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FINITE ELEMENT SIMULATION OF PLATES UNDER NON-UNIFORM BLAST LOADS USING A POINT-LOAD METHOD: BLAST WAVE CLEARING

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Abstract. *There are two primary challenges associated with assessing the adequacy of a protective structure to resist explosive events: firstly the spatial variation of load acting on a target must be predicted to a sufficient level of accuracy; secondly, the response of the target to this load must also be quantified.*

If a target is embedded within a finite reflecting surface then the process of blast wave clearing will occur. Diffraction of the blast around the target edge causes a low pressure relief wave to propagate inwards towards the centre of the target, reducing the late-time development of pressure and resulting in high spatial non-uniformity of the blast load. This paper presents experimental measurements of the dynamic displacement-time histories of steel plates subjected to blast loads where the plate was situated within a finite reflecting surface to allow for clearing effects to take place. Associated finite element modelling is presented, where coupled blast-target interaction is modelled explicitly using the Arbitrary Lagrangian-Eulerian solver in LS-DYNA.

An alternative method is presented, where the loading is applied as discrete load predictions at individual nodes. The results show that vast computational savings can be made when modelling the load in this manner, as well as better agreement with the experimental measurements owing to a more accurate representation of the applied load.

1 INTRODUCTION

The malicious use of high explosives for terrorist attacks is becoming more common and the threat more diverse. Accordingly, there is a pressing need for engineers to be able to evaluate the response of key structural elements under many different configurations of explosive type, size and location – thereby giving an indication of the types of event which are likely to lead to component (or structural) failure. Numerical analysis is predominantly used for this purpose as such an experimental programme is likely to be prohibitively expensive. In the early stages of design, however, complex numerical schemes are not time-effective and instead simple, quick running analyses should be preferred.

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Semi-empirical blast pressure predictions[1] allow for the blast load to be applied directly to a finite element model of the structure, negating the need to explicitly model the explosive detonation, blast wave propagation and fluid-structure interaction. This, clearly, has considerable time savings, however semi-empirical blast pressure predictions in the literature assume the target forms part of a semi-infinite reflecting surface. When the blast wave interacts with the edges of a target, a phenomenon known as blast wave clearing occurs, and the assumption that the target is subjected to the fully reflected blast pressure may be inaccurate, particularly if the structure is small in relation to the 'length' of the blast wave[2].

This paper presents experimental measurements of the dynamic displacement-time histories of steel plates subjected to blast loads where the plate was situated within a finite reflecting surface to allow for clearing effects to take place. The experimental results are compared against coupled finite element analyses where blast-target interaction is modelled explicitly using the Arbitrary Lagrangian-Eulerian solver in LS-DYNA[3], and uncoupled finite element analyses where the loading is applied as discrete load predictions at individual nodes, based on the Tyas[4,5] implementation of Hudson's[6] clearing pressure predictions. The results are used to make comments on whether complexity is always warranted in numerical modelling with respect to analysis time and accuracy of results.

2 BLAST WAVE CLEARING

When a blast wave reaches the free edge of a finite target, the reflected shock front travels away from the surface whilst the incident shock front immediately adjacent to the free edge continues unimpeded past it. This causes diffraction around the free edge, and a rarefaction relief wave – driven by pressure equalisation between the higher pressure reflected region and lower pressure incident region – propagates along the target face, as in Figure 1. This relief wave serves to reduce the pressure acting at any point it propagates over, and can only influence the blast pressure acting at that point once it has travelled inwards from the free edge, usually at ambient sonic velocity (~340 m/s). The peak pressure is thus unaffected by clearing, but the late-time pressure and reflected specific impulse will exhibit some reduction caused by clearing, providing the relief wave reaches the point in question before the loading is complete.

