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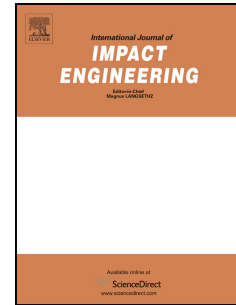
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## **The use of digital speckle radiography to study the ballistic deformation of a polymer bonded sugar (an explosive simulant)**

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### **Abstract**

This paper reports an initial study into the benefits of determining two-dimensional flow fields for low velocity impact on a small-scale model of explosive reactive armour (ERA) using digital speckle radiography (DSR). The model system consisted of a polymer-bonded sugar (PBS) (otherwise known as a sugarmock) confined between two mild steel plates. The DSR technique relies upon creating a layer within the specimen that is seeded with lead particles. So although radiography itself is mechanically non-invasive, the lead layer needed may change the mechanical properties of the material. DSR revealed where regions of intense shear occurred in normal impact. These regions are likely to be where a polymer-bonded explosive (PBX) would initiate.

### **1. Introduction to digital speckle radiography (DSR)**

Digital speckle radiography (DSR) is an X-ray technique<sup>[1-4]</sup> that makes use of digital speckle algorithms originally developed for digital speckle photography (DSP)<sup>[5-7]</sup> to measure displacement fields within optically opaque deforming specimens<sup>[8]</sup>. Measurements are made on a plane within a specimen which is seeded with high-density, X-ray opaque particles. DSR can also be used to study events where debris clouds obscure the specimen (as often occurs in ballistic impact) or if impact results in light emission.

DSR has already been successfully applied in our laboratory to the study the dynamic deformation of polymers and cements<sup>[6]</sup>, sand<sup>[9, 10]</sup>, failure fronts in glass<sup>[11]</sup>, ballistics<sup>[2, 12]</sup> and explosives<sup>[3, 13]</sup>.

Film-based X-ray images are restricted to a single exposure per experiment from a particular viewpoint which must be compared with a reference image obtained before the experiment. The full 3D flow field within the specimen can be constructed by varying both the flash delays and the depth of the speckle planes within the sample over a series of experiments if the mode of deformation is reproducible shot-to-shot<sup>[7]</sup>. In the algorithm we use, separate

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fiducial speckle patterns are required when using X-ray film to record speckle arrays before and after impact in order to account for rigid body motion during the scanning process. As with DSP, the accuracy of the technique can be improved by the use of a stereoscopic system to measure and account for out-of-plane motions<sup>[2, 14, 15]</sup>. An alternative method making use of holes in an X-ray opaque plate has been developed by Riegel & Grosch<sup>[16]</sup>.

## **2. Why study the response of explosives to impact?**

The ability to predict the response of energetic materials to impact is critical to the design of reliable systems and applications involving explosives. One application where impact on explosives is part of their intended design use is a relatively recently developed method of protecting vehicles against ballistic impact, particularly shaped charges: Explosive Reactive Armour (ERA)<sup>[17, 18]</sup>. An ERA consists of an insensitive high explosive confined between metal plates. When impacted, the shock waves generated can lead to detonation of the confined explosive, thrusting the confining metal plates apart and defeating the projectile<sup>[19-21]</sup>. ERA units must be sufficiently sensitive to achieve prompt detonation from the expected threat whilst remaining insensitive to slower projectiles that are more easily defeated through more conventional armour systems. In addition, sympathetic detonation of adjacent ERA units must be avoided. The three-dimensional interaction of shock waves at the lateral boundaries between units and the resulting material reactivity is not straightforward. In order to aid the design of appropriate units and to inform numerical models, a thorough understanding of the mechanisms involved during impact and detonation must be acquired. This can be achieved through a combination of experiments and modelling. The experimental research reported in this paper represents one stage in this process.

It is well established that low velocity projectile shape affects the response of an explosive<sup>[22]</sup>. To better understand the response of explosives to impact under different impact conditions, the chief mechanisms prompting ignition and detonation during impact must be identified. These include shear, friction, and pinch<sup>[23-28]</sup>. To this end, researchers at the Lawrence Livermore National Laboratory devised a relatively simple test (the Steven test) to investigate the effect of these parameters for confined explosives subject to low velocity impact<sup>[22, 29, 30]</sup>. In this test, an explosive disc is confined within steel and a projectile fired along the axis of the disc normal to its plane. By varying the projectile and target dimensions and materials, the importance of shear, friction and pinch can be quantified in terms of a threshold impact velocity at which explosive reaction is observed. Whilst many investigations have been performed to measure sensitivity thresholds for different configurations<sup>[31-35]</sup>, quantitative data regarding the detailed

response of the explosive is scarce. Grantham *et al.*<sup>[3]</sup> showed that DSR could be applied to the Steven test geometry in order to measure internal displacements and strains during impact. The goal of the research reported in the present paper was to address the question as to whether the DSR technique is suitable for obtaining quantitative measurements of the response of a confined polymer-bonded explosive (PBX) to impact. In particular, could the mechanical mechanisms that are known to lead to initiation be observed.

