Comparison of Numerically Simulated Blast Effects in Urban Environment with Experimental Data

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ABSTRACT
This paper addresses the validation of software tools for modelling blast effects in an urban environment against high-quality experimental data provided by the Technical Support Working Group (TSWG), USA. The experiments were conducted by Energetic Materials Research and Testing Center (EMRTC), USA, in a simulated urban environment test range constructed from multiple modules. Explosive event details and pressure gauge measurements are being exchanged with the intention of validating and improving current blast modelling software tools. The analysis has confirmed that there is no single model that is "perfect", and that the majority of available blast modelling codes are capable of modelling blast effects in the chosen environment with a reasonable degree of fidelity. Computational Fluid Dynamics (CFD) codes are more accurate, since they are able to consistently predict peak pressure and impulse levels. For the test cases studied here Fast Running Model (FRM) codes are less consistent than CFD codes, especially at pressure gauge locations that are not in direct line-of-sight from the charge location, but they still generally produced reasonable overall predictions of peak pressure and impulse. However, for some of the tests, FRM codes generated relatively large pressure errors at some sensor locations due to their inability to properly model the interactions of more complex multiple shock fronts and reflections.

KEYWORDS
Numerical Simulation, Blast Propagation, Peak Pressure and Impulse.

INTRODUCTION

The Defence Science and Technology Organisation (DSTO) is studying the blast effects from explosive threat events. Explosive event details, blast gauge pressure measurements and modelling code data are being exchanged with TSWG with the intention of validating and improving current blast modelling tools. This paper summarises the assessment of several modelling tools against the experimental data for the TSWG Straight Street Test (SST) scenarios.

The experiments for the SST scenarios were conducted by Energetic Materials Research and Testing Center (EMRTC) located in Socorro, New Mexico, USA. EMRTC have a Simulated Urban Environment test range constructed from multiple concrete blocks called urban modules, assembled to represent different urban environments. The modules contain pressure gauge ports so that pressure can be measured on any surface of the modules during an explosive test.

A number of explosive test firings were carried out by EMRTC with several explosive types in a canyon formed by two urban model blocks (see Figure 1). Pressure gauges were arranged in a regular pattern on the surface of one wall, and 25 gauges were monitored during the explosive events. A variety of charges were placed centrally between the block walls, in front of the last vertical array of gauges, at two different charge heights above the ground (see Figure 2).

Figure 1. Straight Street Test firing.

The activated pressure gauges recorded the reflected shock pressures from the explosive event as a function of time and the results compared to the outputs from the evaluated blast simulation codes. Pressure gauges closely adjacent to the explosive charge initiation point are subjected to the severe effects of explosive detonation products, including the fireball, and this close-in region is not modelled by any of the Computational Fluid Dynamics (CFD) or Fast Running Model (FRM) codes. Examination of the pressure time histories indicated some anomalous experimental results, believed to be associated with gauge mounting issues, around the maximum levels of peak pressure.

