Proceedings Paper:

Farrimond, D., Ratcliff, A., Dennis, A. et al. (5 more authors) (2023) MicroBlast - a benchmarking study of gramme-scale explosive trials. In: Proceedings of the 26th International Symposium on Military Aspects of Blast and Shock (MABS26). 26th International Symposium on Military Aspects of Blast and Shock (MABS26), 04-08 Dec 2023, Wollongong, Australia. Military Aspects of Blast and Shock (MABS) .

MICROBLAST - A BENCHMARKING STUDY OF GRAMME-SCALE EXPLOSIVE TRIALS

D. G. Farrimond[1], A. Ratcliff[1], A. A. Dennis[1], S. E. Rigby[1], A. Tyas[1,2], S. D. Clarke[1,2], T. J. Lodge[1,2] and W. Tolman[3]

[1] *University of Sheffield, Department of Civil and Structural Engineering, Mappin St, Sheffield City Centre, Sheffield, S1 3JD;*
[2]*Blastech Ltd, Cedus Labs, Harpur Hill, Buxton, Derbyshire, SK17 9NL*
[3]*Ministry of Defence, Bristol, BS34 8JH, England.*

KEY WORDS:
Blast parameter variability, gramme-scale, benchmarking, urban explosions.

ABSTRACT

Explosions are a pressing and pervading threat in the modern world. The extensive damage caused by recent large scale urban explosions such as Tianjin (2015) and Beirut (2020) has highlighted a key gap in our knowledge. That is, we still do not yet understand, nor can we reliably and rapidly predict, blast loading in complex cityscape environments. Accordingly, determination of consequences related to risk, structural damage, and casualty numbers, is severely limited. Current experimental approaches do not have the sophistication nor fidelity required to accurately measure blast loading in urban environments, and there is a significant and growing disparity in the complexity with which numerical models and experimental work can operate. Because of this, key insights gained from detailed modelling studies have not been validated, and we do not yet fully understand how blast waves propagate and interact with multiple obstacles. This paper presents the development of a series of experimental studies aimed at addressing this shortfall. The ultimate objective of this work is to develop the *MicroBlast* facility: an ultra small-scale testing apparatus for rapid, high-rate, high-resolution, multi-parameter measurements of blast loading in complex environments. Here, we present results from preliminary trials aimed at establishing the reliability and repeatability of small-scale explosive testing, in increasingly complex layouts. The results are directly compared to commensurate larger-scale test data to confirm scalability of gramme-scale detonations.

INTRODUCTION

To adequately protect people, and their surrounding infrastructure, from devastating explosive effects, a comprehensive understanding of the loading conditions from a given charge shape, mass and composition, alongside the ability to predict these are required. For free-air, unobstructed events, these behaviours are well understood, with highly accurate empirical methods, e.g. [1], derived from large scale military-grade explosive trials (>100kg), that can predict blast parameters with high levels of accuracy and can rigorously validate computational fluid dynamic (CFD) and/or finite element analysis (FEA) simulations [2]. There has been research conducted which considers the reliability of the aforementioned empirical method through experimental validation using mid-sized explosive charges [3]. Therein, it was established that not only were the results undertaken repeatable within 10% of the mean from nominally identical trials but also within 7% of the empirical prediction method. Further work verifies the synergetic behaviour between both experimental and numerical research through the identification of systematic errors in even the simplest of free-air and reflected methodologies [4].

For these simple scenarios, numerical simulations are computationally inexpensive and perform optimally. When a blast wave propagates in the presence of obstacles, the loading differs substantially from that of a free-air blast due to highly non-linear physical processes such as reflection, diffraction, coalescence of multiple shock fronts [5], alongside shielding and confining effects of nearby obstacles [6]. Whilst some of these mechanisms will reduce the effects of a blast, others can induce more detrimental effects and thus a combination through complex environments creates a more challenging scenario to predict. Numerical simulation has highlighted the requirement of an accurate representation of the blast waveform in more complex environments when conducting qualitative risk assessments [7] but there is a distinct lack of experimental validation for these scenarios to provide certainty in CFD.

