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High Fidelity Simulation of Free-field Blast Loading: The Importance of Dynamic Pressure

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IMPORTANT INFORMATIVE STATEMENTS

High Fidelity Simulation of Free-field Blast Loading: The Importance of Dynamic Pressure

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Abstract. The increased incidence of blast-induced traumatic brain injury (bTBI), in part due to increased survivability resulting from improved personnel protection, has spurred research efforts to gain a better understanding of this injury. This laboratory has taken a multidisciplinary approach using models of increasing complexity, beginning with the development of an Advanced Blast Simulator (ABS), which enables high-fidelity simulation of free-field blast waves, including sharply defined static overpressure rise times, underpressure and secondary shock waves. These aspects of the ABS in themselves satisfy most goals of blast effects research, which generally seek to validate their exposures through comparison of the incident (static) pressures and durations to a free-field blast wave. However, it is critical to note that the dynamic pressure component of a blast wave can play a significant role in the loading of a given specimen yet is often neglected in measurements. Numerical simulations show that the dynamic component of blast can be highly variable within a shock tube particularly due to open-end effects. Testing near the open end location should particularly be avoided if the researcher is trying to replicate realistic primary blast scenarios from representative IEDs. A miniature probe has been developed and adapted from a catheter pressure transducer and is capable of measuring the shock tube blast conditions including the static and total dynamic pressure components to allow the researcher to comprehensively measure the simulated blast exposure conditions. Failure to adequately account for all aspects of a given blast exposure on a target, biological or otherwise, may lead to incorrect cause and effect conclusions as to the mechanism of damage.

1. INTRODUCTION

The incidence of blast-induced traumatic brain injury (bTBI) among military personnel in combat roles is on the rise, in part due to increased survivability resulting from improved personnel protection systems [1-3]. A number of research organizations are currently undertaking experimental and computational modelling efforts to gain a better understanding of the mechanisms of bTBI. Comparison of blast exposure in bTBI studies is difficult for several reasons. Most researchers do not fully define the exposure conditions (often stating only the peak overpressure, or overpressure and duration) making it difficult to define injury curves. However, other mechanisms such as the dynamic pressure may significantly affect the loading. There has been disagreement in experimental methods between testing specimens inside versus outside of shock/blast tubes, and direct comparison of results obtained using these two approaches which produce very different loading conditions [6]. To further complicate matters, often the maximum point on the pressure trace is reported, and in many cases such measured peaks are corrupted due to gauge artifacts and the actual value is usually much lower.

The DRDC Suffield project differs from others in that models of increasing complexity are being studied, starting with simple fluid-filled shells, as opposed to beginning with detailed biologically complex computational models with a large number of unknowns. In support of this research, computational modelling of shock interaction with structures under high loading rates was needed to gain understanding into the complex dynamics of the bTBI process.

1.1 Static and Dynamic Pressure in Blast Waves

Investigations of bTBI injury must at a minimum consider loading conditions consistent with explosive detonations in the free field. The blast from a detonating explosive generates a region of high pressure that expands outwards. Unlike an acoustic compression wave, a blast wave can be idealized as an instantaneous rise in pressure followed by an exponential-like decay to ambient (positive phase), followed by a partial vacuum and then a return to ambient pressure (negative phase). The passage of the shock wave causes the surrounding air particles to be accelerated producing a net particle velocity in the direction of the wave. There have been a number of equations developed to express these characteristics in terms of a curve fit, the most popular being the Friedlander waveform equation which has some basis in theory. The Friedlander waveform corresponds to a spherical explosive expansion in air, and is shown in Figure 1 (positive-phase equation and idealized blast waveform). This simplification defines the positive phase portion of the blast wave reasonably well, however the negative phase portion is not well predicted, nor is there any accounting of the secondary shock [5].

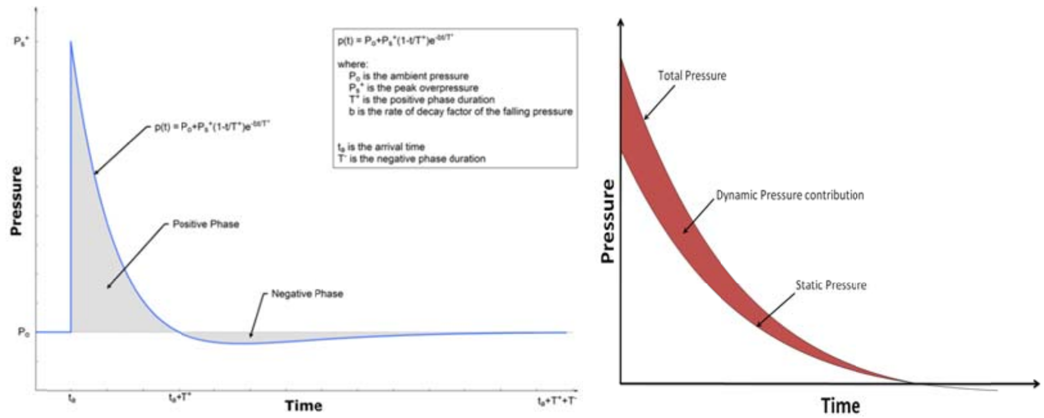

Figure 1. (left) Idealized Friedlander wave (right) Comparison between static pressure and total pressure, showing impulse resulting from dynamic pressure

Blast exposure is defined in multiple ways: pressure histories, peak pressure and positive phase duration or maximum positive-phase impulse. These values in fact refer only to the static overpressure condition which is referenced since it is the most easily measured gas-dynamic condition and published injury criteria relate these values. However, static pressure alone does not fully define the blast exposure; two pressure measurements that report the same static pressure history may produce vastly different loading conditions and injury due to dynamic pressure effects.

