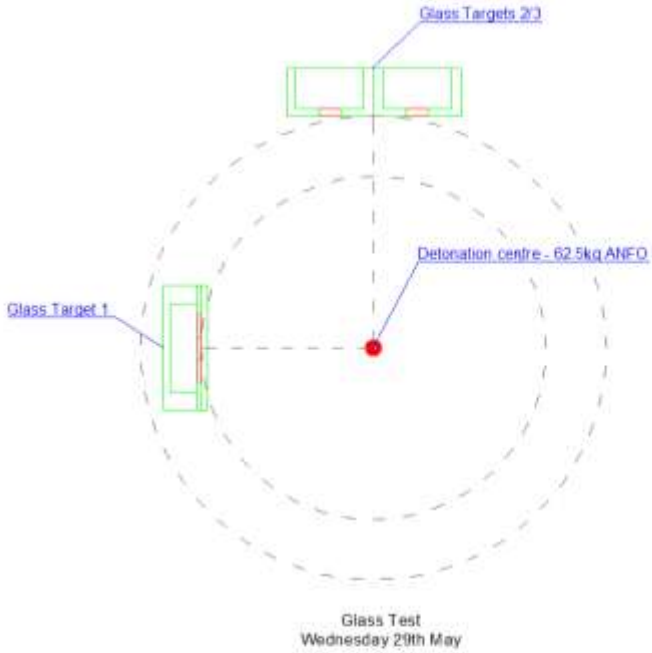
4.9 Glass Testing Arena

The GFRP tests were conducted in a separate arena. Four blast tests were conducted over the course of one day using the same arena layout.



The explosive used for these tests was 62.5kg of bagged ANFO.

4.10 Concrete Barrier Test Layout

To rows of concrete barriers were setup forming a typical traffic lane. An ANFO charge was placed midway between the barriers halfway long their length.

The barriers on one side were connected using steel channel sections and embedded anchor bolts. The barriers on the other side were not connected.

4.11 Main Arena

The arena layout for test 1, 2, and 3 are shown in Figure 7, Figure 8, and Figure 9 respectively. The arena was covered in a layer of clean sand between tests in order to fill the crater and minimise rocks and debris being thrown against the targets.

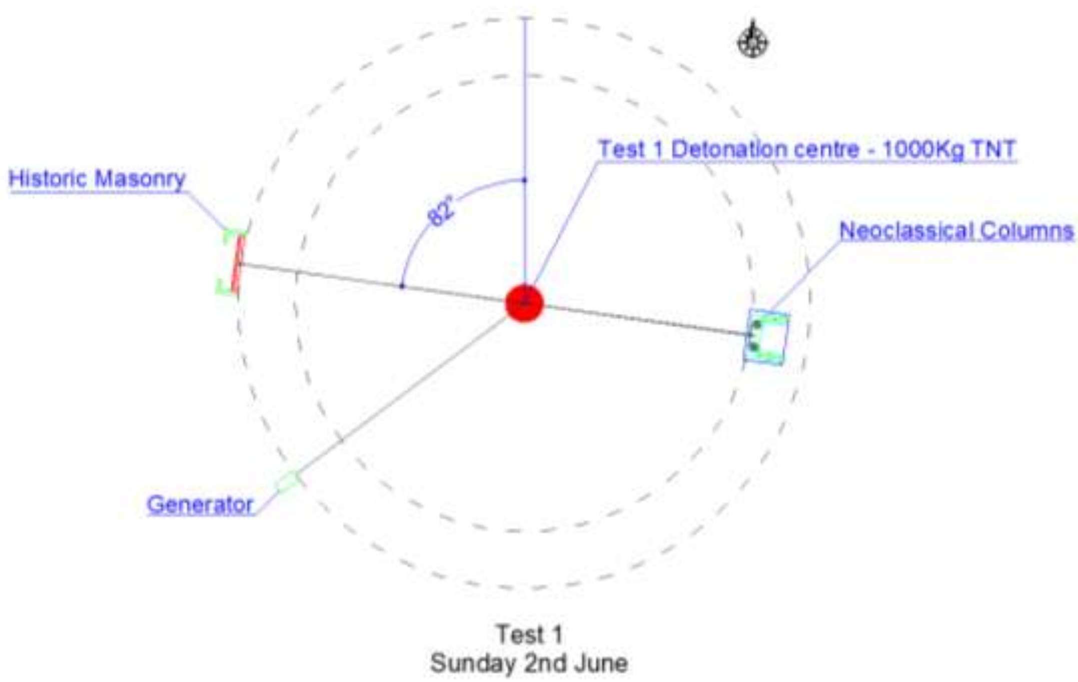


Figure 7 Test 1: Layout of targets in arena

For the second test, two new targets were added. These were the HSS Targets, and the FRP wall.

