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THE AUSTRALIAN NATIONAL FACILITY FOR PHYSICAL BLAST SIMULATION

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ABSTRACT: The National Facility for Physical Blast Simulation (NFPBS) has been established at a site north of the University of Wollongong, New South Wales, Australia. This facility is designed for systematic experimental studies of blast wave propagation and loading regimes, blasts damage to elements of civilian and military infrastructure, blast injury protection and other important blast related areas of research. The simulator is a state-of-the-art design having a test section of 1.5 x 2 m with dual-mode Driver capable of operating with compressed gas or gaseous explosive. Using an oxy-acetylene gas mix as Driver, blast simulations of 350 kPa incident level will be possible; peak levels and durations will be adjustable to 30 ms by Driver settings and adjustable distance to the test section. The simulator will be capable of a range of blast-test configurations including full-reflection wall targets, diffraction model targets, as well as behind-wall and blast-ingress scenarios. The NFPBS is based on the 'Advanced Blast Simulator' (ABS) concept. Various ABS designs have been adopted by several universities and government laboratories in the US and Canada pursuing blast-effects studies. Preliminary results from the NFPBS will be presented for both compressed gas and gas detonation modes of blast wave simulations.

INTRODUCTION

The past two decades have seen a significant increase in the number of terrorist attacks on embassies, commercial centres, government structures, industrial facilities, and residential buildings. From a structural standpoint, these attacks have highlighted the vulnerability of existing civilian infrastructure to the dynamic effects of high pressure, short duration blast loading. Civilian, government and military organizations have been addressing these vulnerabilities by developing new blast resistant design guidelines and retrofit procedures to mitigate blast hazards. The current state of blast resistant design methods is based largely on empirical observations of actual explosive testing. However, due to the dangerous, expensive and uncontrolled variables of experimental blast research, the body of experimental blast data is very limited and many aspects of the blast response of structures remain unknown. A proper blast simulator facility is required to allow systematic, highly controlled blast experiments at much lower cost, greater safety and higher fidelity than field trials. A large-scale blast simulator is equivalent in importance in blast protection research as the wind tunnel is to aerodynamics research particularly since many aspects of material failure can only be investigated using full-scale structural elements.

This paper describes the recently commissioned, National Facility for Physical Blast Simulation (NFPBS) in Australia for systematic experimental studies and development of high-performance blast protection technologies. Experimental test capabilities are the foundation for any research program in blast vulnerability and remain the ultimate method for validating blast protection technologies. Experimental capabilities generally fall into two categories: free-field trials and blast simulator facilities. For systematic experimental studies of blast loading, damage, and personal injury, field trials are exceedingly expensive and inefficient (e.g. depend on weather conditions). Blast Simulators are shock tubes specially designed to simulate the

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distinctive shock wave profiles produced by free-field explosions. The NFPBS overcomes the challenges associated with live explosive testing such as very high cost, safety, efficiency and repeatability of test results; more extensive and sophisticated instrumentation can also be applied in a laboratory setting with better controls on the test-target setup. The facility will be utilised for routine high-quality blast experiments to develop concepts of protecting infrastructure, from individual components such as windows, doors, columns, plates and walls, to system models such as bridges, dams, tunnels and buildings, and to models of city or urban environment.

The NFPBS is the result of direct collaboration between eight Australian universities, University of Sydney, University of Wollongong, the University of Western Sydney, the University of Western Australia, the University of Newcastle, the University of Melbourne, Queensland University of Technology, University of Technology Sydney and the Defence Science and Technology Group (DSTG) of the Australian Department of Defence. In 2013, this group of universities and DSTG proposed to develop and establish the NFPBS facility, which would be of high significance to blast-structure-interactions research for universities, government and industry in Australia.

The Advanced Blast Simulator design (Ritzel 2015) selected for the NFPBS facility is based on the concept of intrinsically replicating the wave-dynamics of actual free-field explosive blast including generation of an entropy gradient and a 'true' negative phase with secondary shock. Variants of standard shock tubes have a very limited capacity for blast-wave simulation. The primary components of an advanced blast simulator design include a Driver section followed by a specially shaped Transition Section which continues to geometrically expand then smoothly re-converge the flow; the tailored shockwave then enters the Test Section where experiments would be conducted. The Driver operates either in dual-mode using compressed gas or gaseous detonation dependent on the required pressure/impulse range. A special End-wave Eliminator (EWE) device is set at the end of the Test Section in order to eliminate reflected rarefactions or shocks affecting the Test Section as well as mitigating noise and gas efflux into the lab space.