In shock and blast tubes, static pressure gauges are generally mounted in the tube sidewall while in free-field testing gauges are mounted on sharp-edged plates placed normal to the flow direction. The static pressure (often just called "pressure") is related to the thermodynamic state of the fluid, and does not indicate the degree of the kinetic energy of the flow. The dynamic pressure represents the magnitude of the kinetic energy of the blast flow, $0.5\rho v^2$, where ρ is density and v is the velocity of the flow. The dynamic pressure is associated with the blast wind and therefore the drag exerted on exposed objects [4]. While it is commonplace to only measure and report the static pressure, the dynamic component of the blast should not be neglected as it contributes substantially to the damage potential of the blast [3]. Moreover, poorly designed blast simulators or badly placed test articles in standard shock tubes can grossly misrepresent the dynamic pressure relevant to blast-wave flows while seeming to approximate the proper static pressure. Figure 1 shows a representation of the static and total pressure and the addition that the dynamic pressure provides. As the blast wave encounters an object or the test specimen, the particle velocity is arrested and the pressure temperature and density are increased at the object surface. This is named the reflected region. Reflected pressures at this region also grow proportionally with the blast wind, furthering the need to properly measure the dynamic pressure.

The dynamic pressure is a more challenging value to measure than the static pressure since it depends on both the density and velocity of the flow and usually requires a sensor to face into the flow, greatly increasing its vulnerability to particulate impact and damage. The total, or stagnation, pressure can be measured through the use of a Pitot pressure gauge; under certain simplifying conditions of incompressible isentropic flow relevant to the Bernoulli equation the total pressure is simply the sum of the static and dynamic pressure. In the case of a spherically expanding blast in the free field, the dynamic pressure can often be estimated using empirical relationships; however these estimates are not easily applied inside blast tubes and definitely not near the open shock tube end.

1.2 Shock Tubes and Advanced Blast Simulators

Shock tubes are a valuable tool for controlled, repeatable experiments in the development of gauges, gas-dynamic shock phenomena, and material testing. A traditional shock tube consists of a Driver section, separated from a Driven section by a frangible membrane. The Driver section is pressurized to a level where the membrane bursts, resulting in the driver gas expanding down the tube, driving a shock-front ahead of that expansion. Shock tubes typically have a constant cross section along the length and dependent on the Driver length and test location in the Driven section, test articles will usually be exposed to a flat-topped shockwave (discontinuity with no decay) with constant-entropy in-flow conditions. Because these shock conditions are unlike those in an actual free-field blast, standard shock tubes can only approximate explosive blast conditions when the shock tube is very carefully configured.

The Advanced Blast Simulator (ABS) is a special variant of shock tube designed to generate tailored shock profiles replicating those of actual blast, including negative phase, secondary shock, and in-flow entropy gradient [7]. The ABS design is characterized by a Driver and adjacent Transition section which have divergent area; the flow is then gradually and smoothly re-converged by the Transition section into a constant-area Driven Section. A special section at the end of the ABS, called the End-Wave Eliminator, ensures no adverse waves are generated from the end condition as well as mitigating noise and gas efflux into the laboratory space. The wave-dynamics due to this geometry replicate those of an actual blast such that the waveform is not flat-topped but includes all the relevant decay conditions of free-field explosive blast. A schematic of a typical ABS is shown in Figure 2.

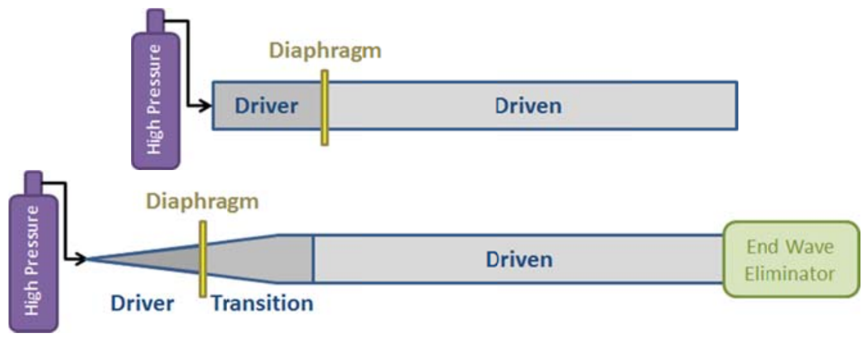

Figure 2. Comparison between regular shock tube (top) and advanced blast simulator (bottom)

Laboratory ABS experiments offer significant advantages over free-field blast trials. The blast exposure parameters on a test subject (such as peak level or duration), can be more easily adjusted, resulting blast waveforms are highly repeatable, there is a lower trial cost/time for setup and operation and advanced instrumentation can be incorporated that would not be feasible in the field.