PBXs are composed of fine explosive crystals (typically  $\mu\text{m}$  –  $\text{mm}$  sized) held together by a polymer binder (typically 2-10% by mass)<sup>[36]</sup>. PBXs have a relatively high tensile strength and low sensitivity to mechanical stimuli (such as shock) whilst retaining excellent explosive properties<sup>[36]</sup>. The reduced sensitivity of a PBX compared to pure explosive crystals makes them safer to manufacture, store, transport and handle<sup>[36]</sup>. Also the mixture can be extruded and cut into a variety of shapes, sheets and cords for their intended use<sup>[36]</sup>. As it is hazardous to perform impact experiments on PBXs<sup>[37]</sup>, polymer bonded sugars are often preferred, particularly in university laboratories<sup>[38-40]</sup>. A polymer-bonded sugar (PBS) (or sugarmock) is a particulate composite material in which sugar rather than explosive crystals is mixed into a polymer binder. PBSs allow safe investigation of the effect of various parameters, such as particle size and distribution, on mechanical properties<sup>[40-43]</sup>. These parameters are of interest as they are known to affect the material strength of a PBX<sup>[44-46]</sup>.

The thickness of the front plate in targets consisting of confined explosive is known to affect the threshold impact velocity for reaction<sup>[47]</sup>. This comes about through changing the degree of bulging and hence the stress field within the explosive which can in turn change where zones of intense shear form. For this reason, we performed a parallel study<sup>[15, 48-50]</sup> into an experimental method of determining the dynamic response of thin metal plates to impact and comparing the results with model predictions. In the research reported in this paper, we report the response of small-scale layered targets containing a PBS.

### 3. Experimental arrangement

Projectiles were fired using a light gas-gun<sup>[51]</sup> into a target chamber pumped down to a rough vacuum in order (i) to silence the gun; (ii) reduce (and often eliminate) impact flash due to trapped gas; and (iii) to reduce bow shocks in the air ahead of the projectile that could disturb the alignment of the target (figure 1) and hence reduce measurement accuracy. The projectile was mounted on a sabot to provide stability during acceleration down the barrel. To avoid projectile tumbling and to maintain target alignment, the impact occurred when the sabot was still partially inside the barrel. The impact velocity,  $810 \pm 5$  m/s, was measured at the end of the

barrel using laser light gates. The X-ray system was triggered (after an appropriate delay set using a delay generator) by the impact of the projectile on an impact sensor placed at the surface of the target.

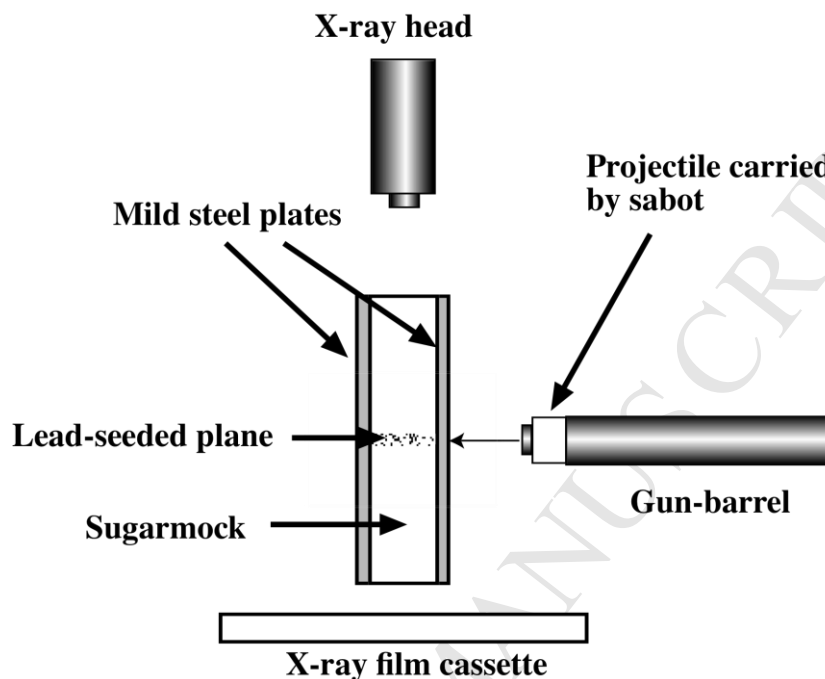


Figure 1. Schematic diagram of experimental arrangement.

A short flash from an X-ray tube placed above the evacuated impact chamber projected an image of the randomly scattered lead particles forming the speckle plane onto X-ray film contained within an armoured cassette placed beneath the target. In each experiment, two radiographs were taken on separate pieces of film: one before (for reference) and one during the impact. A delay generator was used to vary the time from impact that the flash X-ray was triggered. Three normal impacts were performed, at 5, 8 and 10  $\mu\text{s}$  after impact, and one oblique (10  $\mu\text{s}$  after impact), the angle of impact being  $30^\circ$  to the horizontal.

The PBS material was made by mixing icing sugar (particle size  $\sim 38 \mu\text{m}$ ) into a polymer binder hydroxy-terminated polybutadiene (HTPB), the sugar loading being 75% by mass. This material was intended as a simulant for Detasheet, a PETN-based PBX. It should be noted that the mechanical response of the sugarmock material used in these experiments was not fully characterised, but in general, its response under tension was more brittle than the PBX it was intended to simulate. These experiments cannot therefore provide quantitative data applicable to Detasheet. But the PBS was still worth studying in order to identify regions of intense deformation and flow which, if they form in the PBX, could lead to initiation<sup>[27, 52, 53]</sup>. The

targets used in these experiments consisted of a PBS sheet,  $15.0 \pm 0.1$  mm thick, confined between two mild steel sheets of similar area but with thicknesses of  $0.82 \pm 0.05$  mm.

The mid-plane of the PBS slabs was seeded with lead filings (see figure 1) between 0.5 mm and 1 mm in size. The area density of lead particles used was a compromise between ensuring that the seeded layer did not have mechanical properties substantially different to the surrounding PBS material yet were still able to generate a resolvable pattern on the X-ray film. Previous studies showed that a 15 to 20 % coverage was about right<sup>[54]</sup>. This level of coverage meant that the resulting area density of speckles on the X-ray film was much lower than for conventional laser speckle<sup>[55-57]</sup>.