With large scale urban explosions such as those in Tianjin (2015) and Beirut (2020) causing huge devastation to both infrastructure and civilian well-being, research efforts in blast loading and characterisation are primarily focussed on explosive events within complex environments. Comprehensive reviews of the current understanding of shock loading interaction with obstacles [8] and within urban environments [9] have been previously reported, but there is still much effort required to definitively quantify the behaviour of blast loading within increased complexity settings.

CFD simulations have been utilised for scenarios with more complex shock wave-structure interactions and were compared to equivalent experimental trials [10-12], but there still is a significant scientific shortfall in this area. Current experimental approaches do not have the sophistication nor fidelity required to accurately measure blast loading in complex environments which therefore induces an uncertainty in numerical analysis of these situations. Replicating real-world urban layouts at full-scale is unrealistic from both an economical and environmental perspective. Therefore, using Hopkinson-Cranz scaling [13, 14], experimental work can reduce charge masses to gramme-scale to consequently achieve miniature urban environments which are inexpensive to replace but provide comparable results to a real-world scenario. Early work by Trelat et al [15] considered replicating large scale explosives events through small scale gaseous explosions which exhibited reasonable correlation with CFD simulations. Cheval et al [16, 17] was able to build upon the aforementioned works through conducting similar small-scale explosive work resulting in extracted blast parameters for free-field and reflected scenarios exhibiting reasonable agreement with semi-empirical prediction tools [1].

This paper establishes an experimental benchmark of consistent and reliable results when detonating small-scale military grade explosives in the order of a few grammes. Through creating a scaled down representation of the historic free-field test arena at the University of Sheffield, the results are compared to commensurate larger-scale test data. The main findings from these trials are that small-scale explosive trials are as repeatable as larger-scale events when significant care is taken over the experimental setup and data analysis due to the sensitivity of scaling laws for gramme-scale charges.

EXPERIMENTAL PROCEDURE

A total of 20 far-field arena tests were conducted at the University of Sheffield (UoS) Blast and Impact Laboratory in Buxton, UK. A total of 180 individual pressure-time histories were recorded as part of this study with the aim of establishing a reliable experimental benchmark for gramme-scale charges. The 20 trials were split into two different categories designed to achieve the following conclusions:

- **Work Package 1:** 18 trials of which consisted of 3g PE10 hemispherical charges detonated between two rigid reflecting walls to achieve simple free-air and reflected shock recordings (scaled versions of those reported in [4]) to establish the repeatability of the resulting data from the detonation of gram-sized explosives.
- **Work Package 2:** 8 trials which consisted of 1g PE10 hemispherical charges detonated with five finite-sized reflected walls four of which should exhibit clearing behaviours within the positive phase (scaled version of trials reports in [18]) to assess the scalability of blast wave interaction mechanics and again quantify the consistency of increased complexity shock wave-obstacle interactions.

A selection of different piezo-resistive pressure gauges were used throughout this testing regime to determine whether the mechanical responses of different gauges effected the recorded data.

During Work Package 1, two Kulite HKM-375 piezo-resistive pressure gauges were used to record the reflected pressure-time history at two reflected wall (1.2m in height, 1.83m in width) locations. The gauges were threaded through and made flush to the surface of a steel plate covering the reflective surface. The centre of the gauges were located 10mm above ground surface level to ensure the pressures recorded were as normal to the charge as feasibly possible. In both incident gauge locations, a Kulite HKM-375 and StrainSense XPM-5 piezo-resistive pressure gauge were used to assess the effects of the instrumentation's physical recording face. The XPM-5 offers a small recording face of 3.8mm diameter when compared to the HKM-375's 8.1mm diameter which was hypothesised to make a significant difference in recording the sharp rise time of an incident wave as it passes over the face of the gauge. Figure 1 shows a schematic of Work Package 1 test setup for reference. It is important to note that the charge location moved between the reflected gauges along the dotted line during the testing regime therefore R_a and R_b vary but always sum to 2.28m.

