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OPTICAL DIAGNOSTICS IN NEAR FIELD BLAST MEASUREMENTS

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Abstract

The understanding of structural and material response to air-blast loading is a necessary pre-requisite to the development of effective blast protection and mitigation systems. Computational tools have advanced significantly, enabling extensive simulations of the loading and ensuing structural response that occur as the result of an explosive detonation. Experimental techniques, however, have lagged behind in providing robust, high fidelity measurements regarding the transient response and spatial distribution of specific impulse across a structure.

This article discusses recent advances in these techniques at the University of Sheffield and describes the results that can be obtained. It details proof of concept testing via a bilateral collaboration between the UK and South Africa involving single-blind experimentation using high-speed imaging, digital image correlation and comparisons with results from near-field blast experiments performed at the University of Sheffield CoBL facility.

Secondly, it describes some of the continued developments since the success of those early trials, resulting in a new optical diagnostics for blast capability at the University of Sheffield. This article demonstrates the usefulness of improved diagnostics and techniques in blast experiments and shows the efficacy and versatility of high-speed imaging and DIC for determining impulse profiles and transient structural behaviour. Ultra-high speed imaging is also shown to be a useful tool for visualising detonation fronts in explosive charges and the expanding fireball.

1 Introduction

Improved diagnostics for measuring structural response and loading characteristics resulting from explosive detonations are vitally important. High fidelity experimental data is critical in supporting the efforts of blast engineers and researchers in understanding and predicting blast loading and its effects on structures and materials. There are considerable challenges in measuring and recording data, including the high pressures and temperatures, the short load duration, excessive vibrations introduced into mounts, triggering challenges, electromagnetic interference, and the bright explosive flash. In recent years, improvements in instrumentation and novel experimental approaches have provided renewed impetus to the goal of better experimental measurements from laboratory scale explosion tests [1-3].

We have pursued these challenges at Sheffield by a combination of strategic collaboration with industry and academic partners, and in-house development of robust and reliable systems. This paper reports on the use of optical diagnostics for transient blast measurements. First, it describes tests performed in a single-blind study at the Universities of Sheffield and Cape Town which aimed to measure the impulse distribution resulting from explosive detonations in air, and shows how a high-speed stereo-imaging system can be used in combination with digital image correlation to give transient out-of-plane displacements and the initial velocity field of a blast-loaded structure. Secondly, it describes an upgraded stereo-imaging system at Sheffield with enhanced capabilities and provides some preliminary results on how it can provide additional insights. It then shows some recent advances in our capability to visualise detonation using ultra-high speed imaging.

2 Proof of concept: using high-speed stereo imaging for determining specific impulse in structural response experiments

2.1 The Characterisation of Blast Loading apparatus at Sheffield

The Characterisation of Blast Loading (COBL) apparatus [1] was developed to measure pressure at discrete locations across a rigid target plate to characterize the load arising from an explosive detonation in the near-field. A summary of the COBL test method is shown in Figure 1 and a more detailed front view of the COBL rig is shown in Figure 2.

COBL comprises a 100 mm thick steel target plate which acts as a nominally rigid boundary. Seventeen EN24 steel Hopkinson pressure bars (each 10 mm diameter, 3.25 m long) are mounted through holes drilled in the target plate and set with their loaded faces flush with the underside. Spatial and temporal pressure histories are obtained by analysing the Hopkinson bar signals, allowing a map of specific impulse distribution across the target face, at discrete locations.

High-speed footage of the fireball generated from the detonations can be filmed using a Photron Fastcam SA-Z camera at 200 kfps (resolution 386x176). An example of the footage obtained is shown in Figure 1. The camera footage is useful for identifying features of the fireball and shock propagation in the near-field, although 200 kfps is not sufficiently quick to capture the detonation propagation through the explosive charge itself.

2.2 Sheffield experiments

Experiments performed at Sheffield used the COBL test facility. This involved detonations of spherical (100g PE4) and 3:1 cylindrical (78g PE4) charges located at stand-off distances (SODs) from the target plate surface of 55.4 mm and 168 mm respectively.