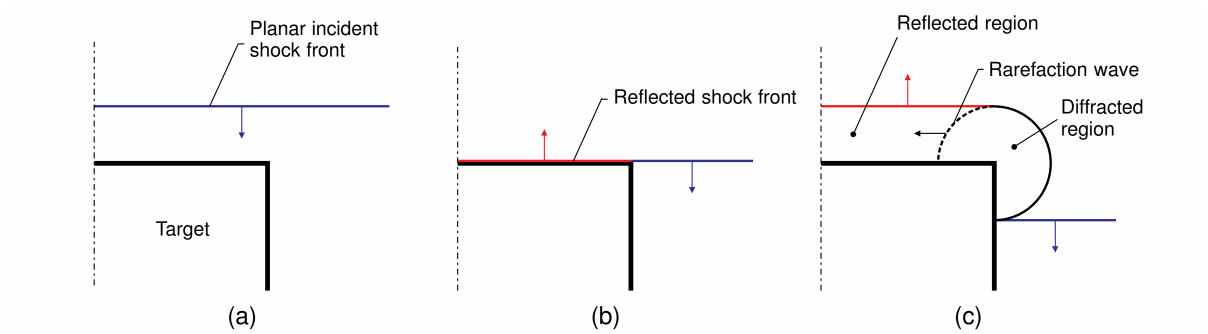

Figure 1: Diffraction of a blast wave around a finite target; (a) propagating incident wave, (b) shock front reflection and instantaneous pressure imbalance, (c) propagation of a rarefaction clearing wave driven by flow conditions[7]

This has been addressed somewhat in the literature. Semi-empirical clearing predictions[1] typically involve generating a representative pressure-time history which is intended to model the reduction in global impulse imparted to the target. It has been shown by the authors that this approach is only valid for small targets where the clearing effect is relatively uniform across the target face[2], and that dynamic target displacement is sensitive to the combined effect of negative phase pressures and clearing relief[8]. Hudson developed a method for predicting clearing where the relief wave is approximated as an acoustic pulse[6]. The pressure acting at a point on a target is thereby given by the superposition of the reflected pressure and the relief pressure associated with the clearing wave. Tyas et al.[4,5] provided validation of these predictions, and the experimental results were shown to be in excellent agreement with the pressures given by the Hudson predictions. This methodology has been extended by the authors to model the full pressure distribution acting on a finite target, enabling the Hudson method to be used in finite element modelling[9].

3 EXPERIMENTAL PLATE DEFORMATIONS

A total of 10 experiments were conducted at the University of Sheffield Blast & Impact Laboratory in Buxton, UK. Hemispherical PE4 charges were detonated on a level, reinforced concrete ground slab, 6 m away from the front face of a purpose-fabricated finite reflecting surface, as in Figure 2(a), comprising a 1.8 m long by 0.6×0.6 m reinforced concrete block clad in 20 mm thick steel plate. A steel housing frame was attached to the front of the concrete block and was clad in 15 mm thick steel plate, into which a 305 mm wide by 320 mm high porthole was cut, as in Figure 2(b). A small clamping plate was attached to the front face of this steel frame, allowing a 0.835 mm thick mild steel plate to be held in place whilst permitting inward displacement of the target plate. The boundary conditions were such that horizontal displacement was allowed at the supports, but inward displacement and rotation was constrained. The plate spanned the horizontal dimension only (305 mm span) and was slightly undersized in the vertical dimension to prevent the plate from striking the frame whilst displacing. The mounted steel frame provided housing for a Microelektronik M7 laser displacement gauge which was aimed at the rear face of the deformable plate, aligned with both vertical and horizontal plate centrelines, i.e. measuring the point of greatest displacement. The laser displacement gauge sat on a bracket which was clamped to the concrete block, the inertia of the block effectively offered insulation from any blast induced vibration. The power and signal cables were fed through a hole punched in the concrete ground slab, maintaining a smooth reflecting surface of the steel-clad concrete block for the blast wave to propagate over.

A total of five charge masses – 50, 75, 108, 140 and 175 g PE4 – were tested, with one repeat per test. The charges were placed on a 50 mm thick sacrificial steel anvil for each test in order to prevent repeat damage to the ground slab.