For Work Package 2, one of the rigid reflective surfaces was removed and replaced with four finite sized reflected surfaces (120 × 120mm loaded area, 270mm depth) which were designed to replicate a scaled version of 250g PE4 hemispherical blast wave clearing trials in Ref [18]. On the remaining rigid reflective surface, a single Kulite HKM-375 piezo-resistive pressure gauge was used to record the reflected pressure-time history providing a benchmark to Work Package 1. For the rigid obstacles with a finite size, a combination of Kulite HKM-375, Kulite XTEL-140 and Strainsense XPM-5 gauges were used to assess the more complex clearing behaviours. Figure 2 represents a schematic of the Work Package 2 test setup. For reference, where the distance each object is away from the charge centre is a scaled distance equivalent to those tested in Ref [18].

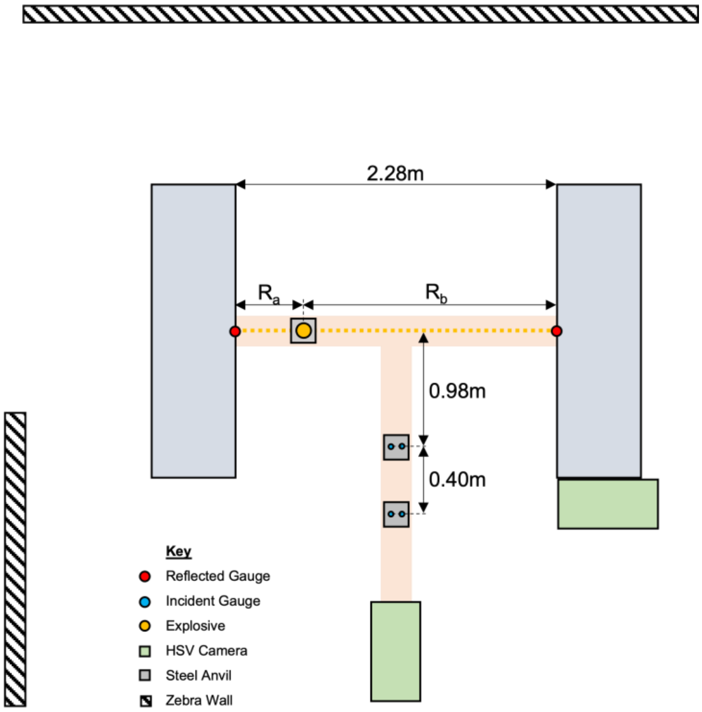

Figure 1: Schematic drawing of Work Package 1 trial procedure detailing the location of pressure gauges and high-speed cameras (NOT TO SCALE)

Due to the sensitivity in ensuring an accurate charge mass at these scales, an AWS portable milligram weighing scale, with accuracy of +/-0.001g was used for charge preparation. For each of the trials, the hemispherical explosive charges were formed using a 3D-printed mould.

In each test the charges are surface detonated using a Euronel non-electircal detonator (0.8g TNT equivalent mass of explosive) at standoff distances of between 0.456-1.882m. The charges were placed on a small steel plate (100 × 100 × 25mm) prior to detonation, in order to ensure a flat surface and to facilitate locating in the pre-cut channel in the concrete slab, which was backfilled with sand and levelled off prior to each test.

The pressure-time histories were recorded using a 16-bit digital oscilloscope and TiePie software, with an average sampling rate of 312.5 kHz at 16-bit resolution. The recording was triggered automatically using TiePie's 'out window' signal trigger on a bespoke break-wire signal, formed by a wire wrapped around the detonator. The 'out window' trigger initiated with a voltage drop outside the normal electrical noise experienced in the break-wire. This coincides with the detonation of the charge breaking the circuit.