2.3 Cape Town experiments

Experiments at BISRU (Cape Town) involved detonating 50 g spherical and 3:1 cylindrical PE4 charges at SODs of 44 mm and 145 mm respectively. The blast loading was directed at deformable Domex 355MC steel plates with a circular exposed area (diameter 300 mm) that were mounted via a clamp frame to a pendulum.

The global impulse transfer to the plate was estimated from the pendulum swing, while the transient response was obtained from high-speed stereo images of the rear face motion, shown in Figure 3, following the methods developed by Curry and Langdon [2]. The Cape Town experiments were performed single-blind, without knowledge of the Sheffield test results. The pendulum is a well established way to capture the global impulse transfer to a specimen during a blast test, provided sufficient care is taken to distinguish any impulse applied to the mounting frames.

2.4 Results

Digital Image Correlation (DIC) was used to post process the images obtained from the BISRU blast tests. The displacement and velocity profiles across the plates were obtained. The transient displacement histories exhibited a sharp increase in displacement up to a peak displacement, followed by an elastic recovery of the plate, as expected. It was evident that the spherical detonations produced repeatable responses in the plates, while the cylindrical detonations show more variation.

The displacement-time and velocity-time profiles along the plate centre-line are shown in Figure 4 and Figure 5 as typical examples. They show peak velocity occurred after approximately 0.06 ms, and that the plate deformation at this time was relatively small (and very localized) compared to its peak, indicating that the loading and response were in the impulsive regime.

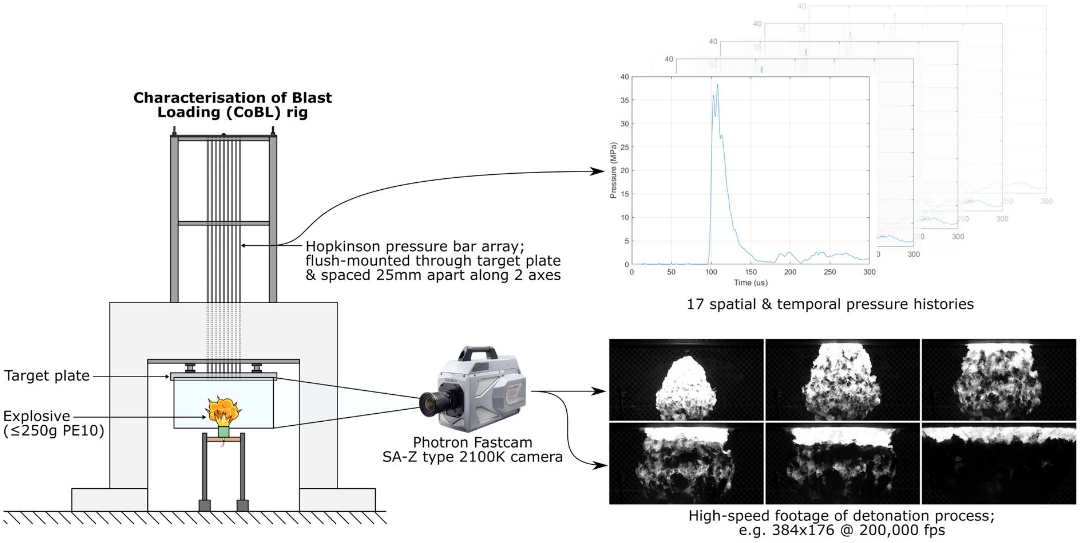

Figure 1 General test metholdogy using the COBL facility

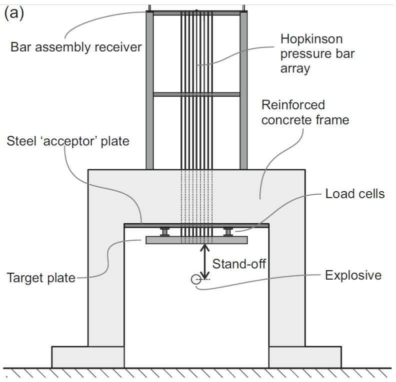

Figure 2 Schematic showing COBL rig (University of Sheffield) with a cylindrical charge in position

