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VALIDATION OF SEMI-EMPIRICAL BLAST PRESSURE PREDICTIONS FOR FAR FIELD EXPLOSIONS – IS THERE INHERENT VARIABILITY IN BLAST WAVE PARAMETERS?

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Abstract. *A considerable amount of scientific effort has been expended over many decades on developing means of predicting the loading generated when a blast wave impinges on a structure. Semi-empirical 'look-up' predictive methods, such as those incorporated in the UFC-3-340-02 manual, the ConWep code or the *LOAD_BLAST module of LS-DYNA, offer a simple means for predicting the blast loading generated in geometrically simple scenarios. However, reported test data frequently show considerable spread and lack of repeatability, which is often attributed to some inherent variability in the blast waves developed from detonations, although no definitive physical interpretation has been forwarded as to the source of such inherent variation. As such, the semi-empirical predictions are often viewed as only 'ball-park' or 'order of magnitude' estimations.*

This paper presents experimental measurements of reflected pressure-time histories from a series of well-controlled small scale blast tests. Data fitting techniques are used to obtain experimental reflected pressure and impulse values which are compared to corresponding semi-empirical predictions. We find that it is possible to produce reliable and highly consistent, repeatable results that match predictions remarkably well and therefore show that existing semi-empirical blast predictions can be used with confidence as a first-order approach for quantifying the blast load a structure will be subjected to. Our results presented here suggest that for small scale far-field loading in simple geometrical scenarios, test-to-test variability can be reduced by ensuring that test parameters are tightly controlled.

1 INTRODUCTION

1.1 Background

The pressure resulting from a high explosive detonation is characterised by an abrupt increase in pressure above ambient conditions, p_0, to a value of peak over-pressure, given as $p_{so,max}$ for incident (or 'side-on') blast waves and $p_{r,max}$ for reflected blast waves. Following this near-discontinuous increase in pressure is a temporal decay back to ambient conditions, the duration of which is known as the positive phase duration, t_d. Over-expansion of the air following the

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shock front causes a period of 'negative' (below atmospheric) pressure known as the negative phase, with peak values of $p_{so,min}$ and $p_{r,min}$ for incident and reflected waves respectively, acting over a duration of t_d^-. An ideal blast wave is shown in Figure 1, where the impulse, i, is defined as the integral of the pressure with respect to time, i.e. the area under the pressure-time curve.

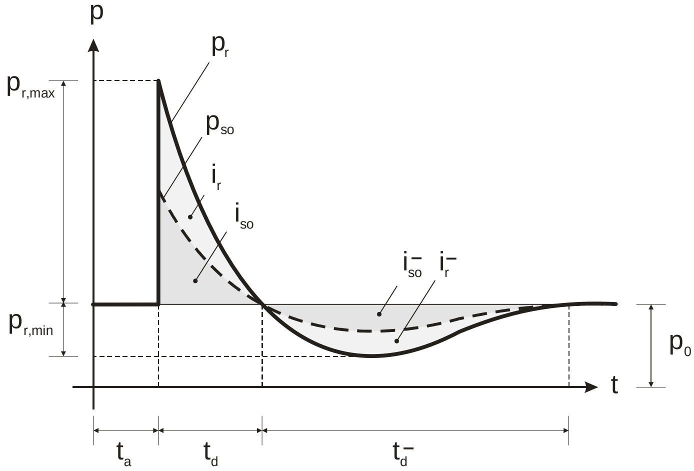

Figure 1: Idealised pressure-time profile for a blast wave

A considerable amount of scientific effort has been expended over many decades on developing means of predicting the loading generated when a blast wave impinges on a structure. Esparza[1] provides some 23 references to blast trials dating back to 1946, with the most widely known study being the 1984 compilation by Kingery and Bulmash[2], hereby referred to as the KB method. This semi-empirical predictive method utilises curves fit to a compilation of data based partly on computer analyses and partly on measurements from a number of medium to large-scale experimental blast trials, and enables the pressure, impulse, arrival time and duration to be predicted for values of scaled distance, Z, between 0.067 and 39.67 m/kg$^{1/3}$. The scaled distance is given as $Z = R/W^{1/3}$, where R is the length from the blast source to the point of interest (also known as the 'stand-off'), and W is the mass of explosive, expressed as an equivalent mass of TNT.