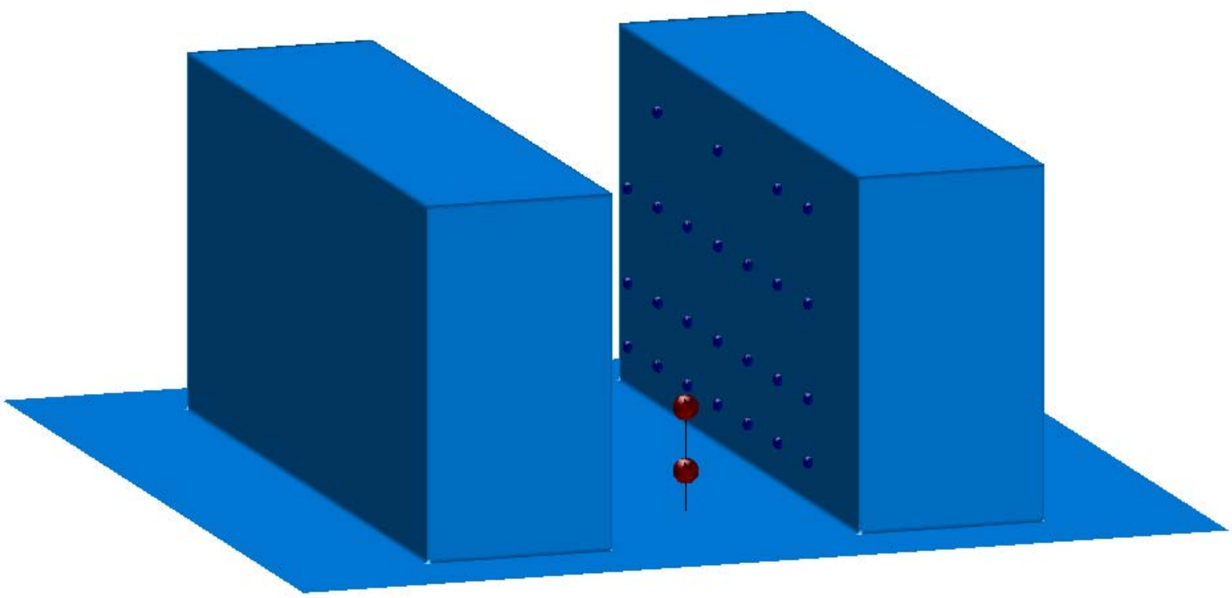

Figure 2. Two charge positions and 25 activated pressure gauges.

NUMERICAL SIMULATION

The geometry, charge location and gauge positions are readily described in the right-handed Cartesian coordinate system (x,y,z) with the origin at the ground level at the centre of symmetry with z-axis directed upwards and x-axis directed towards the vertical projection of the charge location at the ground level $z = 0$. In this coordinate system the right block with gauges shown in Figure 2 is described by the inequalities

$$-7.32\text{m} < x < 7.32\text{m} \quad 2.44\text{m} < y < 6.10\text{m} \quad 0\text{m} < z < 6.86\text{m}.$$

In this paper Test #13 is analysed in detail and pressure traces are compared at Gauges #1 and #14. In the chosen coordinate system, Gauge #1 and Gauge #14 are respectively located at

$x = -6.71\text{m}, y = 2.44\text{m}, z = 0.76\text{m}$ (Gauge #1),
$x = 4.27\text{m}, y = 2.44\text{m}, z = 1.98\text{m}$ (Gauge #14),

and the spherical charge is centred at $x = 4.27\text{m}, y = 0\text{m}, z = 1.98\text{m}$.

In this test the explosive device was composed of 18.2kg ANFO plus 2.3kg C4 booster charge. All experiments were conducted at high altitude, and for this particular test firing the atmospheric pressure and temperature were recorded to be $p = 80.6\text{kPa}$ and $T = 19°\text{C}$, respectively. It is worthwhile noting that the ambient pressure was well below the standard atmospheric pressure. For high-fidelity codes the most important parameters of explosive are heat of detonation and density. Some codes, such as AIR3D, use take into account the speed of detonation that slightly increases the arrival time of a shock.

Two types of numerical models were validated against the experimental data, namely CFD and FRM codes. FRM codes are meshless and run much faster than CFD codes. However, CFD codes are generally more accurate in resolving complex interaction of blast waves reflected from solid objects when considering oblique shocks, and particularly when pressure gauges are not in the direct line-of-sight from the charge.

AIR3D Software

AIR3D is a high-fidelity CFD code developed at Cranfield University, UK (Rose, 2006). The numerical algorithm employs an improved Advection Upstream Splitting Method (Wada and Liou, 1997). It is a second-order solver compiled for both 32-bit and 64-bit platforms, which fully utilises CPU multi-core architecture. As implemented, the software has no facility to vary ambient environmental conditions (e.g. temperature and ambient air pressure), and can only model spherical charges. For this model AIR3D was run using a 2.54cm (1 inch) cell size.

DBLAST Software

DBLAST is a first-order CFD solver developed by DSTO (Antanovskii, 2008, 2009). The numerical algorithm is based on a conservative Godunov-type solver combined with the exact Riemann solver (Toro, 1999). Arbitrary ambient pressure and temperature of air can be specified. DBLAST was run using a coarser mesh 5.08cm (2 inch) cell size due to computer memory limitations.

