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STANDARDS AND STRATEGIES FOR BLAST TESTING OF STRUCTURES AND DEVICES

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ABSTRACT

Blast-resistant structures and devices are an increasingly common design requirement for various stakeholders that perceive themselves to be at risk from explosion events. Government and financial institutions, the military, and industrial facilities are just a few examples that require protective features. Since theoretical methods of analysis can be too complex to be practical and require validation, and approximate methods are limited in their applicability, the testing and certification of protective structures and devices is often the preferred and/or necessary avenue.

Consequently, field tests are often conducted to evaluate and/or certify new products for blast resistance. Such experiments can be performed on full-scale or scaled specimens and, frequently, several test specimens are exposed to blast loads simultaneously in an ‘arena’ configuration. However, field tests present the researcher with a number of challenges, such as low repeatability and inconsistent real-time data collection. Ideally, best practice guidelines and test standards should be followed to minimize the risk of errors and ensure experimental consistency. Although a number of testing standards exist, their focus is mainly on blast resistant windows and doors and, in general, they do not provide guidelines to maximize the quality of experimental data collected. Therefore, there is a need for the development of guidelines for field experimentation.

Alternatives to field blast experiments, such as shock tubes or blast simulators can, in certain cases, alleviate the need for conducting field tests and improve data quality and repeatability. Naturally, these devices have limitations and do not completely replicate the effects of a blast. As a result, there is also a need for best practice guidelines for laboratory experimentation and criteria to evaluate the applicability of these techniques.

This paper reviews the standards and techniques used in field and laboratory blast tests as well as best practice strategies to obtain consistent quality data. Topics related to specimen design and preparation, instrumentation techniques, data acquisition and testing logistics are discussed. The goal is to establish the foundation for generally accepted guidelines for testing of structures and devices. The best practices developed by drawing on over 7 years of blast testing experience are then exemplified using a blast test series conducted in July this year and compared to existing standards. It is envisaged that the guidelines presented herein will aid blast specialists when they plan, conduct and evaluate future blast experiments, leading to more reliable and better quality experimental results.

Key words: Blast testing, instrumentation, data acquisition, testing standards, field and laboratory experimentation

1. Introduction

The violent and chaotic nature of explosive events with the potential for extremely high loads over short durations makes characterizing the loading and response of structures to blast loads a significant challenge. A variety of analysis strategies have been developed to deal with these events ranging from complex computational fluid dynamics codes with fluid-structure interaction to simplified single degree of freedom models and many in between. All of these techniques are appropriate for certain situations and knowing the range of applicability for a model is essential for every analyst. In any case, the results obtained from such analyses must be validated through experimentation. Blast testing can be performed on full-scale and reduced-scale specimens, or in the laboratory using a variety of equipment. There are advantages and drawbacks to each testing method, ranging from the interpretation of the results to issues related to specimen preparation, adequacy of the testing facilities and cost.

A major challenge is the lack of available standards on blast loading experimentation. The few existing standards for air blast testing apply primarily to windows and doors. However, there is a desire to expand on these to apply to other structures and devices [1]. The recently published ASCE /SEI 59-11 [2] and CSA S850-12 [3] standards for blast protection of buildings contain provisions for performance qualification by full-scale testing. However, no specific guidance is provided on how to conduct such a performance qualification test and what would constitute acceptable evidence of performance. This demonstrates the need for best practice guidelines for field blast testing.

2. Review of Blast Testing Standards

A number of testing standards have been developed by organizations based in the United States and Europe that provide test methods for blast loading. These standards have a limited scope, focusing primarily on the certification of glazing systems under blast loading. A summary of the current standards is shown in Table 1 and the standards are discussed below.

Table 1 Current standards for blast testing

Standard	Year	Title
ASTM F1642	2004	Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings.
ASTM E2639	2012	Standard Test Method for Blast Resistance of Trash Receptacles
BS EN 13123-1	2001	Windows, doors and shutters - Explosion resistance - Requirements and classification - Part 1: Shock tube
BS EN 13124-1	2001	Windows, doors and shutters. Explosion resistance. Test method. Shock tube
BS EN 13123-2	2004	Windows, doors, and shutters - Explosion resistance - Requirements and classification - Part 2: Range test
BS EN 13124-2	2004	Windows, doors, and shutters - Explosion resistance - Test Method - Part 2: Range test
GSA TS01	2003	Standard test method for glazing and window systems subject to dynamic overpressure loadings
ISO 16933	2007	Glass in Building - Explosion-resistant security glazing - Test and classification for arena air-blast loading
ISO 16934	2007	Glass in building - Explosion-resistant security glazing - Test and classification by shock-tube loading

The American Society for Testing and Materials (ASTM) has published the “Standard Test Method for Glazing and Glazing Systems Subject to Airblast Loadings” standard (ASTM F1642-04 [4]) which defines a hazard rating system for glazing systems. The hazard ratings are based on the fragments generated due to a blast test, specifically their size, number, and their location after the test. Similarly, the U.S. General Services Administration (GSA) has developed the “Standard Test Method for Glazing and Window Systems Subject to Dynamic Overpressure Loadings” (GSA-TS01[5]) which, like the ASTM F1642-04, defines hazard ratings based on the location of fragments and debris after a blast test. Both of these standards are intended to evaluate the hazard level of a glazing system for a particular blast-loading scenario. As such, no specific loading requirement is provided, as this is determined based on the needs of a project. The hazard levels of GSA-TS01and ASTM F1642-04 are broadly similar to each other as shown in Table 2; however, ASTM F1642-04 provides more detailed requirements in terms of fragment size and position than GSA-TS01.