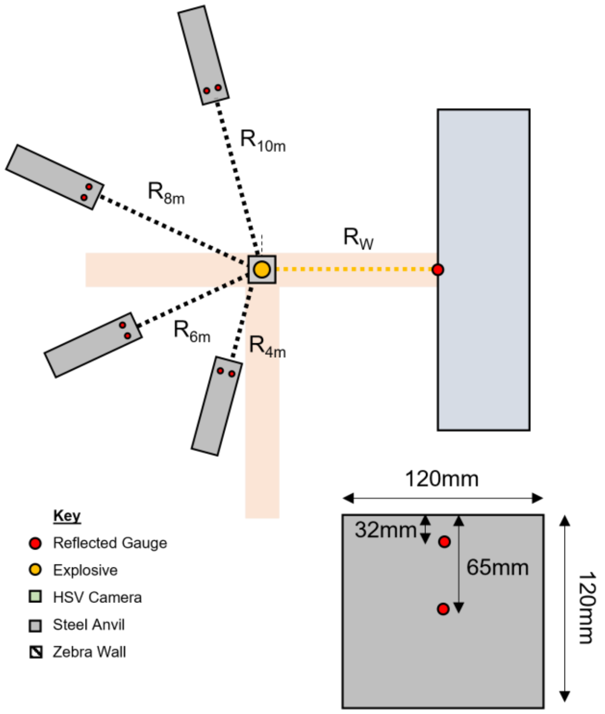

Figure 2: Schematic drawing of Work Package 2 trial procedure detailing the location of pressure gauges (NOT TO SCALE)

RESULTS

Prior to any analysis or scaling being applied to the data, it is important to establish how the raw recordings compare to one another. Figure 3 displays a compilation of 5 as-recorded positive phase pressure-time history profiles from nominally identical trials of 3g hemispherical PE10 detonations when recording reflected and incident pressures at 0.912m and 1.384m respectively. Overlaid on these traces are the generalised pressure-time history profiles corresponding to pressure, impulse, arrival time and duration predictions for a user defined explosive charge mass and stand-off - in this case it is for a 3g PE10 hemisphere (1.22 TNT equivalence after [4]) combined with a 0.8g TNTe detonator. The parameter predictions are evaluated using the open-source MatLab script *'Blast.m'* which utilises digitised data from UFC-3-340-02 [19].

Qualitatively, each set of results are in excellent agreement, with minimal variations in the blast pressure histories between the 5 recordings at each standoff, providing clear evidence of repeatability in the blast parameters recorded. The remarkable comparison between the prediction curves and the corresponding experimental data also provides justification that within the far-field range ConWep/UFC-3-340-02 provides a significant representation of the raw data. One important thing to note is that the prediction curves tend to exhibit larger durations than what the experimental data presents. This is a consistent finding within all free-air trials which have been conducted at UoS [3,20]. Future work will look to provide adjustments to the prediction curves to account for this.