The positive phase of the blast load is well understood, with the KB positive phase blast parameters well-established in the current literature and widely accepted as standard practice for predicting blast loads – KB predictions are implemented into the UFC-3-340-02 manual[3], the ConWep[4] computer code and the *LOAD_BLAST[5] module of LS-DYNA.

The positive phase of the blast load can be described by the 'modified Friedlander equation'[6]

$$p_r(t) = p_{r,max}\left(1 - \frac{t}{t_d}\right) e^{-b\frac{t}{t_d}} \tag{1}$$

where b is known as the waveform parameter and controls the decay of the pressure-time curve. The KB method presents a relationship for b in terms of Z, however it is usually recommended that this parameter is determined from the integral of the Friedlander equation

$$i_r = \int_0^{t_d} p_r(t)dt = \frac{p_{r,max}t_d}{b^2}(b - 1 + e^{-b}) \tag{2}$$

which, given knowledge of i_r, $p_{r,max}$ and t_d, can be solved to find b for any scaled distance of interest. Positive and negative phase blast parameters are typically presented in the form of design charts[3] or tabulated data[7]. Whilst inclusion of the negative phase is important for low stiffness systems where the characteristic response time of the structural system is long, and hence the negative phase loading can commence before the structure has reached maximum deflection[8], it is not considered in this article.

1.2 Blast parameter variability

Despite the fact that the KB predictions have been available for three decades, there is still uncertainty in published literature as to their accuracy. Reported test data frequently show considerable spread and lack of repeatability, with some researchers demonstrating variations in pressure of 70-150% and variations in impulse of 50-130% for nominally similar tests when compared to the KB predictions[9].

In a review of predictive methods, Bogosian et al.[10] showed that there was generally good correlation between the KB predictions and compiled data from blast trials, but with some considerable spread. According to Smith[11] *'it is evident that even nominally identical, well-controlled experiments involving explosives can produce results with a significant spread'*, whilst Netherton[12] states '*it is readily observed via physical testing that the blast load experienced by a target structure – for apparently similar circumstances – will not always be the same*'. Borenstein[13] conducted a sensitivity analysis on blast loading parameters, citing *'random characterization associated with the explosives*' as a reason for uncertainty in blast loading.

However, no compelling physical reason has been put forward for the purported inherent variability and uncertainty in the blast load parameters. Furthermore, other researchers such as Rickman and Murrell[14] and Tyas et al.[15] observed no such variability and demonstrated remarkably good test-to-test repeatability and correlation between empirical data and the KB predictions.

This presents a question, which becomes the focus of this of this article: is there inherent variability in the parameters of blast waves from nominal identical explosive events? This question will be investigated through experimental measurements of reflected pressure-time histories from a series of well-controlled small scale blast tests. Data fitting techniques will be used to obtain positive phase pressure and impulse parameters in order to discern whether it is possible to produce reliable and highly consistent, repeatable results that match predictions remarkably well, or if there is indeed some inherent variability in the blast waves produced from nominally identical high explosive events.

2 EXPERIMENTAL SETUP

A number of blast trials were conducted at the University of Sheffield Blast & Impact Laboratory, Buxton, UK. as part of a wider study into the effects of angle of incidence. Hemispherical PE4 explosive charges were detonated orthogonal to a Kulite HKM 7 bar pressure gauge embedded at ground level within the external wall of a reinforced concrete bunker. A further three pressure gauges were embedded in the wall: two at ground level, 2 m and 3 m horizontal distances along the bunker wall (away from the line of the centre of the explosive), and one 2 m above ground level, directly in line with the centre of the explosive. The pressure gauges were embedded flush with the surface of small steel plates which were affixed to the bunker wall to ensure a smooth and regular reflecting surface. The test arrangement can be seen in Figure 2.

