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Characterisation of blast loading:

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The Blast & Impact Research Group at the University of Sheffield is currently involved in several projects aimed at providing a better understanding of the blast pressure acting on targets under different threats. These projects fall broadly under two distinct scenarios: the combined soil-throw/blast load acting on a vehicle underside resulting from the detonation of a shallow-buried improvised explosive device; and the free-air blast load acting on a structural component which either wholly or partly forms a non-infinite reflecting surface. The research is largely experimentally based, and is augmented with numerical analysis. This paper provides a brief overview of the work conducted to date.

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Introduction

Over recent years, the use of explosives for malicious attacks has undoubtedly become more common and the potential threat more varied. There are two principal events of which we must be aware and against which we must design our infrastructure to resist; namely high explosives detonated on or near the ground surface, and high explosives buried beneath a soil overburden.

These two threats are typically deployed against different targets. Small hand-held explosives, or improvised explosive devices (IEDs), are used primarily against crowds of people and large vehicle-borne explosives are used primarily against structural elements within high value buildings such as government offices or embassies with the specific intention of causing collapse. Buried explosives are more commonly deployed against military vehicles such as armoured personnel carriers. These situations, clearly, present very different challenges to the engineer.

As a first step, in order to protect our infrastructure against such events, we first must be able to quantify the output of an explosive device to some degree of confidence. This is where the Blast & Impact Research Group at The University of Sheffield has focussed its attention for the past few years. This paper presents an overview of the experimental work undertaken to date, and is split into three subsequent sections. The first two sections relate to two distinct projects comprising large bodies of experimental work in capturing the total impulse and discrete pressure-time loads applied to rigid targets from buried explosives respectively. The third section summarises the work done to date on quantifying free-air blast loads.

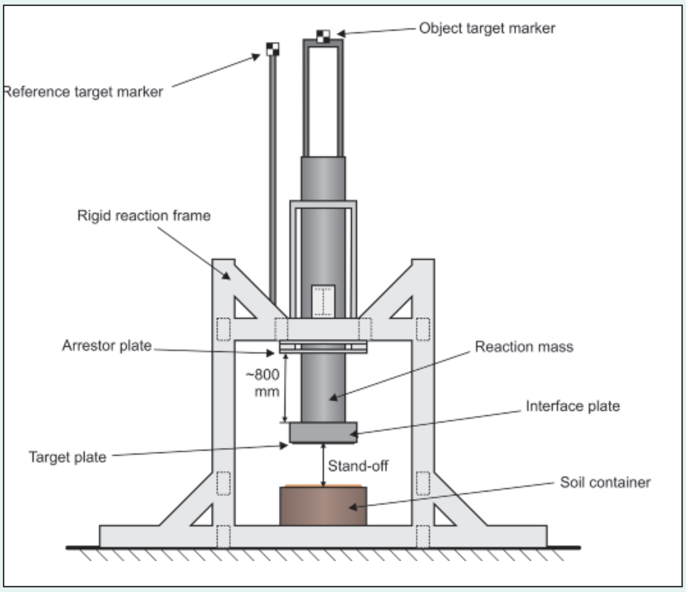
Free-flying mass approach

Experimental research into quantification of the combined soil-throw/blast load acting on a vehicle underside resulting from the detonation of a shallow-buried IED has largely focussed on measuring the deformation of thin plates subjected to such events [1], or the global impulse captured by free-flying plates [2- 4] or pendulum-type devices [5- 7]. Tight control of the test parameters remains difficult to achieve, motivating some research groups to remove the blast engineering aspects altogether and focus only on the sand-throw [8]. The role of geotechnical parameters on the impulse generated by buried explosives is not yet fully understood nor comprehensively characterised.

In order to investigate the role of geotechnical parameters on the impulse generated by buried explosives, a bespoke test frame was fabricated on behalf of the Defence Science and Technology Laboratory (Dstl), shown schematically in Figure 1. The apparatus, built to represent a half scale version of STANAG threat level 2 [9], comprises a large reaction mass (~1500 kg) supported by a rigid reaction frame. An interface plate is welded to the bottom of the reaction mass to which a thin (12.5 mm) steel target plate or a surrogate vehicle underside can be attached. A soil container is situated directly beneath the target plate, with a cylindrical explosive buried in the centre of the soil container to some prescribed burial depth. Full details of the experimental arrangement are available in Clarke et al. [10].

