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Using optical diagnostics for near field blast testing

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ABSTRACT: The ability to measure the structural and material response to air-blast loading is vital to developing a proper understanding of near-field blast loading and response. Computational modelling has advanced significantly but, until recently, experimental techniques lagged behind. This paper discusses recent advances in these experimental techniques. The first part describes a bilateral test programme between the UK and South Africa. The high-speed imaging and digital image correlation system at Cape Town gives repeatable and accurate impulse distributions across a central strip of a panel, useful for model validation. Flexural wave behaviour was observed from the transient velocity and displacement profiles, giving good insights into the mechanics of plate response from blast loads. The second part demonstrates the value of high-speed stereo-imaging for measuring the transient response of blast loaded fibre reinforced polymer panels and sandwich structures. The peak displacements. elastic rebounds and transient oscillations provide valuable insights into the damage propagation within these types of structures. The final part of the paper 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. The imaging system operates at higher frame rates and can cover a wider region of interest on the structure. Ultra-high speed imaging is also shown to be a useful tool for visualising detonations fronts in explosive charges and the expanding fireball.

1 INTRODUCTION

As we are frequently reminded, explosions are a dangerous and relatively frequent occurrence, whether they arise from terrorism, military action or accidents. To support the efforts of blast protection engineers, civil engineers and researchers in understanding and predicting blast loading and its effects on structures, high fidelity experimental data required – for predictive model development and validation, fundamental understanding of the mechanics of the loading and the transient structural response that ensues.

Optical diagnostics offer exceptional potential for measuring the dynamic structural response and loading characteristics arising from explosive detonations. However, there are considerable challenges involved, due to the extreme high pressures and temperatures, the exceptionally short load duration, triggering challenges for the instrumentation, electromagnetic interference, and the bright explosive flash that risks saturating the CCD. Fourney et al. (2005) and Sutton et al. (1983) were instrumental in developing this potential in the early days, followed by Tiwari et al. (2009) and Aune et al. (2016). However, each one reported issues due to challenging lighting, or triggering, or depth of field limitations.

In recent years, improvements in instrumentation and novel experimental approaches have provided renewed impetus to the goal of better experimental measurements from lab-scale explosion tests (Clarke et al. 2015, Curry & Langdon 2017, Clarke et al. 2020). These approaches offer potential for measurements in the near-field, especially of the loading.

In this paper we describe 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 (DIC) to give transient displacements and the initial velocity field of a blast-loaded structure. It also demonstrates the usefulness of high-speed stereo-imaging for measuring the blast response of composite structures. Then 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 of explosives using ultra-high speed imaging.

2 USING OPTICAL DIAGNOSTICS FOR SPECIFIC IMPULSE MEASUREMENT

2.1 *The CoBL test arrangement (Sheffield)*

The Characterisation of Blast Loading (CoBL) test facility (Clarke et al. 2015, 2020) was developed at the University of Sheffield to measure pressure at discrete locations across a rigid target plate, in order to characterize the load arising from an explosive detonation in the near-field. It comprises a 100 mm thick steel target plate which acts as a nominally rigid boundary. Seventeen EN24 steel 10 mm diameter, 3.25 m long, Hopkinson pressure bars 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 obtaining by analysing the Hopkinson bar signals, allowing a map of specific impulse distribution across the target face, at discrete locations.

A summary of the CoBL test method is shown in Figure 1. High-speed footage of the fireball generated from the detonations can be filmed using a Photron Fastcam SA-Z camera (usually operated at 200 kfps, resolution of 386x176). The camera footage is useful for identifying features of the fireball and shock propagation in the near-field (Rigby et al., 2020), although 200 kfps is not sufficient quick to capture the detonation propagation through the explosive charge itself.