Experimental testing involving advanced blast simulators is investigated in detail in this paper, using numerical modelling to gain understanding into the full flow-field details. In particular the implications of several blast tube end conditions and test specimen placements will be described with specific focus on differences in both static and dynamic pressure features.

2. DRDC SUFFIELD RESEARCH CENTRE ADVANCED BLAST SIMULATOR

An advanced blast simulator was used to reproduce blast conditions in the laboratory. The ABS 30 is 5.79 m in length and consists of four sections: a Driver section, a Transition section, a Driven test section and an End Wave Eliminator (EWE). Figure 3 shows the ABS 30 at Defence Research and Development Canada – Suffield Research Centre.

2.1 Overview

The Driver is a hexagonal pyramid section of diverging cross-sectional area that is pressurized via a feedback system to a predetermined pressure. A series of acetate sheets form a diaphragm and separate the Driver section from the Transition section. Acetate sheets were used to ensure consistency and to reproduce idealized free-field blast waves [1]. The arrangement of the acetate sheets has been selected such that they rupture at a predetermined Driver pressure. The Transition section permits wave shaping of the expanding wave from the Driver and tailors the wave such that it becomes a planar wave in the Driven test section. The Transition section consists of a hexagonal cross section at the diaphragm interface and expands into a circular cross section where it mates with the 30.5 cm diameter cylindrical Driven section. An end wave eliminator is mounted at the end of the ABS, which includes an internal shock diffuser within an anechoic containment tank. The shock diffuser is a perforated flow-diverter that is adjusted to eliminate reflected waves propagating upstream as well as redirecting the shock-flow to the tank volume. The EWE is therefore designed to both eliminate anomalous waves at the Driven section as well as mitigate shock-flow efflux and noise in the lab space.

Figure 3. DRDC Advanced Blast Simulator

2.2 Instrumentation

Instrumentation was used to control and monitor the performance of the ABS and the test subjects. The ABS was equipped with an Endevco 8530B pressure transducer in the Driver section. This transducer provided feedback and control to the Driver filling module and ensured that a fixed and consistent Driver gas pressure was used for each experiment. Helium was used as a Driver gas as it more accurately simulated a blast wave and the low molecular weight produced higher peak pressures, shorter durations and a much less prominent negative pressure phase. Starting at 2.78 m from the diaphragm interface, PCB 113B pressure transducers were mounted flush with the tube sidewall at 0.5 m intervals. All transducers were mounted in machined hard-nylon (Delrin®) plugs to decouple and reduce ringing from the metal ABS. Signals were recorded at 500 kHz sampling rate on a GaGe Octopus 8389 CompuScope PCIe digitizer board. Although the resultant blast wave has been shown to be planar prior to arriving at the gauge located 2.78 m from the diaphragm, the primary test location for the ABS was situated at a distance of 4.28 m downstream of the diaphragm. This location permits specimen access and also houses two high speed camera ports and two light ports.

Instrumentation consisting of a combination of static and double ended Pitot probe has been developed from three pressure gauges (Figure 4). This design allows for the measurement of total pressure in the upstream and downstream portions of the tube along with a static pressure measurement between the two Pitot probes. The pressure gauges used are Millar Mikro-tip SPR-524 catheter transducers that measure 1.2mm in diameter and are inserted into a 14 gauge needle.

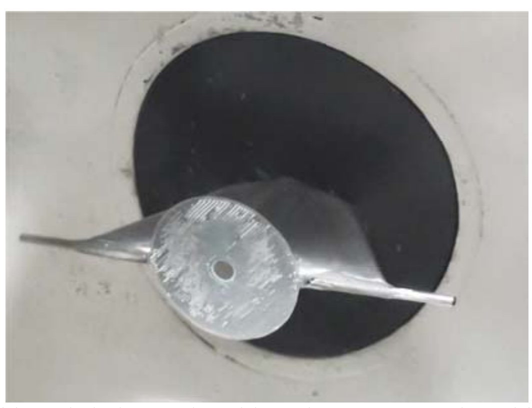

Figure 4. Double ended Pitot probe with static port mounted on sidewall of ABS.

To validate the results for total pressure, experimental measurements using the Pitot probe gauge were compared to numerical simulations using the waveform reconstruction technique (presented in [8]). Figure 5 shows the numerical and experimental static, dynamic, and total pressures at a location inside the ABS 30. The excellent agreement in the results gives confidence that the newly developed instrumentation can be used to measure both static and total pressures from the blast tube. It is important to note that in the experimental test case, the initial peak on the total pressure curve also shows a reflection, which is the result of the blast wave impacting the sensor.