VAPO Software
Vulnerability Assessment and Protection Option (VAPO) software is an engineering-level FRM code specifically designed for building damage and personnel vulnerability assessment. VAPO was developed by the Defense Threat Reduction Agency (DTRA), USA. The FRM model employed by VAPO defines image bursts for nearby reflecting surfaces (in order to satisfy reflective boundary conditions), calculates the effective range to the target points of interest for the source and each image burst, evaluates the shock wave parameters, and combines the shock waves using the Low Altitude Multiple Burst (LAMB) shock addition rules (Hikida and Needham, 1981; Frank *et al*, 2008; Needham, 2010). It currently has no facility to vary ambient conditions, and the available explosive charge types are based on TNT equivalence. VAPO modelling was conducted using the default code settings.

BLASTX Software
BLASTX is an engineering-level FRM code developed by Engineer Research and Development Center (ERDC), USA (Britt *et al*, 2001). Both VAPO and BLASTX are based on the same algorithm (LAMB approximation), however, the simulation results are quite different. Unlike VAPO, ambient pressure and temperature can be specified in BLASTX.

RESULTS AND DISCUSSION

Pressure/time history predictions were made using the four modelling codes with spherical charges of equivalent mass to the test charges and the predicted results compared with the test results. The test and model charge sizes and burst heights were:

> 18.2kg ANFO plus 2.3kg C4 booster charge at heights 0.76m and 1.98m,
> 19.1kg C4 charge at heights 0.76m and 1.98m, and
> 2.3kg C4 charge at 1.98m.

Pressure time histories from the test and predicted explosive events were analysed in detail.

The assessment methodology is based on a selection of representative data traces that show the overall performance differences between the codes and experimental data. The most important parameters extracted from pressure time histories are peak pressure (P) and peak impulse (I). These parameters are typically used for damage assessment of structural members using the so-called P-I diagrams (iso-damage curves), and hence need to be predicted reasonably accurately. For the selected events the measured and predicted values for the 25 pressure gauge locations are shown in Figure 3. In this event an 18.2kg spherical charge of C4 explosive was detonated at 1.98m height of burst. As expected, the closest pressure gauge (#14) to the charge records the highest peak pressure and the test data is quite consistently predicted by the FRM codes (normal reflection of the shock wave). The CFD codes under-predict the peak pressure at this gauge. The AIR3D prediction is superior to DBLAST as it is a higher-order solver running on a finer mesh. However, it is known from experience that these CFD solvers generate nearly identical results when tests are modelled on sufficiently fine mesh.