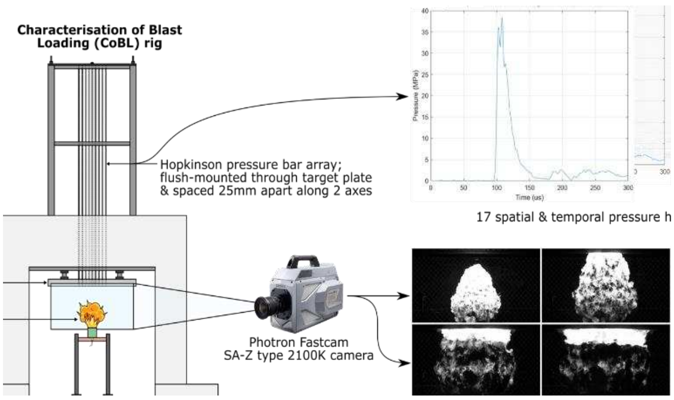

Figure 1. General test methodology using the CoBL facility

Carefully controlled explosion detonations were performed at Sheffield using the CoBL test facility. Spherical (100g PE4) and 3:1 cylindrical (78g PE4) charges located at predetermined stand-off distances from the charge surface (spheres at 55.4 mm and cylinders at 168 mm) were detonated. The data recorded from the Hopkinson pressure bar array was used to determine the specific impulse distribution at each bar location, for later comparison to the optical diagnostic technique developed at BISRU.

2.2 *High speed stereo-imaging blast tests (BISRU)*

Experiments at BISRU (Cape Town) involved detonating 50g spherical and 1:3 L:D cylindrical PE4 charges at SODs of 44 mm and 145 mm respectively. The charge sizes were determined by scaling the Sheffield experiments. 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 using the pendulum swing, while the transient response was obtained from high-speed stereo images of the rear face motion of the deforming plates, shown in Figure 2, following the methods developed by Curry & Langdon (2017, 2021).

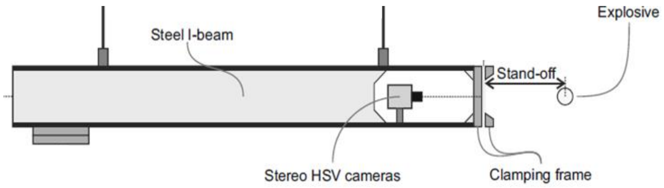

Figure 2. Schematic (side view) of the blast pendulum

The Cape Town experiments were performed single-blind, without knowledge of the Sheffield results. The pendulum is a well-established way to capture the global impulse transfer to a specimen during a blast test (Bonorchis & Nurick 2009), provided sufficient care is taken to distinguish any impulse applied to the mounting frames.

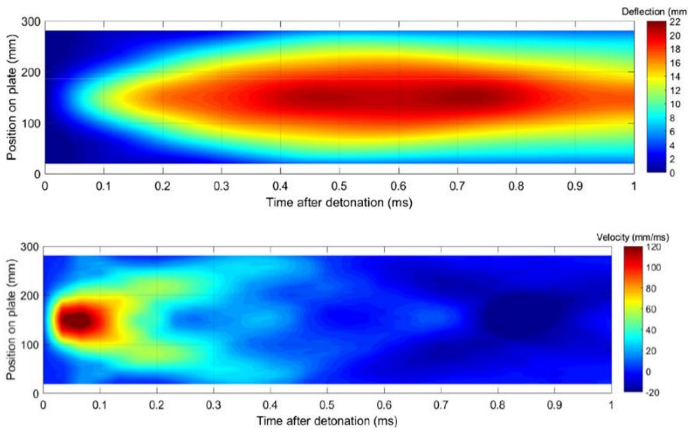

Figure 3. Typical transient results obtained using DIC: transient displacement (top), transient velocity (bottom)

DIC was used to post process the images from the BISRU 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, followed by elastic recovery. 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 3 as typical examples. They show peak velocity occurred after approximately 60 μs, and that the plate deformation at this time was highly localized and relatively small compared to its peak, indicating that the loading and response were in the impulsive regime.

Flexural waves travelling through the plates is evident in the images in Figure 3, 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, see Rigby et al. (2019b).

