Optical Measurement, Characterization, and Scaling of Blasts from Gram-Range Explosive Charges

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Abstract

Experiments involving large-scale explosive charges are expensive and hazardous to researchers and test facilities. It was recently shown that very small charges - 1 gram or less - can be used to provide some of the information usually obtained in a large-scale test, but more safely and economically and with better instrumentation. Optical shadowgraphy and high-speed digital imaging are used to measure the shock-wave Mach number as a function of distance from the explosion center. These data then yield a peak overpressure and duration, which are the key parameters in determining the potential damage from an explosion. A scaling analysis yields an approach to relate the gram-range blast to a large-scale blast from the same or different explosives. This approach is particularly suited to determining the properties and behavior of exotic explosives like triacetone triperoxide (TATP) and other terrorist-related explosives. Results show that the concept of TNT equivalence is inadequate to describe these explosions. Finally, the possibility of gram-range explosive testing of blast-resistant materials is examined.

Introduction

Explosives are used for many civil and military applications, but limited fundamental scientific knowledge about the explosion process exists to support new development. An explosive event can be characterized by the propagation of the shock wave and the variations of physical properties associated with it. Once characterized, the ability to scale the event is essential to scientific testing and applications, eventually resulting in new technology development.

Characterization of an explosive requires understanding of the energy released during detonation. Typically TNT equivalence is reported, where explosion parameters or energy release are compared to the same results from an “equivalent” mass of TNT. This method is useful for comparative experiments but does not document the detailed differences in shock wave profiles when different explosives are used [1]. Shock propagation speed determines overpressure and duration profiles [2], and explosives with different shock speeds will have fundamentally different property profiles. These property differences result in different explosive impulses, damage potentials, and multiple “TNT equivalences” for the same blast [3]. To better characterize explosives, shock wave radius and duration profiles as functions of time should be presented instead of typical TNT equivalences [4]

Shock wave propagation from large-scale blasts has been scientifically documented [5], but these tests are expensive and dangerous to researchers and test facilities. Recently, Kleine et al. performed explosive tests with 0.5 to 5 mg of silver azide and a laboratory-scale optical schlieren method [4]. These experiments pioneered the use and scaling of small explosive charges to provide a more economical and safe experiment. With the Hopkins scaling law, mass, distance, and time can be scaled for explosives over a wide size range [6]. Under the right circumstances, testing can be conducted at a laboratory scale and results extrapolated to large scale.

The present research extends the gram-range explosive charge characterization and scaling. The explosive characterization is performed to understand parameter inputs to an explosive materials test.

Scaling arguments then allow small-scale materials testing to be extended to full-scale. Our eventual goal is to provide a laboratory-scale testing procedure for candidate blast-resistant materials.

Experimental Procedure

Two different explosive materials have been used to document differences in explosive parameters in this research. Triacetone triperoxide (TATP), a primary explosive, was selected because of its recent use in terrorist activities [7]. Pentaerythritol tetranitrate (PETN) is a common and well-documented secondary explosive used in detonators for high explosives [8]. These explosives are formed into spherical charges ranging in mass from 0.5 to 5 grams total, including a small fraction of non-explosive nitrocellulose binder. The charge sizes used here reflect decisions made for ease of handling, manufacture, and safety considerations.

The charges are detonated at the focus of a z-type optical focused shadowgraph system [9]. The focused shadowgraph technique allows the shock wave to be precisely imaged in the plane of the charge when the event is recorded with a high speed digital camera. The Photron APX RS digital camera records the explosive event at frame rates from 10,000 to 250,000 frames per second. Each sequence of images is processed to locate and track the shock wave from the explosion center to the edge of the field of view. The position versus time history of the shock wave can then be used to determine Mach number and physical properties throughout the event. Position versus time data is extracted from the digital images using an image processing routine written specifically for the task. A typical video frame from an explosive test is shown in Figure 1.

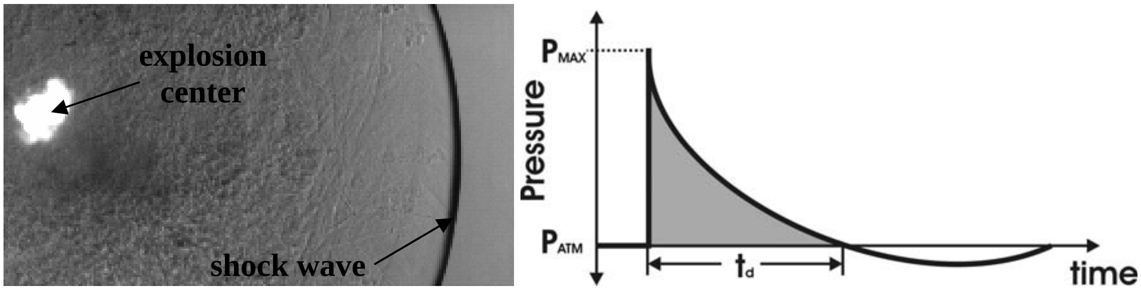

Figure 1: A typical digital image of the shock wave from a 1g charge (left) and a diagram of a shock pressure trace (right). Positive impulse is the shaded region under the pressure curve from time of rise to return to zero.