DESCRIPTION OF THE NFPBS ADVANCED BLAST SIMULATOR

The NFPBS Advanced Blast Simulator (ABS) (Figure 1) is a state-of-the-art design capable of generating a shock wave that replicates the wave-dynamics of an actual free-field explosive blast. This includes reproduction of the negative phase (i.e. pressure dipping below ambient) and a secondary shock which follows sometime after the initial shock wave. This section briefly describes the different subassemblies and components which make up the simulator. An overview of these different sections is illustrated in a schematic in Figure 2.

Figure 1: NFPBS Advanced Blast Simulator (ABS) configuration as-built

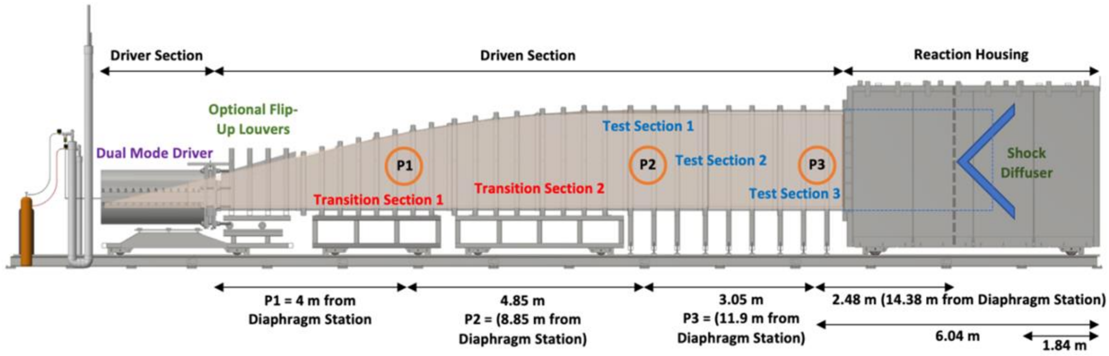

Figure 2: Schematic of NFPBS Advanced Blast Simulator (ABS)

DRIVER SECTION

The Driver has a divergent wedge-shaped profile (of opposite of convergent, for increasing in cross-section continuously). and can operate either in Compressed Gas (CG) or Gaseous Detonation (GD) mode, depending on the requirement. Generally, CG mode produces shock waves with a more pronounced and adjustable negative phase with corresponding strong secondary shock while GD mode produces much stronger blast simulations with a weak negative phase.