For comparison to the Sheffield results, the initial velocities were used to infer a continuous specific impulse distribution which, after suitable scaling, was compared to CoBL specific impulse distributions.

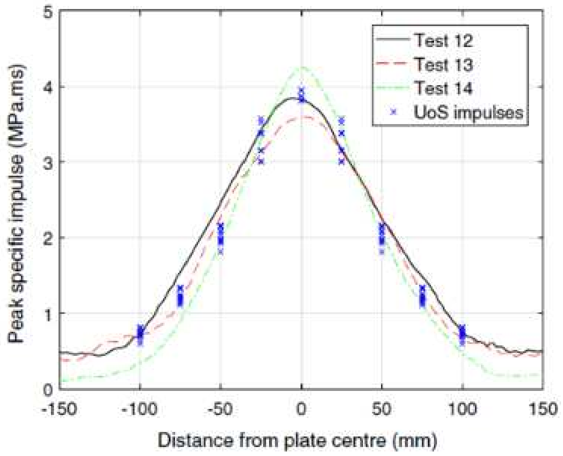

Figure 4. Specific impulse distributions obtained from spherical charge detonations at Sheffield and BISRU

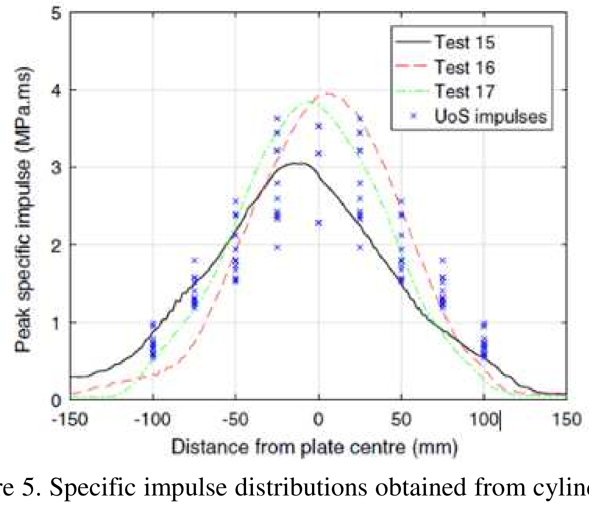

Figure 5. Specific impulse distributions obtained from cylindrical charge detonations at Sheffield and BISRU

For the spherical charge detonations, shown in Figure 4, good agreement between the Sheffield and BISRU test techniques was demonstrated. The spherical detonations produced repeatable specific impulse distributions. However, the specific impulses measured using CoBL showed greater spread for the cylindrical tests. Imaging of the fireball enabled Rigby et al. (2019b) 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 5).

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.

From the BISRU work it was found that, 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 obtained reliable measurements of out of plane displacement and velocity.

2.3 *Energy equivalent impulse approach*

Both test approaches showed considerable spatial localization of the specific impulse across the target structure for both cylindrical and spherical charges in the near-field. A simple approach that accounts for impulse localization is now presented.

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 Rigby et al. 2019a 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 by Rigby et al. (2019a) where plates of varying properties were subjected to impulsive loads of varying intensities and uniformity. The results are shown here in Figure 6, 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). 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.

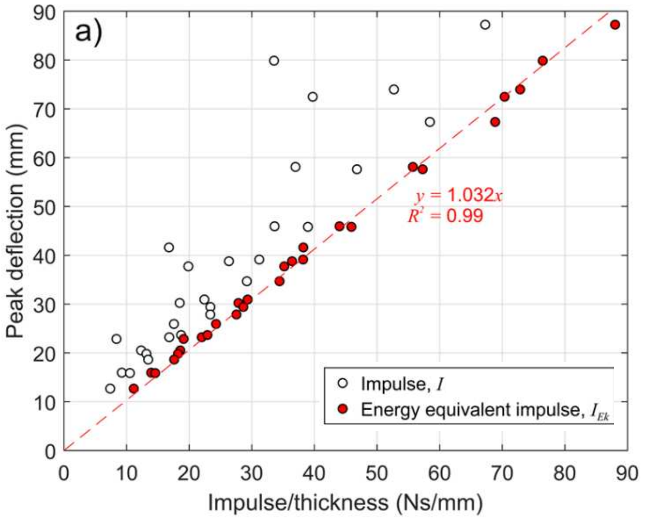

Figure 6. Peak deflection plotted against total impulse (weak positive correlation) and energy equivalent impulse

