Laboratory-scale techniques for the measurement of a material response to an explosive blast

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ABSTRACT

Laboratory-scale experiments were performed to measure the deformation of thin plates in response to varying explosive impulse. Experiments were conducted with a known explosive mass suspended in air at a known distance from an aluminum witness plate clamped in a ''shock-hole'' fixture. Through the use of well-characterized PETN and TATP explosive charges, the explosive impulse applied to each witness plate was determined a priori. The witness-plate response was measured using high-speed digital cameras to determine time-resolved, three-dimensional surface motion and maximum plate deformation. The results show that the maximum dynamic plate deformation is a straightforward function of applied explosive impulse, as determined from the explosive characterization. The experimental trend is the same despite the two different explosives used, highlighting that explosive impulse, determined through a blast characterization, is the controlling parameter in material blast response. A new experimental technique is used here to measure the dynamic blast response and the experimental errors are documented. Ultimately, applications of laboratory-scale explosive testing to computational code validation, material response scaling, and high-speed material property definition are discussed.

1. I

Explosive blast research is important in understanding the damage caused by an explosion and also for the development of blast-resistant materials. Typically, explosive blast tests are conducted on full-scale models or structures to determine the actual material response [1]. Even the smallest of these full-scale tests can require 10–100 kg explosive charges at distances of up to 100 m from the test article, which forces these tests outdoors into relatively uncontrolled settings [2]. At this scale, instrumentation becomes difficult and expensive, often yielding only point-wise piezoelectric pressure profiles at limited locations and a qualitative rather than quantitative evaluation of material deformation. Optical methods to reveal shock waves in such field testing, such as background distortion and sunlight shadowgraphy, are often crude and weather-dependent [3]. Overall, the instrumentation difficulties and prohibitive cost of large-scale blast testing often result in limited experiments and even-more-limited data. Although not able to completely eliminate full-scale testing, laboratory-scale experiments nonetheless provide unique data collection opportunities and new insights into the physical phenomena.

The majority of the published laboratory-scale research focuses on how a ''witness plate'' is deformed due to an explosive blast. These tests typically result in post-test measurements of maximum plate deflection and qualitative plate shape [4]. Nurick et al. persurface shapes by using two high-speed digital cameras in stereo and digital image correlation software. This non-contact optical method is simple to implement and requires only optical access to the deforming surface, and thus is used in the present research.

Although previous experimental investigations have developed complex methods for measuring plate deformation, they suffer a lack of full knowledge of the explosive energy input and explosive impulse. Explosive impulse is defined as the integral of shock wave overpressure with respect to time, and represents momentum assocptical surface that can be identified and analyzed by the software. The random dot pattern is spray-painted onto the backside of each aluminum witness plate before it is placed into the test fixture. The dot pattern should have many dots, each occupying an area of approximately 5 camera pixels, across the field to be analyzed.

Fig. 3 shows a typical dot pattern on a witness-plate surface as seen from the two cameras. The field-of-view shown is typical of all present experiments, and focuses on the centerline of the plate as discussed in Section 3.1. The circular shock-hole plate fixture edge can be seen in the images, with horizontal fiducial marks on the fixture to indicate the horizontal diameter of the opening. By imaging this field-of-view, each experiment thus produces temporally-resolved witness-plate deformation data for the central plate diameter, which are analyzed to determine maximum deformation.

The plate fixture is illuminated with three 600 W continuous Calumet flood lights. The lights are positioned at oblique angles to the plate surface to decrease glare reflection from the plate into the camera lenses. The illumination was experimentally chosen to fully and evenly illuminate the plate surface and allow camera shutter speeds as short as 4 μs, thus minimizing image blur during the explosive event. Greater illumination, if available, would allow a decrease in lens aperture and possibly a further increase in shutter speed. Trial-and-error methods with the dot pattern show that black dots on a white field require less illumination than the opposite, and are therefore used throughout the present work. Illumination requirements change with field-of-view, choice of lens, and f-stop setting.

2.3. Explosive charges

Well-characterized explosive charges are used, so that the explosive loading of each witness plate is accurately known. Two

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is actually measured in order to allow the required frame rate and spatial resolution to properly capture the plate motion. For the present research, the horizontal diameter of the exposed plate surface is centered within the field-of-view and approximately 0.03 m of the plate surface above and below this diameter is imaged, as shown in Fig. 3. This strip-wise view conforms to the Photron APX-RS camera's rectangular field-of-view capability at high frame rates.

Before limiting the field-of-view to this region, however, illumination and careful paint application along with fragment-free explosive charges are important to maximize useful data collection. To improve paint adhesion to the aluminum plate, the surface is lightly roughened with 100-grit sandpaper prior to paint application.

3.2. Experimental error estimation

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plate deformation occurs here, was approximately ± 0.05 mm. The final fixture position was also determined to be within ± 0.05 mm of the original fixture position, indicating that the fixture does not have any significant translational motion during the event.

Through superposition, the total experimental error in all plate surface measurements was determined to be ± 0.10 mm. This error is applied to all dynamic deformation measurements, for all impulse conditions and for the camera position and resolution that remained fixed during the present experiments.