Table 2 Comparison of hazard levels

GSA Performance Condition (Hazard Level)	**ASTM F1642-04 & ISO 16933 Hazard Rating**
1 (None)	No Break No Hazard
2 (None)	Minimal Hazard
3a (Very low)	Very Low Hazard
3b (Low)	
4 (Medium)	Low Hazard
5 (High)	High Hazard

The European Committee for Standardization (CEN) has developed standards for classifying the explosion resistance of windows, doors and shutters. The British Standards (BS) versions are referenced here. The CEN standards are divided into shock tube tests (EN13123-1 [6]/EN13124-1[7]) and range tests (EN13123-2 [8] /EN13124-2[9]). Unlike the ASTM and GSA standards indicated above, the CEN standards specify a specific design basis threat (satchel bombs) which a system must withstand. After a test, the specimen must meet a set of criteria in order to be certified. This includes not being able to gain unauthorized access through the blast face of the specimen and having no openings through which a 10 mm diameter blunt rigid bar can be gently passed.

The International Organization for Standardization (ISO) has developed a test standard from the CEN standards for classifying explosion resistant security glazing [1]**.** Like the CEN standards the ISO standards are divided into arena testing (ISO 16933[10]) and shock tube testing (ISO 16934 [11]). However, unlike the CEN standards, the ISO standards define the classification loadings based on the peak reflected pressure and impulse instead of a specified charge and standoff distance. The ISO standards also differ from the CEN standards since they are intended to classify a glazing sheet mounted in a specific test frame, while the CEN standards test an entire glazing assembly. Additionally, the ISO standards extend the certification range to include a design basis threat in the form of satchel bombs and vehicle bombs. The ISO standards also provide a hazard rating similar to that in ASTM F1642-04, allowing a test specimen to reach a particular classification with varying hazard ratings. For example, a specimen could be classified as passing “EXV10(X)” with a Low Hazard rating.

One standard, that addresses a device other than windows and doors, is ASTM E2639, which is a standard test method for blast resistance of trash receptacles [12]. Unlike the glazing test standards, this standard does not specify any hazard or classification criteria to be met but provides a standard method for characterizing performance of trash receptacles to internal blasts.

2.1 Charge Selection

Each test standard treats the charge selection for arena testing differently. ASTM F1642 recommends using hemispherical or spherical charges detonated either at ground level or between 0.6 m and 1.2 m above the ground. However, other configurations are allowable if appropriately accounted for and documented. No restriction is specified on the composition or weight of the explosive charge. The GSA Test Standard requires a hemispherical charge placed at ground level. However, like ASTM F1642, other configurations are allowable if appropriately accounted for and documented.

The classification tests in EN 13124-2 are based on charge weight and standoff loading scenarios corresponding to spherical TNT charges. Alternative explosive sources are allowable if approved by an accredited body and the European Committee for Standardization certification committee. The standard places strict controls over the diameter and mass of the TNT charge with the mean diameter to be within 0.66% and mass to be within 2% of the values specified in the standard. The position of the charge is also tightly controlled. The standoff distance is required to be within 25 mm of the specified distance. The charge is to be suspended, or supported on a low-density material such as polystyrene foam, over a hard, firm and level surface such as concrete that extends between the charge location and the test structure. The elevation is required to be within 50 mm of the specified elevation, which ranges between 500 mm and 800 mm depending on the size of the charge. EN 13124-2 also specifies a 10-20 g plastic explosive or equivalent booster charge detonated by a low voltage detonator positioned at the centre of the TNT sphere.

Unlike EN 13124-2, the ISO 16933 standard does not specify a charge composition, weight, or standoff. Instead, the classification criteria are provided in terms of mean peak reflected pressure and impulse. The classification criteria are also divided into two loading regimes, vehicle bombs and satchel bombs. The satchel bombs are effectively the same as the CEN standard with the addition of two more levels with lower loadings. The vehicle bombs are entirely new and no corresponding classifications exist in the CEN standards.

The standard test method for trash receptacles (ASTM E2639) suggests the use of a bare C4 charge, unless otherwise agreed between the testing laboratory and test sponsor. The charge is packed into a cardboard cylinder with a height to diameter ratio of 1.0 to 1.5. If the trash receptacle is being tested against a fragmentation charge, rings of 9 mm Type 440, Grade 25 stainless steel spheres are attached at the centre of the cylinder length. The position of the charge within the trash receptacle is selected from one of four specified locations by agreement between the testing laboratory and the test sponsor.

2.2 Test Frame

Test frame construction is largely left to the test conductor. However, the standards do specify some requirements for the test frames. Both ISO 16933 and ASTM F1642 require that the test frame deflections do not exceed, under blast loading, L/360 along the lines of support for the glazing system, where L is the length of the lines of support. The EN 13124-2 and GSA test standards do not specify a deflection limit, merely indicating that the test structure should be sufficiently strong to withstand the blast forces without deformation.