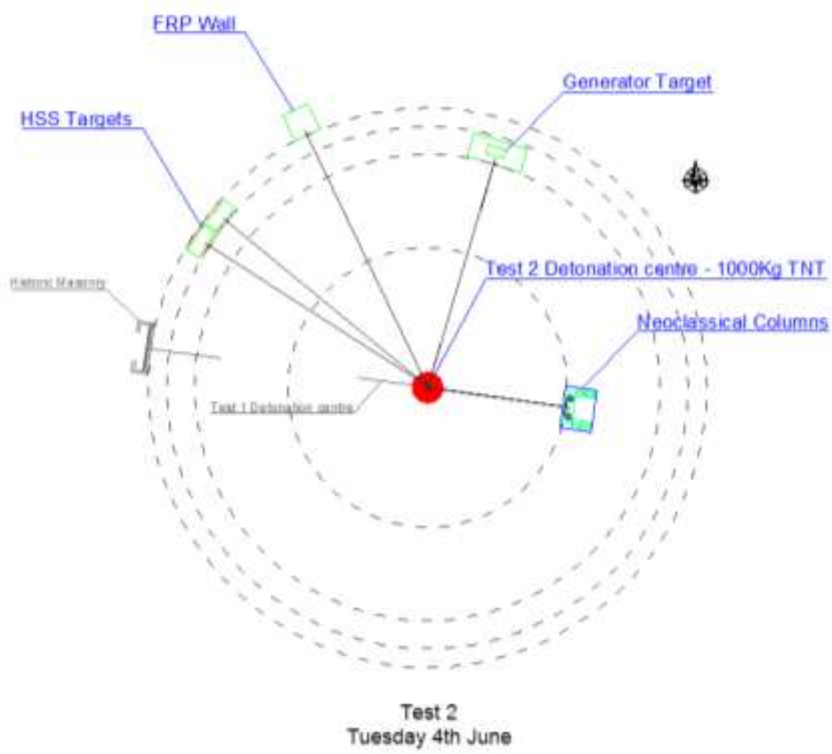


Figure 8 Test 2: Layout of targets in arena

The third test used the same targets as the second test. However, the charge size was reduced to 500kg and the standoff distances were changed.

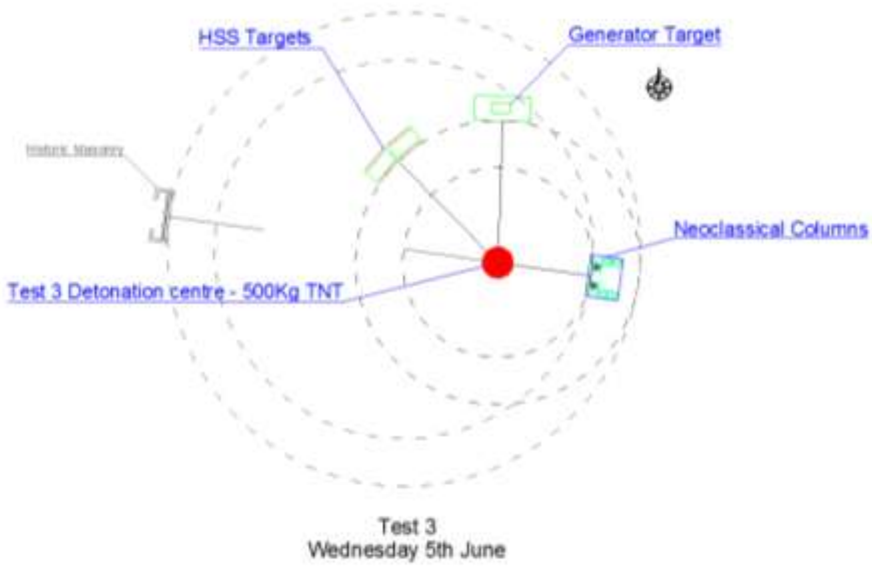


Figure 9 Test 3: Layout of targets in arena

The explosive charge used in these tests was a cast hemisphere of TNT, which was detonated from the centre of the base of the hemisphere with an electronic detonator.