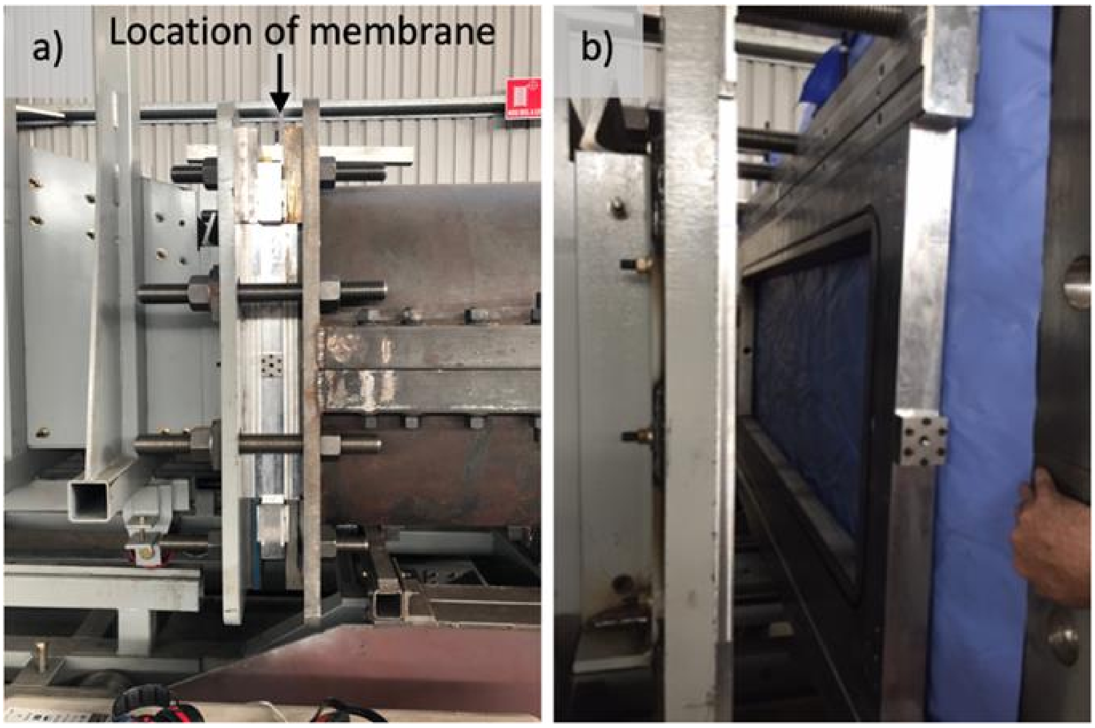

Figure 3: Compressed gas Driver mode: a) Location of membrane (i.e. diaphragm station); b) Clamping of a frangible membrane across the opening of the Driver to create a gas tight barrier

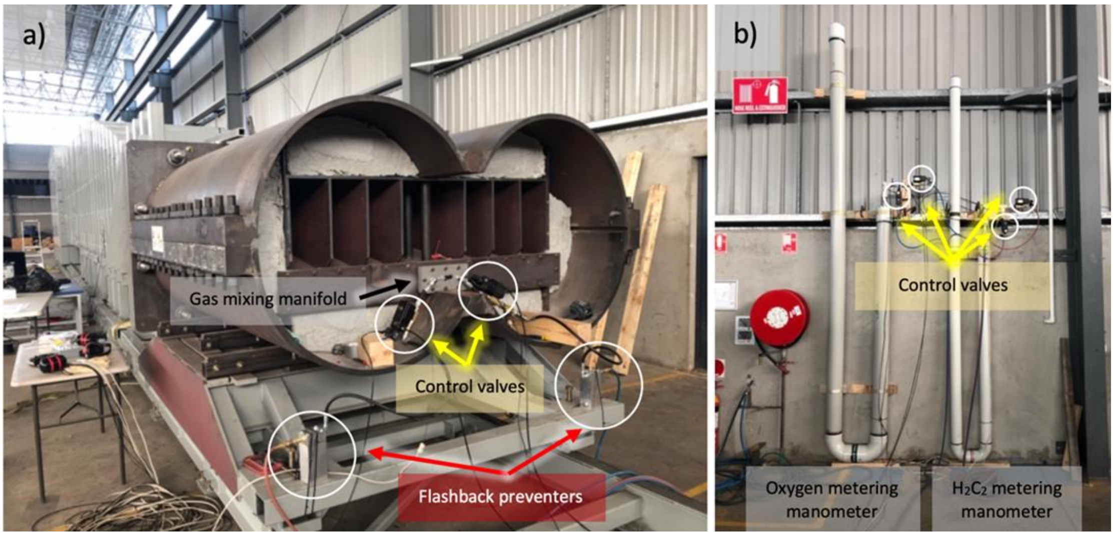

Figure 4: Gaseous detonation Driver mode: a) Flammable gas delivery system; b) Manometers for precise metering of combustion gases

In CG mode the ABS is operated in a similar manner to a conventional shock tube: a gas, typically air, nitrogen, or helium, is introduced into the Driver, raising the pressure above ambient. A frangible membrane (Figure 3) is used to separate the high pressure contained in the Driver from the ambient pressure in the driven section downstream. Upon reaching the desired pressure in the Driver, the membrane is ruptured quickly to allow high pressure gas to expand into the ambient pressure contained downstream. The release of the elevated pressure gas acts as a "piston" rapidly compressing the ambient air at the interface of the high pressure/low pressure gas volumes creating a propagating shock wave. The characteristic "Friedlander" blast wave shape is created by the expansion of the gas out of the divergent Driver and through the initial divergent Transition Section; once formed, the wave is smoothly re-converged into the Test Section.