The treatment of clearing effects also differs significantly between the standards. EN 13124-2 specifies a minimum of 200 mm of perimeter structure at the sides and top of the test specimen. In contrast, the ISO 16933 standard does not explicitly specify a particular test frame geometry. However, the classifications are based on test frames having face dimensions of approximately 3 x 3 m and the standard requires a test frame to have minimum face dimensions of 2.4 x 2.4 m essentially including clearing effects in the classification levels. Since the specimen size for ISO 16933 is specified as 1100 x 900 mm, this leaves a perimeter structure of at least 650 mm around the specimen. Annex C in ISO 16933 provides a useful guide on applying the classifications to large facades where clearing is negligible. The American standards (ASTM 1642 and GSA) do not address clearing effects, leaving this consideration to the testing laboratory or agency.

2.3 Instrumentation

Instrumentation requirements vary between the standards with all the testing standards requiring at least one free-field pressure gauge placed at the same standoff distance as the test specimen.

The most onerous standard in terms of instrumentation is ASTM F1642, which requires a minimum of three reflected pressure gauges (per reaction structure) and one free-field pressure gauge for an arena test. The reflected pressure gauges are to be positioned along the horizontal centreline of the test specimens in targets holding more than one test specimen. In the case of a single specimen, two gauges are to be placed along the horizontal centreline and one above the specimen along the vertical centre line. No guidance is provided in terms of analyzing any variability in the three pressure-time histories; however, the pressure-time history for each pressure gauge must be included in the test report. The free-field pressure gauge must be positioned at least 7.6 m from any structure at the same standoff as the test specimen(s).

The ISO 16933 standard also requires a minimum of three reflected pressure gauges (per reaction structure) and one free-field pressure gauge. However, the location of the reflected pressure gauges is not specified. The reflected pressure gauges are required to be arranged in such a manner that the pressure and impulse at the centre of each test specimen can be determined. The free field gauge is required to be at least 5 m or the width of the reaction structure, whichever is greater, from any reaction structure, at the same standoff as the test specimen.

The GSA test standard requires a minimum of two reflected pressure gauges and, interestingly, one interior pressure gauge per test structure. The purpose of this interior pressure gauge is unclear, as it is not used in determining the hazard level of the window system. No specific requirements are indicated for the locations of the reflected pressure gauges. There is also no requirement for a free-field pressure gauge in the GSA test standard.

EN 13124-2 is the least onerous standard in terms of instrumentation, requiring only one free-field pressure gauge at the same standoff distance as the specimen. The position of this free-field gauge must be at least the standoff distance from any obstruction, including the test structure.

The ASTM E2639 test standard has no requirement for pressure measurements; however, optional guidance included with the standard suggests locating a minimum of four free-field pressure gauges at standoff distances of 1.5, 3, 6 and 9 m, and up to 16 pressure gauges ranging from 1.5 to 38 m from the centre of the trash receptacle being tested. The suggested height of these gauges is 0.9 and 1.8 m.

Table 3 Instrumentation comparison among standards

Standard	Free-Field Gauges	Reflected Pressure Gauges	High Speed Cameras
ASTM F1642	1	3	
ASTM E2639	4 (recommended)	-	1
BS EN 13123-2 and BS EN 13124-2	1	-	-
GSA TS01	1 (interior)	2	1
ISO 16933	1	3	-

High-speed video recording is not specifically required by most of the glazing test standards. The one exception is the GSA test standard which requires at least one high-speed camera, with a minimum frame rate of 1,000 frames per second, to record the response of each test specimen from within the test structure. Also, ASTM E2639 requires high-speed digital video recording at a minimum frame rate of 2,400 frames per second to record the explosive event as well as any fragmentation or deformation of the trash receptacle.

The data acquisition system receives minor attention in the test standards. ISO 16933 requires a minimum sampling rate of 100,000 samples per second. The standard also requires the record to capture the complete pressure-time trace including the negative loading phase. EN 13124-2 requires a sampling frequency of only 10,000 samples per second and a recorded pressure-time history at least five times the positive phase pressure duration. The other standards do not specify a particular sampling rate or record duration and leave it to the testing laboratory to ensure that the sampling frequency and duration is adequate to record the peak positive pressure reliably. The inclusion of anti-aliasing filters is specifically mentioned in ASTM F1642, ISO 16933 and ASTM E2639 in order to reduce the effect of extraneous frequencies resulting from sources such as AC power.

2.4 Blast Design Standards which Include Provisions for Testing

The recently published blast design standards, ASCE 59-11 and CSA S850-12, specify blast testing as a means of performance qualification of structural and non-structural components. The ASCE 59-11 standard provides reporting requirements for performance qualification by full-scale testing. Specific requirements for testing are not set out in the standard, although adequate instrumentation must be provided to "completely characterize the charge and the response of the component." ASCE 59-11 also references ASTM F1642-04 for testing glazing and glazing systems, and ASTM F2247-11 for testing doors.

CSA S850-12 provides guidance intended to establish some degree of standardization and quality assurance in blast testing by providing direction where no standards exist. The guidance is divided into blast testing of building components and blast testing to determine the properties materials under blast loading. The CSA standard provides a guide for testing planning and the development of a test specification, as well as providing some guidelines for designing and conducting a test. In particular, using a minimum of three test specimens is suggested as well as measuring the blast load by averaging at least three different measurements taken on the sample. Additionally, the standard recommends that the reaction structure should not mechanically influence the sample being tested. Like ASCE 59-11, the CSA S850-12 standard also provides reporting requirements for blast testing.