4.12 Instrumentation

All data was recorded using a Hi-Techniques, Inc. meDAQ data acquisition system with on-board signal conditioning. The data was recorded at $2x10^6$ 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 a protective firing bunker. 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.

4.12.1 Glass Arena

In the glass tests, 19 channels were used in total. This consisted of one LVDT and one break circuit per window pane (7 per test), four reflected pressure gauges, and one free-field pressure gauge. 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. A free field pressure gauge was mounted on a 1.5 m tall support at the same standoff distance as the target.

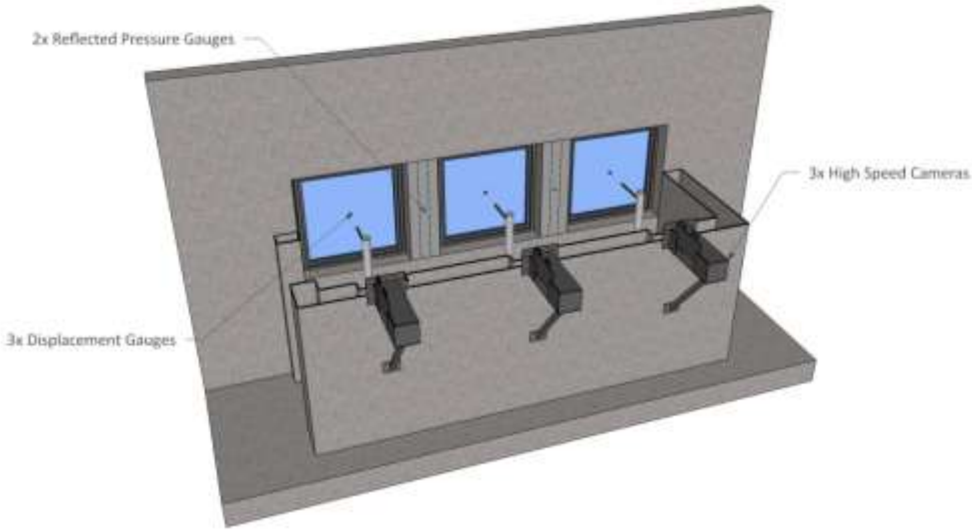


Figure 10 GFPM Target Gauge Locations

In addition to the instrumentation three Phantom high-speed cameras were used as shown in Figure 10. The 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.

4.12.2 Main Arena

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 11. As two of these targets were used per test, this brings the total number of channels of instrumentation to 28 for the HSS tests.

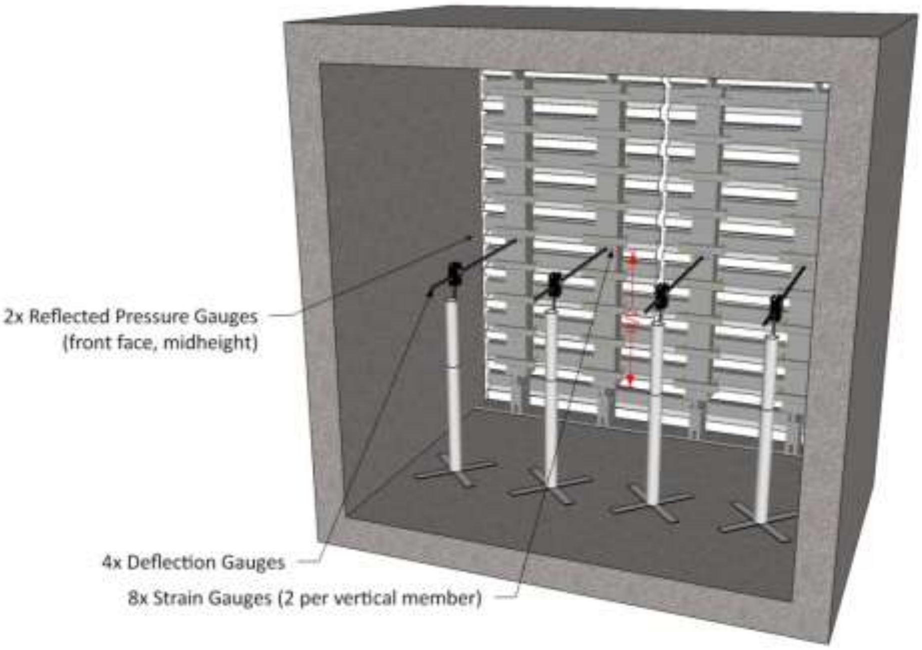


Figure 11 HSS Target Gauge Locations

The Neoclassical multi-drum columns used two channels of instrumentation: an accelerometer on the base of the columns, and a free-field pressure gauge at the same standoff distance as the columns.