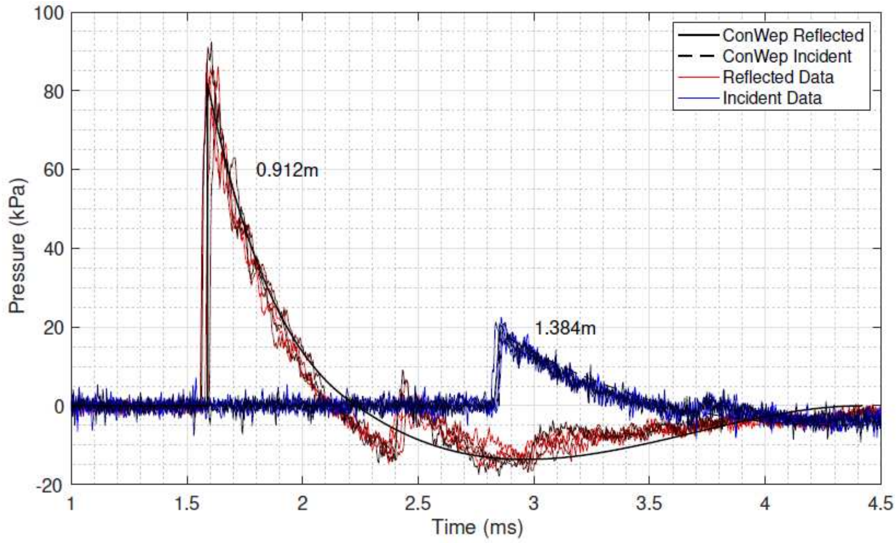

Figure 3: Pressure-time history plots from 5 nominally identical trials recording using reflected and incident gauges from the detonation of 3g PE10 hemispheres.

Figure 4 displays the data from 5 nominally identical trials with the two types of incident gauge. As these were located within 10mm of each other, the overall standoff was considered the same for the purpose of a qualitative analysis. The clear consistency across all the recordings looking at each gauge separately suggests that a gauge related mechanical response issue occurs in the early stages of the shock wave arriving for the larger measuring faced gauge, Kulite HKM-375, resulting in a rounded peak. This feature can be omitted by utilizing Friedlander curve-fitting methods to the last 75% of the positive phase [21] which was validated by both Rigby et al [3] and Farrimond et al [20]. The smaller measuring face gauge are essential for use when recording incident pressures.

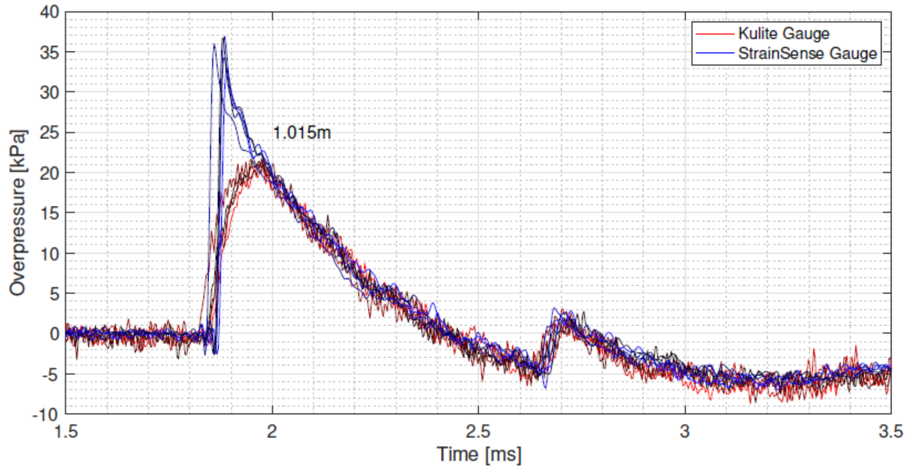

Figure 4: Pressure-time history plots from 5 nominally identical trials recording using two types of incident gauge to assess their mechanical response from 3g PE10 hemispheres.

The entire data set from Work Package 1, once processed, was compared directly to the semi-empirical ConWep prediction equations as presented in Figures 5a-d. It is important to note that the data presented is scaled according to the TNT equivalent mass of the charge itself, 4.46g TNT, inclusive of the mass of the detonator. At these scales, the explosive yield of the detonator was found to play a significant role in the output blast parameters and therefore is critical to be accounted for all future trials. The data compares remarkably well with the semi-empirical predictions which not only shows consistency of the data but also validates the tools within far-field regimes for gramme-scale charges.