3. Alternatives to Arena Testing

Arena blast testing has several disadvantages. It is expensive, and finding a suitable location to undertake the tests can be a challenge. As a result, alternatives to arena blast testing have been developed. There are essentially two laboratory alternatives to arena blast testing. These are the shock tube and the blast simulator.

3.1 Shock Tube

The shock tube, in its simplest form, is a tube split into two sections by a diaphragm. A pressure difference is formed across this diaphragm by compressing a gas on one side. The diaphragm bursts at a pre-determined pressure and the higher-pressure gas is released rapidly into the lower pressure region, resulting in the formation of a shock wave. A specimen placed at the end of the lower pressure region will be subjected to the shock wave. A wide variety of improvements have been developed to modify the shock wave to make it more similar to a blast wave.

There are advantages to using a shock tube for blast testing instead of an arena blast test. Shock tube tests are highly controllable and repeatable, which makes them ideal for conducting parametric studies and repetitive, consistent experiments. From a practical perspective, they are also cheaper and faster to perform in comparison to arena tests. However, shock tubes are limited to testing relatively small specimens, generally less than 2 x 2 m. Therefore, testing large specimens or a full size structure is normally not possible. Typically, only one specimen can be tested at a time, as a result testing of a large number of specimens could become time consuming and expensive with arena testing becoming more beneficial from this perspective. Lastly, attaining a true blast pressure-time history with an accurate positive and negative phase with a shock tube can be challenging. Shock tubes are designed to create plane shock waves; however, shock waves resulting from explosive detonations are (hemi-) spherical in the far field and dependent on the shape of the charge in the near field. However, the approximation of a planar shock wave is usually acceptable for a far field explosion when the triple point is above the height of the structure being considered [13]. Also, the negative phase of the blast load cannot be easily replicated in a shock tube.

Shock tubes are well suited to performing glazing certification tests since the samples are relatively small and large numbers of specimens are not required. Consequently, the European Committee for Standardization has released standards EN13123-1 and EN13124-1, and the International Organization for Standardization has released standard ISO16934 for shock tube loading. In addition, ASTM F1642-04 and GSA-TS01-2003 have both been frequently applied to shock tube tests. ISO 16934 is predominately the same as ISO 16933; however, different classification criteria are used for shock tube testing. The classification is small to large vehicle bombs represented by 30 to 2500 kg TNT charges at standoff distances of 33 to 50 m [1]. EN 13123-1 is also the same as EN 13124-2 in most respects. However, like the ISO standards, different classification criteria are used. There is also one less classification level in the shock tube tests. To verify the blast pressure-time history, EN 13123-1 requires that the measured pressure-time history be compared with the Friedlander equation in order to make sure that the peak pressure, impulse, duration, and decay coefficient meet the requirements of the standard. This analysis is not required for arena testing according to EN 13124-2.

3.2 Blast Simulator

The Blast Simulator was developed at the University of California, San Diego (UCSD). The simulator is a system made up of an array of high-speed nitrogen and oil driven impactors called blast generators [14]. Each blast generator has an impacting mass with a customized polyurethane impacting surface designed to create a pressure-time history resembling that of a blast load [15]. The blast simulator can be configured in order provide an impulsive load to the surface of a variety of shapes of test specimen.

One advantage of this system is the control and repeatability of testing which the blast simulator can provide. In addition, larger test specimens can be tested than with a shock tube. A significant disadvantage of this system is that only positive phase loading can be provided due to the way the system works. For many structural components the negative phase is not significant, but in certain cases the negative phase can be important to the performance of the specimen under blast loading. In addition, it is not possible to replicate clearing effects or reflections with a blast simulator.

The blast generator is a relatively new development and the University of California, San Diego (UCSD) is the only facility, which has a full blast simulator system in operation. As a result, no standards address the use of a blast simulator for performing blast testing. The blast generator at UCSD has been used for testing structural elements such as walls, beams, and columns.

3.3 When to choose an alternative over field tests

As discussed, laboratory alternatives to field blast testing offer some advantages and disadvantages when compared to field blast tests. However, the selection of a particular method of testing is not always obvious. Both the blast simulator and shock tube have difficulty achieving accurate negative phase pressures. If the effect of the negative phase is expected to be important, such as when the natural frequency of response of the sample being tested causes a rebound during the negative phase of loading, field experimentation is the better option. Also, for large targets and tests of full-scale structures and structural systems blast testing remains the only viable option.

Shock tubes work well for testing relatively small targets having a response that is significantly faster or slower than the duration of the blast loading. While generally limited to testing a single specimen at a time, carefully controlled parametric studies are possible, leading to a very effective means of characterizing the response of an element.

The capabilities of the blast simulator, as a new alternative to field experimentation, is still being explored. However, to date it has been used effectively for testing structural elements such as beams, columns, and walls. Laboratory tests in general can be more practical if extensive instrumentation is required. In particular, high-speed video of specimens in field blast tests is often obscured by flame and dust, which is not an issue in laboratory simulations.

4. July 2012 Blast Testing Series

The Explora Foundation facilitated a test series in July 2012 in order to support research projects at the University of Toronto into the effects of blast loading on various building components. Two blast tests were conducted in this test series, the first consisting of five targets, the second consisting of seven targets. Only two of the targets are discussed herein. The purpose of the first target was to test the response of hollow structural section beams subjected to blast loading. The intent of the second target was the testing of panes of annealed glass under blast loading to help calibrate a computer analysis program for glazing, which was jointly developed by the University of Toronto and Yolles, A CH2M HILL Company, Toronto [16].