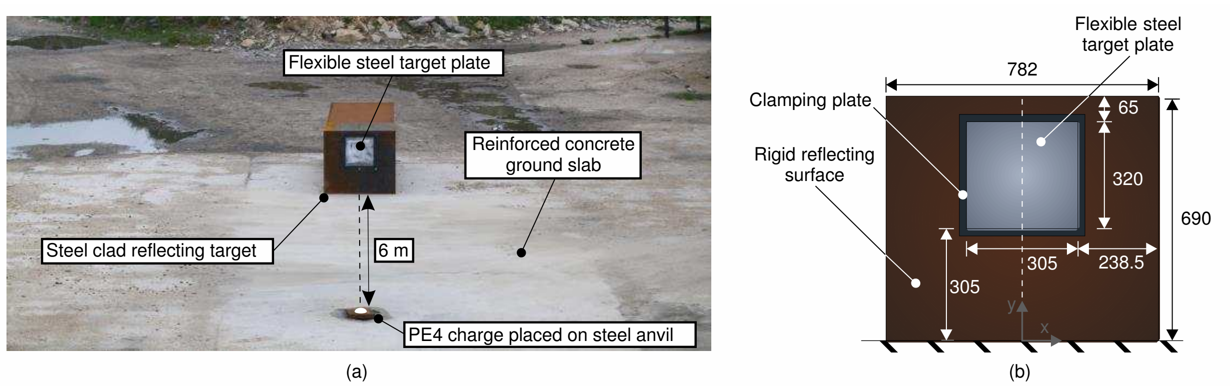

Figure 2: (a) Photograph of test arrangement, (b) dimensions (in mm) of the finite reflecting surface

4 NUMERICAL ANALYSES

For each charge mass, two separate analyses were run using LS-DYNA[3]. For one series of analyses the detonation and blast wave propagation were modelled using the Arbitrary Lagrangian-Eulerian (ALE) solver, and the target deformation was modelled using fluid-structure interaction. For the second set of analyses, the loading was applied directly to the target. The following sub sections detail the setup of each modelling approach.

4.1 Arbitrary Lagrangian-Eulerian

For the coupled ALE analyses, the models were initially run in 2D axi-symmetry until the blast wave had propagated 6 m. For this initial propagation, the model was meshed with radially-symmetric shell elements so that blast wave propagation was aligned predominantly with element direction to reduce computational losses [2]. This information was then re-mapped onto a 3D domain [10], comprising 20 mm cubic solid elements, with sufficient distance around the target to ensure expansion edges from the edge of the domain would not contaminate the results throughout the duration of the analysis [7]. Half-symmetry was utilised by fixing all nodes along the vertical boundary against horizontal displacement. The ground surface and edges of the reflecting target were also modelled using rigid boundaries, as is shown in Figure 3. Note that the geometry of the reflecting surface does not match the experiment exactly due to mesh size limitations.

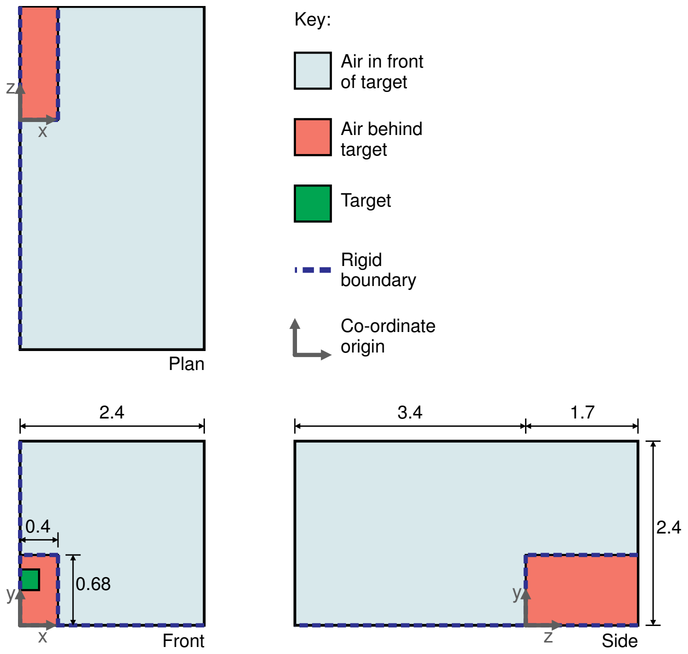

Figure 3: Parts, co-ordinate origin and dimensions (m) of the 3D domain[7]

The target was modelled using shell elements, and contact was achieved using the CONSTRAINED_LAGRANGE_IN_SOLID keyword, with the air separated into two parts: air 'in front' and 'behind' the target to allow for better modelling of the suction forces caused by clearing. The plates were modelled as linear elastic (E = 210 GPa, ρ = 7850 kg/m^3 and ν = 0.3) one-way spanning beams (spanning the horizontal dimension) with full rotational restraint and translational restraint in the z plane at the supports, and a shell thickness of 0.835 mm. The models were run for 168 hours (1 week) on *iceberg*, the University of Sheffield High Performance Computing server.