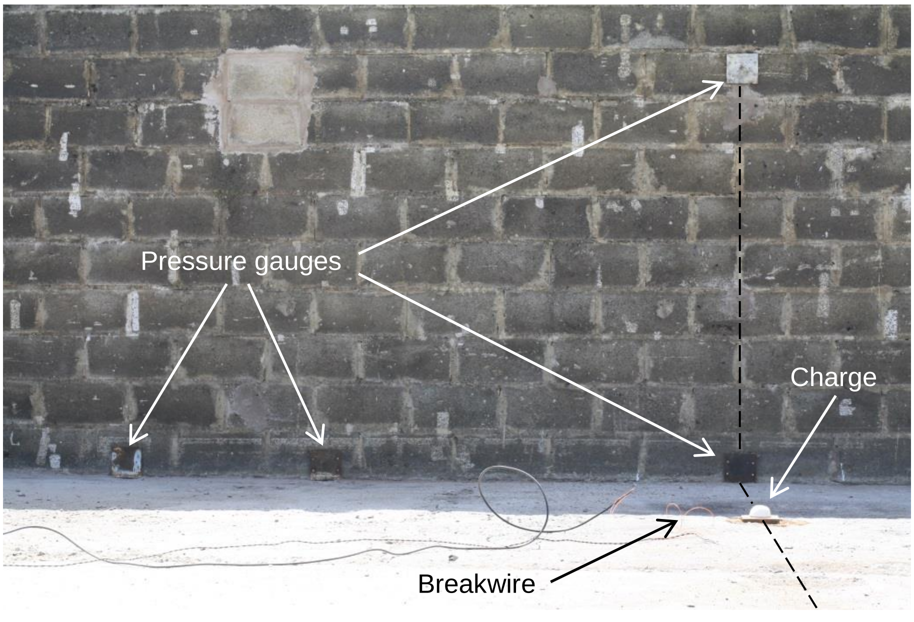

Figure 2: Pressure gauge location and general test arrangement.

The bunker formed a large, effectively rigid target such that fluid-structure-interaction effects could be ignored[16]. The charges were detonated on a 50 mm thick steel plate, placed on a level, flat concrete ground slab which was swept clean after each test, enabling the detonation to be considered as a hemispherical surface burst propagating over a rigid ground surface.

The experimental trials were conducted with charge masses ranging from 180 to 350 g PE4, and with stand-offs ranging from 2 to 6 m, giving a range of scaled distances between 5.39 and 10.02 m/kg$^{1/3}$, with angles of incidence ranging between 0 and 56.3°. 82 pressure-time histories were recorded in total. Pressure was recorded using a 16-Bit Digital Oscilloscope at a sample rate of 200 kHz, triggered via a voltage drop in a breakwire embedded in the charge periphery to synchronise the recordings with the detonation. The distance from the centre of the charge to the bunker wall was measured for each test using a Hilti laser range meter and was triangulated against two points on the bunker wall to ensure the charge was orthogonal to the bottom-centre pressure gauge.

3 RESULTS

3.1 Example curve fitting

An exponential 'Friedlander' curve (equation 1), was fit to each pressure-time trace in order to negate the effects of sensor ringing and any electrical noise which may have been recorded. The arrival time and positive phase duration, t_a and t_d respectively, were given by the experimental recordings, and $p_{r,max}$ and b were determined from a least squares fit to the recorded data. To prevent any early spurious sensor ringing from contaminating the trend line, only data from ~0.25t_d onwards was used for the curve fitting. The impulse was then determined from integrating the fitted curve (equation 2), rather than temporally integrating the recorded pressure-time signal, again to prevent the spurious oscillations from contaminating the results.