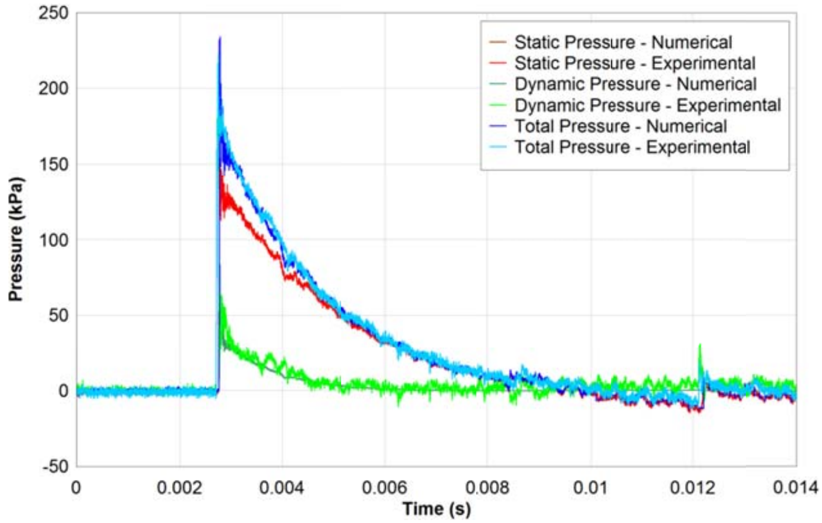

Figure 5. Comparison of numerical and experimental static, dynamic, and total pressure results

3. NUMERICAL MODELING

Numerical simulations of the ABS were carried out using the Chinook computational fluid dynamics (CFD) solver developed by the Lloyd's Register Applied Technology Group. The Chinook code has been extensively validated against a wide range of analytical and experimental solutions involving shock and blast, including high-quality explosive blast measurements from DRDC Suffield Research Centre trials. The code employs an explicit time-stepping approach to solve the Euler equations for mass, momentum, and energy with second-order spatial accuracy. Chinook also features one- and two-way coupling with LSTC's LS-DYNA finite element code for fluid-structure interaction analyses involving both small and large deformations.

In order to investigate the suitability of various test specimen placements and tube end conditions to replicate free-field blast conditions, two Suffield ABS 30 configurations (with modifications to the EWE) were simulated using CFD: an ideal, very long blast tube and an open-ended blast tube. Detailed flow investigations were performed at locations both inside and outside of the blast tube, allowing for direct assessment of the effect of test specimen placement. All numerical simulations of the ABS flow physics (i.e. no test specimen present) were carried out using a two-dimensional, axi-symmetric domain.

4. INTERNAL BLAST TUBE TESTING

4.1 Ideal Blast Tube

An idealised, very long blast tube most accurately imitates the blast wave resulting from a free-field explosive. It is the ideal tube configuration for blast testing a specimen in a laboratory setting due to the complete absence of any tube-end effects. The wave is planar as it travels along the tube with a decaying peak shock pressure. At measurement locations, there is an instantaneous rise to peak pressure, followed by a smooth pressure decay into the negative phase followed by a secondary shock.

Figure 6 shows the static and dynamic pressure profiles at various locations on the tube centreline downstream of the Driver, based on numerical modelling of an infinitely long ABS. The arrivals of the peak static, dynamic and total pressure recorded at each location is coincident, providing a "single pulse" shock loading. As expected, the shock inside the tube persists downstream and the pressure decays and duration increases as the shock propagates downstream.

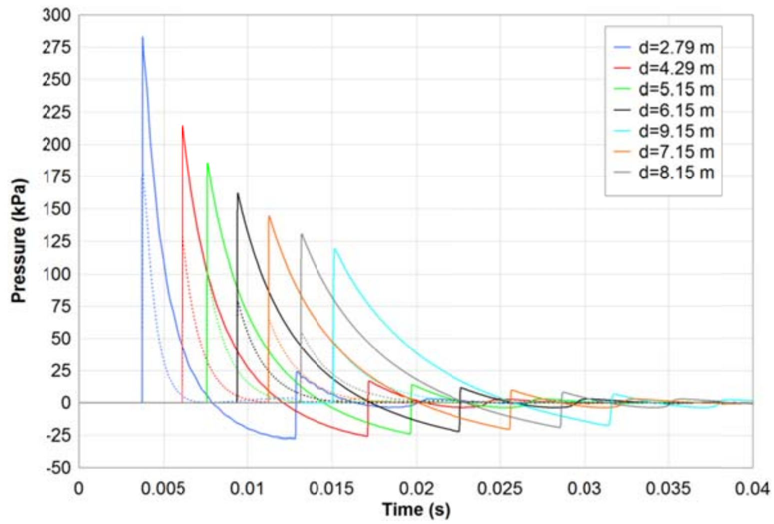

Figure 6. Numerical static and dynamic pressure records inside the idealised blast tube (Solid lines are static pressure and dashed are dynamic pressure, *d* is the distance from the diaphragm.)

4.2 Open-Ended Blast Tubes

Very long blast tubes are usually not practical in a real-world laboratory setting. As a result, many researchers utilize an open-ended blast tube. Blast solutions inside the tube are identical to those from the ideal blast tube up to the point that the shock reaches the end of the tube. At this point, the shock transitions to an axi-symmetric muzzle blast outside of the tube, with a substantially higher rate of peak pressure decay. Inside the tube, this expansion generates a rarefaction wave which travels upstream, reflects at the end of the Driver, and travels back downstream as a shock.

The numerical pressure results obtained at measurement points inside the open-ended tube are compared with results from a very long tube at the same relative positions (see Figure 7). This illustrates the importance of understanding the shock dynamics present in open-ended blast/shock tubes. As with the ideal blast tube, the peak static and dynamic pressures occur concurrently at points inside the tube. However, the loading profile at a test location is only representative of a free-field blast between the time at which the primary shock reaches the test specimen, to the time at which the rarefaction wave from the tube end travels back upstream to the test location. This can radically reduce the time duration that test results are accurate. In the case of test articles where cumulative effects are of interest (i.e. results over a specific time period cannot be extracted), the additional shock dynamics present in open-ended configurations can make it difficult to draw accurate conclusions.