4.2 Uncoupled Lagrangian with Hudson load curves

Vast computational savings can be made if the loading is determined from some manner other than explicitly modelling the formation of the blast wave and interaction with a finite target structure. As noted previously, the Hudson clearing predictions offer a means for doing this.

For the uncoupled analyses, the loading was generated as nodal point-loads using a bespoke MatLab load curve generator[11]. With reference to Figure 4, each node will experience the superposition of: (a) the full reflected pressure given by ConWep[12], assumed to arrive planar, be uniform across the whole plate, and be equal in magnitude to the pressure acting at the bottom-centre of the reflecting surface; (b) the x component of clearing, given as a function of the Hudson clearing lengths, η_{x1} and η_{x2}, to each vertical free edge; and (c) the y component of clearing, given as a function of the clearing lengths, η_{y1} and η_{y2}, to each horizontal free edge. In this case, as the target is supported on a rigid ground surface, the secondary vertical clearing length is given as the distance from the node to the ground surface and back to the top of the target, representing reflection of the clearing wave off the rigid boundary. Each node is therefore loaded by three distinct load curves. Assignment of this is completed automatically by the MatLab script for any given mesh, where the point-load is simply given as the pressure multiplied by the element area. For this study, the mesh was chosen as 64×64 shell elements.

The Hudson load curve generation was run for each charge mass and the plate was modelled with identical material properties and support conditions to the ALE analyses. The typical analysis time was in the order of minutes, including the time taken to generate the mesh and load curves.

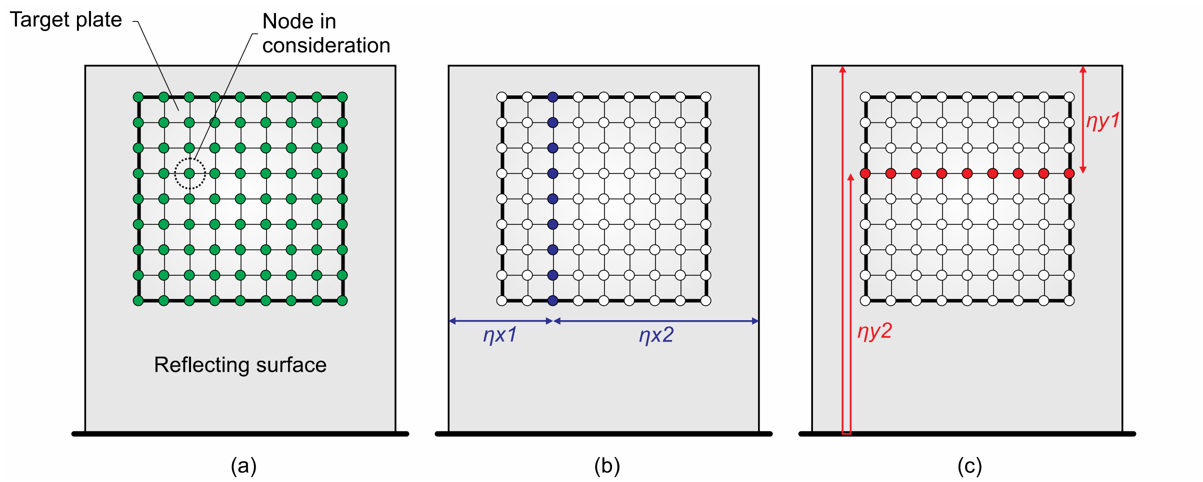

Figure 4: Hudson[6] load curve generation for each node; (a) reflected pressure applied to each node, (b) *x* component of pressure relief calculated based on horizontal clearing lengths to free edge, (c) *y* component of pressure relief calculated based on vertical clearing lengths to free edge[7,9]

5 RESULTS AND DISCUSSION

Figure 5 shows the experimental, coupled (ALE), and uncoupled (Hudson) numerical displacement-time histories. For the Hudson analyses, the loading was applied at t = 0 and the displacements were time-shifted to correspond with the beginning of the experimental displacements. The time-base of the ALE results were maintained from the numerical analyses. The peak displacements for each analysis are summarised in Table 1, where the ratio of peak numerical displacement to mean peak experimental displacement is also given.