3 USING OPTICAL DIAGNOSTICS TO MEASURE STRUCTURAL RESPONSE

Fibre reinforced polymer (FRP) composites are a class of materials with much greater elastic capacity than traditional blast protection materials such as metals and cellular materials. Under blast loading, the final permanent deformation of FRP composites can be very small, while the transient deformations can be many times larger. In certain circumstances, there are high rebound displacements in the opposite direction to the blast wave, due to elastic recovery and vibration within the structure. Thus, optical diagnostics provide the opportunity to obtain information about the peak, transient and final deformed shapes of blast loaded FRP composite structures.

In recent work (Gabriel et al., 2021), we measured the transient mid-point displacement blast response of near-equivalent mass glass FRP composite laminate panels with sandwich panels comprising glass FRP skins with a polymeric foam core. The loading was generated by detonating small charges of PE4 explosive down a "blast tube" to produce a spatially near-uniform loading across the front surface of the fully clamped composite test panels.

As part of the experimental series, high-speed stereo-imaging equipment was mounted to the pendulum to film the panel response, following Curry & Langdon (2017). Two high-speed cameras filming at 30 kfps (exposure time = 31 μs) and LED lighting were positioned to provide a clear field of view of the rear speckled surface. DIC software was used to process the images to obtain the out of plane transient displacement across the mid-line of the panels. Some typical responses are shown in Figure 7 (FRP composite laminates) and Figure 8 (sandwich panels).

In Figure 7, it is evident that transient response was dominated by elastic effects, with an initial steep rise in displacement followed by viscously damped oscillations (for at least 3 cycles). Furthermore, there was no significant permanent displacement. Considerable delamination occurred in the panels and cracking was observed on the front surface, as shown in Figure 9.

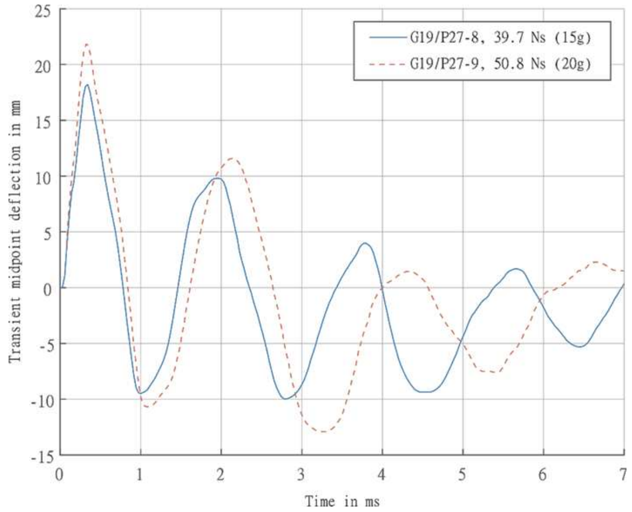

Figure 7. Graph showing experimentally determined transient mid-point displacement-time histories for FRP panels

For the sandwich panels, Figure 8, the subsequent fall in displacement after the initial sharp rise was greater than the drop in displacement observed in the FRP composite laminates. The peak displacement in the direction opposite to the blast was much greater.