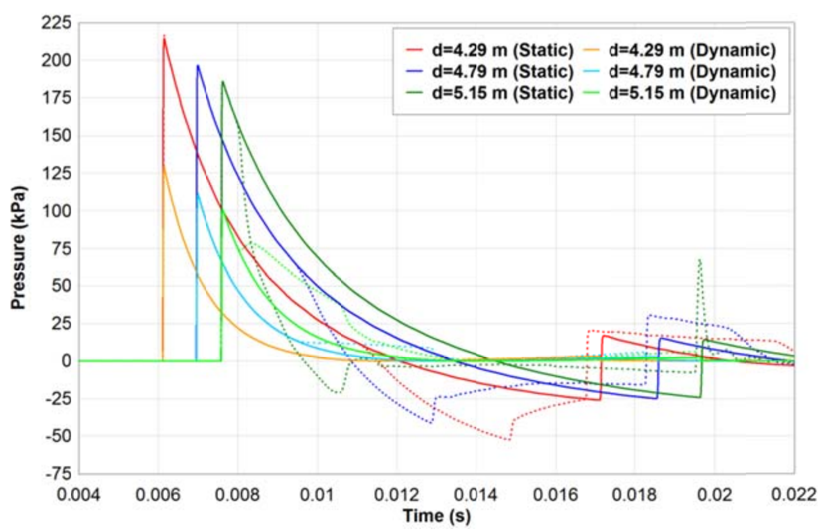

Figure 7. Numerical static and dynamic pressure comparison between ideal and open-ended blast tube (Solid lines are from ideal shock tube and dashed are from open-ended tube simulations, *d* is the distance from the diaphragm)

The difference in static-, dynamic-, and total-pressure values, as well as the positive phase duration, between the ideal and open-ended blast tube is highlighted in Figure 8, for a gauge at the tube exit. The expansion conditions of the open tube results in significant deviations from more ideal free-field waveforms, and dynamic pressure impulse values that are almost double those from a very long tube.

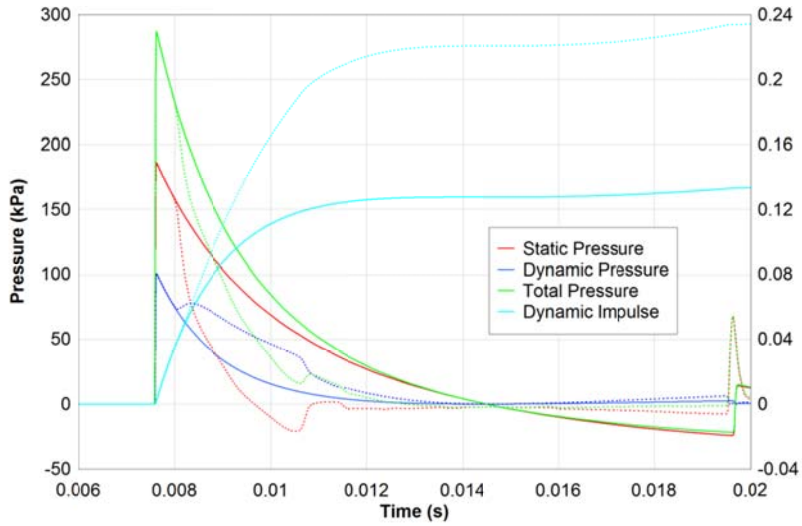

Figure 8. Numerical static, dynamic and total pressures comparison between ideal and open-ended blast tube (Solid lines show results from ideal shock tube and dashed are from open-ended tube)

4.3 Practical ABS Experiments

The EWE on the DRDC ABS has been shown to successfully reduce the anomalous tube-end effects resulting from use of an open-ended tube. Figure 9 compares results obtained experimentally from a pressure gauge 0.855 m from the end of the ABS 30 with and without the use of the end wave eliminator. When the EWE is not used, the rarefaction wave caused by the expanding flow at the tube exit travels upstream, causing the significant pressure drop at the 8 ms mark. When using the EWE, the pressure decay is steady and more similar to that from a very long blast tube.

To verify the effectiveness of the end-wave eliminator, total pressure measurements were recorded by gauges pointing upstream and downstream. As expected, the gauges pointed upstream showed that the total pressure was higher than the static pressure, as the direction of the velocity was exactly opposite the gauge direction (high dynamic pressure component). The gauge pointing downstream recorded the same pressure as the static gauge, indicating that there was no substantial flow travelling back up the tube, and that the end wave eliminator was successful in mitigating the rarefaction wave.