After detonation, the reacted detonation products and soil particle barrage impart an impulse to the target which causes the target plate and reaction mass to accelerate upwards. The apparatus was designed such that the reaction mass was given a free upward flight of ~800 mm, with the vertical motion being arrested either by gravity (if the initial velocity is less than 4 m/s) or by impact of the interface plate with the lower face of the arrestor plate which is attached to the underside of the rigid reaction frame. Two target

Figure 1: Schematic of the free-flying mass impulse capture apparatus [10].



markers are attached to the rig, one fixed to the rigid reaction frame ('reference'), the other attached to the rising mass ('object'). Both target markers are raised up on masts to ensure they are not obscured by soil throw during the test. A high-speed video camera (Dantec Dynamics NanoSense Mk.2, framing at 4000 fps) is used to film these target markers, and image tracking software is used to give the displacement-time histories of both markers. Post-test, the motion of the reference target marker is subtracted from that of the object target marker to eliminate the effects of shock induced vibration of the camera. The peak rise can be used to calculate the initial velocity, which is then multiplied by the mass of the moving object to give the total impulse imparted to the plate. A secondary camera was situated within a reinforced concrete bunker and was positioned to film the breakout of the charge and resulting sand throw. An example of the footage from the lower camera is shown in Figure 2.

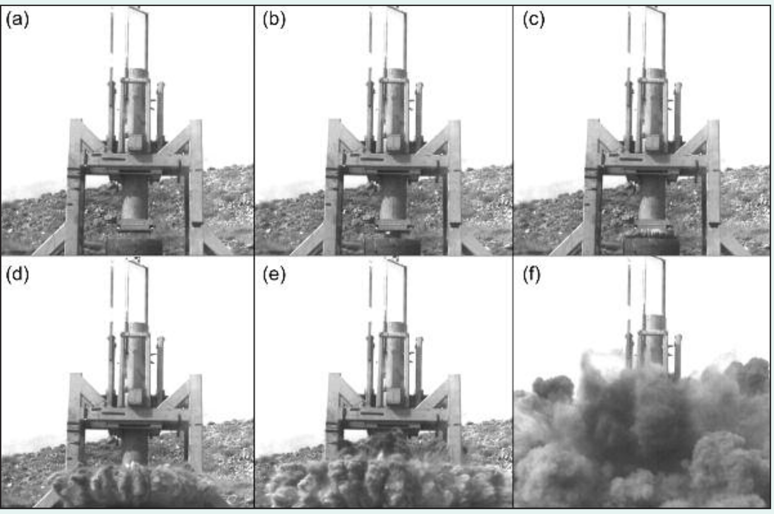


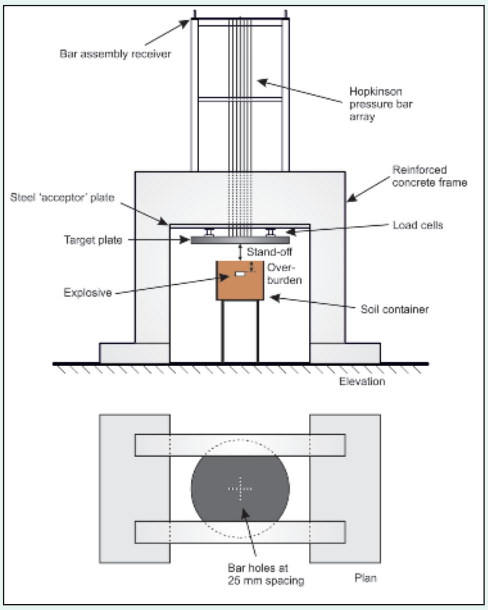
Figure 2: Frames from high speed video of an indicative test; a) pre firing, b) initial vertical throw, c) cloud reaches container edge, d) expansion clearing frame, e) expansion into free air, f) target movement clearly visible from object target marker.

The work has thus far provided valuable insights into the relevant geotechnical parameters governing the output from a buried explosive event. The authors have shown that for a fixed bulk density, an increase in moisture content leads to an increase in generated impulse when all other variables are kept constant [11]. This work was extended to study the influence of particle size distribution [12], where it was shown that non-uniform sand exhibits greater test-to-test variation. Tight control of the geotechnical conditions (density errors of ±0.2% and moisture content errors of ±0.1%) has enabled extremely repeatable results to be gathered. This database has since been used to draw conclusions on the geotechnical causes for repeatability of buried charge testing [13], and the variations in total imparted impulse and peak dynamic plate deformations has allowed the authors to begin to unlock the mechanisms governing buried explosive loading [10].