The projectiles used were mild steel discs  $12.7 \pm 0.1$  mm in diameter and  $3.00 \pm 0.05$  mm thick, mounted on the front a cylindrical polymer sabot, hollowed to reduce the total mass and hence increase the maximum achievable impact velocity (figure 2).

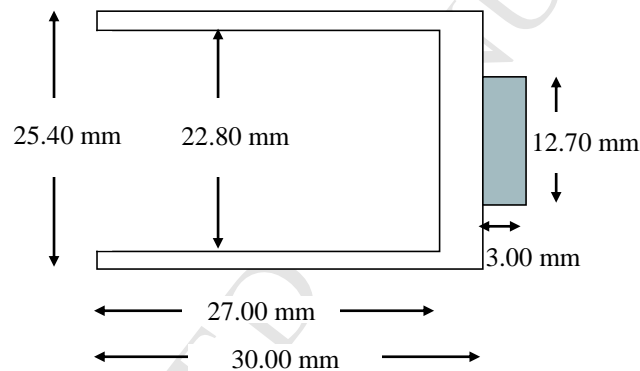


Figure 2. Schematic diagram of the projectiles used in this study.

The flash X-ray system used was a Scandiflash 150 keV system, providing a single pulse, short duration (70 ns) X-ray flash with a 3 mm source size. The X-ray source was positioned with its tube axis parallel to the normal of the plane seeded with lead filings. The armoured X-ray film cassette used consisted of an intensifier screen (3M Imation Trimax) behind which was X-ray film (3M Trimax XDA Plus). The cassette was placed parallel to and below the seeded plane within the evacuated target chamber. The short duration of the X-ray flash minimised blur of the speckle pattern due to motion within the seeded plane.

There are several problems connected with the fact that the X-ray source used was neither collimated nor a point source. First, the intensity was not even across the image plane: it depended upon both the beam structure and the distance to the X-ray source. Second, the resolution of the speckle pattern depended upon the distance between the object and image

planes (see figure 3a). However, the contrast change across a radiograph is usually insufficient to cause decorrelation, provided that the physical displacements are small compared with the variation in contrast<sup>[51]</sup>. For severe differences in contrast, a Gaussian function can be fitted and subtracted to correct for the effect of the X-ray beam intensity profile<sup>[54]</sup>. This was found not be necessary in the work reported here.

The finite beam width results in the formation of a penumbra at each speckle, reducing the sharpness of the speckle pattern in the radiograph. Speckle blur becomes more severe with increasing distance between the object and image planes. This means that the separation of the lead filings must be increased to avoid overlap in the images (figure 3). The object-to-image distance was limited by the requirement that the specimen size should be sufficiently large that it could be considered to be of infinite lateral extent during the early stages of impact. The speckle patterns obtained had adequate resolution, but a finer, more dispersed pattern than used here would improve the correlation results. Higher electron-density particles (tungsten, for example) would also increase the contrast.