Piezoelectric pressure gages are also used to document the shock pressure duration at various distances from the charge center. The positive pressure phase duration is measured and used to determine the positive impulse, the integral of pressure from time of shock arrival to the end of the positive duration [10]. The negative impulse phase is generally ignored [6]. A diagram of a typical pressure trace as a function of time is given in Figure 1. Gage inertia and response time present problems for recording peak overpressure, so the Rankine-Hugoniot relation is used to determine peak overpressure from the measured shock Mach number. The Rankine-Hugoniot relation is valid when the perfect gas law assumptions are satisfied, which allows its use throughout the event except close to the charge, where the high temperature behind the shock wave causes real-gas effects [11].

For materials testing, an explosive charge is placed at a standoff distance from a “witness plate” determined to give a desired impulse to the plate. The explosive impulse is varied based on desired impulse to the plate. The plate is edge-clamped, with a circular plate surface exposed to the explosive. The plate is placed parallel to the light in the z-shadowgraph system to allow the incident and transmitted shock waves to be imaged. By measuring the strength of the incoming shock wave and the transmitted shock wave, an estimate of absorbed energy can be developed. A schematic of the plate holder and typical test video frame are given in Figure 2.

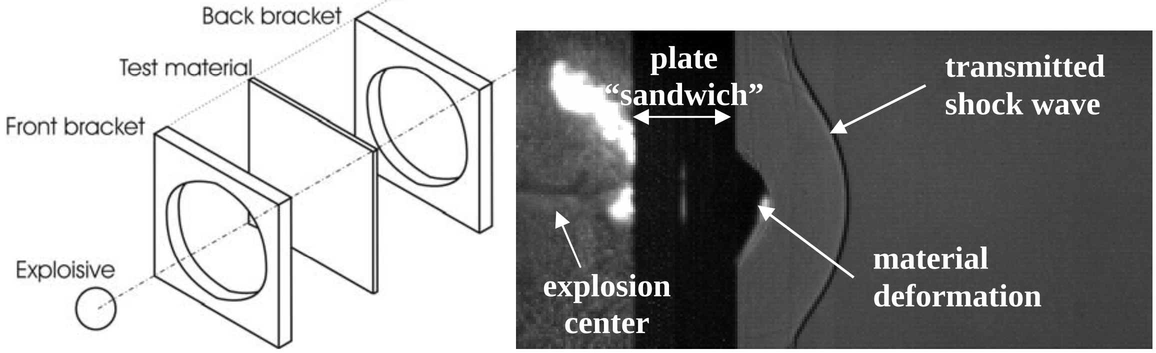

Figure 2: A schematic of the plate setup (left) and a typical experimental video frame (right). The transmitted shock wave can be tracked and its speed and strength compared to the unimpeded wave or transmitted waves from different test materials.

Experimental Results

Characterization of the two explosives, TATP and PETN, requires documentation of the shock wave position and pressure duration as functions of time and verification of the scaling laws. In order to verify the scaling laws, a series of charges of different masses were exploded and the shock wave positions were recorded with the high speed digital camera. The data was scaled using the method developed by Dewey and used by Kleine, for scaling to Normal Temperature and Pressure (NTP) [4, 5]. The scaling is given in equation 1, with the scale factors in equation 2.

$$R_S = R/S \qquad t_S = ct/S \tag{1}$$

$$S = (W/W_{std})^{1/3}(101.325/P)^{1/3} \qquad c = (T/288.16)^{1/2} \tag{2}$$

Variables with subscripts S are the scaled values. R is the radius, t is time, P is pressure, T is temperature, W is explosive mass, and W_{std} is the mass being scaled to, in this case 1g. Once scaled, the data points can be fit to equation 3 with coefficients A, B, C, and D, where a_0 is the speed of sound at NTP. For curve fits to data close to the charge center, B should be set to 1 to guarantee an asymptote to the speed of sound as time increases [12].

$$R_S = A + Ba_0t_S + C\ln(1+a_0t_S) + D\sqrt{\ln(1+a_0t_S)} \tag{3}$$

Graphs of the measured and scaled data for TATP and PETN are given in Figure 3. The measured data spread due to faster shock propagation with increasing charge mass. The scaled data show all trials collapse to one curve to within the error of the optical and image processing systems. Each set of data represents a sample of the data recorded, multiple charges at each mass were exploded and the data showed high repeatability between charges. The scaled data for each explosive was combined from all tests and fit by least squares to equation 3, with B set to 1. The equation was then differentiated and manipulated to yield Mach number as a function of radius, the most important result, which is given in Figure 4 (left). From this graph all physical property information can be generated using Rankine-Hugoniot or a real-gas equation of state. Another important result of the plot is that the Mach number is down to 1, or a sound wave, within 0.5m. This decay shows these charges are safe for indoor testing and researchers require only hearing protection during a test.