4.1 Test Site

The test site was chosen because it was a clear flat site located sufficiently away from built-up areas in order to detonate the quantity of explosives required. The test arena was laid out in order to minimize reflections interfering with the loading of the targets. Diagrams indicating the arena layout for the two tests are shown in Figure 1 and Figure 2. Photographs of the test site and test arena are shown in Figure 3 and Figure 4 respectively.

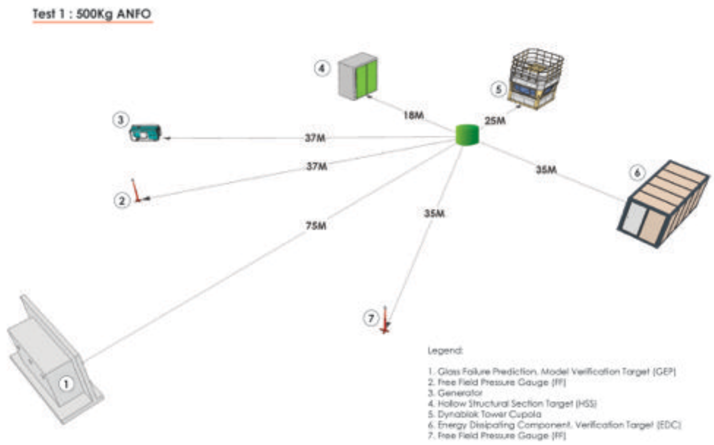

Figure 1 Test arena layout for test 1

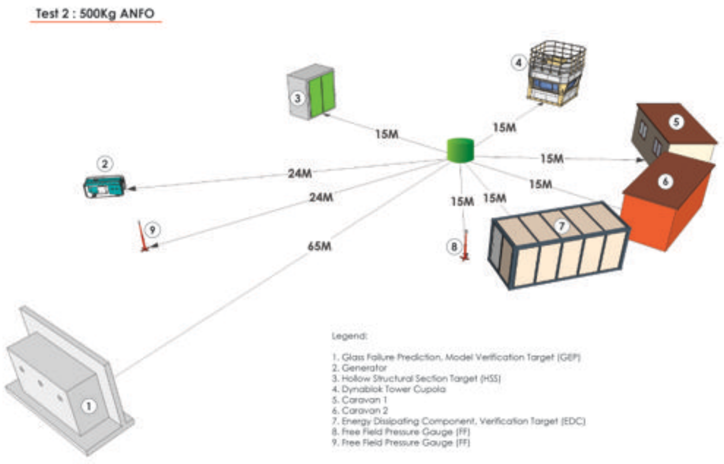

Figure 2 Test arena layout for test 2

Figure 3 Arena test site

Figure 4 Test arena

4.2 Hollow Structural Section Target

Hollow structural sections were 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 150x150 mm 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.

The target consisted of a reinforced concrete cube with one side open, which had outside dimensions of 3x3 m and was 1.8 m deep. The walls were 300 mm thick. Steel supports were anchored into the top and bottom of the open side. 150x150 mm RHS were connected using pin and slotted-hole supports in order to allow free flexural deformations of the beams. A cladding system was designed to transfer the blast loads to the vertical HSS beams without significantly affecting their flexural behaviour. 1x1x1 m concrete cubes were placed around the target to reduce clearing effects. Figure 5 shows the completed target prior to testing.

Figure 5 Hollow structural section target prior to testing

After the first test, the bottom support angle rolled inwards about the inner line of anchor bolts. As such, the HSS verticals did not sustain plastic deformation and were re-used for the second test. The cladding had cosmetic damage only, as shown in Figure 6, and was re-shaped back into place for the second test. Modifications were made to both the top and bottom supports so that they would remain attached to the reaction structure during the second test.

In the second test, although the bottom support for the HSS verticals was pulled away from the target during the negative phase of the blast, both the top and bottom supports remained intact during the positive phase. The vertical members had a distinct permanent deformation following the second test, which indicates that they experienced plastic bending.

While useful data can be extracted from the results of the first test, the fact that the bottom support moved makes it difficult to get an exact response of the members over the course of the blast. The second test was more successful since the bottom support remained intact for the positive phase of the blast and the HSS vertical members experienced bending into the plastic range. The entire front was pulled out during the negative phase of the blast, which makes it difficult to separate the response of the vertical members from the response of the entire cladding unit during the negative phase. The cladding design performed well during both blasts and appeared to transfer the entire blast load into the vertical members without contributing significantly to the flexural resistance of the members.

Figure 6 HSS Target after test 1

Figure 7 HSS Target after test 2

4.3 Glass Model Validation Test

The Glass Failure Prediction Model (GFPM) has been used to develop glass design standards for static wind loading. Recently, there has been increasing interest in utilizing the GFPM in blast applications [16]. However, the applicability of the GFPM under blast loading has never been evaluated. This test was conducted to derive the GFPM parameters under blast loading conditions in order for a comparison to be made to established values in the literature and to validate a new glass curtain wall analysis software package for blast loading.