Fixed target approach

Leading on from the free-flying mass test programme, The University of Sheffield was commissioned by Dstl to fabricate a second testing apparatus. For this, a test frame was built of two steel fibre and bar reinforced concrete frames spaced 1 m apart, with a 1400 mm diameter, 100 mm thick effectively rigid steel target plate spanning between the two frames, as in Figure 3. A central 10.5 mm hole was drilled through the thickness of the target plate with subsequent holes at 25 mm spacing (centre to centre) parallel and perpendicular to the span of the concrete beams. 10 mm diameter, 3.25 m long steel Hopkinson pressure bars (HPBs) were inserted through the bar holes and suspended such that their ends sat flush with the underside of the target. Up to 17 bars can be located within a 100 mm radius circle centred above the charge location for any test, with the ability to load subsequent bars at any distance up to 250 mm away from the target centre. Semiconductor strain gauges were affixed to the perimeter of the HPBs to record any change in axial strain of the bar with time. This can then be converted into a pressure-time history acting at the loaded face of the bar, with the apparatus therefore giving a temporal description of the pressure acting at discrete points on a rigid target.

Figure 3: Schematic of the spatial and temporal pressure distribution measurement apparatus [14].



So far, this work has largely comprised initial studies investigating explosives engineering issues such as: explosive size; detonator type and placement; and potential contamination of the results from the cable umbilical striking the attack face of the target [14, 15]. With the preferential experimental arrangement determined, a series of commissioning shots were performed with bare PE4 spherical charges suspended underneath the target face [16, 17]. The results show good agreement with semi-empirical predictions [18], and indicate that the apparatus can be used as a research tool for investigating the fundamental mechanisms of explosive loading, as well as offering valuable data for validation of numerical modelling approaches.

Free-air blast characterisation

In addition to the two large bodies of experimental work dedicated to measuring the output from buried explosives, several smaller experimental programmes have been undertaken in the broad field of blast load characterisation from free-air explosives, i.e. small explosive charges detonated on a rigid surface. Whilst predictions for air blast pressures acting on effectively infinite reflecting surfaces are prevalent in the literature [18], the process is complicated when considering targets of finite lateral dimension. In this situation, diffraction of the blast wave around the target edge causes a rarefaction relief wave to travel inwards along the loaded face. This is known as blast wave clearing. The subject is somewhat addressed in the literature; design guidance recommends

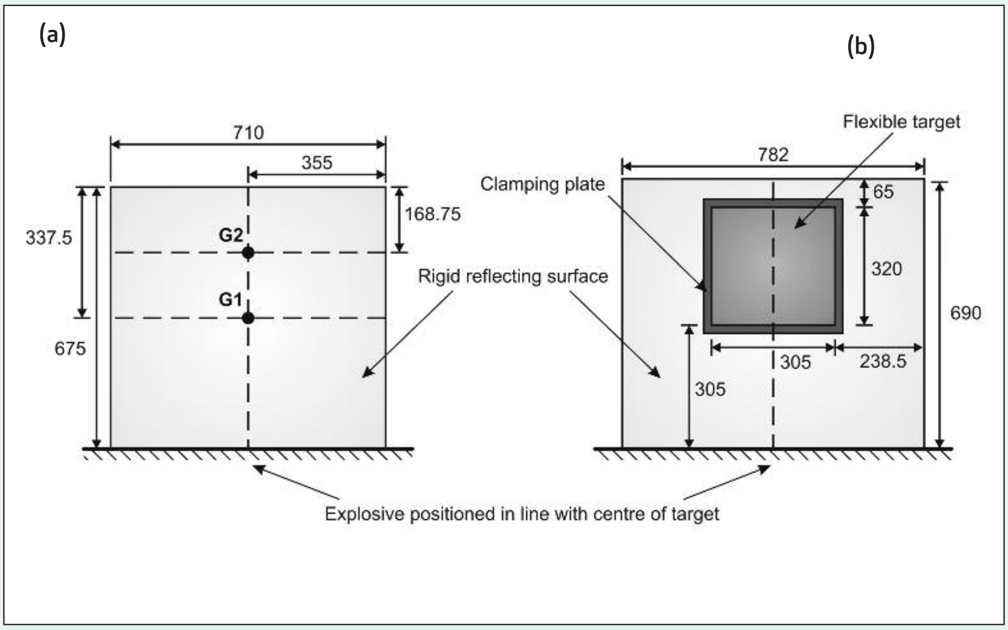


Figure 4: Dimensions of the finite reflecting surface in mm; a) reflected pressure measurements, b) plate deflection trials.

application of either a representative pressure-time history which acts over the whole target face [19], or a correction factor to the total impulse imparted to the target [20]. Neither methods properly treat the mechanism of clearing, which has been investigated in the literature to a certain extent [21, 22] yet not properly resolved. Further research into and quantification of its effect is still limited. Accordingly, clearing has since become a topic of focus for members of the Blast & Impact Research Group at The University of Sheffield.