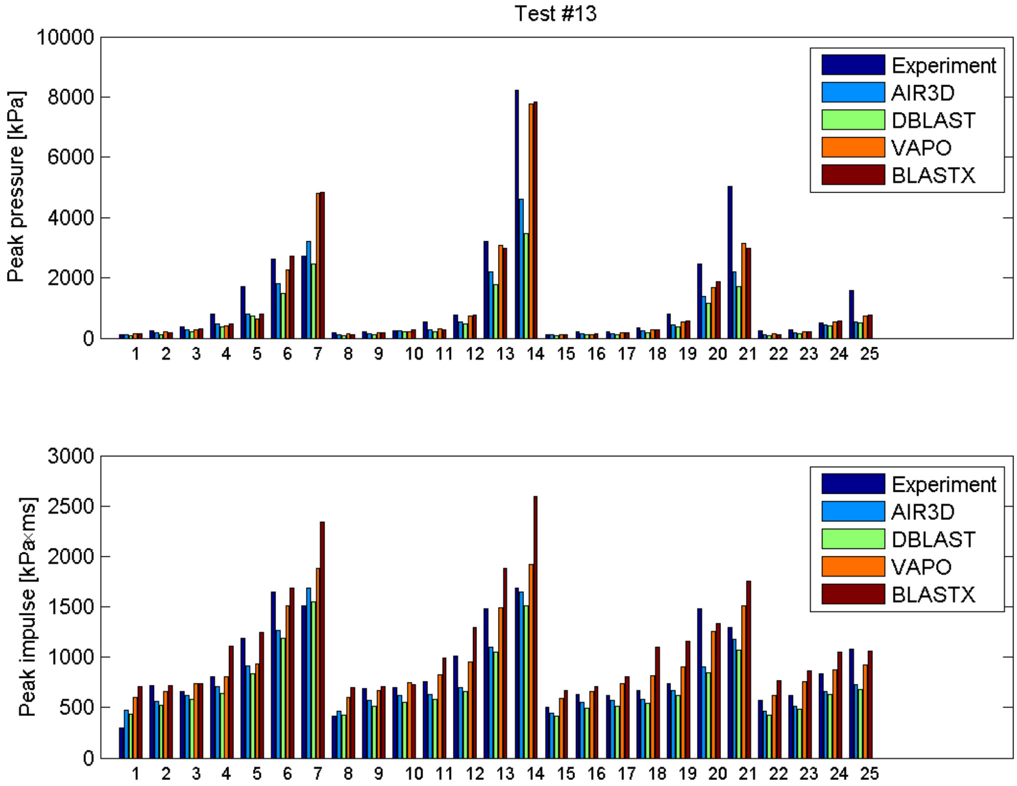

Figure 3. Comparison of measured and predicted peak pressure and impulse (pressure gauge numbers shown on x-axis).

Figure 4 shows overlayed pressure traces. It is seen that the arrival time of the shock wave is generally well predicted by all the codes. Note that the experimental pressure trace records typically exhibited spurious negative overpressure (impulse does not tend to a constant value at longer times, an effect which has been previously noted and is probably due to the thermal heating effects of the charge detonation products on the pressure gauge.