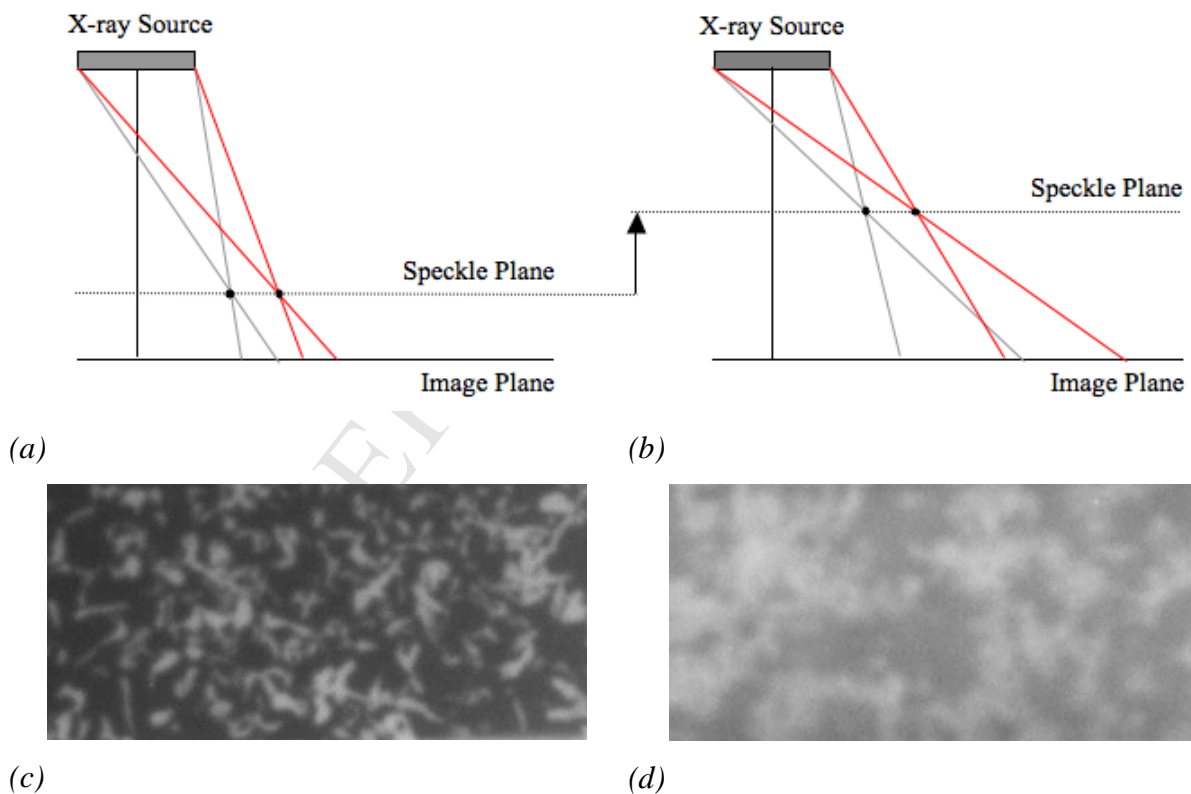


Figure 3. (a) Schematic diagram showing projection of two speckles using a finite width X-ray source where the speckle plane is close to the image plane: images are resolved. (b) Schematic diagram showing projection of two speckles using a finite width X-ray source where the speckle plane is further from the image plane: images overlap. (c) Radiograph of speckle pattern where



*the object-to-image distance was  $18.0 \pm 0.5$  mm. Speckles were resolved. (d) Radiograph of speckle pattern where the object-to-image distance was  $53.5 \pm 0.5$  mm. Speckles overlap.*

The X-ray films were scanned and converted into an appropriate digital format. A fiducial (i.e. fixed, non-deforming) speckle pattern in the field of view was essential (figure 4) in order to correct for any translations and rotations of the X-ray film produced during the scanning process. This fiducial pattern was formed from lead filings (between 0.5 mm and 1 mm in diameter) set in epoxy and placed close to but mechanically isolated from the target specimen. Any rigid body motion between the reference and deformed images was calculated by fitting regression planes to the displacement fields of the fiducial pattern of the form:

$$\begin{pmatrix} u_{fiducial} \\ v_{fiducial} \end{pmatrix} = \begin{pmatrix} a_u & b_u & c_u \\ a_v & b_v & c_v \end{pmatrix} \begin{pmatrix} dx \\ dy \\ 1 \end{pmatrix}, \quad (1)$$

where  $(u_{fiducial}, v_{fiducial})$  represents the  $u$  and  $v$  displacements and  $a$ ,  $b$  and  $c$  are the constants to be calculated. The corresponding rigid body motion can then be calculated for the target speckle pattern and corrected.

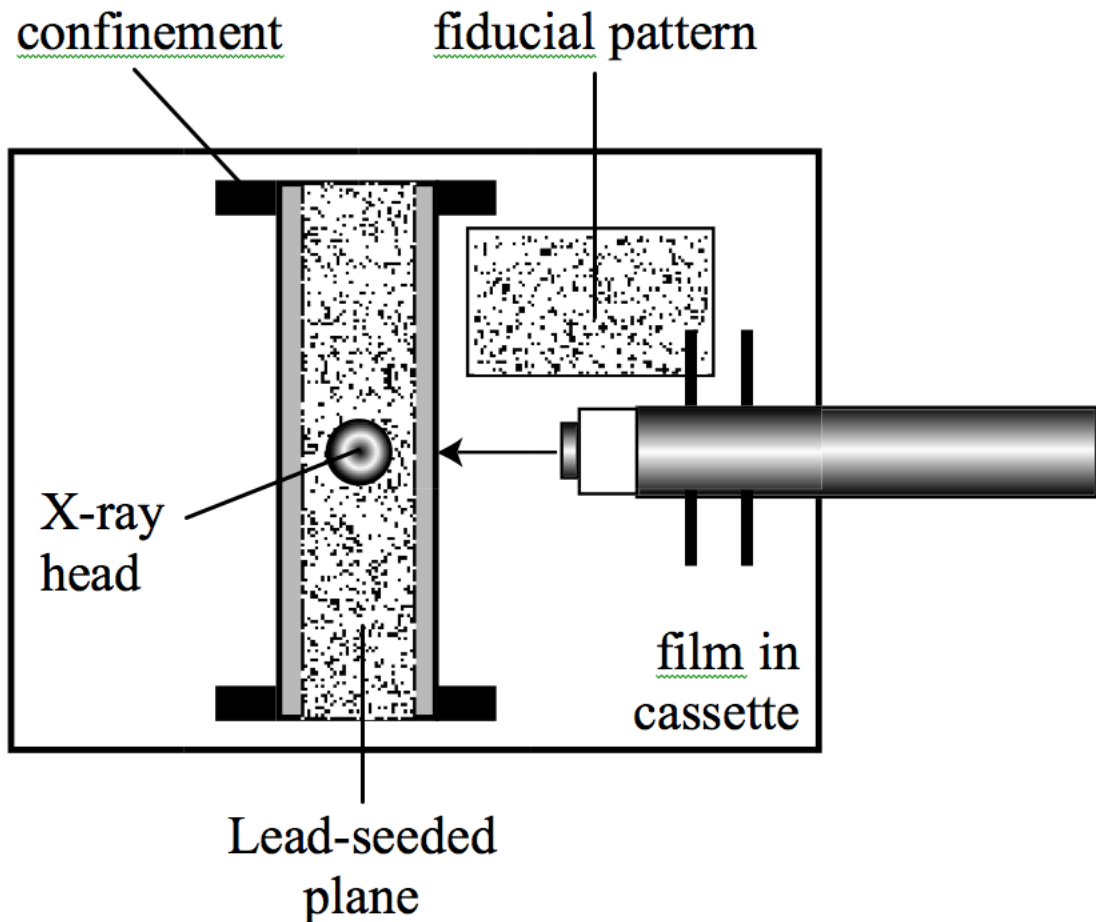


Figure 4. Schematic diagram of top view of experimental arrangement showing in particular the position of the fiducial pattern necessary to compensate for any rigid body displacements and rotations between the radiographs taken before and that during impact.