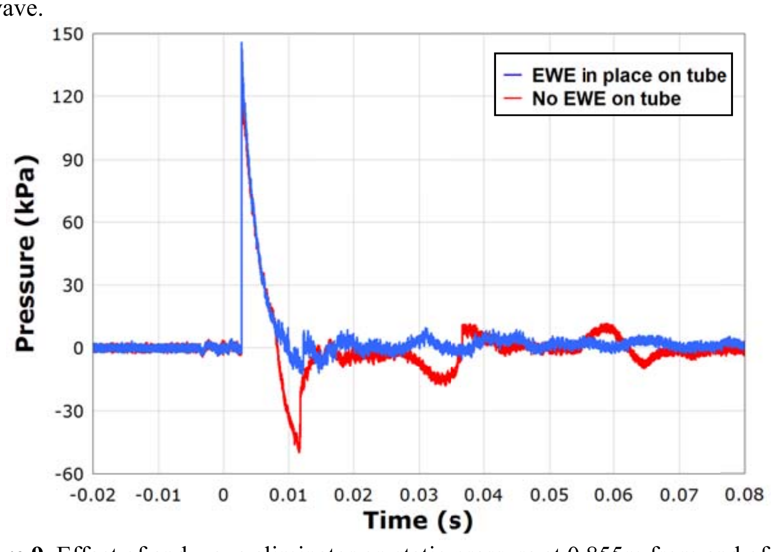

Figure 9. Effect of end wave eliminator on static pressure at 0.855m from end of tube.

5. EXTERNAL BLAST TUBE TESTING

For a variety of reasons, some researchers have opted to place test specimens outside of open-ended shock/blast tubes. This practice is often justified using the argument that the peak pressure (and possibly the positive-phase duration), are equal to the values for a specific free-field explosive blast. What is missing from this analysis is consideration of dynamic pressure effects. Numerical simulations were performed using the ABS 30 without the inclusion of the EWE to investigate open-ended effects.

5.1 On-axis testing

Figure 10 shows the results from four numerical pressure gauges monitoring the static and dynamic pressure. The gauges are located outside the tube along the tube centerline, at distances of zero, one, two, and three tube-diameters from the open end of the tube. The results show that as the distance from the end of the tube is increased, the magnitude and duration of the dynamic pressure is increased compared to the static pressure component. Even at the edge of the open end of the tube (*0D*), the static and dynamic pressures are not representative of a free-field blast. At this location, the static and dynamic pressure components begin as a Friedlander wave. However, there is an anomaly point during the decay. In the case of the static pressure, this point corresponds to a sudden increase in the rate of pressure decay. In the case of the dynamic pressure, an inflection point is observed, where instead of the dynamic pressure decaying to zero, it rises and then decays to ambient over an increased duration.

This non-ideal dynamic pressure behaviour is not evident when using conventional pressure sensors in a typical fashion, and therefore no experimental insight into the role dynamic pressure has in loading a test specimen at the end of the tube can be determined. For distances close to the end of the tube, the static pressure duration is greatly reduced and pressure does not have a constant exponential decay factor. The peak static pressure decays rapidly as the shock is vented into the ambient air and the static pressures outside of the tube are particularly low compared to the pressures just inside the blast tube. As the distance from the end of the tube is increased, the arrival time of the peak dynamic pressure shifts away from the arrival time of the peak static pressure. Test objects placed in the flow outside the tube will experience multiple loading events: the initial static pressure followed by a loading from the dynamic pressure. As a result, higher total pressures are observed at locations one-tube-radius past tube exit compared to equivalent point within a very long tube. However, a reduction in total pressure is observed for points farther away. Higher impulses (more than double) are observed outside of the tube due to the long-duration dynamic pressure component compared to equivalent points within a very long tube.

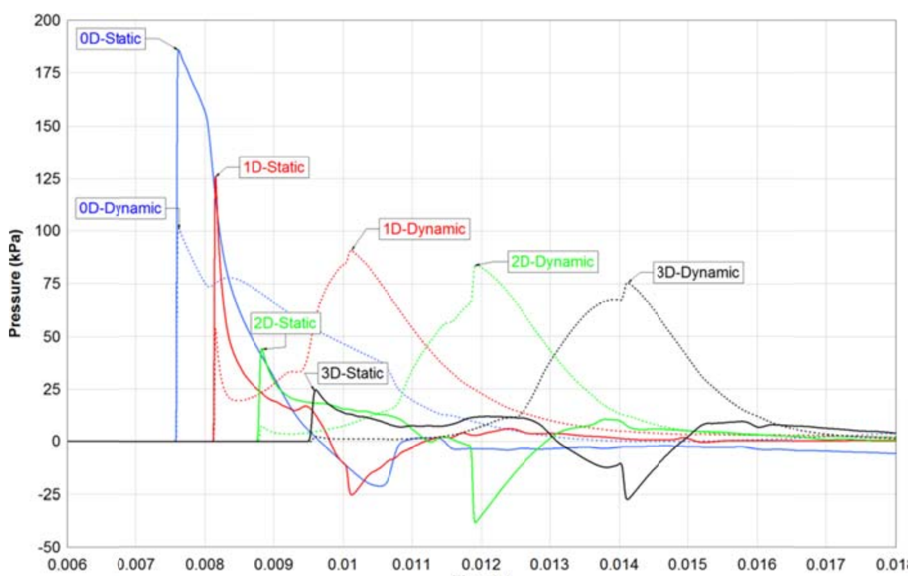

Figure 10. Numerical results for static and dynamic pressure histories for open-ended tube. Distances are presented in tube diameters from centerline of open-end (*0D*, *1D*, *2D*, *3D*).