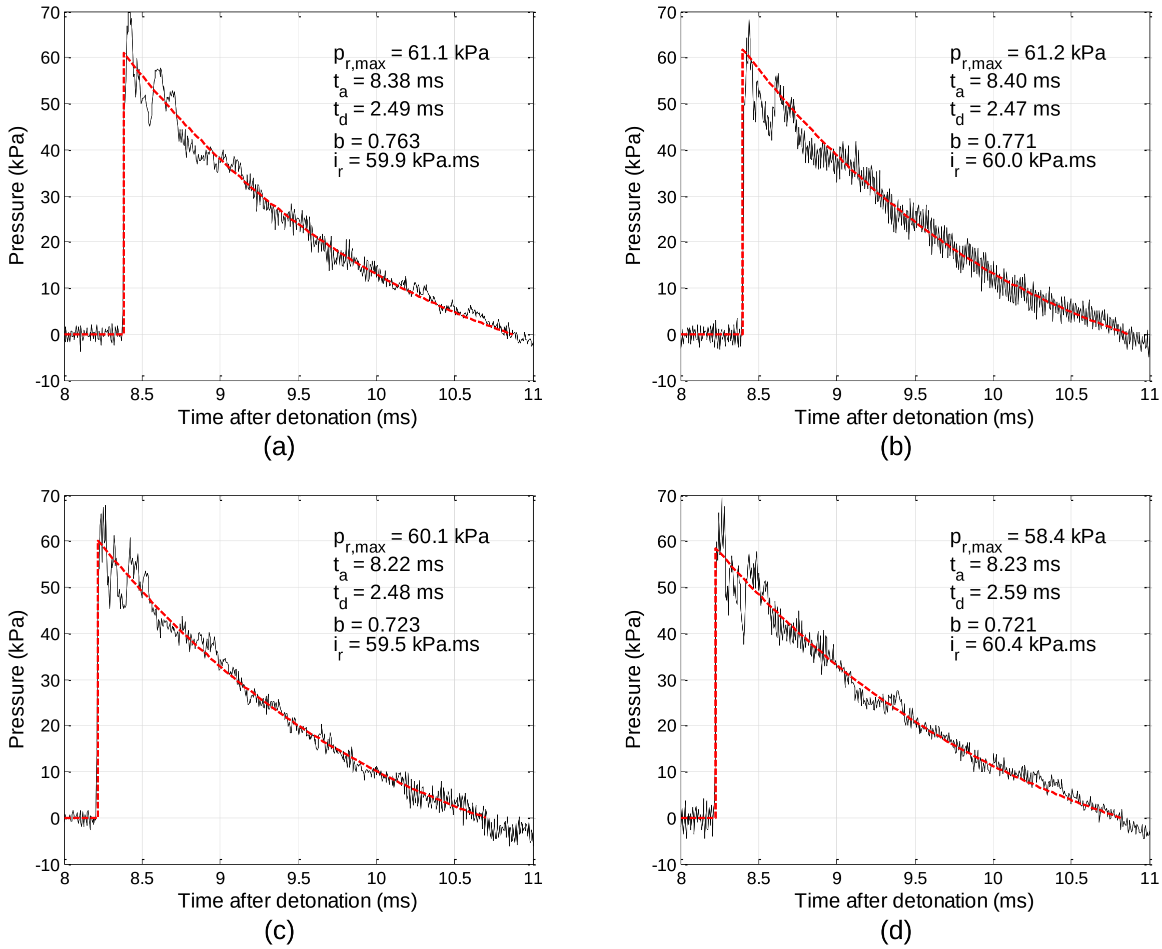

Figure 3: Pressure-time histories and best fit curves recorded 4 m orthogonal distance and 2 m along bunker wall from 250 g hemispherical PE4 charge

Figure 3 shows pressure-time histories and best fit curves recorded for four repeat tests with 250 g hemispherical PE4 charges. In these tests, the charge was located 4 m orthogonal distance from the bunker wall and recordings are shown for the pressure gauge located 2 m along the bunker wall away from the line of the centre of the charge, giving an angle of incidence of 26.6° and a slant distance of 4.47m (6.68 m/kg$^{1/3}$ assuming a PE4 equivalence of 1.2). The notion of a peak recorded reflected pressure is clearly not valid because of limitations of the instrumentation, however it can be seen that the exponential curve fit can be used to accurately approximate the form of the positive phase of the blast load. With the peak pressures differing by no more than 2.8 kPa, and the impulses differing by no more than 0.9 kPa.ms, excellent test-to-test repeatability has been shown for this example.

3.2 Compiled data – comparison against ConWep

Incident and reflected arrival times and positive phase durations of the blast load are identical and hence these parameters are not a feature of angle of incidence. This is not the case for peak reflected pressure and impulse, which will display some dependency on the angle at which the blast wave strikes the target. Hence, whilst it is appropriate to compare time parameters against ConWep (KB empirical predictions) for all normal and obliquely reflected data, limitations in existing empirical predictions prevent the same comparisons being presented for pressures and impulses. Instead, only normally reflected pressures and impulses can be validly compared against empirical data.