3.3. Description of material deformation

Qualitatively, the witness-plate motion is initiated by its midpoint acceleration, at the point of first shock incidence and maximum impulse. This motion drives the plate shape for approximately the first 500 μs of the event. Thereafter a deformation wave, reflected from the circular shock-hole fixture boundary, dominates the plate motion and ultimately determines the final plate shape. This deformation wave is not considered further here, but has been examined by Hargather [23]. The present work focuses on measuring the initial maximum plate deformation, which is independent of the deformation wave reflection from the clamped boundary.

To analyze the initial plate motion, five physical locations on the witness-plate surface are identified as shown in Fig. 8: LL, L, M, R, RR. These five points are symmetrically positioned, with point M being the plate midpoint. The deformation contours shown in Fig. 8 are those at the time of maximum witness-plate deflection.

By analyzing the deformation-time history of each of these points, as shown in Fig. 9, the initial plate deformation process can be understood. The center of the plate, M, is accelerated first and, as it deforms, the remainder of the plate surface also begins to deform with it, starting at the innermost points L and R. The center point reaches its maximum deformation and then begins to move in the reverse direction. The other points reach their maximum deformations fractions of a millisecond later. The arrival of an in-plane deformation wave can be observed at points LL and RR at about $t = 0.3$ ms after the initial deformation. This deformation wave propagates toward the plate center and arrives at the next points, L and R, at about $t = 0.5$ ms. The deformation wave arrival is noted by the change in slope of the plate deformation at these times, but is more easily seen in Fig. 10.

Fig. 10 shows several deformation profiles across the witness-plate diameter during the first 667 μs of the explosive event. After reaching its maximum deformation at approximately time $t = 0.1$ ms in Fig. 9, the plate midpoint deflects back in the direction of the explosion, as also seen from Fig. 9. This is the beginning of plate oscillations that occur for approximately 10 ms before eventually damping and leaving the plate in its final deformation state.

After the plate has reached its initial maximum deformation, before the $t = 167$ μs curve in Fig. 10, a deformation wave enters the measurement region near the circular shock-hole fixture boundary, as noted above. This deformation wave appears to be a reflection from the clamped plate boundary. This wave grows in amplitude as it approaches the center of the plate. It can first be seen at $t = 333$ μs in Fig. 10, but is more clearly visible at the two later times shown in the figure. The deformation wave eventually reaches the center of the plate and decreases in amplitude, but continues t..3099g its maxi increases with increasing impulse for each explosive material, which is a result of the characterization procedure [19]. The error in deformation measurement, as discussed in Section 3.2, is approximately ± 0.10 mm and is represented by the symbol size in Fig. 11.

Fig. 11 reveals one benefit of using more than one explosive material in these experiments: error reduction in the region of impulse overlap. The error for TATP at an impulse of 20 Pa s is large, but at the same impulse, PETN has a much smaller error bar (the error for TATP is larger because the TATP must be placed closer to the plate surface to obtain the same impulse). The present experimental data have increasing error at decreasing stand-off distance from the explosive, as discussed elsewhere [19,23]. Thus, measurement error can be minimized by conducting experiments at larger stand-off distances with larger charge masses.

The stand-off distance can be increased without limit, although at larger distances the shock wave becomes almost planar and impacts the entire plate surface at once. This change in plate loading affects the results but is not presently studied. The present results use both PETN and TATP charges across a range of stand-off distances limited to 0.15 m or less (Tables 1 and 2). By judiciously experimenting with various explosive materials, the raes.

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research conducted with witness plates of various thicknesses and exposed surface areas would build a broader understanding of the scaling of material responses. Ultimately the techniques can be applied to exotic materials to explore the range of non-linear loading responses produced by novel materials. These comparatively-inexpensive laboratory experiments can thus be used to scale material responses and to estimate full-scale results before conducting expensive full-scale experiments.

These techniques are also well-suited to compliment computational simulations. They provide high-resolution experimental data, with known and highly-controlled boundary conditions, which are ideal for computational code validation. Such experimental results could be used to validate material models or blast computations on a small-scale experiment before modeling a full-scale problem. Laboratory-scale experimental blast data could also be used to inversely determine non-linear and rate-dependent material properties of aluminum or of novel blast-resistant materials.

5. C

A new method is presented to conduct quantitative material blast experiments in the laboratory. The approach focused on developing a detailed understanding of the applied explosive load and the resulting material deformation. It was shown that the maximum deformation of simple aluminum witness plates, clamped in a shock-hole fixture, scales according to the applied explosive impulse, as determined from an explosive characterization.

The use here of two different previously-characterized explosives has improved the understanding of the explosive loading during a material blast experiment. The technique of propagating the explosively-driven shock wave through air before impacting the witness plate is new to the present work. Through this approach, the exact loading conditions on the plate are well known, and can thus be used directly to scale results or validate computational models.

A linear impulse-deformation relationship was found for the present experiments, as previously reported elsewhere [27]. However, the ability to scale material deformations across explo-