In 2011, Tyas et al. [23, 24] conducted a series of experiments to measure the cleared blast pressure acting at points on a finite reflecting surface. In this study, a reinforced concrete block was clad with 20 mm thick steel plate and had two pressure gauges mounted on the front face (labelled G1 and G2), as shown in Figure 4(a). 250 g hemispherical PE4 charges were located 4, 6, 8 and 10m from the target face and pressure was recorded at the two gauges for each test. The main purpose of this test series was to validate clearing predictions proposed by Hudson in 1955 [25].

The study was extended by Rigby et al. in 2013 [26] to study plate deflections to cleared blast loads. The previous test apparatus was modified by attaching an additional steel frame (clad in 15 mm thick steel plate) to the front of the reinforced concrete block. A 305 mm wide, 320 mm high porthole was cut into the front of the steel frame with the bottom of the porthole 305 mm above ground level. A laser displacement gauge was housed within the steel frame and was aimed at the centre of the rear face of the target, giving the displacement-time history at the point of largest displacement. Ten tests were conducted in total, with hemispherical PE4 charges ranging from 50-175 g, located 6 m from the front face of the target. The charge mass/stand-off combinations were chosen to ensure that the plates would remain elastic and the influence of clearing could be more readily observed. The arrangement is shown in Figure 4(b).

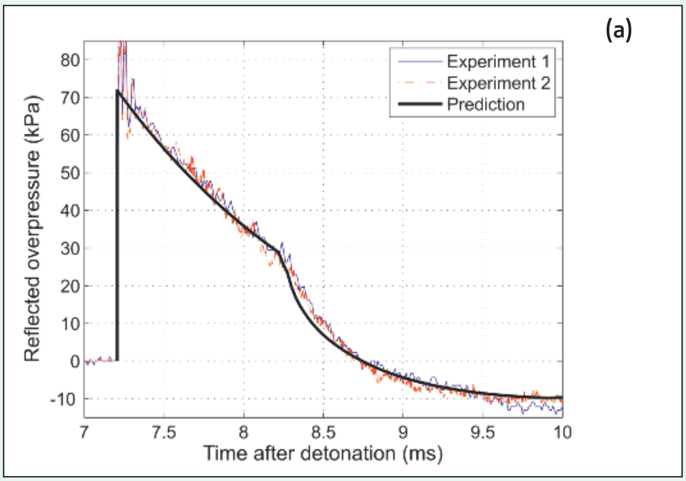


Figure 5: a) Experimental validation of cleared blast pressure predictions [23, 24], b) Experimental validation of plate displacements under cleared blast load [26].