Charge mass (g PE4)	Peak displacement (mm)					Ratio (-)	
	Experiment			ALE	Hudson	ALE	Hudson
	Test 1	Test 2	Mean				
50	5.39	5.18	5.28	6.11	5.83	**1.15**	**1.10**
75	7.33	7.20	7.27	8.11	7.60	**1.12**	**1.05**
108	9.13	9.53	9.33	9.90	9.90	**1.06**	**1.06**
140	11.29	11.97	11.63	11.67	11.86	**1.00**	**1.02**
175	12.88	12.61	12.75	13.10	13.50	**1.03**	**1.06**

Table 1: Peak experimental displacements and peak coupled (ALE) and uncoupled (Hudson) numerical displacements. Ratio of numerical to mean experimental displacement is also given

The experimental results demonstrate a high level of repeatability: the largest difference between two tests occurred for the 140 g shots where the peak displacements are ±3% from the mean. This gives us confidence that, for this range of far-field scaled distances at least, target response to a cleared blast load is essentially deterministic. This builds on previous observations from the authors[13], and allows the experimental data to be used to rigorously validate the two numerical modelling approaches. It is important that experimental data is viewed in this manner, rather than simply being used to verify that a numerical model is within certain limits.

Qualitatively, the ALE analyses match the experimental displacements well for the first 3-4 ms of analysis. The ALE models generally reach peak displacement around 2 ms later than the experimental recordings. It is known that the re-mapping procedure can accurately conserve impulse when mapping from 2D to 3D, and that LS-DYNA can accurately model normal reflection of blast waves[7]. The discrepancies between the rebound times therefore indicate that the clearing wave may not be properly modelled in the ALE analysis, which is likely due to the relatively coarse mesh. This could possibly be improved by reducing the element size; however the required computational resources would exceed those available to the authors. Quantitatively, the model is able to predict the