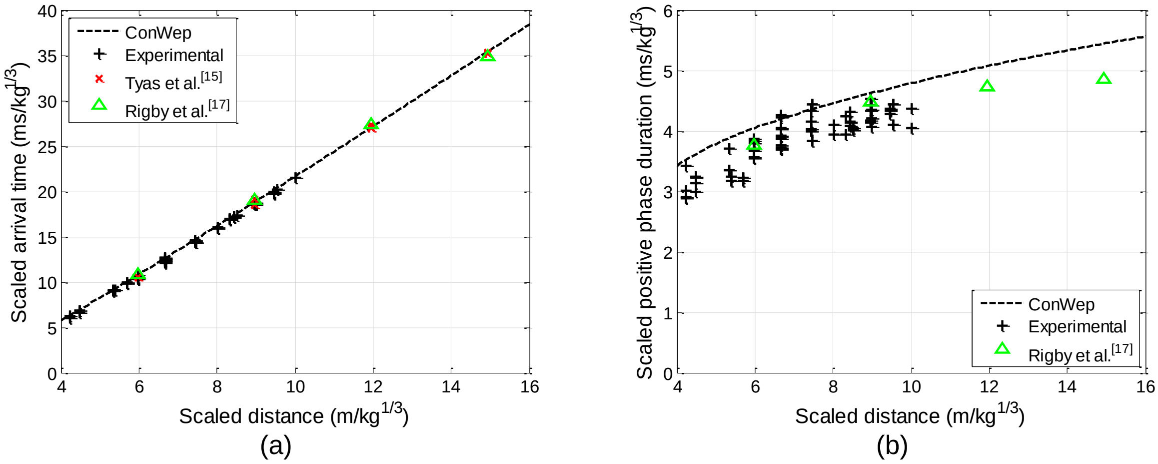

Figure 4: (a) Scaled arrival times and (b) positive phase duration for experimental trials compared to empirical (ConWep) predictions. Positive phase durations are not available from the Tyas et al.[15] dataset due to the presence of clearing waves from target edges.

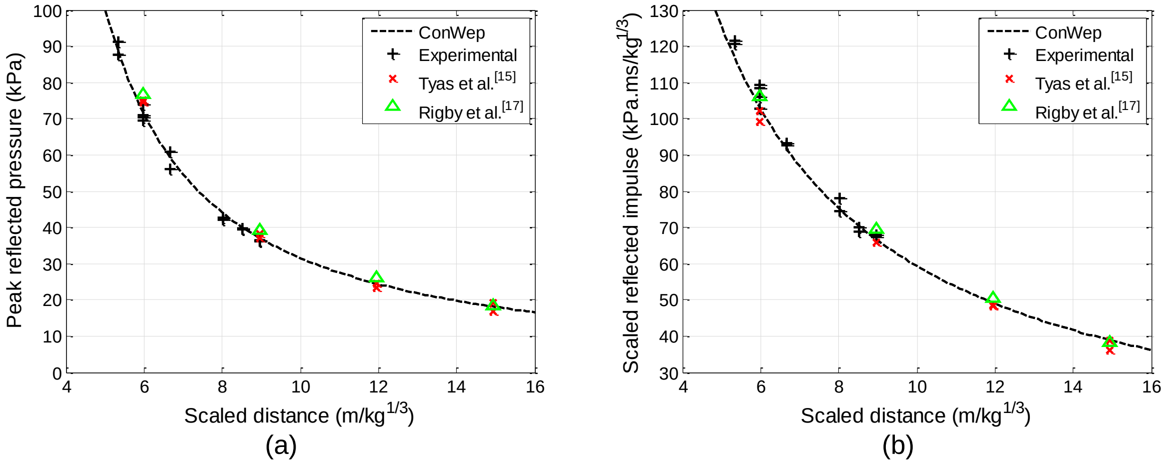

Figure 5: (a) Peak reflected pressure and (b) scaled peak reflected specific impulse for experimental trials compared to empirical (ConWep) predictions for normally reflected pressure recordings

Figures 4(a) and 4(b) show scaled arrival times and scaled positive phase durations for the entire data set respectively. Figures 5(a) and 5(b) show peak reflected pressure and scaled peak reflected specific impulse for the normally reflected recordings only. ConWep predictions are shown in both plots, along with parameters from curves fit to data from Tyas et al.[15] and Rigby et al.[17] In the experimental work of Tyas et al.[15], the reflected pressure was measured on a finite-sized target, and hence clearing relief waves were seen to arrive at the pressure gauge locations during the positive phase. For the purpose of this study, curves were fit to data recorded prior to the onset of clearing. Hence positive phase durations are not available for this dataset due to the reduced duration of loading caused by clearing.