There are a few important things to highlight from Figures 5a-d which are as follows:

- As the scaled distance reduces, the reflected pressure and specific impulse magnitudes are lower than the semi-empirical predictions. This is believed to be related similarly to the mechanical functionality of the pressure gauges used itself. When the shock wave arrives at the gauges in these positions, it is known that it exhibits higher levels of variability related directly to fluid-dynamic instabilities forming within the fireball and not yet reaching a spherical expansion equilibrium. Not only this but the shock wave, as it impinges on the gauge, may not be fully planar at this stage, meaning another asymmetric loading occurs on the gauge.
- Both types of incident gauges do a reasonable job at capturing shock wave loading after processing, however the specific impulse is lower than the semi-empirical predictions. The physical mechanism of this feature is unknown for certain but is suggested that the prediction tools may hold ambiguity for this parameter with similar result presented by Tang et al [22].
- Experimentally recorded time duration presents to be consistently shorter than the prediction tools estimates, which is similar to findings in other articles [22]. This parameter is however generally difficult to assign due to the ambiguity in where the overpressure definitively returns to atmospheric.

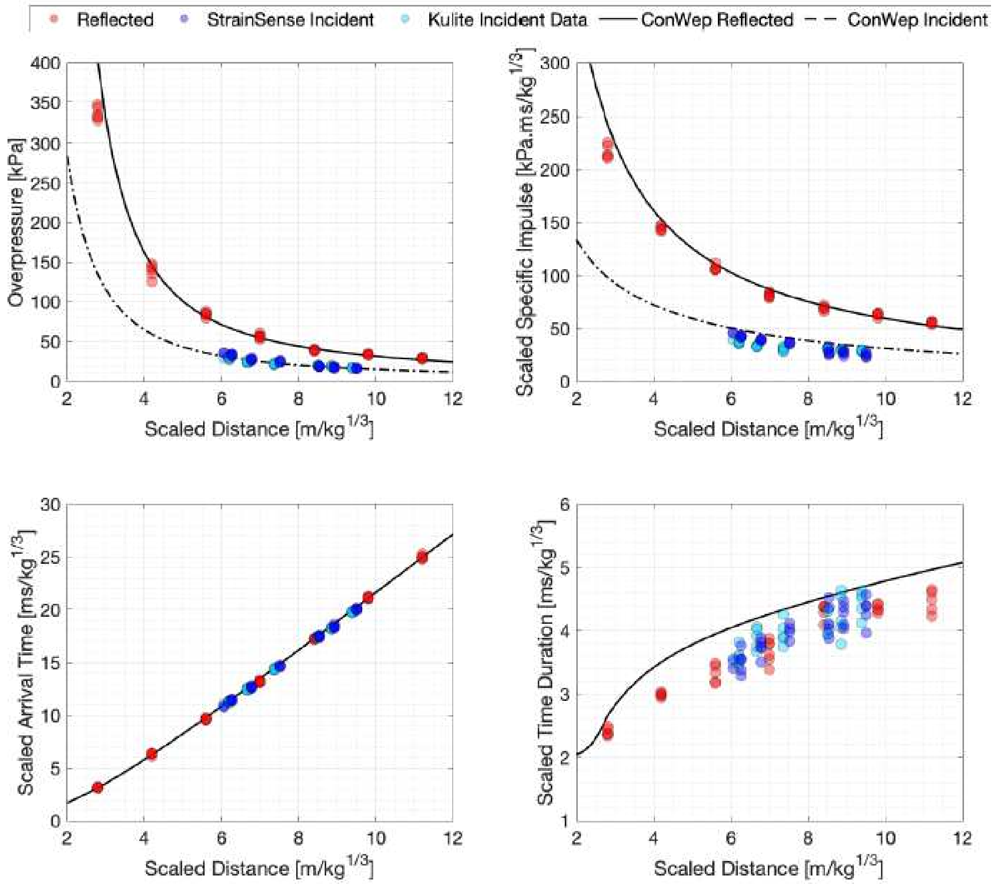

Figure 5: Compiled blast parameters from 3g hemispherical PE10 trials as a function scaled distance, compared with CW predictions: a) Peak reflected overpressure, b) Scaled reflected peak specific impulse, c) Scaled arrival time, d) Scaled positive phase duration.