The historic masonry wall had 16 channels of instrumentation assigned to it. This included eight displacement gauges, six reflected pressure gauges, one accelerometer, and one free-field pressure gauge.

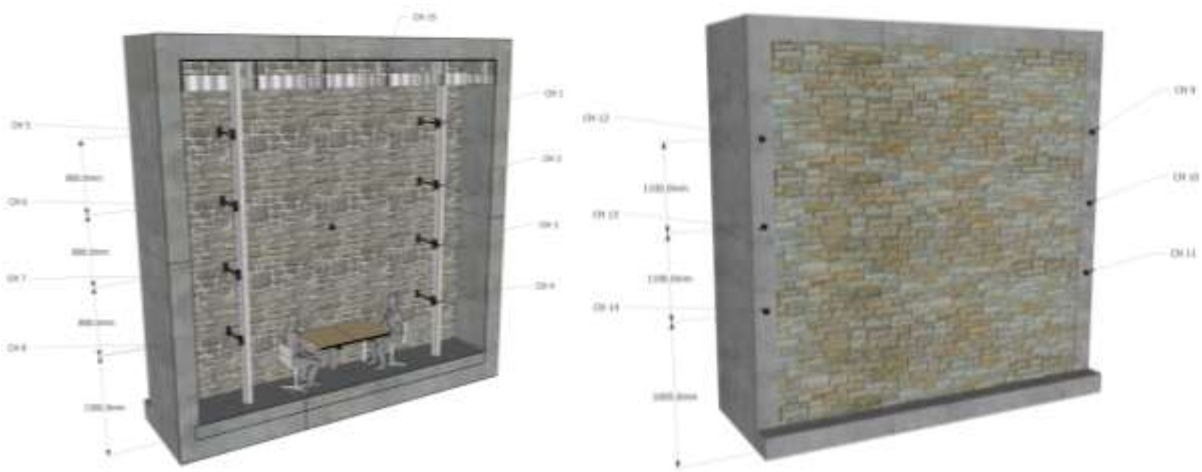


Figure 12 Historic masonry gauge locations

The fibre reinforced plastic element wall target used a total of three channels of instrumentation.

Two types of high-speed camera were used in the main arena tests. Three phantom high speed cameras were used to film the entire arena from different perspectives. They recorded at a frame rate of approximately 2500 fps. Additionally, two 600 fps cameras were used to film specific targets.

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 test 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 13 and Figure 14 show the tent being erected and in use.

Figure 13 Tent being erected on-site

Figure 14 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.

6. Testing

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 Sample Results

Up to 39 channels of instrumentation was used in a single test (Main arena - Test 1). The measurements ranged from free-field and incident pressure, acceleration, to displacement and strain. A sample of some of these measurements is provided below:

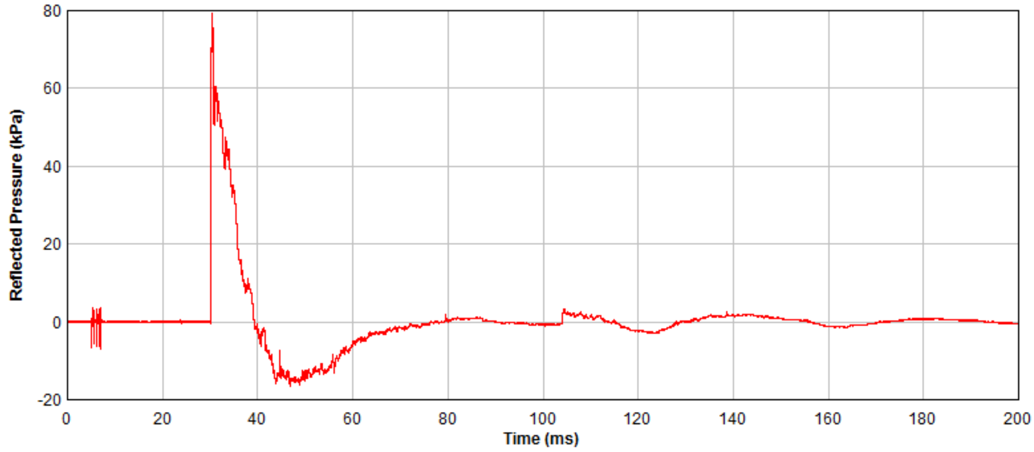


Figure 15 Glass target reflected pressure

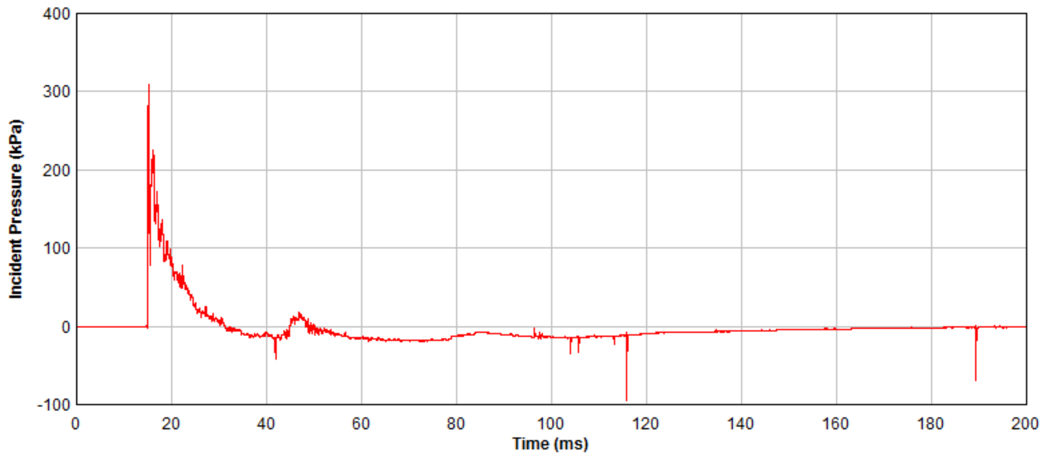


Figure 16 20m Free-field pressure-time history

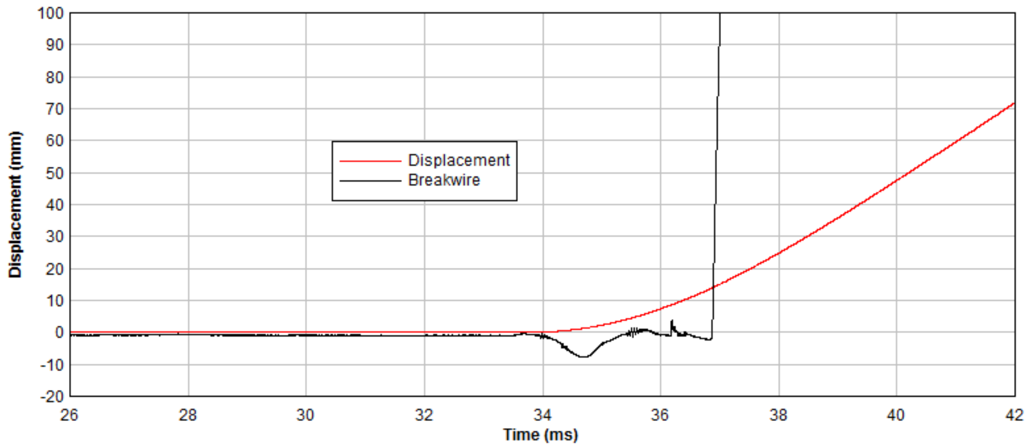


Figure 17 Glass displacement with break signal

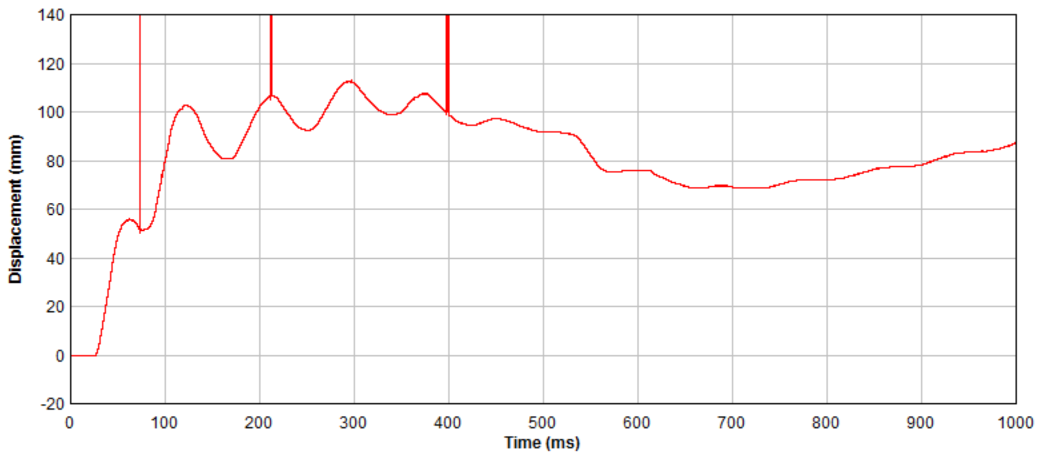


Figure 18 Historic masonry wall displacement

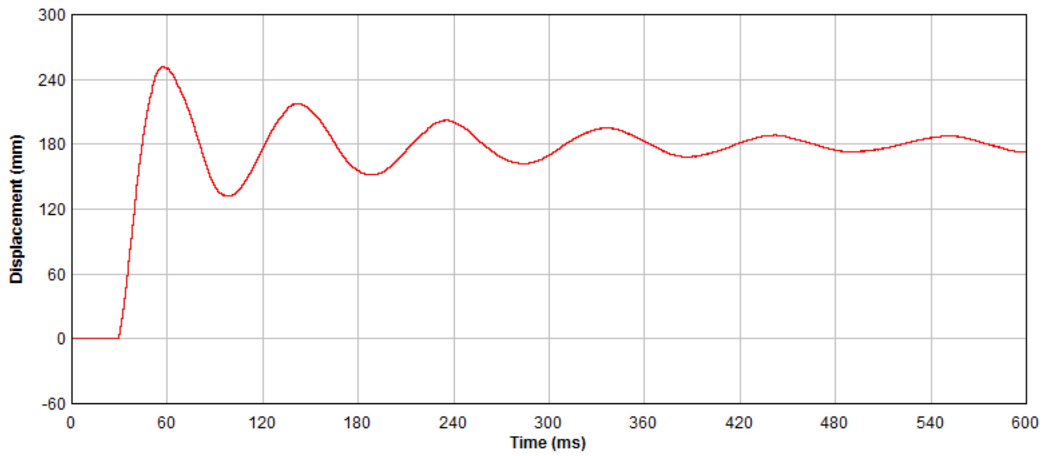


Figure 19 HSS displacement

This was a very heavily instrumented and complex test series; however, the quality of the test data obtained was very high.

6.3 Observations

In the glass tests, all of the glass panes broke as expected. The data gathered from these tests will be used to develop a glass pane analysis to develop a new glass curtain wall analysis software package for blast loading being developed at the University of Toronto in collaboration with the Explora Foundation.

In the test of the concrete barriers, both rows of barriers were thrown away from the blast. The barriers connected with the steel channels did not appear to perform appreciably better than the un-connected barriers.

In the first main arena test, the neoclassical columns collapsed. On closer analysis of the high-speed video the cause of this collapse appears to be the failure of one of the straps restraining the pediment. If this strap had not failed, the columns would have remained standing. This theory was reinforced by the second main arena test as well as finite element modelling. The historic masonry wall suffered severe damage in the test, the majority of the inner wythe collapsed, however, the outside wythe remained intact.

The generator enclosure was severely damaged; however, the generator itself only suffered minor damage and was able to be repaired in a short period of time.

In the second main arena test, the HSS elements all deformed plastically as intended. The cladding system designed to transfer the blast load to the elements performed well. The fibre reinforced plastic element wall failed in this test. Both shear and flexural failures were observed. This shows the brittle failure mode of these elements, which may make them unsuitable for blast applications.