Grantham<sup>[54]</sup> has shown that the most significant source of error (ranging from  $\pm 5\%$  to  $\pm 20\%$ ) in the final displacement measurements is produced by the plane fitting operation. This makes close proximity of the fiducial pattern to the specimen pattern vital to minimise rotation errors. Rigid body motion is random, being caused by factors such as the position of the film within the cassette and misalignments during scanning. The errors associated with correcting the deformation data for rigid body motion are independent of the local deformation field and depend only upon (i) the quality of the data and (ii) the limits of the algorithm scaled by the distance to the centre of rotation.

Calibration experiments involving known rigid-body displacements showed the importance of pre-processing data to remove uncorrelated and spurious points as well as points which experience the edge effect, prior to fitting a plane to the fiducial speckle pattern to maximise

accuracy. In addition, a series of radiographs were taken in which the PBS was rotated through known angles (several degrees) measured using a rotation stage (sensitive to  $\pm 0.08^\circ$ ). The data were pre-processed and a plane fitted to the fiducial speckle pattern using a sub-image of width 32 pixels. Whilst the error in a non-integer translational displacement was found to be 0.06 pixels, the angle of rotation of the PBS was determined with an uncertainty of typically  $\pm 5\%$ . This then is the limiting accuracy of measurements of the PBS internal flow field.

The DIC algorithm calculates displacement in pixels in the image plane. In order that this can be converted to displacement in mm in the object plane, an appropriate scaling factor (mm / pixels) must be applied. This was determined by taking a radiograph of a grid of known pitch placed in the same plane as the specimen speckle pattern<sup>[54, 58, 59]</sup> and then performing a 2D Fourier transform on the image of the grid in order to select the appropriate frequencies in Fourier space. It is necessary to do a 2D Fourier transform since any rotation of the grid with respect to the spectral axes will result in the resolved components on each axis being a different frequency to the true grid pitch. The image is then inverse Fourier transformed and the phase is calculated and unwrapped<sup>[58, 59]</sup>. The phase plane gradient gives the grid periodicity in pixels from which an accurate scale-factor for the imaged speckle pattern can be determined.

## 4. Results

### *(a) Normal impact*

The radiograph shown in figure 5 shows the experimental arrangement for a normal impact. Part of the fiducial speckle pattern is shown in the top left corner of the image. Wires seen just in front of the impact site connect to the impact sensor. The screws form part of the lateral confinement at the sides of the target. The rear confining plate appears to be thicker than the identical front plate because the X-ray beam was positioned directly above the front plate. In this radiograph, the projectile has already perforated the mild steel front plate, pushing out a circular disk which has become fused to the projectile nose (figure 6a). Subsequent impact by the sabot enlarges the hole in the front plate (figure 6b). Petaling of the front plate was also sometimes observed post-impact. The rear plate was also perforated (figure 6d). The region of the sugarmock in the path of the projectile disintegrated, leaving a hole that tapered towards the rear plate (figure 6c). The rest of the sugarmock layer was fragmented into approximately five pieces (figure 6c).

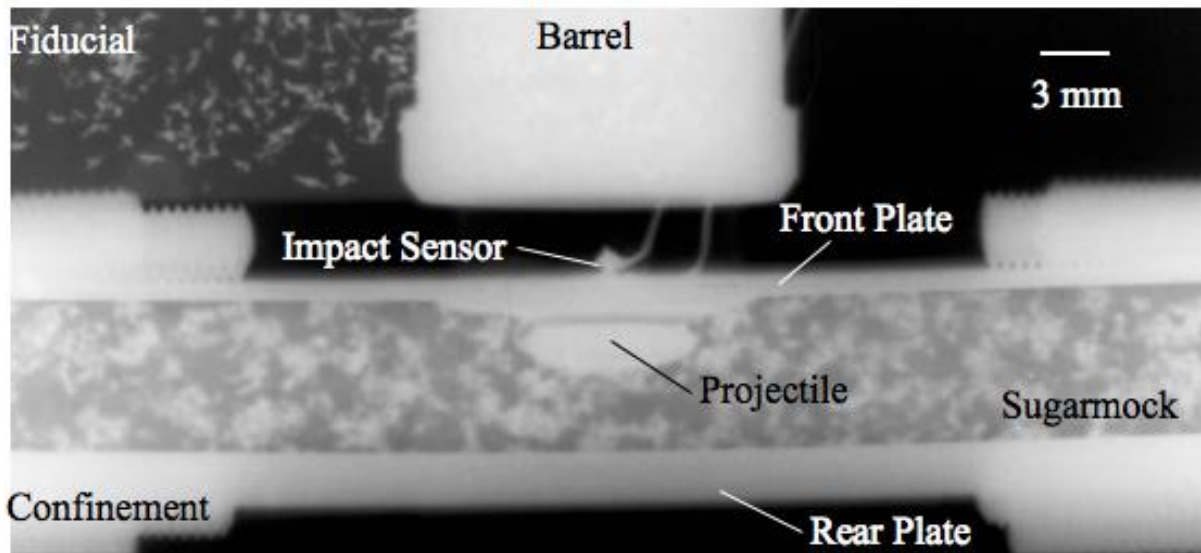


Figure 5. Labelled radiograph taken  $9 \mu\text{s}$  after impact. The sabot is transparent to X-rays.