Peak pressure and impulse data are summarised in Table 1 and Table 2 respectively, along with ratios of experiment/ConWep for comparison.

R (m)	*W* (g PE4)	*W* (g TNT)	*Z* (m/kg$^{1/3}$)	Peak Reflected Pressure (kPa)						
				ConWep	Test 1		Test 2		Test 3	
					$p_{r,max}$	Ratio	$p_{r,max}$	Ratio	$p_{r,max}$	Ratio
4	350	420	5.34	88.5	91.3	**1.03**	87.6	**0.99**	-	-
4	250	300	5.98	71.8	73.9	**1.03**	69.5	**0.97**	-	-
“				”	70.9	**0.99**	70.3	**0.98**	-	-
“				”	76.8*	**1.07**	74.5*	**1.04**	75.1†	**1.05**
4	180	216	6.67	59.3	60.9	**1.03**	56.2	**0.95**	-	-
6	350	420	8.01	44.0	42.0	**0.95**	42.7	**0.97**	-	-
6	290	348	8.53	40.0	39.8	**1.00**	39.3	**0.98**	-	-
6	250	300	8.96	37.1	36.1	**0.97**	36.5	**0.98**	-	-
“				”	39.2*	**1.06**	38.1*	**1.03**	36.9†	**0.99**
8	250	300	11.95	24.5	26.1*	**1.06**	24.5*	**1.00**	23.2†	**0.95**
10	250	300	14.94	18.1	18.3*	**1.01**	19.1*	**1.06**	16.8†	**0.93**

Table 1: Experimental and ConWep peak reflected pressures and ratio of experiment/ConWep for normally reflected pressure recordings
*Curves fit to data from Tyas et al.[15]
†Curves fit to data from Rigby et al.[17]

R (m)	*W* (g PE4)	*W* (g TNT)	*Z* (m/kg$^{1/3}$)	Scaled Positive Phase Reflected Impulse (kPa.ms/kg$^{1/3}$)						
				ConWep	Test 1		Test 2		Test 3	
					$i_r/W^{1/3}$	Ratio	$i_r/W^{1/3}$	Ratio	$i_r/W^{1/3}$	Ratio
4	350	420	5.34	116.7	120.7	**1.03**	121.6	**1.04**	-	-
4	250	300	5.98	103.2	102.7	**1.00**	106.0	**1.03**	-	-
“				”	109.3	**1.06**	108.4	**1.05**	-	-
“				”	106.0*	**1.03**	102.1*	**0.99**	99.3†	**0.96**
4	180	216	6.67	91.6	93.3	**1.02**	92.8	**1.01**	-	-
6	350	420	8.01	75.1	74.5	**0.99**	78.1	**1.04**	-	-
6	290	348	8.53	70.3	70.1	**1.00**	68.8	**0.98**	-	-
6	250	300	8.96	66.6	67.2	**1.01**	67.8	**1.02**	-	-
“				”	69.4*	**1.04**	65.7*	**0.99**	65.8†	**0.99**
8	250	300	11.95	49.1	50.5*	**1.03**	48.6*	**0.99**	48.2†	**0.98**
10	250	300	14.94	38.8	38.1*	**0.98**	38.7*	**1.00**	36.1†	**0.93**

Table 2: Experimental and ConWep scaled positive phase reflected impulse and ratio of experiment/ConWep for normally reflected pressure recordings
*Curves fit to data from Tyas et al.[15]
†Curves fit to data from Rigby et al.[17]

3.3 Compiled data – comparison against mean values

To give an indication of the repeatability of the test data, the mean values of peak pressure, scaled impulse, scaled arrival time and scaled duration were evaluated for each set of pressure-time recordings with a common scaled distance and angle of incidence. This varied between 2–8 individual pressure-time recordings per set, depending on the gauge configuration and number of repeat tests.

Figures 6–9 show the mean-normalised arrival time, duration, pressure and impulse respectively for the entire test series, where, for example, the mean-normalised pressure was evaluated by taking the peak pressure of a particular test and dividing it through by the mean peak pressure of the data set of which it belongs to. Again, the data also includes results from previous trials [15, 17].