To confirm the behaviour of the small-scale charges were consistent with that of larger scale charges which have been well characterised at UoS, the testing methodology was developed to establish standoff distance values which when scaled by mass and TNTe of 1.22 were identical. Figure 6 displays pressure-time histories from these representative trials which have been time shifted so the arrival times align to compare the overall trends qualitatively. Clearly the behaviour each shock interaction with the gauges are highly comparable providing evidence to the idea that the small scale charges are representative of larger trials for an entire blast event. It is important to note that this behaviour was hypothesised with ideal behaviour explosives like PE10, whereas others which exhibit non-ideal detonation processes, this scalability would not be achieved [24].

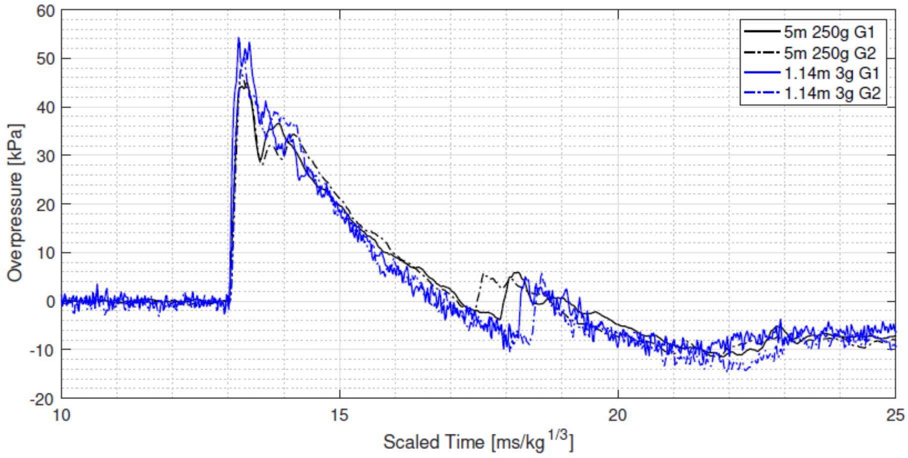

Figure 6: Four reflected pressure-time history plots time shifted so arrival times aligned from both 3g and 250g PE10 hemispherical detonations which have been recorded at standoff distances that when scaled are equivalent.

The cross-validation of the data acquired during the historic trial results presented in [18] and those collected during WP2 has been undertaken with one example being presented in Figures 7a and 7b. It is clear from this example that the experimental work from these two separate trials compare significantly well when scaled accordingly. This gives rise to the experimental scalability of explosive characterisation when introducing complexity. Important to highlight are simulated predictions of the event, two of which (Hudson and DYNA simulation) are results presented within Rigby et al [25] and the other being a coarse IG Viper::Blast comparison. Overall, there is consistency within the predictions on the whole thus providing validation of the synergetic relationship and importance of numerical and experimental analysis. Visibly the Viper::Blast simulation seems to slightly overpredict the positive phase and does not capture the sharp rise effectively. This feature is believed to be a direct result of using a coarser mesh than required which results in discrepancies in the discrete measurements of pressure but conserves specific impulse predictions; similar to the findings presented in [26].