7. Workshops

In parallel to the test blast tests, a series of workshops on aspects of blast theory and testing, protective design, and resilience were given by recognised experts in their respective fields. Abstracts from the workshops are provided below:

Title: Blast Theory and Trials Requirements
Presenter: Dr. Frederick Hulton, MSc PhD, Eur Ing, CEng, FICE - Explora Security Ltd (UK)
Abstract: The aim is to introduce the audience to research and development trials, and in particular the use of full scale trials in support of design and development. This introduction is divided into three parts. The first part covers explosions, their effects and their interaction with structures. It explains some of the uncertainties in predicting explosive effects. The second part explains why trials may be needed and what the aims of trials may be and how trials can increase understanding. Then the use of trials in development and design is discussed. The third and final part introduces the audience to the practical problems of designing and organising trials, the conduct of trials, and of observation and record. Then the records and observation must be interpreted, and both records and interpretation must be reported. The session concludes with some examples from past trials.

Title: Protective Design
Presenter: Dr. Pat Heffernan, Associate Professor - Royal Military College (Canada)
Abstract: The introductory workshop on Protective Design will build on and reinforce the basic blast theory discussed in the morning (Blast Theory and Trials Requirements). The trade-offs between resilience and robustness will be introduced as they pertain to the prioritized objectives of protective design. Load calculation methods, suitable to the specifics of the environment, will be discussed. The construct of the "Design Basis Threat" will be introduced. Whole structure response to blast will be reviewed and discussed prior to isolating individual elements for design. Performance objectives as they pertain to individual elements will be discussed and the commonly applied tables for ductility ratios and end-rotations as performance/damage criteria will be introduced. The essentials of ductility will be reviewed. Designing for "safe-fail" in accordance with the overall objectives of design will be examined. Common methods of design will be introduced, such as SDOF models (flexure), and compared to results of other, more complex methods. The importance of experimental validation for new systems will be discussed. The workshop will discuss these essential topics at the introductory level and will not delve into detailed calculations. Attendees should come away with a greater appreciation for the philosophy of designing against blast and appreciate the trade-offs in design choices.

Title: Blast Test Instrumentation
Presenter: Fred Sandstrom, Principal Scientist - Applied Research Associates (USA)
Abstract: This workshop will discuss instrumentation design for blast tests and how best to apply it at scale and full size. Topics such as gauge selection and installation, data acquisition, and processing will be covered. This workshop will include practical participation in the setup of test instrumentation.

Title: Infrastructure Resilience
Presenter: Alec Hay, BSc, Eur Ing, CEng, FICE, PEng - University of Toronto CRCI (Canada)
Abstract: An operation is enabled by infrastructure, personnel and the organisation, all within an operating context. The whole is symbiotic. Therefore to deliver resilience, one must define the operational requirement and develop a whole-of-operation resilience concept that is common to each of the enablers. The resilience planning for each enabler is therefore linked to the others and cannot be considered in isolation. This multi-disciplinary top-down approach is counter to the "protection" approach that remains necessarily asset-focused. A resilience approach necessitates a revised understanding of the multi-dimensional nature of infrastructure within a comprehensive operating environment and all-hazards context. It also requires a clear concept of balanced demand and dependency management to deliver resilient enablers and operation. The net result is an assurance of continued operation despite catastrophic events that may remove entire assets. Resilience planning is necessarily a first-principles practice and so the presentation is pitched at the conceptual level, illustrated by case-studies.

These workshops provided additional value to the attendees of the test series as well as providing continuing professional development credits. In addition, these workshops provided a forum for discussion of these important topics.

8. Conclusions

The Explora Foundation demonstrated its ability to plan, coordinate, oversee, and instrument a test of this scale and complexity. Having successfully carried out the three main arena tests in just four days as well as conducting four glass arena tests in one day was an immense achievement with direct benefits to all stakeholders. All participants deemed the test series a success.

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.

The inclusion of workshops run in parallel with the blast tests provided additional value for attendees to the tests by putting the testing in context and providing a forum for discussion.