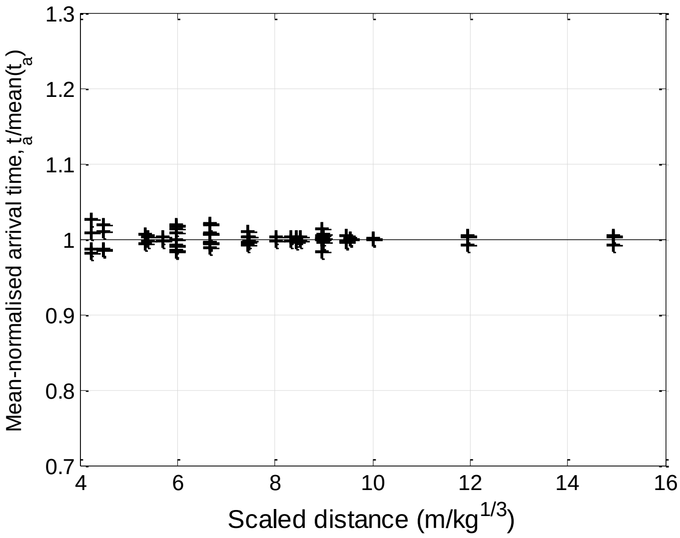

Figure 6: Arrival time normalised against mean values for each set of repeat tests

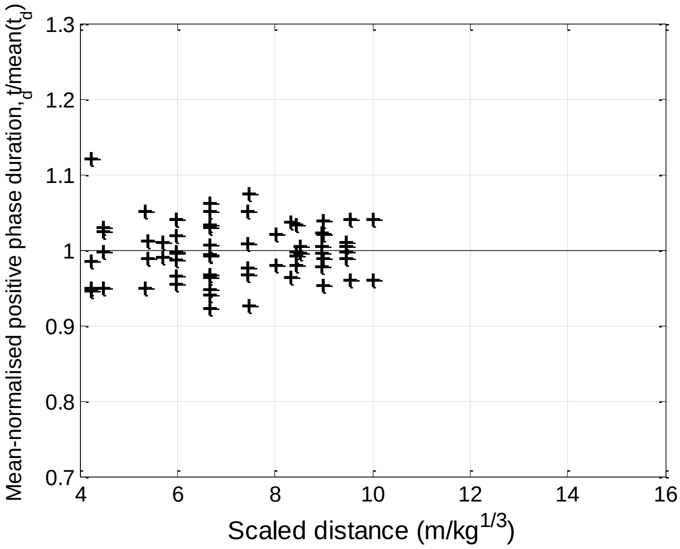

Figure 7: Positive phase duration normalised against mean values for each set of repeat tests

4 DISCUSSION AND CONCLUSIONS

Figures 4 and 5 show that the experimentally measured blast parameters are generally predicted to a high degree of accuracy by the ConWep code, based on the KB data – Tables 1 and 2 show a maximum difference of 7% between the experimental data and ConWep predictions. Interestingly, the mean value of the ratio between these two values is 1.00 for peak pressure and 1.01 for peak impulse for the entire test series. The results presented here, therefore, suggest that for far-field loading in simple geometrical scenarios, existing semi-empirical blast predictions are in fact remarkably accurate and can be used with confidence as a first-order approach for quantifying the blast load a structure will be subjected to.

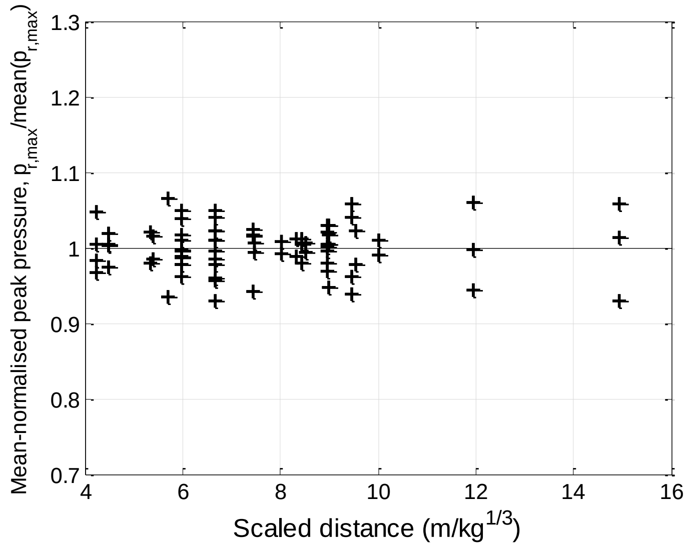

Figure 7: Peak pressure normalised against mean values for each set of repeat tests