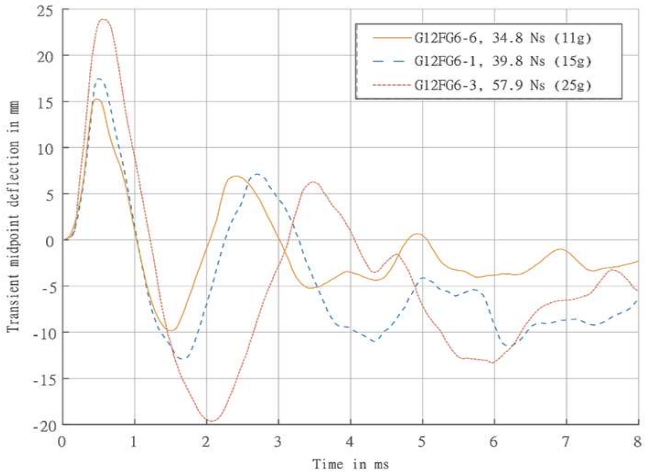

Figure 8. Rear transient mid-point displacement-time histories for sandwich panels with FRP composite skins and a foam core

During the initial rise, compression loading in the core would suppress the formation of core cracking despite the high shear loads generated. The rebound could have caused the core to go through tension after the initial compression which may result in core thickness recovery and, while not observed on the panels tested, interface bond failures. The minor damage on the cores observed from these tests also suggested that the rebound tensile stress did not exceed the tensile strength of the core.

The transient measurements aided in the development of a proposed sequence of damage within the sandwich panels (Gabriel et al., 2021). These observations would not have been possible without the use of high-speed stereo-imaging and DIC.

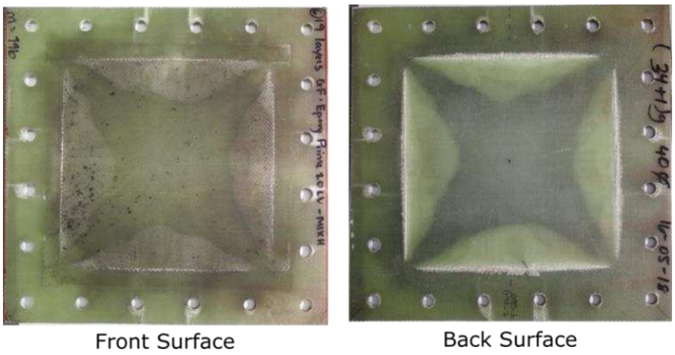

Figure 9. Photographs of a typical blast-loaded FRP composite laminate panel showing delamination (35 g charge mass)

4 NEXT GENERATION OF OPTICAL DIAGNOSTICS

4.1 *Optical diagnostics for structural blast tests*

Stereo-imaging with DIC has been shown to be a reliable technique for obtaining displacements, velocities and specific impulse distributions across a blast loaded deformable structure. However, the system has several limitations, due to available lighting, maximum frame rate and region of the plate that can be filmed. To overcome these, we are developing new systems that (i) increase the frame rate and (ii) expand the area of the structure that can be examined.

The new experimental arrangement is shown schematically in Figure 10. It comprises a clamping frame attached to a rigid steel test-frame. A key difference here is the use of a stationary clamp frame (c.f. Curry & Langdon 2017, 2021). Since optical methods are able to obtain the specific impulse, there is less need to infer the global impulse by using a swinging pendulum. This eliminates the technical challenges involved in isolating the camera mounts from vibration.

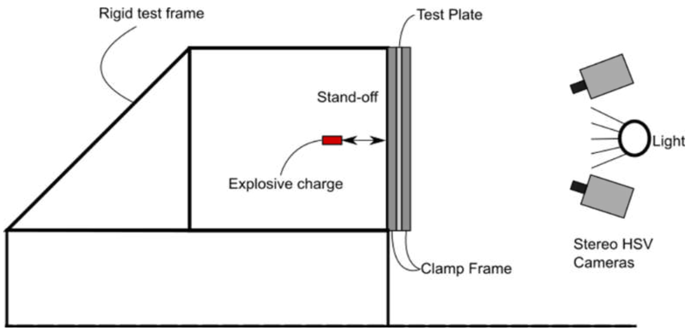

Figure 10. Schematic of Sheffield stereo-imaging blast test facility at Sheffield

It is instrumented with two Shimadzu HPV-X2 cameras capable of filming at rates up to 5 million fps at full resolution and illuminated by a Luminys 30k 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 compromises. In this case, there are capability trade-offs in the camera technology, where increasing frame rate often means reduced image resolution. Techniques can be used to overcome some of this (Perron & Grediac, 2021). The more significant compromise between the frame rate and the duration over which the cameras can record is a limiting factor in structural response tests – this could be overcome by using multiple camera systems, although this complicates triggering and may not be possible without obscuring the field of view.