In GD mode, the geometry of the Driver and downstream simulator sections remains identical with the compressed gas Driver mode. However, the elevated pressure region within the Driver is instantaneously created by detonation of combustible gas mixed with air and/or oxygen. Typical combustible gases include acetylene ($C_2 H_2$) and ethylene ($C_2 H_4$). The resultant shock wave propagates downstream in the simulator containment volume in the same fashion as compressed gas mode previously described. GD mode is capable of generating much higher shock levels than CG mode and has the operational advantage of not requiring the setup of a frangible diaphragm.

The gas delivery system (Figure 4Figure 4:) is designed to be operated from a safe distance, made possible by control valves that can be remotely operated from a control room. The decanted volume of combustible gas is precisely metered using a water filled U-tube manometer open to the atmosphere which has proven to be simple, accurate, and highly reliable. The water fill provides a gas tight seal preventing escape of the gas and provides the means for establishing fill system pressure to ensure positive flow of the metered gas into the simulator. The standpipe also serves as the primary pressure relief for the gas delivery system by limiting the maximum water column to less than 4m hydrostatic pressure.

DRIVEN SECTION (TRANSITION SECTION AND TEST SECTION)

Downstream of the divergent-area Driver Section, the connecting Transition Section continues to expand then smoothly and steadily re-converges the flow as a planar wave entering the constant cross-section geometry of the Test Section. The blast wave's rate of expansion is smoothly reduced to zero by the time the blast wave arrives at the Test Section. The length of the Transition Section is set to provide sufficient run out for perturbations in the initial blast to dissipate before reaching the Test Section while minimising the rate of change of the wall curvature.

Unlike a conventional shock tube, a fully formed blast-wave is generated from the Driver. Therefore it is possible to locate targets at various distances from the first Transition Section as required for particular exposure levels similar to free-field blast where closer standoff gives stronger shock level with shorter duration. The NFPBS ABS is designed to be modular, that is, the Test Section is comprised of three segments which can be configured as required to increase or reduce the testing standoff distance (Figure 5).

The Transition Section incorporates a set of louvers in the top panel optional venting for reflected shocks propagating upstream from reflective targets which would otherwise be reflected again from the closed end of the Driver to propagate downstream and interfere with experiments (Figure 6). The louvers can also be used to reduce the blast wave duration for diffraction targets. The louvers can be selectively fixed shut by blocking-plate assemblies or allowed to open in a controlled manner by the force of the detonation. The extent and speed of venting is controlled by the adjustable mass of the louvers as well as recoil restraints if required.

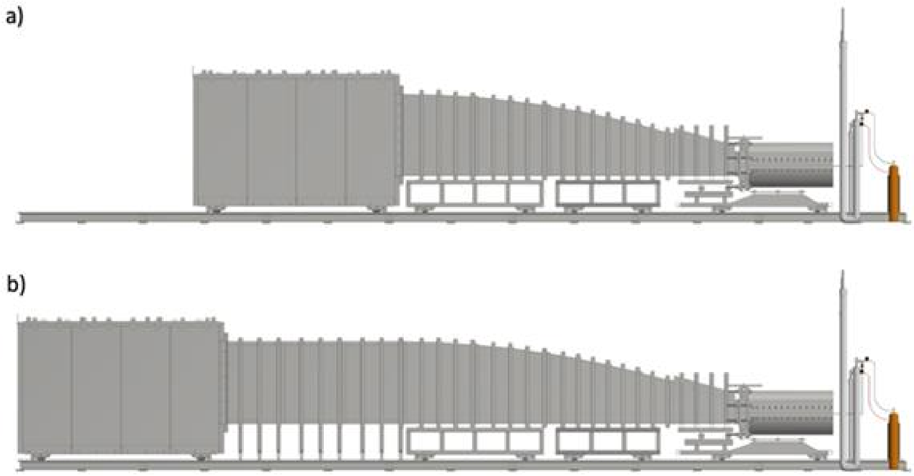

Figure 5: Modular design allows for adjustment of standoff distances: a) Reduced standoff distance; b) Full standoff distance