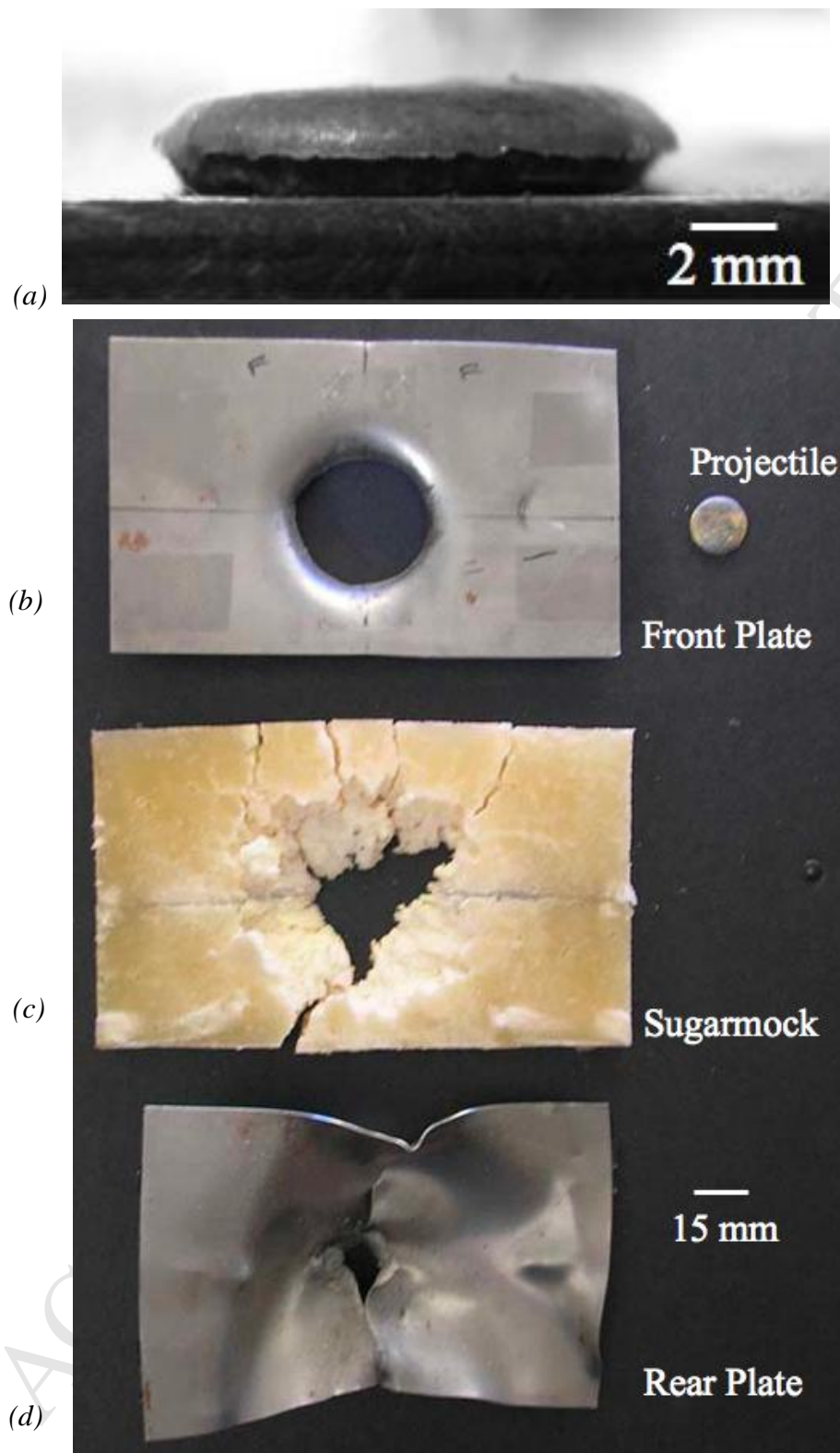


Figure 6. (a) Recovered projectile (side view). (b) Recovered front plate with top view of projectile for comparison. (c) Recovered PBS sugarmock layer. (d) Recovered rear plate.

Radiographs taken at various times after impact (different experiments) are shown in figure 7. The projectile can be seen to penetrate the front plate forming a small bulge (figure 7a) before shearing out a thin plug from the front target plate (figure 7b). The width of the deformed region of the front plate in figure 7c is far larger than the diameter of the projectile due to impact of the sabot (which is transparent to X-rays). The rear plate can be seen to bulge in figure 7c before the projectile has struck it. This suggests that the sugarmock, although a relatively soft material, is sufficiently confined that the pressure within it causes the mild steel plate to deform.