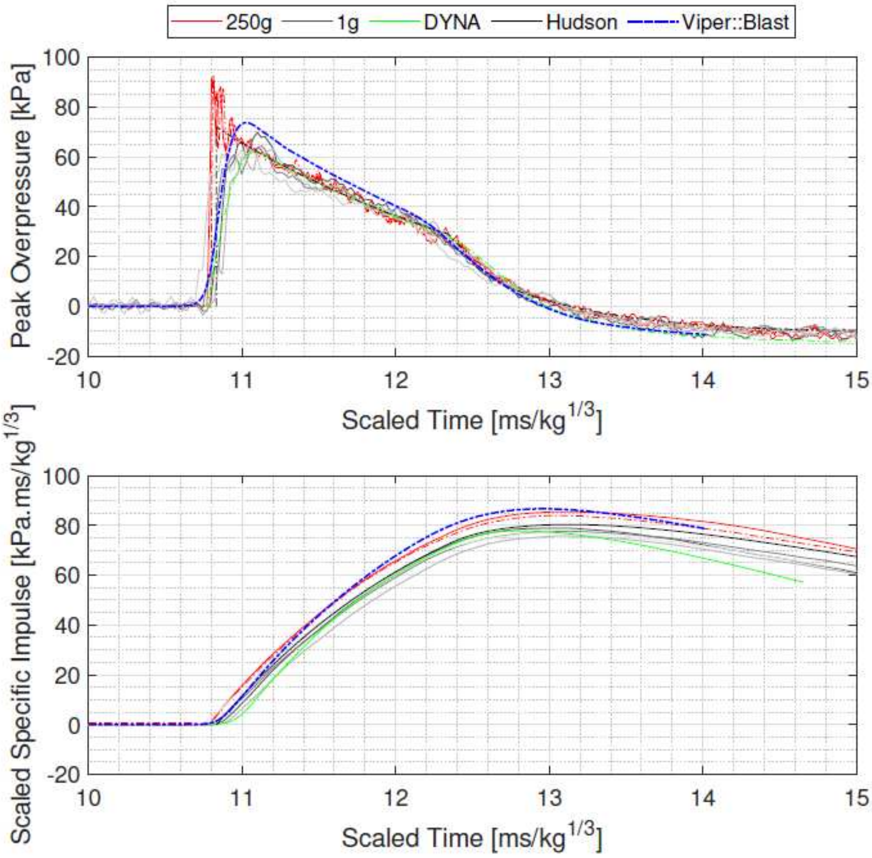

Figure 7: Central gauge position results from both historical data captured for larger scale clearing trials [17] and those detailed within this paper: a) Pressure-time histories, b) Specific impulse time history.

CONCLUSIONS

With large scale explosive events being a threat which very few build environments are designed for, there is a distinct requirement to rapidly assess their consequences on both infrastructure and civilians. Despite CFD simulations providing accurate representations of simplistic experimental trials, anything more complex is unlikely to have been validated against experimental data, resulting in a lack of confidence in numerical modelling accuracy. Understanding these complex settings can only be achieved through the synergetic relationship between numerical simulation and experimental data. With that, it is essential to utilise explosive scaling laws to develop a high-fidelity, small-scale experimental facility which has the potential to replicate cityscapes and other larger and more complex domains.

Through extensive testing of gramme-scale (1-3g) PE10 hemispheres within far-field scaled distance regions, there has been definitive evidence to suggest that all blast parameters are consistent when comparing nominally identical raw data sets and are also representative of similar scaled trials of greater explosive masses. A key finding from these trials is that the smaller the explosive mass becomes, the more sensitive the results are when scaled. At these masses, it was highlighted that the equivalent explosive TNT mass of the detonator, albeit as low as 0.8g, contributes to the overall blast parameters extracted and therefore requires consideration when scaling data accordingly. This has been overlooked in other larger scale trials because the explosive mass of a detonator is insignificant but is a critical finding to prove the scalability of small-scale explosive events.

The aim of the *MicroBlast* project is to develop a testing capability which can explore complex geometries with the best possible levels of geometric fidelity to directly compare with CFD simulations. With the consistency of recorded data from free-air, normally reflected and clearing induced pressure-time histories, the use of gramme-scale explosives has been verified to use within the *MicroBlast* facility to represent the behaviour of large-scale explosive within cityscape domains when appropriately scaled.

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