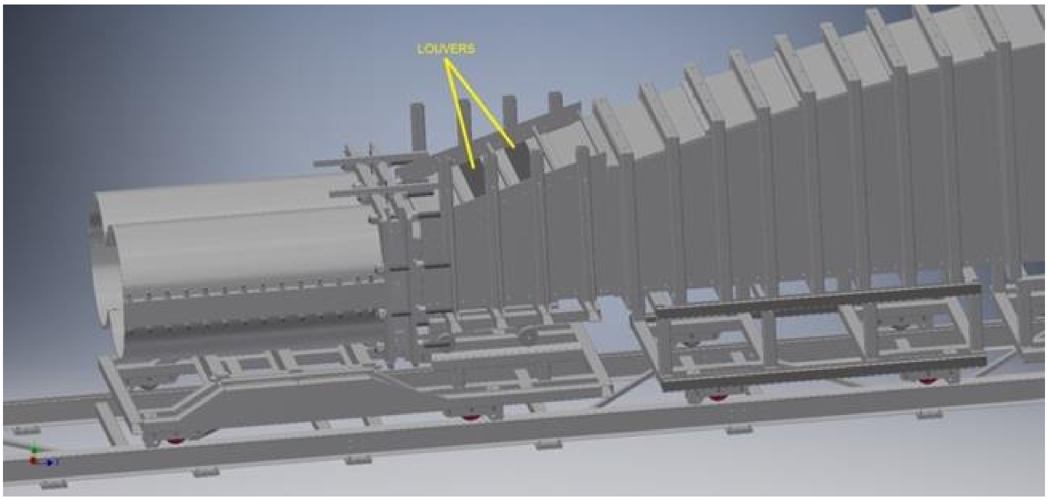

Figure 6: Flip-up louvers to allow for controlled venting of reflecting shock waves reflecting back from reflective targets

REACTION HOUSING

The Reaction Housing at the end of the Test Section has three potential roles dependent on the experiment objective. For studies of loading and damage to diffraction targets set up in the Test Section, it is necessary to mitigate waves reflecting from the end of the Test Section once the primary blast wave has passed. For this role, the Reaction Housing serves as an 'End-Wave Eliminator' (EWE) and is configured with an internal shock diffuser having the form of a porous wedge. The porosity of the wedge can be adjusted to optimise its effectiveness in dissipating waves passing into the volume of the Reaction Housing which serves as a 'dump tank' (Figure 7a). The Reaction Housing has sufficient volume to dissipate the incoming shockwave as well as mitigate noise and gas efflux into the laboratory space.

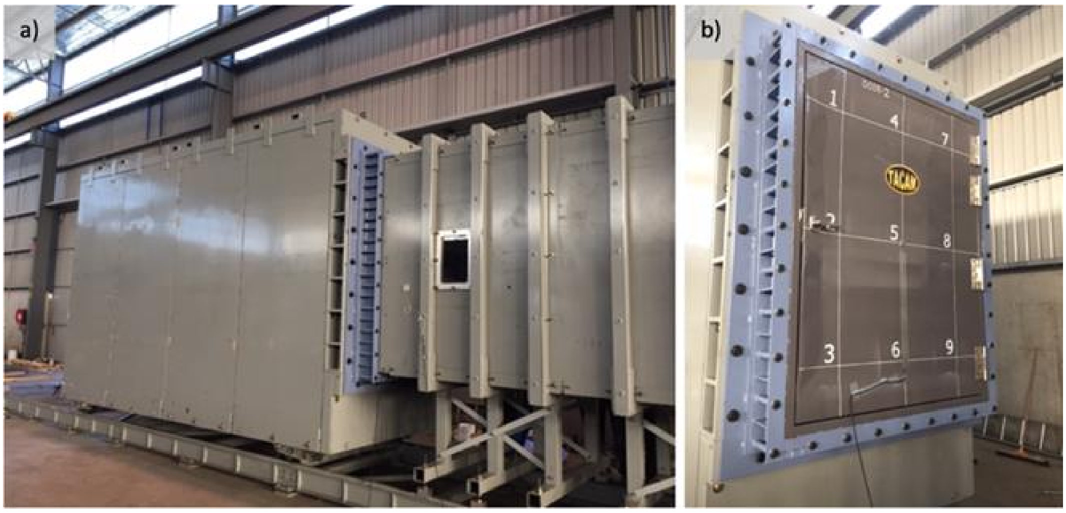

Figure 7: Mounting of reflective targets: a) Reaction Housing with a reflective target in pre-testing position; b) Test specimen mounted on Reaction Frame