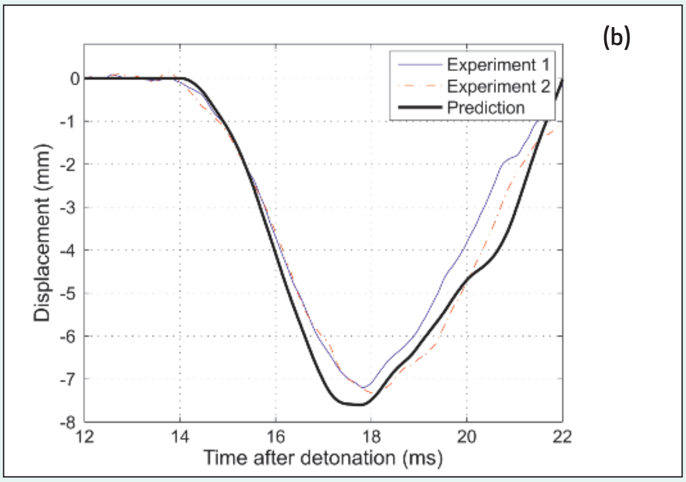


Figure 5(a) shows the pressure-time histories recorded at G1 for the two tests at 4 m stand-off, alongside the Hudson predictions [25]. Figure 5(b) shows the displacement-time history for the two tests using 75 g PE4, alongside results from a finite element model with the plate modelled as a linear elastic steel plate using Lagrangian shell elements. Here, the load was applied using a modification of the Hudson clearing predictions as discrete load curves [27]. These well-controlled experimental trials have allowed the authors to demonstrate the accuracy and validity of the selected numerical approaches. From this, the authors have been able to investigate the mechanism of clearing for smaller targets using Arbitrary-Lagrangian-Eulerian numerical analyses [28], and quantify the influence of clearing on the dynamic displacement of targets subjected to blast loads using the Single-Degree-of-Freedom method [29, 30]. These studies have provided useful insights into the physics of blast-target interaction, and developed a wealth of information that can be used by practising engineers to more efficiently and safely design infrastructure to resist against blast loads.

Other similar research from the Blast & Impact Research Group has used experimental work with high explosives to demonstrate: the importance of negative phase pressures following the positive loading duration of a blast event [31]; the ability of blast experiments to produce reliable, repeatable results [32]; and the influence of angle of incidence on blast parameters such as peak pressure, impulse, and duration of positive pressures acting on the target [33].

Summary

This article has presented an overview of current work being undertaken by the Blast & Impact Research Group at The University of Sheffield on the subject of characterisation of blast loading. To date, a large body of experimental trials have been performed using high explosives, and their influence on the loading imparted to a target has been well characterised. Areas of study include the global impulse and discrete pressure-time loads imparted to targets resulting from the detonation of shallow-buried explosives, as well as several smaller bodies of work in quantifying the free-air blast load acting on non-infinite sized targets. The experimental work has demonstrated strong repeatability and very good agreement with performed numerical analyses, enabling the authors to investigate the underlying physics present. Work is still ongoing on these topics.

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References

[1] Pickering EG, Chung Kim Yuen S, Nurick GN, Haw P. The response of quadrangular plates to buried charges. International Journal of Impact Engineering, 49:103–114, 2012.

[2] Fourney WL, Leiste U, Bonenberger R, Goodings DJ. Mechanism of loading on plates due to explosive detonation. Fragblast: The International Journal for Blasting and Fragmentation, 9(4):205–217, 2005.

[3] Anderson CE, Behner T, Weiss CE. Mine blast loading experiments. International Journal of Impact Engineering, 38(8-9):697–706, 2011.

[4] Fox DM, Huang X, Jung D, Fourney WL, Leiste U, Lee JS. The response of small scale rigid targets to shallow buried explosive detonations. International Journal of Impact Engineering, 38(11):882–891, 2011.

[5] Ehrgott JQ, Rhett RG, Akers SA, Rickman DD. Design and fabrication of an impulse measurement device to quantify the blast environment from a near-surface detonation in soil. Experimental Techniques, 35(3):51–62, 2011.

[6] Bergeron DM, Trembley JE. Canadian research to characterize mine blast output. In: 16th International Symposium on the Military Aspects of Blast and Shock (MABS16), Oxford, UK, 2000.

[7] Hlady SL. Effect of soil parameters on landmine blast. In: 18th International Symposium on the Military Aspects of Blast and Shock (MABS18), Bad Reichenhall, Germany, 2004.

[8] McShane GJ, Deshpande VS, Fleck NA. A laboratory-scale buried charge simulator. International Journal of Impact Engineering, 62:210–218, 2013.

[9] NATO. Procedures for evaluating the protection level of logistic and light armoured vehicles. Allied Engineering Publication (AEP) 55, Vol.2 (for Mine Threat), 2006.

[10] Clarke SD, Fay SD Warren JA, Tyas A, Rigby SE, Reay JJ, Livesey R, and Elgy I. Geotechnical causes for variations in output measured from shallow buried charges. Submitted for possible publication in International Journal of Impact Engineering, 2015.

[11] Clarke SD, Warren JA, and Tyas A. The influence of soil density and moisture content on the impulse from shallow buried explosive charges. In: 14th International Symposium on the Interaction of the Effects of Munitions with Structures (ISIEMS14), Seattle, USA, 2011.

[12] Clarke SD, Warren JA, Fay SD, Rigby SE, and Tyas A. The role of geotechnical parameters on the impulse generated by buried charges. In: 22nd International Symposium on the Military Aspects of Blast and Shock (MABS22), Bourges, France, 2012.

[13] Clarke SD, Fay SD, Tyas A, Warren J, Rigby S, Elgy I, and Livesey R. Repeatability of buried charge testing. In: 23rd International Symposium on the Military Aspects of Blast and Shock (MABS23), Oxford, UK, 2014.