Figure 11 shows the results of the CFD simulation illustrating the static and total pressures inside and outside of the open-ended blast tube. Initially, prior to the shock reaching the end of the tube, the peak static and total pressures have the same arrival time and the interior wave is one dimensional. The total pressure is somewhat higher than the static pressure, due to the dynamic component. In Figure 11*c*, *d* and *e* the static shock front is seen to expand spherically outwards, however the large total pressure (dominated by the dynamic component), is shown lagging. Vortices and areas of low pressure are observed around the walls of the tube and travel downstream. The dynamic pressure takes the form of a jet leaving the tube, with high contributions along the tube axis.

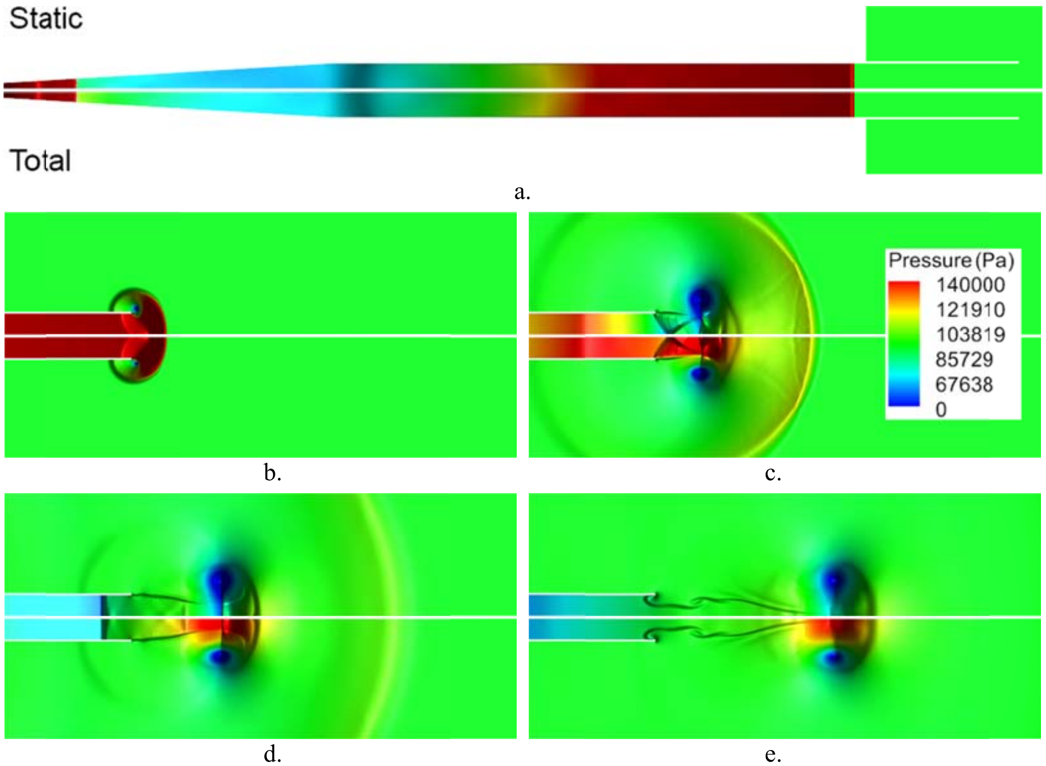

Figure 11. CFD simulations of open-ended blast tube. The top half of each figure gives the static pressure results, with total pressure values given on the bottom half.

Comparing the peak dynamic and peak static pressure of the open-ended simulations to those from the ideal blast tube reveal that the peak dynamic pressure overtakes the peak static pressure (see Figure 12), whereas in the ideal blast tube the ratio between peak dynamic and peak static is relatively constant.

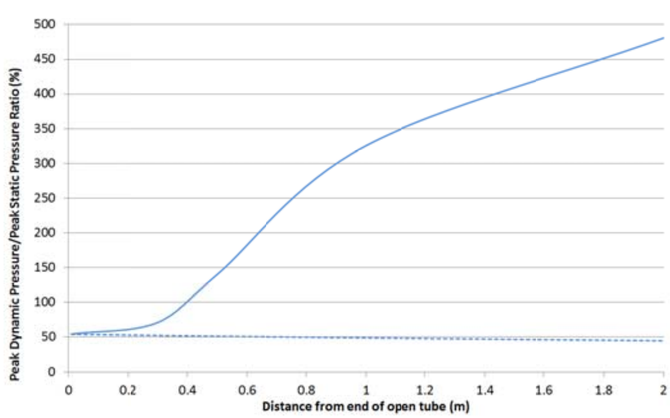

Figure 12. Ratio of peak dynamic to peak static pressure at downstream locations (dashed line is for ideal tube and solid line is for open-ended tube, distance is offset from end of open-ended tube)

5.2 Off-Axis Testing

It has been demonstrated that the majority of the dynamic pressure component of the blast wave and the resultant blast wind exits the tube along the axis of the tube. Some researchers are aware of this phenomenon and have conducted tests at an off-axis angle to mitigate the effect of the blast wind. Numerical simulations were performed to determine if placing a test specimen in these off-axis positions is a viable alternative to testing inside the tube, while maintaining free-field blast conditions.