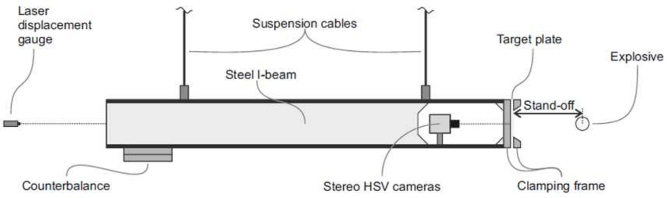

Figure 3 Schematic (side view) of the transient response blast pendulum (BISRU)

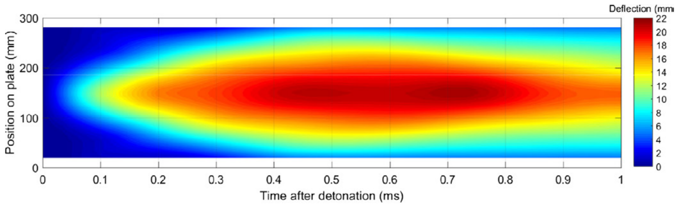

Figure 4 Transient displacement-time profile for a spherical detonation, obtained using DIC [4]

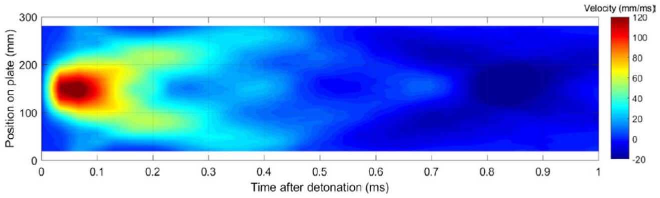

Figure 5 Transient velocity-time profile for a spherical detonation

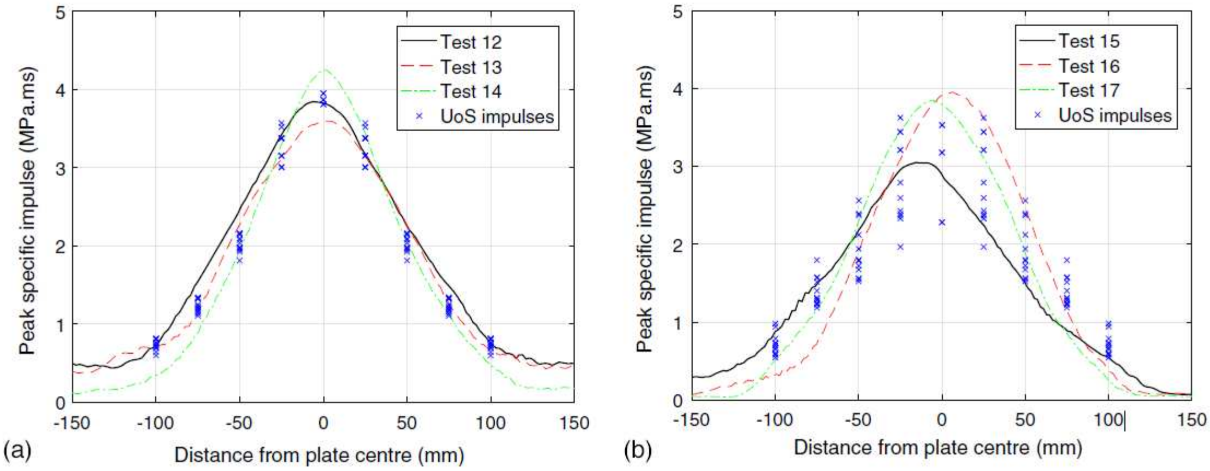

Figure 6 Measured (COBL) and inferred (BISRU) specific impulse distributions for (a) spherical detonations (b) cylindrical detonations [4]

Flexural waves travelling through the plates are evident in the images in Figure 5, and their propagation can be used to explain aspects of the transient mid-point displacement response, especially in the post-peak oscillation response phase. For details of this, see reference [4].