Available lighting and the quality of the speckle pattern are other contributing factors to successful optical diagnostics. The development of reliable, semi-automated, calibration, data capture, instrument triggering and analysis techniques are also necessary. A photograph of the test set-up is shown in Figure 11, with the clamp frame and steel frame support structure shown on the left hand side of the image. To the right, the lighting is positioned to offer an approximately uniformly-lit areas for filming purposes.

The initial trials of this experimental arrangement involved detonating 50g 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. Our current upper charge mass limit is 100g PE4/PE10, but the system can be scaled up. The results have been positive, with clear images obtained from the cameras. The next phase of trials will focus on optimising the speckle pattern, triggering and calibration.

Figure 11. Photograph of blast test arrangement, immediately prior to detonation

4.2 *Optical diagnostics for detonation and shock characterization*

The higher frame rates of the Shimadzu HPV-X2 camera system (up to 5 Mfps) is particularly useful for visualising events such as propagation of detonation fronts through an explosive charge. This highly transient phenomena can be occurs during the first few microseconds following activation of the detonator, with typical velocities of detonation of the order 4000-8000 m/s, depending on the explosive material.

To examine this, we end-detonated 48g cylindrical charges of PE10 at 200 mm SOD. The charge shape and test arrangement were designed using computational modelling (Pickering et al., in prep.) to improve the planarity of the detonation front.

The cameras successfully recorded the propagation of the detonation front through the charge during the first few microseconds after detonation. The footage also depicted the lateral expansion of the fireball from the point of detonation. Images from the footage are shown in Figure 12, with the camera filming a side view. The detonation front is approximately planar as it propagates through the cylindrical explosive charge within a few microseconds. The lateral expansion of the detonation product fireball behind the wavefront is clearly evident. This is a considerable improvement on our shock front visualization approach within the extreme near-field and within the charge itself.

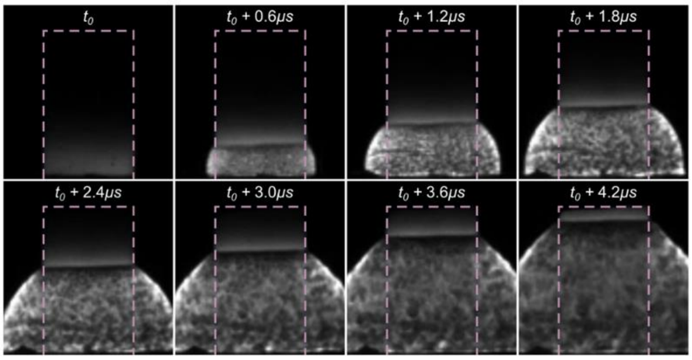

Figure 12. Camera footage showing detonation front, filmed at 1 Mfps (dotted line = initial charge shape outline overlaid)

5 CONCLUDING COMMENTS

The findings show the considerable potential of optical diagnostics for non-contact measurement of the loading and transient response of structures subjected to near-field explosions.

The initial velocity profiles obtained using stereo-imaging and DIC techniques produced specific impulses that matched well with the discrete specific impulse measurements obtained using CoBL. The inferred impulse method is sensitive enough to detect spatial variations in loading caused by surface instabilities in the expanding detonation product cloud from cylindrical charge detonations. High-speed stereo-imaging combined with DIC offers great potential for measuring the transient response of structures with high elastic capacities, such as FRP composites.

The lessons learned have informed the development of more advanced optical diagnostics at the University of Sheffield. It is capable of capturing different event types in the detonation-to-response blast event chain, from propagation of the detonation front, to displacement of downstream targets.

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