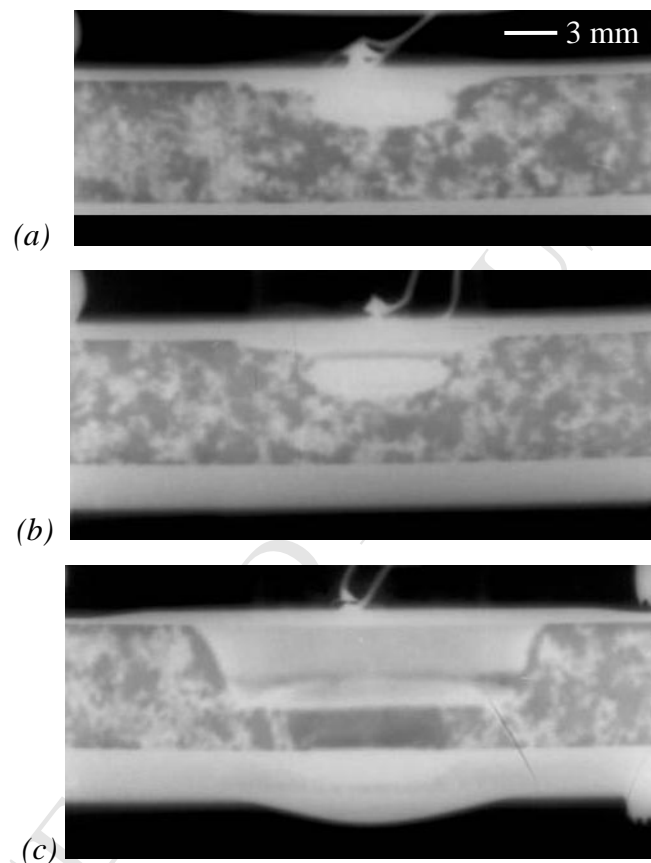


Figure 7. Radiograph images for normal impact at  $810 \pm 5 \text{ m s}^{-1}$ .  
Times after impact: (a)  $6 \mu\text{s}$ , (b)  $9 \mu\text{s}$  and (c)  $19 \mu\text{s}$ .

The displacements of the speckles within the radiographs shown in figure 7 were analyzed to give the material flow within the sugarmock as a set of displacement vectors (figure 8). The speckle size was large compared with the specimen, limiting the quantity of data that could be extracted owing to edge effects. A  $2.5 \pm 0.1 \text{ mm}$  width sub-image size ( $32 \times 32 \text{ pixels}^2$ ) was used in the correlation algorithm. Clearly, in the immediate vicinity of the projectile where the front



plate bulges into the sugarmock, correlation of the speckle pattern is not possible. The uncertainty in all measurements is  $\pm 5\%$ .