The initial velocity profiles were used to infer a continuous specific impulse distribution which, after suitable scaling, were compared to measured (COBL) specific impulse distributions from the spherical tests at the University of Sheffield (shown in Figure 6a), where good agreement is demonstrated. The specific impulses measured using COBL also showed greater spread for the cylindrical tests. Imaging of the fireball enabled Rigby et al [4] to attribute these differences to surface instabilities in the expanding detonation product cloud. The variations were significant enough to influence the transient displacement profile obtained using DIC, resulting in similar differences in impulse distribution (Figure 6b). This work shows that the two measurement techniques (COBL and high speed video/DIC) give excellent agreement and are both suitable methods for obtaining the spatial impulse distribution across a target structure.

2.5 Lessons learned

With high-speed imaging techniques, the target structure needs to be flexible enough to be sensitive to changes in the initial velocity distribution and the imaging system needs to be sufficiently fast to capture the initial velocity (that is, a high frame rate and low exposure time). The system in Cape Town gives repeatable and accurate impulse distributions across a central strip of a panel, useful for model validation. Flexural wave behaviour can be found from the transient velocity and displacement profiles, giving good insights into the mechanics of plate response from blast loads. Selecting a suitable speckle pattern size and ensuring good adhesion of the paint to the target structure are essential for obtaining reliable measurements of out of plane displacement and velocity.

2.6 Energy equivalent impulse approach

Momentum is a function of the area-integral of initial velocity, and kinetic energy is a function of the area-integral of initial velocity squared. Thus, a concentrated load that imparts the same momentum as a uniformly distributed load will impart a higher kinetic energy. Expressing a distributed load as a single-number equivalent, i.e. total impulse (area-integral of specific impulse) does not account for the full energy of the system. Therefore, we have derived an energy equivalent uniform impulse approach that accounts for the additional energy imparted to a structure from a spatially non-uniform blast load.

The energy equivalent uniform impulse is effectively a root-mean-square of the specific impulse distribution (see [5] for a detailed derivation), and serves to generate a uniformly distributed impulsive load that imparts the same kinetic energy as the distributed load. A parametric study was performed in [5] where plates of varying properties were subjected to impulsive loads of varying intensities and uniformity. The results are shown here in Figure 7, where it can be seen that plate deformation is weakly correlated to total impulse (i.e. momentum), and strongly correlated to energy equivalent impulse (i.e. kinetic energy).

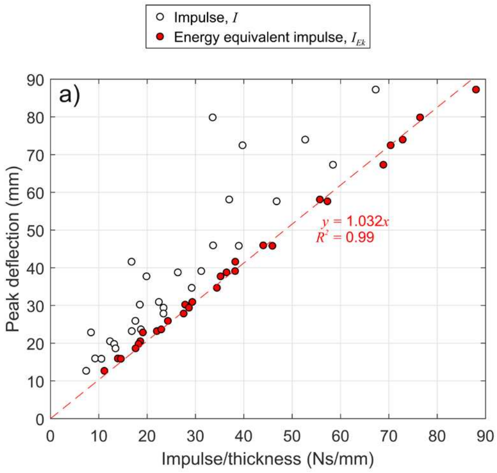

Figure 7 Peak deflection plotted against total impulse (weak positive correlation) and energy equivalent impulse (strong positive correlation) [5]

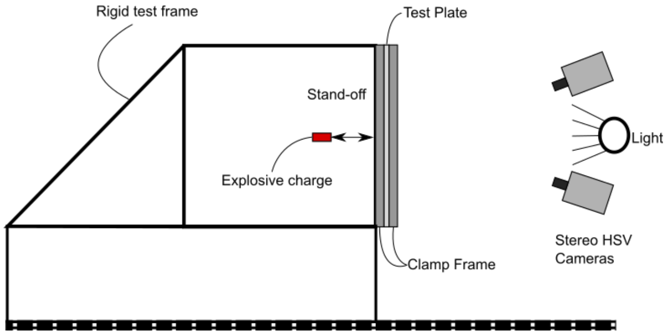

Figure 8 Schematic showing the new Sheffield experimental facility

The ability to transform a spatially varying load into an equivalent single-number equivalent has strong implications for developing future quick-running predictive methods, as well as allowing for implementation into simplified analysis tools such as the single-degree-of-freedom method.