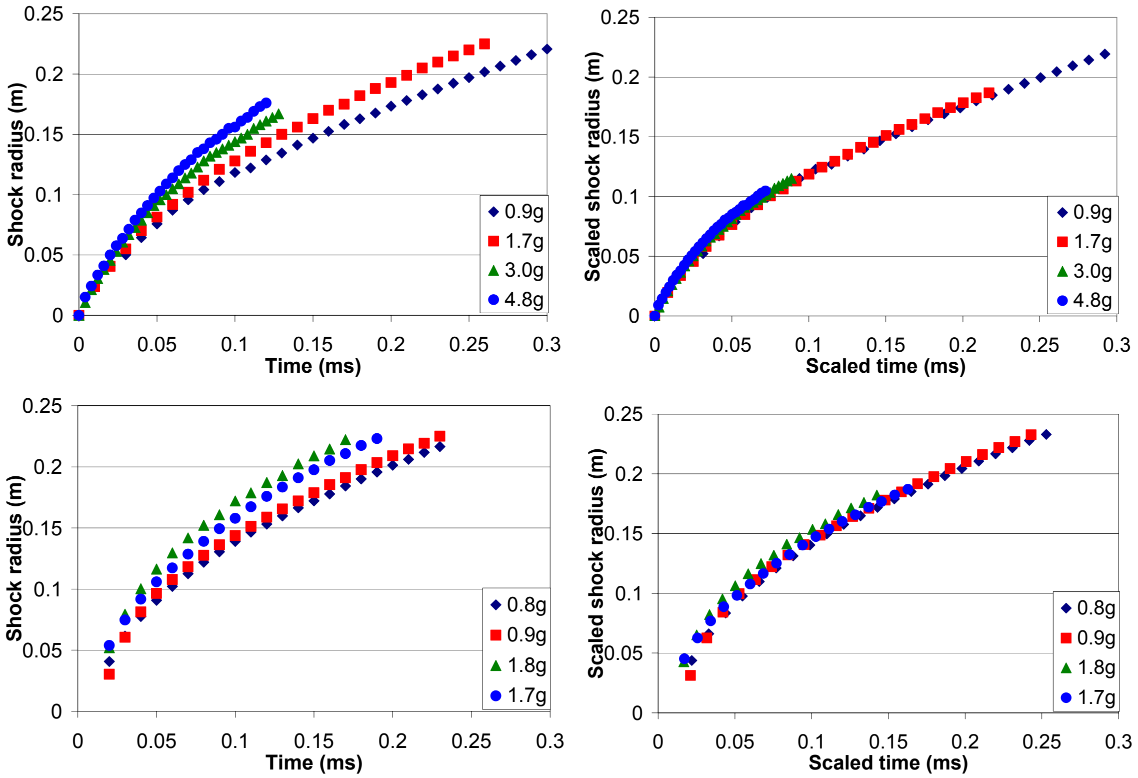

Figure 3: Measured (left) and scaled (right) shock radius as a function of time for TATP (top) and PETN (bottom).

The duration measurement completes the definition of explosive impulse. Kinney and Graham suggest that the duration can be calculated knowing the speed of the shock wave as a function of distance and assuming that the point marking the end of the positive pressure pulse moves at the speed of sound behind the shock wave [2]. This method proved to be valid when actual pressure measurements were made along the theoretical curve. However, limited measurements were made due to gage limitations. The pressure duration traces with the data points recorded are shown in Figure 4 (right).