The target (Figure 4) was a reinforced concrete structure with a width of 5.6 m and a height of 2.8 m. A large opening measuring 3.6 m wide by 1 m high was located 1 m above the base of the structure. This opening was framed with steel hollow structural sections to accommodate three 1 m square glass panes. The distance between the edge of the glass panes and the edge of the target was 1m in order to reduce clearing effects.

Figure 8 Glass panels target

For the first test, the glass panels target was located at a standoff distance of 75 m. The distance was chosen using the computer model being validated. The computer model predicted that this was the maximum distance where the target could be placed and still fail the glass. However, in the first test only one of the three glass panes broke, as shown in

Figure 9. This suggests that the other two glass panes may have been also close to failing. In the second test, the target was moved by 10 m closer to the charge in an attempt to trigger failure in all three glass panes.

Figure 9 Glass pane fracture after first test

However, in the second test none of the glass panes failed. The panels experienced a peak deflection of 15 mm and then oscillated elastically around their original position. One of the deflection gauges also detached from the glass in the second test.

Since the glass panels did not break in the second test, it will be difficult to use the data to validate the Glass Failure Prediction Model. However, the response of the panes under blast conditions was captured, which is useful on its own for validating models and understanding the behaviour of glass under blast loading. This test also demonstrated the effect of material irregularities in glass panes since, at the same standoff distance, one panel failed while the other two were undamaged. Differences in support conditions between the panels (i.e. amount and location of structural silicone) may also have contributed to different behaviour between the panes. However, it appears that the main reason for the discrepancy with the expected behaviour of the glass panes was that, although the measured peak reflected pressure values were close to the predicted values, the measured reflected impulse was approximately 60% of that predicted, thus resulting in a significantly lesser blast load.

4.4 Logistics

Due to the remoteness of the site, logistics played an important role in the success of the test series. In order to minimize the time on site, where high temperatures were present, and improve the ease of target construction, the decision was made early in the planning process to construct all targets as completely as possible in a manufacturing facility and then transport the completed targets to the test site. Except for the strain gauges, no instrumentation was installed at the manufacturing facility due to concerns that it may be damaged during transport. To minimize the time taken to install the instrumentation, the gauges and associated cabling were prepared with rugged, modular connections in advance so that they could be quickly connected on site. This also allowed the soldering and testing of the connections to be done in a clean and comfortable environment, greatly reducing the possibility of connection problems. As a result of the off-site preparations, the test arena was set-up and instrumented in only one day.

4.5 Instrumentation

A Hi-Techniques meDAQ data acquisition system was used with a sampling frequency of 2,000,000 samples per second, recorded over a duration of 500 ms. In total, 19 channels of instrumentation were used for the two targets (27 channels in total for all targets in each test)

The hollow structural section target used 14 channels of instrumentation which consisted of: eight strain gauges, two reflected pressure gauges, and four displacement gauges, as shown in Figure 10. All strain gauges and displacement measurements were taken at mid-span of the RHS vertical members. The reflected pressure gauges were mounted at mid-height of the target in the walls of the concrete cube.

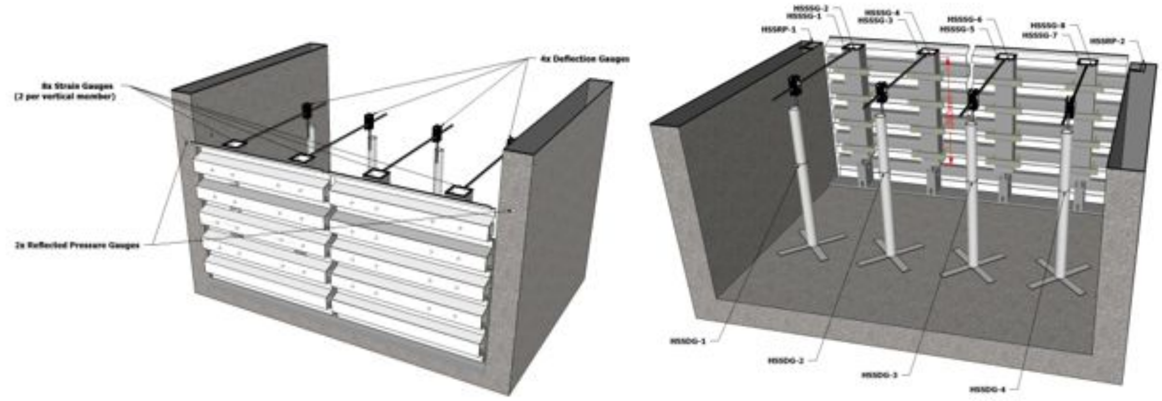

Figure 10 HSS target instrumentation layout (only the lower half shown)

The glass target had five channels of instrumentation, which consisted of three LVDT displacement gauges, and two reflected pressure gauges, as shown in Figure 11. The displacement gauges were mounted at the centre of each pane of glass using double-sided tape.