Appendix A: Test Photos

Construction

Figure 20 Historic masonry wall under construction

Figure 21 Neoclassical multi-drum columns under construction

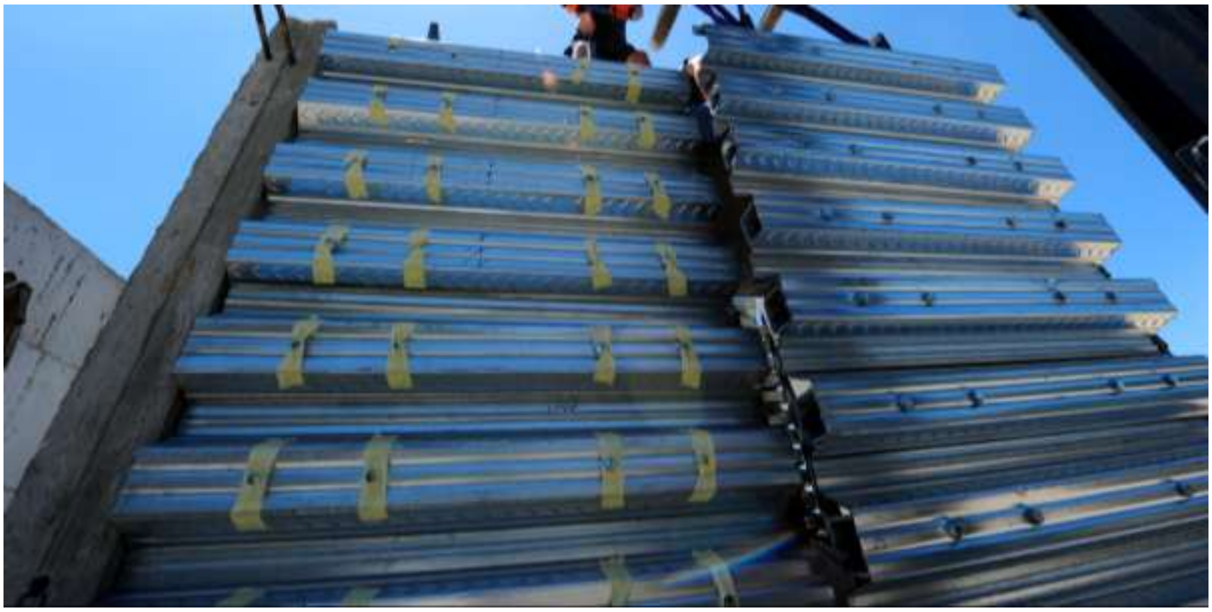


Figure 22 Hollow structural section target under construction

Figure 23 Glass fibre reinforced plastic wall target under construction

Glass Arena Testing

Figure 24 Glass testing arena before testing

Figure 25 Glass target after testing

Concrete Barriers Test

Figure 26 Concrete barriers before test

Figure 27 Concrete barriers after test

Main Arena Test 1

Figure 28 Main arena prior to test 1

Figure 29 Generator target before test

Figure 30 Historic masonry wall before test

Figure 31 Neoclassical multi-drum columns before test

Figure 32 Neoclassical multi-drum columns after test

Figure 33 Generator and enclosure after test

Figure 34 Historic masonry wall after test

Main Arena Test 2

Figure 35 Main arena prior to test 2

Figure 36 HSS target before test

Figure 37 Generator target before test

Figure 38 Neoclassical multi-drum columns before test

Figure 39 Fibre reinforced plastic element wall before test

Figure 40 HSS target after test

Figure 41 Generator after test

Figure 42 Neoclassical multi-drum columns after test

Figure 43 Fibre reinforced plastic element wall after test

Main Arena Test 3

Figure 44 Main arena before test 3

Figure 45 HSS target before test

Figure 46 Generator before test

Figure 47 Neoclassical multi-drum columns before test

Figure 48 HSS target after test

Figure 49 Generator after test

Figure 50 Neoclassical multi-drum columns after test

Figure 51 Explora foundation fellowship recipients

The Foundation is based in London, United Kingdom, but is operating in Canada and intends to do so in the United States in due course; as such the board members are from the UK, Canada and the United States. In each country the Foundation will operate in partnership with individuals, organisations and institutions with compatible aims and objectives. At present the Foundation is an unincorporated association but it is aimed to become a charitable incorporated organisation (CIO) because this better represents the way in which the Foundation intends to operate; however, the Foundation directs the component organisations that provide the research activities and support the scholarship scheme.

Explora Research Limited is a not-for-profit limited liability incorporated company that advances understanding and practice of physical protection through scientific and technological research and development. For more information on the company structure and programmes, please go to Explora Research. Registration details are provided below.

The Explora Scholarship Fund is a charity registered in England & Wales concerned solely with the provision of competitive, higher-level education scholarships, with a primary aim to support those undertaking post-graduate degrees in architecture, engineering and the applied sciences. For more information on the structure, eligibility criteria, selection and fund disbursement arrangements, please go to Explora Scholarship Fund. Registration details are provided below.

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