3 Next generation optical diagnostics at Sheffield

The University of Sheffield is now expanding its diagnostic capability to include ultra-high speed imaging and DIC, with the goals of (i) increasing the frame rate and (ii) expanding the area of the structure that can be examined (to account for the observed asymmetries in the impulse distribution for the case of cylindrical detonations).

3.1 Optical diagnostics for structural blast tests

The new experimental arrangement is shown schematically in Figure 8. It comprises a clamping frame attached to a rigid steel test-frame. A key difference in these tests is the use of a stationary clamp frame that is mounted to the ground (c.f. ref [2, 3]). Since the optical methods are able to obtain the specific impulse applied to the structure, there is less need to infer the global impulse by using a swinging pendulum system.

It is instrumented with two Shimadzu cameras capable of filming at rates up to 5 million fps and illuminated by a Luminys 30 k high speed lab light. The increased frame rate allows our optical measurement techniques to be extended into new time domains showing, in much finer detail, the initial velocity fields resulting from an explosive detonation (and hence the spatial impulse distribution) and the transient evolution of out-of-plane displacement across these structures.

With high-speed imaging, there are always some trade-offs. In this case, there are capability trade-offs in the camera technology, where increasing frame rates usually means reduced resolution of the image. Experimental mechanics techniques can be used to overcome some of this. The more significant trade-off between the frame rate and the duration over which the cameras can record is a limiting factor for the frame rate in structural response tests. Available lighting and the quality of the speckle pattern are other contributing factors to successful optical diagnostics.

The initial trials of this arrangement involved detonating 50 g charges of PE10, at a stand-off distance of 50 mm from the rear of an armoured steel plate clamped into the rigid test frame. A photograph of the test set-up is shown in Figure 9, with the clamp frame and steel frame support structure shown on the left hand side of the image.

Figure 9 Photograph of the blast test arrangement prior to detonation

Our current upper charge mass limit is 100g PE4/PE10, but the system can be scaled up for larger charge detonations as required. The results have been positive, with clear images obtained from the cameras. The next phase of trials will focus on optimising the speckle pattern, precision triggering and calibration.

3.2 Optical diagnostics for detonation and shock characterisations

The Shimadzu camera system is capable of filming at rates up to 5 million fps, which is useful for examining highly transient phenomena such as propagation of detonation fronts through an explosive charge during the first few microseconds. To examine this, we end-detonated 48 g cylindrical charges of PE10 at 200 mm SOD using the COBL rig instrumented with a Shimadzu camera filming at 1 mfps. The test setup, shown in Figure 10, was designed using the hydrocode, Ansys Autodyn 2019 R2, to improve the planarity of the detonation front.

The cameras successfully recorded the propagation of the detonation front through the explosive charge during the first 4.2μs after detonation, and a fireball laterally expanding from the point of detonation. Images from the footage are shown in Figure 11. The dotted outline is the original charge geometry.