[14] Clarke SD, Fay SD, Warren JA, Tyas A, Rigby SE, and Elgy I. A large scale experimental approach to the measurement of spatially and temporally localised loading from the detonation of shallow-buried explosives. Measurement Science and Technology, 26:015001, 2015.

[15] Fay SD, Clarke SD, Tyas A, Warren J, Rigby S, Bennett T, Elgy I, and Gant M. Measuring the spatial and temporal pressure variation from buried charges. In: 23rd International Symposium on the Military Aspects of Blast and Shock (MABS23), Oxford, UK, 2014.

[16] Rigby SE, Tyas A, Fay SD, Clarke SD, Warren JA, Elgy I, and Gant M. Testing apparatus for the spatial and temporal pressure measurements from near-field free air explosions. In: 6th International Conference on Protection of Structures Against Hazards (PSH14), Tianjin, China, 2014.

[17] Rigby SE, Tyas A, Clarke SD, Fay SD, Reay JJ, Warren JA, Elgy I, and Gant M. Observations from preliminary experiments on spatial and temporal pressure measurements from near-field free air explosions. Submitted for possible publication in International Journal of Protective Structures, 2015.

[18] Kingery CN and Bulmash B. Airblast parameters from TNT spherical air burst and hemispherical surface burst. Technical Report ARBRL-TR-02555, U.S Army BRL, Aberdeen Proving Ground, MD, USA, 1984.

[19] US Department of Defence. Structures to resist the effects of accidental explosions. US DoD, Washington DC, USA, UFC-3-340-02, 2008.

[20] Rose TA and Smith PD. An approach to the problem of blast wave clearing on finite structures using empirical procedures based on numerical calculations. In: 16th International Symposium on the Military Aspects of Blast and Shock (MABS16), Oxford, UK, 2000.

[21] Rose TA. An approach to the evaluation of blast loads on finite and semi-infinite structures. PhD thesis, Cranfield University, UK, 2001.

[22] Rickman DD and Murrell DW. Development of an improved methodology for predicting airblast pressure relief on a directly loaded wall. Journal of Pressure Vessel Technology, 129(1):195–204, 2007.

[23] Tyas A, Warren JA, Bennett T, and Fay S. Prediction of clearing effects in far-field blast loading of finite targets. Shock Waves, 21(2):111–119, 2011.

[24] Tyas A, Bennett T, Warren JA, Fay S, and Rigby SE. Clearing of blast waves on finite-sized targets – an overlooked approach. Applied Mechanics and Materials, 82:669–674, 2011.

[25] Hudson CC. Sound pulse approximations to blast loading (with comments on transient drag). Technical Report SC-TM-191-55-51, Sandia Corporation, MD, USA, 1955.

[26] Rigby SE, Tyas A, Bennett T, Warren JA, and Fay S. Clearing effects on plates subjected to blast loads. Engineering and Computational Mechanics, 166(EM3):140–148, 2013.

[27] S. E. Rigby. Blast wave clearing effects on finite-sized targets subjected to explosive loads. PhD thesis, University of Sheffield, UK, 2014.

[28] Rigby SE, Tyas A, Bennett T, Fay SD, Clarke SD, and Warren JA. A numerical investigation of blast loading and clearing on small targets. International Journal of Protective Structures, 5(3):253–274, 2014.

[29] Rigby SE, Tyas A, and Bennett T. Single-degree-of-freedom response of finite targets subjected to blast loading – the influence of clearing. Engineering Structures, 45:396–404, 2012.

[30] Rigby SE, Tyas A, and Bennett T. Elastic-plastic response of plates subjected to cleared blast loads. International Journal of Impact Engineering, 66:37–47, 2014.

[31] Rigby SE, Tyas A, Bennett T, Clarke SD, and Fay SD. The negative phase of the blast load. International Journal of Protective Structures, 5(1):1–20, 2014.

[32] Rigby SE, Tyas A, Fay SD, Clarke SD, and Warren JA. Validation of semi-empirical blast pressure predictions for far field explosions - is there inherent variability in blast wave parameters? In: 6th International Conference on Protection of Structures Against Hazards (PSH14), Tianjin, China, 2014.

[33] Rigby SE, Fay SD, Tyas A, Warren JA, and Clarke SD. Angle of incidence effects on far-field positive and negative phase blast parameters. International Journal of Protective Structures 6 (1), p.23-42 2015.

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