In its second role, the upstream opening is surrounded by a drilled heavy flange (reaction flange) serving as the mounting surface for reflective targets such as walls or doors (Figure 7b). The Reaction Housing is constructed of heavily reinforced steel and weighs approximately 15500kg; it is mounted on heavy casters and is free to roll on a track. Target reaction loads are coupled to the housing by the reaction flange and that energy is dissipated by the recoil.

The use of a massive Reaction Housing that has rigid mounting frame as boundary condition for target walls but is free to move globally is novel. Most test facilities assessing blast loads to walls 'pretend' they have a fixed and non-responsive inertial mounting frame. In reality, all frames under these loads will respond and transfer momentum. In fact, useful information is lost by not registering the momentum transferred to the surrounding structure from a target wall which is a factor highly relevant to the real-world problem of these wall/door components within larger buildings. One concept for building protection is to have deliberate wall-fail pathways that are least damaging for the global structure and personnel. For test facilities with a fixed and non-responsive inertial mounting frame, vibration and shock load would be ultimately passed to the foundation housing, which is both problematic for operations and introduces an ill-defined loss in the response analysis. Alternatively, it is not uncommon to directly fix a wall-mounting frame directly to the end of the Test Section (e.g. University of Ottawa) which is doubly problematic: the transferred load will jolt and often damage or slightly shift the entire simulator as well as not ensuring a true inertial boundary condition for the target wall.

In its third role, the Reaction Housing can be configured for studies of 'behind wall' and blast ingress effects including debris-throw as specified in GSA Test Protocol GSA-TS01-2003 (GSA

2003) for the evaluation of blast-resistant glazing for example. In this capacity the Reaction Housing volume can be fitted with special instrumentation and high-speed video.

PRELIMINARY RESULTS

The dual-mode Driver allows a wide performance range in which gaseous-detonation mode is generally used for target studies requiring strong blast with relatively weak negative phase while compressed-gas mode provides moderate to low shock levels with an adjustable negative phase. However, the use of shaped inserts for the Driver and Transition will allow tailoring of blast-wave profiles in both modes in addition to the controls for blast-wave duration described previously.

The initial phase of commissioning tests was intended to refine the operational procedures for GD and CG modes, qualify the data-acquisition system, provide data on the baseline GD waveform development down the simulator, as well as allow measurements of radiated noise to the surroundings. Figure 8 shows records obtained at the end of the first Transition and at the start of the Test Section for the GD Driver charged to about 1/3 and 1/2 of its capacity respectively. The records show excellent shot-to-shot reproducibility and high-fidelity simulation of free-field explosive blast waveforms. Minor aberrations seen in the records are largely smoothed-out by the middle of the Test Section. Figure 9 shows the record for reflected blast loading on a target door mounted to the front of the Reaction Housing again showing excellent simulation of reflected blast loading.

Qualification of the CG Driver mode of operation is in its earliest stages, and testing to date has been limited to preliminary low-level tests as shown in Figure 10. Using compressed air in the Driver at 260 kPa yields a blast simulation of about 35 kPa overpressure and 15ms positive duration at the start of the Test Section; the Driver is capable of 1.5 MPa. The waveforms demonstrate the enhanced negative phase possible with this mode of Driver operation which can be moderated by increasing the concentration of helium in the Driver gas. As with GD mode, excellent reproducibility is demonstrated.