The detonation front is approximately planar as it propagates through the explosive charge within a few microseconds. The lateral expansion of the detonation product fireball behind the wavefront is

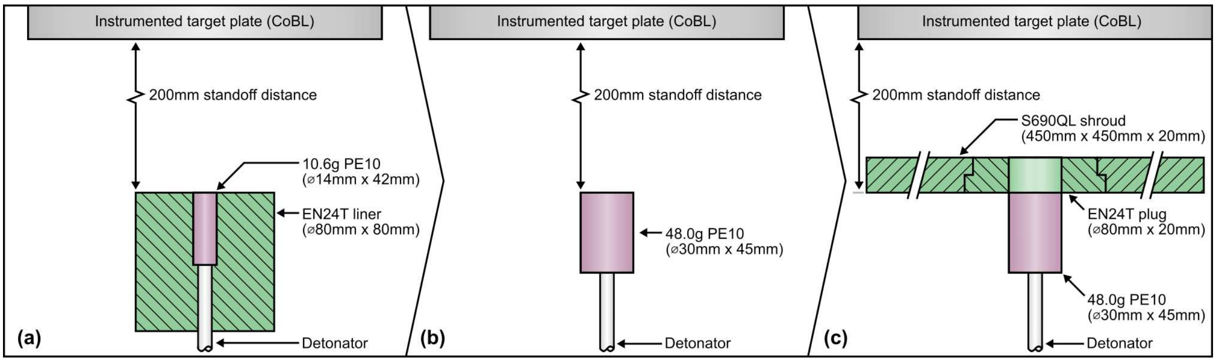

Figure 10 Experimental arrangement for visualising detonation front

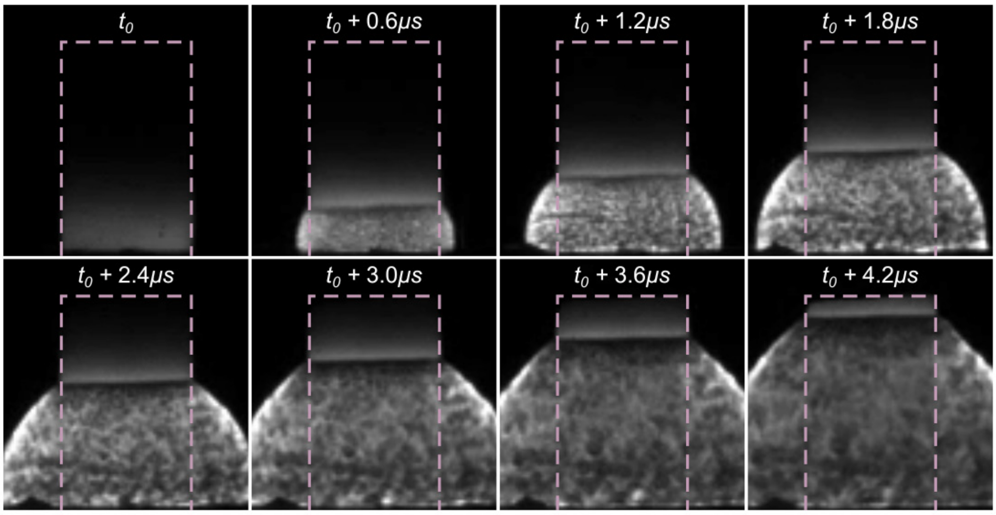

Figure 11 Camera footage of the detonation front with the initial charge shape outline overlaid in purple (1 mfps)

clearly evident. This is a considerable improvement on our shock front visualization approach within the extreme near-field and within the charge itself. When used alongside the Photron SA-Z camera, it opens up the potential to capture images of the detonation wave early-time fireball development, as well as the later fireball and shock wave features and target interaction, from the same experiment, in the near-field.

Concluding Comments

The findings show significant progress in the chase for better experimental measurements that characterize the loading and transient response of structures subjected to near-field explosions. The initial velocity profiles obtained using stereo-imaging and DIC techniques produced inferred specific impulses that matched well with the discrete specific pressure and impulse measurements obtained using COBL at the University of Sheffield. The inferred impulse method seems to be sensitive enough to detect spatial variations in loading caused by surface instabilities in the expanding detonation product cloud from cylindrical charge detonations. The lessons learned from the proof of concept tests informed the development of a more advanced optical diagnostics suite at the University of Sheffield that is capable of capturing different types of events in the detonation-to-response blast event chain, from propagation of the detonation front, to specific impulse and displacement of a downstream target.

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