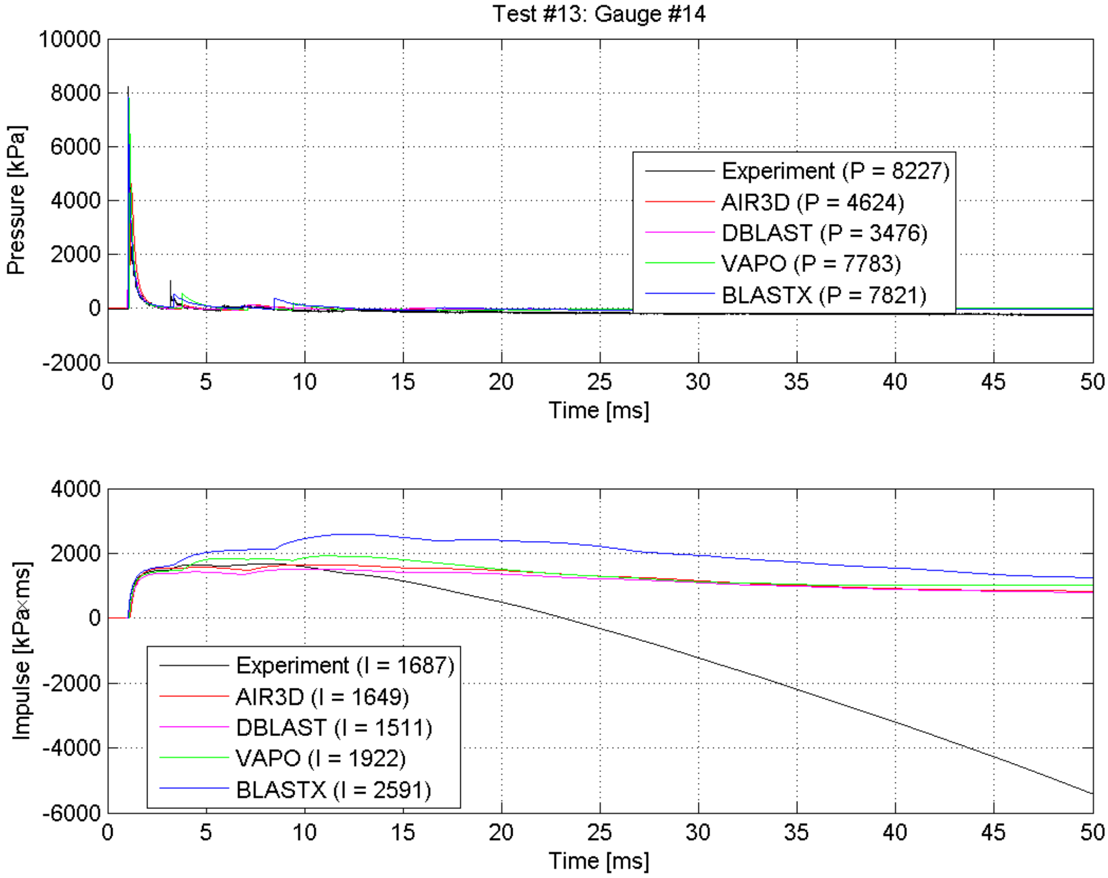

Figure 4. Measured and predicted pressure traces at Gauge #14 (Test #13).

Figure 5 shows another extreme case for the measured and predicted pressure time histories at the most distant Gauge #1. The observed shock record is seen as a complex composite of individual shock waves reflected from the solid blocks and the ground. At this gauge location the CFD solvers are seen to more accurately predict the experimental data. In this case DBLAST predicts the shock arrival time better due to its capability to treat arbitrary ambient conditions but it under-predicts peak pressure and impulse. As expected, the FRM solvers are less accurate and BLASTX predicts the shock arrival time better than VAPO.

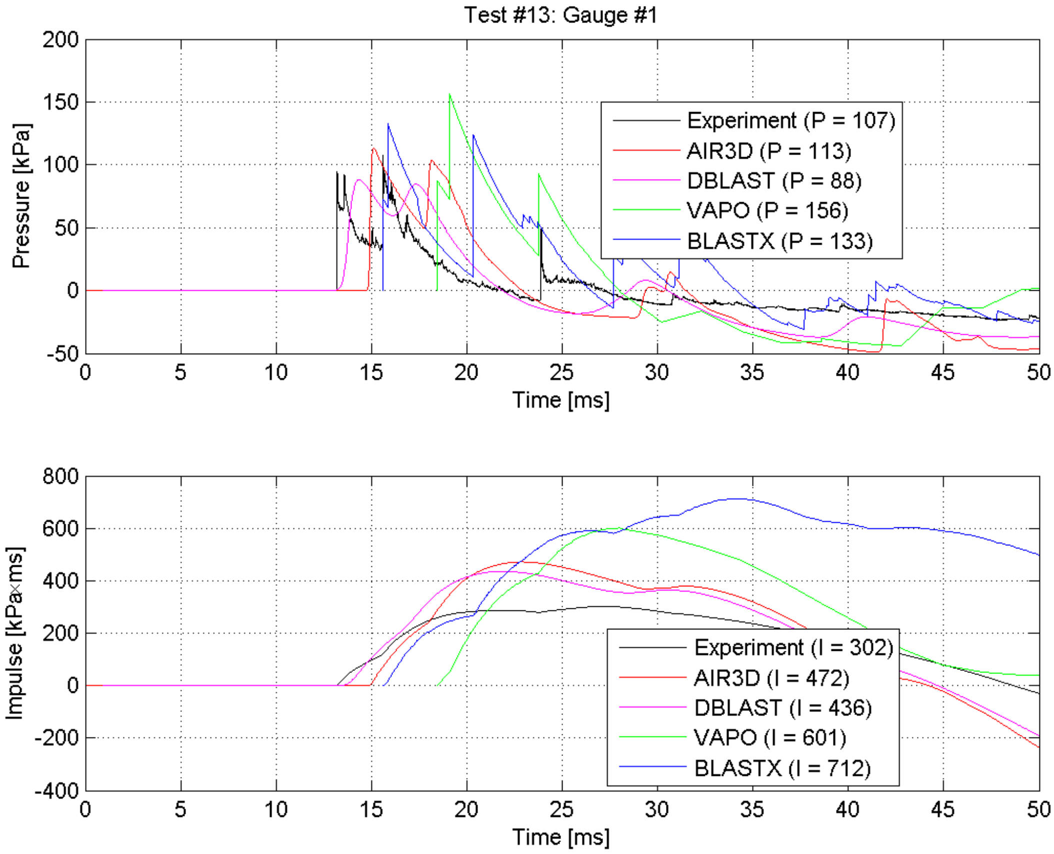

Figure 5. Measured and predicted pressure traces at Gauge #1 (Test #13).