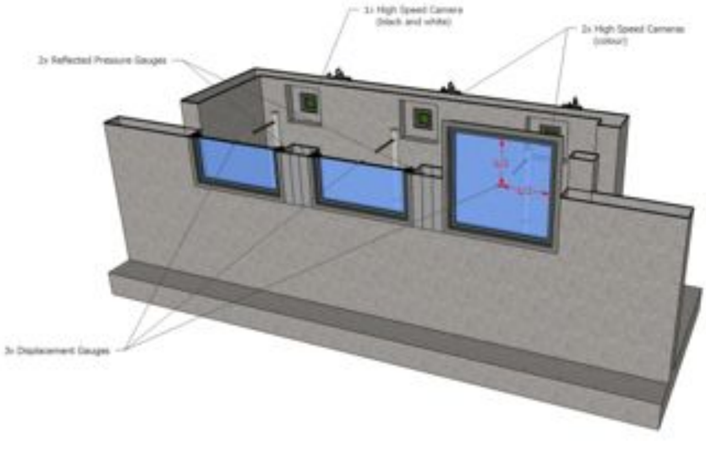

Figure 11 Glass target instrumentation

In addition to the instrumentation of the targets, two free-field pressure gauges were also included in the test instrumentation. These were located on stands at a height of 1.5 m from the ground and away from the targets as shown in Figure 1 and Figure 2.

4.6 High Speed Video Recording

High-speed video was used extensively for this test series. Three Phantom high-speed video cameras were used to record the arena from different viewpoints. An additional three high-speed cameras, installed behind the glass panels, were used to identify the glass fracture pattern under blast loading. The arena cameras had a recording rate of approximately 3,000 frames per second at a resolution of 1280x800 pixels. This combination of frame rate and resolution provided good results.

The high-speed video cameras recording the fracture of glass under blast loading was a more complex undertaking. Previous tests had shown that a recording rate of at least 30,000 frames per second was required in order to capture the failure process in glass. As a consequence, this resulted in a significant reduction in the image resolution. A resolution of 128x64 pixels was the maximum attainable resolution at a recording rate of 30,000 frames per second.

Issues were experienced with the cameras due to the test conditions. The test site reached temperatures of over 40º C in clear sky conditions. The cameras for the glass target were located in protective steel boxes projecting from the rear of the test structure as shown in Figure 12. The confined space in the protective boxes combined with the heat from the sun was causing the cameras to overheat, and fail to trigger. In order to address this, an air conditioning system and associated power generator were deployed to cool down the cameras during the test and ensure their functionality.

This air conditioning system could be deployed because the standoff distance was large enough (65 m in the second test) such that the air conditioner and generator would not be damaged due to the blast loading.

Figure 12 Camera instrumentation behind target

4.7 Charge Selection

Where mentioned in the existing standards, TNT is specified as the explosive of choice. However, for large scale testing, casts of TNT can be prohibitively expensive. The possibility of using ANFO as a substitute for TNT has been considered for some time [17]. In this test series ANFO was chosen as the explosive instead of TNT. ANFO has the disadvantage of being more variable than TNT, however, this was deemed to be acceptable in this test series. Each test in this test series was not necessarily required to reach a particular peak pressure and impulse combination as all of the tests were model validation tests, and as a result, the measured pressure-time history could be used as the input for the models. As a result, any variability in the loading was not as important as in a certification test such as EN 13124-2.

Figure 13 Cylindrical ANFO charge

The explosive charge consisted of 495 kg of commercial Ammonium Nitrate and Fuel Oil (ANFO) poured into a cylindrical cloth barrel, as shown in Figure 13. The final charge had an aspect ratio of 1:1, with a height and diameter of 0.93 m. The ANFO main charge was boosted by a 5 kg C-4 charge placed at the centre of the cylinder. An electric detonator was used to initiate the booster charge. In addition, a break-wire was wrapped around the main charge so that the expansion of the charge case during the explosion broke the wire and opened the electrical circuit that triggered the data recorders and high-speed cameras.

4.8 Consideration of Existing Test Standards

While the existing test standards do not explicitly apply to this kind of blast testing, applying the guidelines of the standards, where applicable, can help ensure the success of the test. This test series did not adhere to all the guidelines provided by the test standard, but did meet or exceed many of them. Both the HSS target and glass target had two reflected pressure gauges instead of the three gauges suggested in several of the standards. While very consistent data was achieved from the two reflected pressure gauges, a third reflected pressure gauge, located above the test specimen would provide additional useful information such as the planarity of the blast wave reaching the target.

The standards generally agree that at least one free field gauge should be provided in each test. Two free field gauges were used this test series, however, since there were 5 targets in the first test and 7 in the second test, a free field gauge could not be positioned at the same standoff as every target. This was not an issue since the free-field gauges were primarily used to check if the detonation had occurred properly.

In terms of the data acquisition system, the one used in this test series greatly exceeded the minimum requirements stated in the standards. The standards specify a minimum sampling rate ranging from 10,000 samples per second (EN 13124-2) to 100,000 samples per second (ISO 16933). In this test series the data acquisition system was sampling at 2,000,000 samples per second. Additionally, data was recorded over a duration of 500 ms, which is much longer than that specified in ISO 16933 (long enough to capture the positive and negative loading phases) and EN 13124-2 (5 times the positive phase duration). The primary reason for using such a long recording duration was to fully capture the displacement-time history of the samples being tested.

Both targets had a distance of 1 m between the edge of the specimen and the edge of the target. This is much greater than the 200 mm specified in EN 13124-2 and the 650 mm used in ISO 16933.

Finally the frame rate of the high-speed cameras exceeded the minima specified in GSA-TS01-2003 (viz., 1,000 frames per second) and ASTM E2639 (2,400 frames per second). As mentioned, the arena high-speed cameras were recording at 3,000 frames per second while the high-speed cameras recording the glass response were recording at 30,000 frames per second.