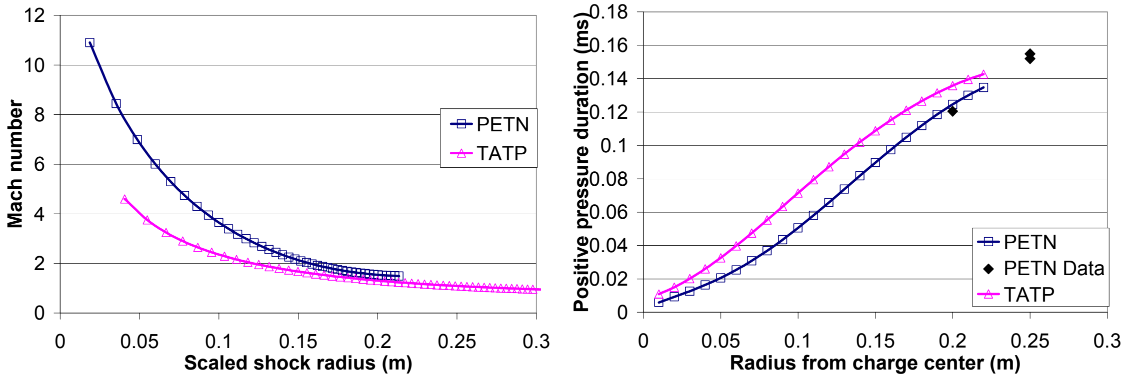

Figure 4: Final characterization of Mach number as a function of scaled radius for PETN and TATP (left) and positive pressure duration as a function of scaled radius from the charge (right).

Initial material testing of simple aluminum plates has been performed to document the aluminum response to an explosive impulse. These preliminary results show the ability to track and extract information from the transmitted shock wave. The optical data is limited by the bracket holding the plate, which blocks some of the profile view, and by the slower frame rate required to obtain a field of view large enough to show the plate. After the test, the plate can be measured to give a maximum deflection and to define an overall failure mode based on the shape and any tearing that occurs [13, 14]. An image of a deformed plate after a test and a graph of transmitted shock strength from the test are shown in Figure 5. The transmitted wave from the plate is only slightly stronger than a sound wave; implying most of the shock energy was used to deform the plate.

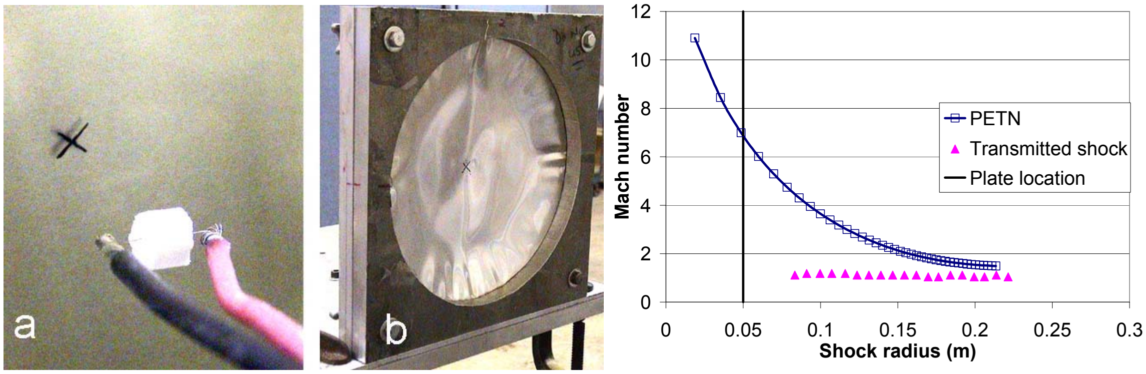

Figure 5: A pre-test image of 1g PETN charge with 5cm stand off from aluminum test panel (a). Post-test image of same plate deformed during test (b). A graph of the shock Mach number as a function of distance showing 1g PETN unimpeded compared to the transmitted shock during aluminum plate test (right). For a sample test frame, see Figure 2.

Future Work

TATP and PETN have been successfully characterized with shock Mach number and pressure duration as functions of distance. The techniques developed and perfected with these explosives will be applied to other explosives including another material of terrorist interest, HMTD.

With a library of characterized explosives, more extensive materials testing can be conducted. Material tests will be conducted with different explosives placed at distances of matching impulse to define material response to impulse. Variations in standoff and charge size will allow for changes in overpressure and duration to evaluate these parameters. Two high-speed digital cameras in stereo with three-dimensional surface tracking software are currently being applied to provide plate deformation as a function of time. From this information, material properties could be inferred [15].

Conclusions

TNT equivalence is insufficient for defining explosive parameters. Shock Mach number and overpressure duration as a function of time are required to define all parameters. TATP and PETN have been characterized by this method, and from this information all relevant physical properties can be determined. The optical methods in the laboratory environment allowed more data to be recorded and more information inferred from the testing than in typical full-scale explosive tests.

This laboratory-scale explosive testing has shown the ability to examine different explosives for their characteristics and to still apply the scaling laws developed for large-scale tests. This scaled testing is well suited for materials testing where multiple evaluations can be performed before final tests are conducted at full scale. With the future addition of surface tracking capabilities, materials tests will provide not only material blast resistance, but also high strain-rate material properties. These tests will help to understand material responses and to develop new blast resistant materials.

References

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