Similar analyses, for the entire pressure gauge set, were conducted for all the other explosive firings, and the results are summarised in the following section.

CONCLUSIONS

This preliminary analysis has confirmed that there is no single blast effects prediction modelling code that is categorically "perfect" and that the majority of available computer blasts modelling codes are capable of modelling blast effects in the chosen environment with a reasonable degree of fidelity. Uncertainties introduced by any of the models are likely to become insignificant when compared to the inherent unpredictability of real Improvised Explosive Device (IED) charges.

On this basis, it is concluded that all of the models are likely to be suitable for predicting basic "engineering level" blast effects in an environment with a relatively straightforward geometry. However, this analysis has further demonstrated that an understanding of the inherent code weaknesses provides confidence in their application to the solution of real world explosive blast loading problems.

CFD codes are more accurate at modelling blast effects overall, since they are able to consistently predict relatively accurate peak pressure and impulse levels. FRM codes are especially limited at gauge locations where oblique shocks occur but still generally produced reasonable overall predictions of peak pressure and peak impulse compared to most of the test firing results. However, on some of the firings, VAPO and BLASTX generated relatively large pressure errors at some sensor positions due to their inability to model the interactions of the more complex multiple shock fronts. When optimally applied AIR3D and DBLAST do not display this type of behaviour.

CFD codes appear better able to model the pressure arrival times for complex events. Although timing is generally of limited consequence when assessing damage using P-I curves, it can become important for more accurate combining pressure waves. In addition, the extremely long run times required to run fine mesh CFD problems, particularly when the scenarios and structures are complex, limits the use of CFD in these scenarios.

All the blast modelling code work reported here used spherical charges, although the test data was generated by using both spherical and upright cylindrical explosive charges. It is recognised that there are significant differences in the blast pressure field output from spherical and cylindrical charges particularly close in to the charge and this is recognised as a region of both test measurement and code prediction uncertainty. There is some capability to model cylindrical charges in the BLASTX code, however, it is limited to a small number of defined charge and cylinder aspects ratios based on test data. If these codes are to be used for detailed studies of blast effects in the near field their prediction limitations need to be recognised. For this type of problem it would be useful to incorporate charge shape effects.

ACKNOWLEDGEMENT

The authors are grateful to Jadranka Sunde (DSTO) for helpful suggestions and comments.

REFERENCES

Antanovskii L. K. (2008) Solving multi-dimensional problems of gas dynamics using MATLAB®. *Tech. Report DSTO-TR-2139*. DSTO, Australia.

Antanovskii L. K. (2009) An accumulated damage model for blast propagation in compartmented structures with progressively failing thin bulkheads. *Tech. Report DSTO-TR-2365*. DSTO, Australia.

Britt J. R., Ranta D. E. and Joachim C. E. (2001) BlastX code, version 4.2, user's manual, ERDC, USA.

Frank S., Frank R. and Needham C. (2008). Fast running model for urban airblast using engineering principles. In: *Proceedings of the 20th MABS Conference, Oslo, Norway.*

Hikida S. and Needham C. E. (1981) Low altitude multiple burst (LAMB) model. In: *Volume I - Shock Description, DNA 5863Z-1, Defense Nuclear Agency, Washington, DC, USA.*

Needham C. E. (2010) *Blast Waves,* Springer, Berlin.

Rose T.A. (2006) A Computational tool for airblast calculations: Air3d version 9 users' guide, Cranfield University, UK.

Toro E. (1999) *Riemann Solvers and Numerical Methods for Fluid Dynamics: A Practical Introduction* (2nd edn), Springer, Berlin.

Wada Y. and Liou M-S. (1997) An accurate and robust flux splitting scheme for shock and contact discontinuities. *J. Scientific Computing (Society for Industrial and Applied Mathematics)*, **18**(3), 633–657.