Figure 13 compares the results of four simulated gauges located outside the tube, off axis at positions of one to two tube diameters downstream and off the axis of the end of the tube. Gauge locations are referenced from the end-center of the tube, are labelled in tube diameters as shown in Figure 13 inset. The gauges located at y = 1D show that the static pressures undergoes a severe negative pressure phase that produces a net negative impulse. The location of these gauges corresponds to the low pressure region visible on Figure 13 corresponding to a vortex position [4]. The dynamic pressure component for these same two gauges occurs over a long duration, and the peak dynamic pressure does not occur at the same time as the peak static pressure. As a result, these locations are not suitable for testing. Gauges located at y = 2D are far enough away from the end of the tube that the majority of the expelling blast wind and dynamic pressure component is reduced. Testing at this location also appears to be outside of the vortex regions and the peak dynamic pressure is coincident with the peak static pressure. Although the dynamic component of the blast is reduced at this location, the static pressure is not representative of a free-field blast wave and testing at this location should be avoided. The results of CFD simulations show that the exiting wave is a complex three-dimensional wave at these off-axis locations, which would further complicate the determination of the actual blast insult delivered to the subject.

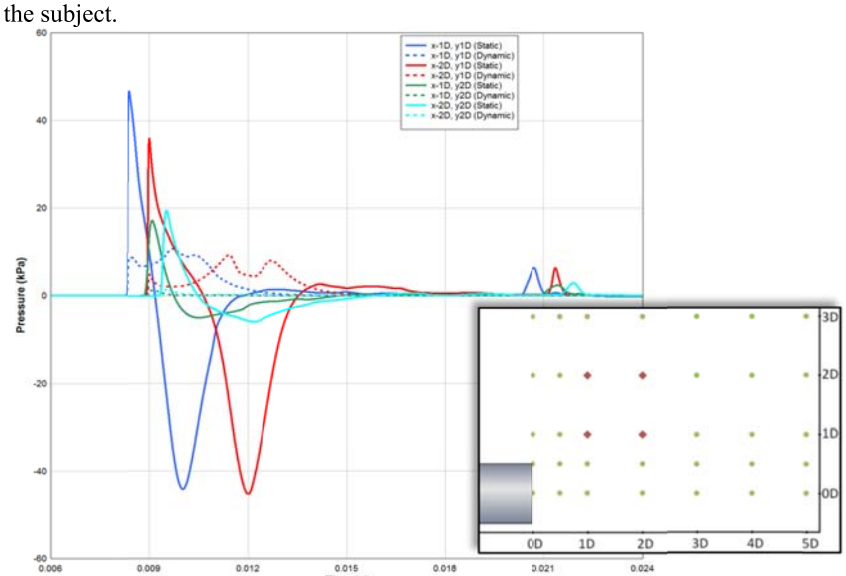

Figure 13. Static and dynamic pressure histories at off-axis locations. Insert graphic showing gauge location in plot (red) and all simulated gauges (green).

6. CONCLUSIONS

DRDC Suffield Research Centre is engaged in experimental blast testing using an advanced blast simulator as part of a research program on blast-induced traumatic brain injury. The DRDC Advanced Blast Simulator, fitted with an end wave eliminator device, creates a near-ideal laboratory scale test platform for evaluation of injury due to free-field explosive blasts. The ABS consists of instrumentation that has been developed to measure static and total pressure.

Numerical simulations using the Chinook CFD code have been performed to gain better understanding into the blast-flow features present in shock and blast tube configurations frequently seen in blast injury publications. While static pressure results can often resemble a typical free-field blast waveform, these simulations have illustrated both the effects of open-ended tubes when testing inside blast tubes, as well as the large spatial variation in static and dynamic pressure when testing outside the tube. In both of these cases, the blast exposure conditions experienced at a test location can vary substantially from an ideal free-field blast waveform. As a result, any conclusions about the level of injury sustained under a specific static-pressure condition are questionable or incorrect.

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Abstract. The increased incidence of blast-induced traumatic brain injury (bTBI), in part due to increased survivability resulting from improved personnel protection, has spurred research efforts to gain a better understanding of this injury. This laboratory has taken a multidisciplinary approach using models of increasing complexity, beginning with the development of an Advanced Blast Simulator (ABS), which enables high-fidelity simulation of free-field blast waves, including sharply defined static overpressure rise times, underpressure and secondary shock waves. These aspects of the ABS in themselves satisfy most goals of blast effects research, which generally seek to validate their exposures through comparison of the incident (static) pressures and durations to a free-field blast wave. However, it is critical to note that the dynamic pressure component of a blast wave can play a significant role in the loading of a given specimen yet is often neglected in measurements. Numerical simulations show that the dynamic component of blast can be highly variable within a shock tube particularly due to open-end effects. Testing near the open end location should particularly be avoided if the researcher is trying to replicate realistic primary blast scenarios from representative IEDs. A miniature probe has been developed and adapted from a catheter pressure transducer and is capable of measuring the shock tube blast conditions including the static and total dynamic pressure components to allow the researcher to comprehensively measure the simulated blast exposure conditions. Failure to adequately account for all aspects of a given blast exposure on a target, biological or otherwise, may lead to incorrect cause and effect conclusions as to the mechanism of damage.

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blast, shock tube, shock wave, computational