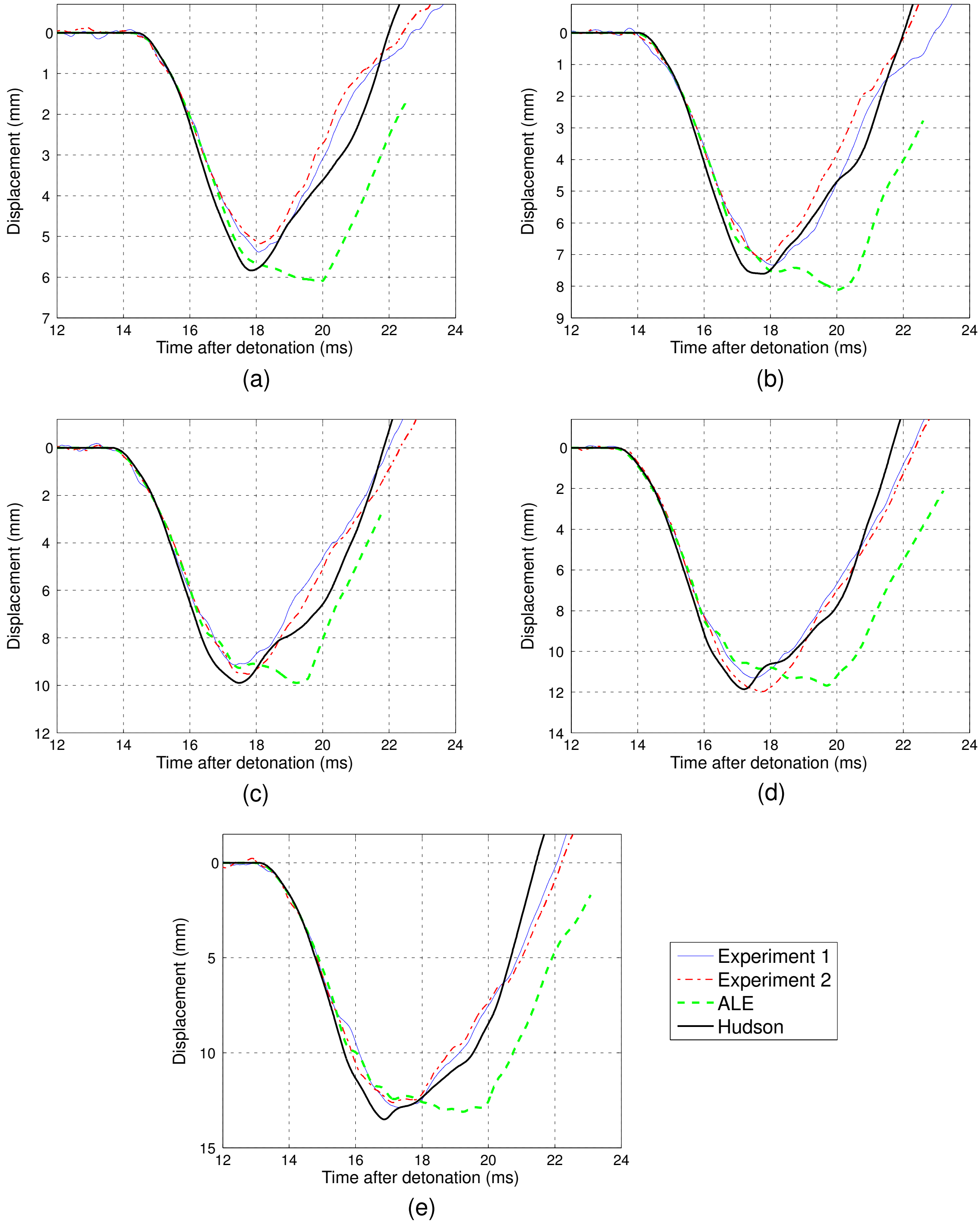

Figure 5: Experimental, coupled (ALE) and uncoupled (Hudson) numerical displacement-time histories at 6 m stand-off; (a) 50 g PE4, (b) 75 g PE4, (c) 108 g PE4, (d) 140 g PE4, (e) 175 g PE4

peak displacement to within 15% of the average experimental peak displacement with a typical error of 7%, which is reasonable.

The uncoupled analyses with Hudson load curves are in very good agreement with the experiments across the entire test series. The time to peak displacement is accurately predicted, as is the time at which the plate centre returns to zero displacement and begins displacing outwards. It is known that the Hudson clearing predictions can accurately model the cleared blast pressure acting at any point on a target[4]. The modelling shown herein suggests that the full distribution of positive and negative phase pressure is also accurately described by the Hudson method. The peak displacements are all predicted to within 10% of the average experimental peak displacement with a typical error of 5%. This indicates that using load curves derived from simple empirical predictive methods and the application of the Hudson clearing corrections can be used with confidence in modelling.

The fact that the uncoupled Hudson analyses generally demonstrate better agreement than the coupled ALE analyses raises an interesting point: *increasing the complexity of a numerical model does not necessary yield an increase in accuracy.* In this example, the ability to model the physical process of clearing came with a compromise, namely a coarser representation of the generation and progression of the clearing waves across the target. This, clearly, gave results that were less accurate than the simple Hudson clearing corrections. It is argued, therefore, that approximate schemes should be preferred over more complex ones, provided the underlying assumptions of the simplified methods are understood and not violated. This is justified by both the small increase in accuracy and the orders-of-magnitude decrease in computational time. Crucially, we would not be able to make this suggestion were it not for the tight control achieved with the experimental data.

Furthermore, the results have demonstrated that target response is extremely sensitive to the accuracy of the loading applied to it. Whenever possible, accurate quantification of the blast load should be treated with as much rigour as modelling target response.

6 SUMMARY AND CONCLUSIONS

The blast load acting on a target with complex geometry can be difficult to quantify. As such, it is not uncommon to see such situations modelled with Arbitrary Lagrangian-Eulerian (ALE) finite elements where the detonation, blast wave propagation and fluid-structure interaction is explicitly simulated. This article aimed to test whether it was possible to accurately model the distribution of blast pressures based on a simple adjustment to semi-empirical blast predictions, and whether these could be implemented into finite element modelling of target response.

A series of experiments was conducted to test this. Thin steel plates situated within a finite reflecting surface were subjected to blast loads and the dynamic displacement at the centre of the plate was recorded for each test. Two numerical methods were investigated: coupled ALE analyses where the full air domain was modelled; and an uncoupled scheme where the loading was applied as discrete load predictions at individual nodes based on the Hudson[6] clearing corrections.

The uncoupled analyses took only a few minutes to run, whereas the coupled models were run for 168 hours before completion. Also, the results show that it is possible to actually increase the accuracy of a numerical simulation through the use of approximate methods. The benefits of using an approximate scheme are clear, however high quality experimental data is required for such observations to be made. Target response to far-field blast events is shown to be essentially deterministic, and ensuring tight control of experimental trials will allow future researchers to perform more rigorous validation of numerical modelling approaches.

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