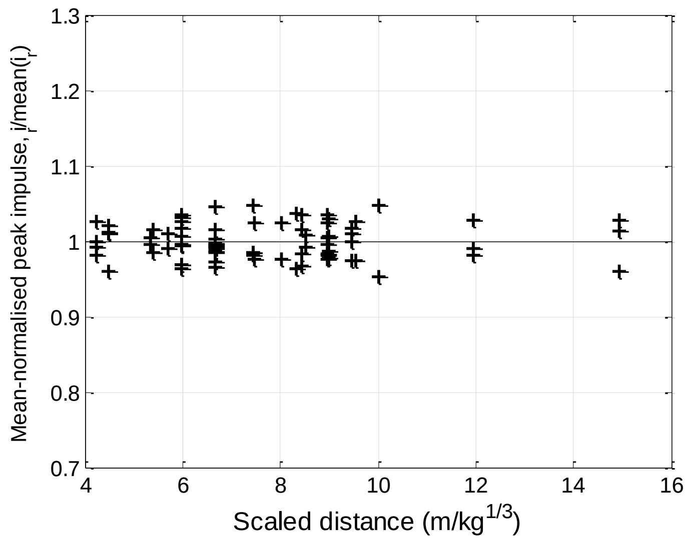

Figure 8: Positive phase impulse normalised against mean values for each set of repeat tests

Figures 6, 7, 8 and 9 show that there is very good test-to-test consistency in the experimentally measured arrival time, and reflected peak overpressure and impulse. Typically, these values are within a range of +/-6–8% of the mean values for reflected pressure and impulse, and +/-2.5% for arrival time. The recorded positive duration shows a slightly higher variability, with one value ~12% higher than the mean, but all others lie within the range +/-9% of the mean value.

The consistency of the experimental results presented here is both striking, and at odds with other reported experimental data. This raises a question which goes to the heart of scientific research in this area: are the parameters of blast waves essentially deterministic, or is there an inherent variability which requires the use of a stochastic approach? The importance of this question cannot be overstated, since its answer it will provide a direction for future research work in this field.

If there is little inherent variability in the output of nominally identical detonations, it suggests that in small-scale, well-controlled experimental blast testing, we should expect a high degree of consistency in experimental data relating to both blast wave parameters, and the response of well-characterised structures exposed to blast loading. This would provide the possibility of developing a dataset of experimental results at small scale, which could then be used for validation and/or calibration of modelling approaches to both blast loading parameters and structural response. If, however, there is an inherent and significant variability in the blast waves generated by nominally identical explosive events, then the extent of this variability must be identified and taken into account when appraising the accuracy of any modelling approach. There is also the challenge of identifying the underlying physical processes which result in such an inherent variability.

The opinion of the authors is that the consistency of the results reported here and in Refs. [14, 15], and the remarkable similarity between these experimental results and KB-based predictions is unlikely to be coincidence. We hypothesise that there is little if any ‘inherent’ variation in the blast wave parameters and that test-to-test variations are due to issues related to control of test variables and/or instrumentation. If such a hypothesis is correct, we should expect to see repeatable results from small-scale, well-controlled tests and these can be used for deterministic appraisal and validation of modelling approaches. Of course, it is much more difficult to retain careful control of all test parameters in larger scale tests, and in attempting to predict the output of detonations in terrorist attacks we have even greater uncertainty over the precise composition, size, shape and position of the explosive charge.

This suggests that there are two pressing and somewhat different problems for the research community. The first is to definitively establish a commonly agreed dataset of blast wave parameters from small-scale, very well-controlled tests. The second is to definitively identify the effect of parameter uncertainty on the blast wave parameters resulting from the detonation of larger-scale or improvised explosive devices.

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