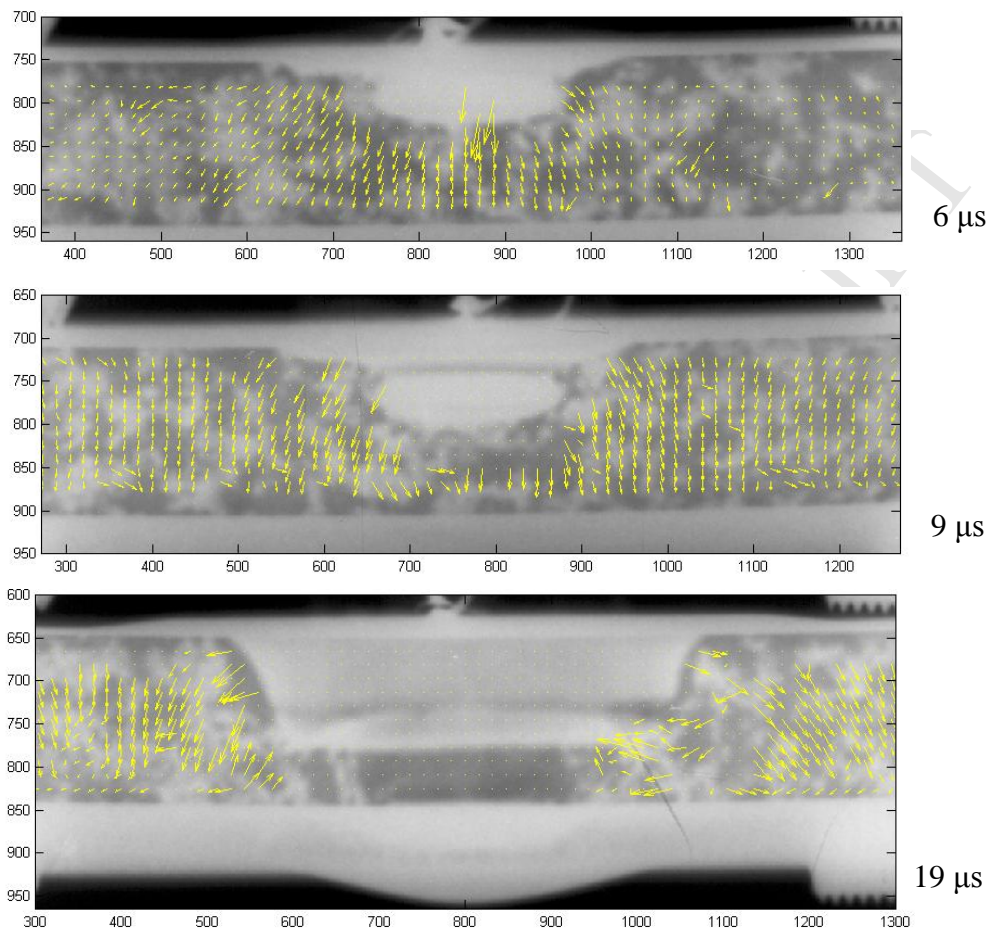


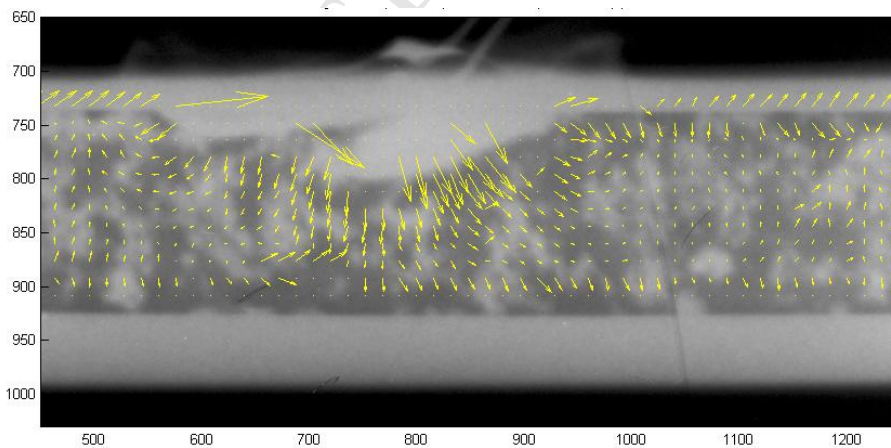
Figure 8. Quiver plots at  $6\ \mu\text{s}$ ,  $9\ \mu\text{s}$  and  $19\ \mu\text{s}$  for a normal impact at  $810 \pm 5\ \text{m s}^{-1}$ . For clarity, only some of displacement vectors calculated are shown. The projectile was moving from top to bottom though the centre of each image. The x and y-axes give the sugarmock dimensions in pixels, with a scale-factor of  $12.6 \pm 0.4\ \text{pixels mm}^{-1}$ .

Initially ( $6\ \mu\text{s}$ ), the sugarmock can be seen to flow radially outwards from the impact site increasing the lateral confinement of the sugarmock ahead of the projectile. The flow field extends approximately 30 mm from the impact site. By  $9\ \mu\text{s}$ , the shock waves due to impact have passed through the portion of sugarmock layer that is within the field-of-view, resulting in net displacement along the impact axis. After the projectile has perforated the front plate, the sabot continues to deform the front plate, expanding the entrance aperture and further compressing the PBS ( $19\ \mu\text{s}$ ). Once the front plate is perforated the pressure in the sugarmock around the edge of the projectile is relieved by flow inwards towards the impact axis and front

plate aperture, producing a region of high shear due to PBS material also being pushed radially outwards. The relatively large amount of decorrelated data in this region of high shear makes it difficult to determine the shear strain history throughout the PBS layer, but the opposing flow directions either side of the shear zone are evident. Material in front of the projectile continues to be pinched between the projectile and rear plate. By this stage ( $19 \mu\text{s}$ ), shock waves will have reached the lateral confinement, affecting subsequent flow.

*(b) Oblique impact*

Figure 9 presents a radiographic image (with displacement vectors superimposed) of the oblique impact ( $30^\circ$  to the target normal) of a confined PBS target  $6 \mu\text{s}$  after impact. Asymmetric deformation can be seen to be localized near the impact site and hence is not influenced by the lateral target confinement. All displacements are of comparable magnitude to those measured for a normal impact  $6 \mu\text{s}$  after impact. Regions of high shear are not visible, although it is always possible they might develop at later times. The angles of impact that could be studied were restricted by the need to ensure that the projectile struck the target before the sabot. A sabot-stripper to remove the sabot upon exit from the barrel would have overcome this problem, though our experience with firing rods this way convinced us that it would be difficult to engineer for disc-shaped projectiles.



*Figure 9. Quiver plot at  $6 \mu\text{s}$  after impact for an oblique impact at  $810 \pm 5 \text{ m/s}$ , impact took place at an angle of  $30^\circ$  to the target normal. For clarity, the displacement vectors are scaled by a factor of 2 and only some of the calculated vectors are shown. The projectile was moving from top to bottom and from left to right. The x and y-axes give the sugarmock dimensions in pixels, with a scale-factor of  $12.3 \pm 0.2 \text{ pixels mm}^{-1}$ .*



## 5. Conclusions and suggestions for future work

During normal impact, flow within the PBS was initially radial and symmetric about the impact axis. The rear plate was observed to bulge before the projectile had traversed the full thickness of the PBS, indicating that some sugarmock material was pinched between the rear plate and projectile. The perforation of the front plate provided local relief for the compressed sugarmock, resulting in shear as some material moved towards the front plate aperture whilst adjacent material continued to be pushed away from the impact site by the bulging front plate. For oblique impact, asymmetric flow of the PBS material was observed which was biased towards the direction of projectile flight.

The accuracy of the measurements ( $\pm 5\%$ ) was limited by the alignment of fiducial patterns between the reference and deformed radiographic images. The need for fiducial patterns can be removed by using a double-exposure method<sup>[56, 60]</sup> though at the cost of slower analysis.

The dimensions of the target were not ideal for DIC analysis. The boundaries of the speckle pattern at the front and rear plates were susceptible to the edge effect and the averaging effects of non-uniform displacement fields either side of the metal confinement. Smaller lead particles would allow the use of smaller sub-images, thus increasing the resolution of the measurements and reducing the range of the edge and averaging effects, but at the price of lower contrast in the radiographs.

Deformation of the target was produced by the sabot as well as the projectile. This was a particularly important consideration for oblique impact where the angles of impact that could be studied was restricted by the need for the projectile to strike the target before the sabot. A sabot-stripper to remove the sabot upon exit from the barrel would overcome this problem, though this is difficult to engineer, particularly for disc-shaped impactors, and would increase the complexity of the experiment.

Despite the ease of seeding an internal plane with lead filings during casting, the resulting sugarmock was more brittle than the PBX of interest (Detasheet). The speckle technique could be applied to targets containing Detasheet itself by pressing lead filings between two layers of the sheet explosive. However, safety restrictions limit the quantity of explosive that can be impacted in our laboratory. Hence the target would need to be smaller and boundary effects would influence the deformation at much shorter times.

Both pinch and shear were observed. Future research using DSR should investigate the evolution of each mode of deformation with time for different projectile nose-shapes. More accurate information on the mechanical response of an ERA to impact could be obtained by

using stereoscopic DSR, as was done in our parallel study of the dynamic bulging of plates<sup>[15, 48-50]</sup>.

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