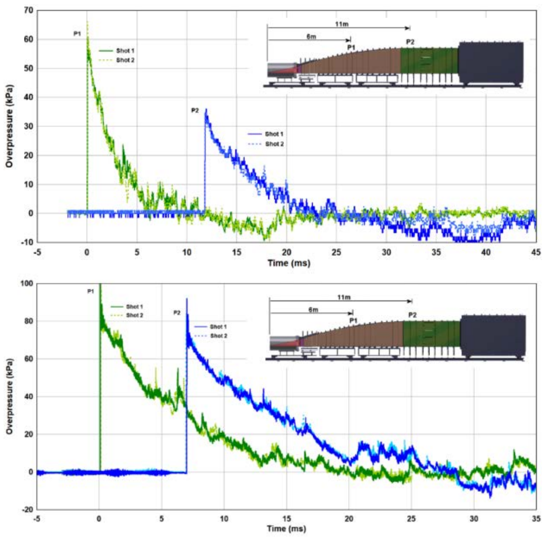

Figure 8: [Upper] Waveform generated using 0.071 m^3 oxy-acetylene GD Driver showing results for two tests overlaid; [Lower] waveform generated using 0.14 m^3 oxy-acetylene GD Driver showing two test results overlaid

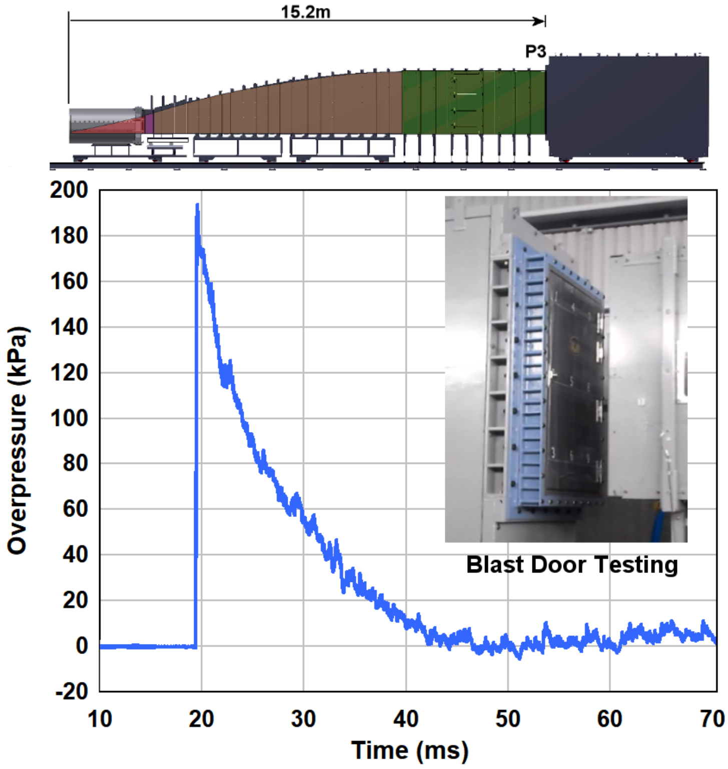

Figure 9: Reflected blast loading on a target door mounted to the front of the Reaction Housing for 0.14 m^3 oxy-acetylene GD Driver

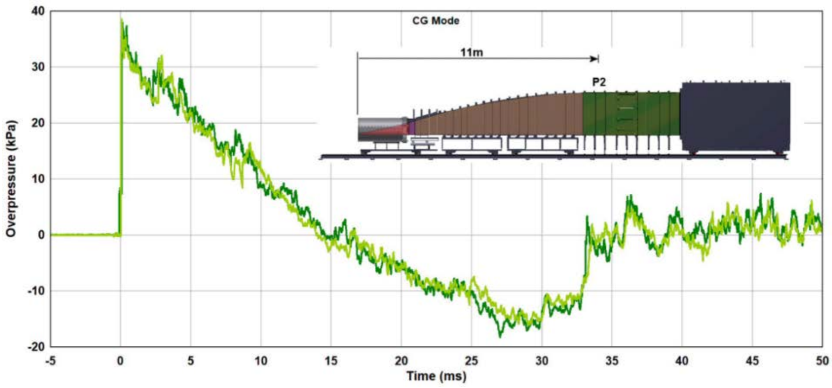

Figure 10: Waveform generated using 260 kPa compressed-air CG Driver showing two test results overlaid

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