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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. Introduction

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. performed the majority of the initial work and established standard terms for the qualitative categorization of witness-plate failures into one of three modes [5]. Dynamic deformation measurements were also performed, with the simplest methods producing point measurements of witness-plate deflection as a function of time [6,7]. Other methods use strain gages to measure strain rates at specified locations on the surface of the material [8]. Optical methods, however, provide the unique ability to measure deformation without contacting the plate surface. A method developed by Nurick and Martin [9], determined plate deformation by measuring when the plate surface disrupted a laser beam parallel to the initial plate surface, but was limited to determining maximum deflection and not surface shape. More recent methods, including those used by Espinosa et al. [10,11], use laser interference and Moire patterns to determine time-resolved, three-dimensional material deformations and shapes. The optical technique evaluated by Siebert et al. [12] and used by Fourney et al. [13,14] and Tiwari et al. [15] is capable of measuring time-resolved, three-dimensional

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surface 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 associated with the shock wave propagation. When a shock wave impinges upon a witness plate, a portion of this momentum is transfered to the plate, resulting in plate motion and deformation. Determining the exact momentum imparted to the plate, however, is difficult and depends upon plate physical properties and deformation response.

Bodner and Symonds [16] developed a ballistic pendulum method to estimate the explosive impulse applied to plates in laboratory blast experiments. Through an energy balance, the ballistic pendulum method estimates the explosive impulse from the change in height of a free-swinging mass [17]. It does not, however, directly measure the primary shock wave energy applied to a witness plate, but rather a total energy impulse delivered to the ballistic pendulum fixture over the entire event. This measurement neither directly accounts for variations in shock strength and overpressure duration, nor does it discriminate between positive and negative blast impulses.

The accurate measurement of the explosive impulse applied to a witness plate is further complicated, in the previous research, by the frequent use of a foam insert between the explosive and plate [16,18]. Foam inserts were used to modify the blast parameters to prevent the plates from failing in shear [16]. This modification of the blast parameters, however, changes the impulse shape and ultimately the resulting plate deformation in ways that are not simple to understand. The actual plate loading conditions cannot be measured in these laboratory-scale experiments, and therefore cannot be directly extrapolated to actual full-scale air-blast experiments.

The present research presents a new method for conducting witness-plate blast deformation experiments in the laboratory. The present method uses explosives that have been characterized using the high-speed optical method of Hargather and Settles [19] and Kleine et al. [20]. By way of this characterization procedure, the shock wave explosive impulse is known as a function of radius from the charge. A charge of known mass is then exploded at a known stand-off distance from the witness plate and the dynamic, time-resolved, three-dimensional material deformation is measured using twin high-speed cameras. The explosive energy from the charge is thus coupled to the witness plate through the air. In this manner, the explosive impulse delivered to the plate via the shock wave is well known and representative of typical blast-loading scenarios.

2. Experimental methods

The primary objective of the present research is to develop the techniques required for measuring material responses to explosive impulses. This research is dependent on accurate characterization of the explosives used and on precise measurement of material deformation. A characterized explosive is exploded at a known distance from a thin aluminum plate, deforming the plate due to explosive impulse. Optical image correlation is used to measure the time-resolved, three-dimensional surface shape of the deforming plate throughout the explosive event. Aluminum alloy 3003, 0.406 mm thickness, was used here as the witness-plate material. The aluminum was purchased from McMaster-Carr, Inc., and had quoted yield strength of 144.8 MPa and a Brinell hardness of 40, meeting manufacturing standard ASTM B209.

2.1. Shock-hole fixture

A single witness plate of aluminum is bolted into a "shock-hole"[1] fixture, as shown in Fig. 1. The exposed portion of the aluminum plate is a 0.25 m diameter circle which is centered on the plate. The rest of the plate remains firmly clamped within the shock-hole fixture by the 12 symmetrically-arranged bolts, which are hand-tightened with a wrench. This fixture eliminates all visible plate wrinkling at the clamped boundary and prevents slippage from the clamped region into the exposed, circular measurement area. The effect of the clamp depth on the applied impulse was not considered here, since recent work by Bonorchis and Nurick showed that clamp depth did not influence the maximum plate deformation [21]. The entire shock-hole fixture is mounted vertically, 1.2 m above the floor on the edge of a rigid platform, in the center of a 12.2×13.7 m room where shock reflections can be ignored.

The witness-plate fixture was also designed to provide the optical access required to make deformation measurements, as described in Section 2.2. The complete setup for the present material deformation research is shown in Fig. 2. The plate fixture location relative to the cameras is fixed and the "stand-off distance" from the plate surface to the center of the explosive charge is a primary variable. As the stand-off distance is changed, the explosive impulse applied to the plate is varied, as discussed in Section 2.3. The face of the plate nearest the explosive will be referred to as the "front" of the plate and the "back" will indicate the face being imaged by the cameras.

2.2. Optical deformation measurement

Vic-3D software by Correlated Solutions Inc. is used in the present research to measure witness-plate deformation [22]. This software uses simultaneous images from two cameras in parallax to mathematically define a surface of arbitrary shape, here the back-side of the witness plate. With the use of two high-speed Photron APX-RS digital video cameras, a time-resolved record of plate shape history can be created and deformation data thus extracted. For the current research, deformation refers to the change in the measured out-of-plane plate position relative to a reference position defined before any explosive loading occurs.

The first step in using this software is to perform a calibration for the orientation of the two cameras relative to each other and to the field-of-view. The cameras must be positioned so that they both image the desired field-of-view, in this case the backside of the witness plate. The cameras are placed at an angle, β, relative to one another as shown in Fig. 2. The stereo calibration accounts for this primary stereoscopic angle and also the corresponding angles in the two other orthogonal planes, all of which are approximately zero in the present research. The angle β between the cameras is in the range of 20–40°, which maximizes the measurement sensitivity for the software used here.

Once calibrated, the software is able to interpret where in space an object is located, based on its appearance from the two camera perspectives. In order to make measurements on a witness-plate surface, the surface is painted with a high-contrast random dot pattern. The random dot pattern provides unique details across the

[1] The term "shock-hole" originates from the US Army Aberdeen Test Center, where such a fixture is used to test explosive perforation or "holing" of witness plates. In the present research, however, such material failure does not occur.