A minimum of three specimens is specified ASTM F1642-04, CSA S850-12, and ISO 16933. This test series met this requirement with the glass target testing three panes of glass in each test. Due to limitations on the size of the test target as well as the desire to test multiple sizes of beams to the same loading, the HSS target did not meet the minimum of three specimens specified in the standards. The HSS target had two sets of two identical beams in each test, with the same beams tested in the second test at a different standoff distance.

While there were some exceptions, in particular the number of reflected pressure gauges the charge composition and the number of specimens for the HSS test, the test series met and exceeded many of the requirements specified in the standards.

4.9 Data Processing

Very minimal data processing was used on the raw data. Using D-Plot, any baseline offset in the results was removed and no filtering was used. In order to determine that the ANFO detonated correctly and was a true detonation not a deflagration, the Friedlander equation was fit to the positive pressure-time history measured using the free-field pressure gauges, as shown in Figure 14. The decay coefficient was then checked to ensure that it was less than 4. The peak pressure is then determined from the Friedlander fit at the time of arrival. This procedure is a recommendation from ISO 16934.

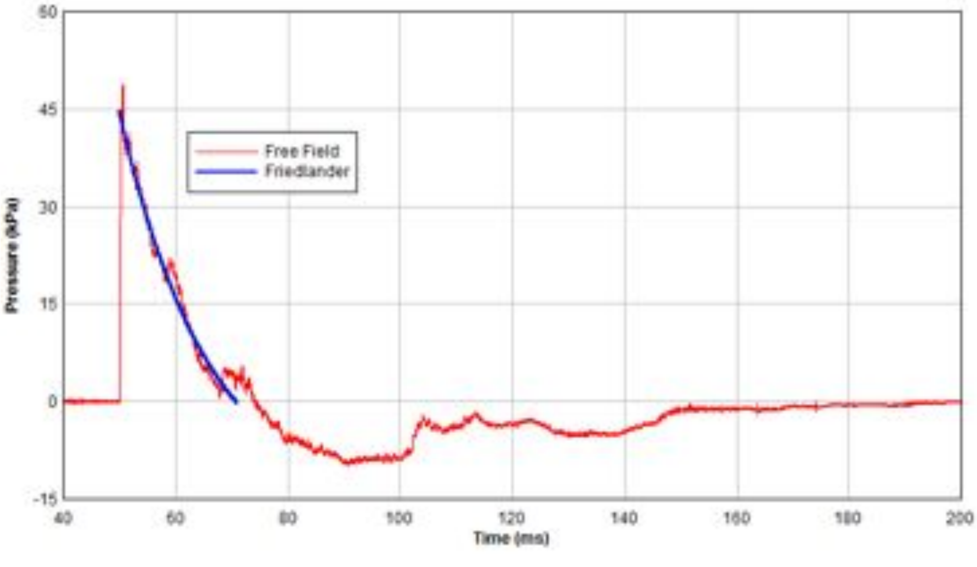

Figure 14 Friedlander fit to free-field pressure-time history - Test 1

In the case of a free-field pressure-time history from the first test, the Friedlander equation was fit to the measured positive phase pressure-time history with a coefficient of determination of 0.98. The decay coefficient in this case was 0.76, which suggests a satisfactory detonation occurred. The measured peak-pressure from the unfiltered results was 48.8 kPa while the peak-pressure determined using the Friedlander fit was 44.8 kPa.

5. Lessons Learned

Conducting a heavily instrumented test series in a remote environment is a challenge. While the success of the test series was a major achievement, there were lessons learned which can be summarized and used to improve future tests. The extent of cooling required for high-speed cameras was underestimated in this test series, especially considering the air temperatures experienced. In the future, the camera boxes will be designed with more effective ventilation and passive cooling in order to ensure the cameras do not overheat, and ensure that an air conditioning system is not required.

Naturally, the design of the test structures can be critical to the success of a test. The connection between the target and the reaction structure must be considered more carefully, with a larger factor of safety over the predicted loads.

Both the reflected and free-field peak pressures matched predictions quite well. However, the impulses were generally lower than expected. The cause of this was unclear, however, clearing effects and variability in the TNT equivalence of ANFO could have had an effect.

6. Conclusions

While every blast test is different, much of the planning and implementation is common to every experiment. Issues such as instrumentation selection and installation, target design and construction, charge selection, data collection, and others re-occur for every test. Since there is no established standard for the testing of components other than windows and doors, experimenters will need to develop their own requirements from scratch for each test. This eliminates the obvious benefits of incorporating the experience of others into any new testing series. In addition, with ASCE 59-11 and CSA S850-12 both allowing for performance qualification by testing there is a clear need for increased standardization for blast testing in order to ensure a consistent standard of evaluation is used.

Laboratory alternatives to field blast testing continue to be developed. However, there is currently no comprehensive guidance about when these techniques can be used, their limitations, and how to ensure good results. Such guidance needs to be developed.

By considering the existing standards some best practice guidelines can be applied to tests of other components. However, due to the difference in purpose and approach there is variability in the requirements in these standards. As a result, there is a critical need to develop best practice standards and guidance for blast testing, which researchers and engineers can rely upon to ensure meaningful experimentation. As more devices and structures undergo performance qualification through testing, a standard that ensures confidence in the results of testing and allows defensible conclusions to be drawn is becoming ever more essential.

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