

# Gram-range explosive blast scaling and associated materials response

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**Summary.** Laboratory-scale gram-range explosive blast testing of materials is shown to be feasible. Blast loading from different explosive compounds is coupled to a witness plate through the air by way of a shock wave of known strength, measured optically. The resulting witness-plate deflection is also measured by a high-speed optical method. An attempt is made to relate the material response to blast loading parameters, especially impulse, by scaling arguments. More work is needed on this topic, and a discussion of future research directions is included. The promise of gram-range testing is to take on at least some of the burden now carried by expensive, dangerous, time-consuming full-scale explosive testing.

## 1 Introduction

Blast resistant material development requires understanding the explosive blast parameters and their effects on a material sample. Explosive blasts have been studied extensively on a large scale [1] [2] and recently on the laboratory scale as well [3] [4]. Material responses to blasts, however, are comparatively poorly understood.

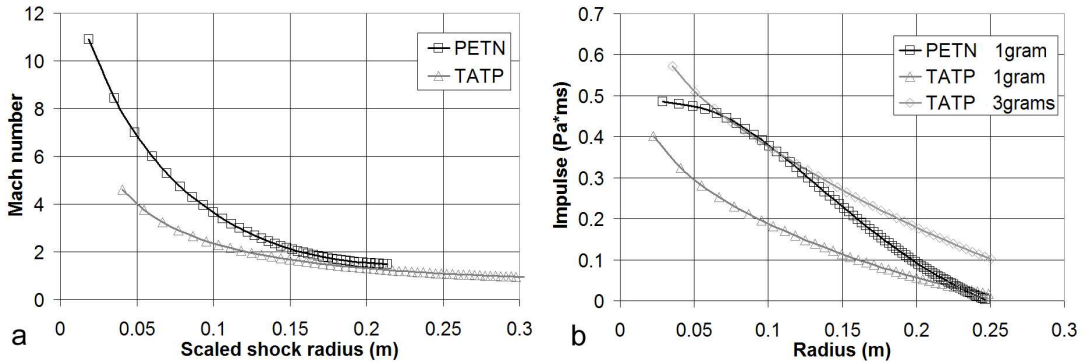
Typical material blast-response tests are conducted at full-scale, with material samples larger than  $1m^2$  [5] [6]. These full-scale tests can require  $10 - 100kg$  explosive charges placed at distances up to  $100m$  away, which forces the tests outdoors into relatively-uncontrolled settings. At this scale, instrumentation becomes difficult and expensive, often only yielding piezoelectric overpressure profiles at limited locations and a visual record of material survival or failure. Optical methods to reveal shock waves in the field (e.g. background distortion and sunlight shadowgraphy [7]) are often crude and weather-dependent. Overall, the researcher may get relatively little data for his time and expense.

In contrast, laboratory experiments provide a controlled environment with much-better instrumentation. Unfortunately few laboratory-scale blast experiments have been performed. An exception is Nurick's group, who have performed extensive lab blast tests on panels of various geometries, materials, and levels of reinforcement [8] [9] [10]. However, these tests are conducted with the explosive charge placed in physical contact with the material sample under test. Coupling blast energy to materials through the air via a shock wave is the more practical case, and it also allows precise optical shock-loading measurements to be made.

The research presented here applies our previous experience with gram-scale explosions to improving the understanding of how blast parameters such as overpressure, duration, and impulse affect the deformation response of a clamped aluminum plate, and how the process might be scaled.

## 2 Experimental procedure

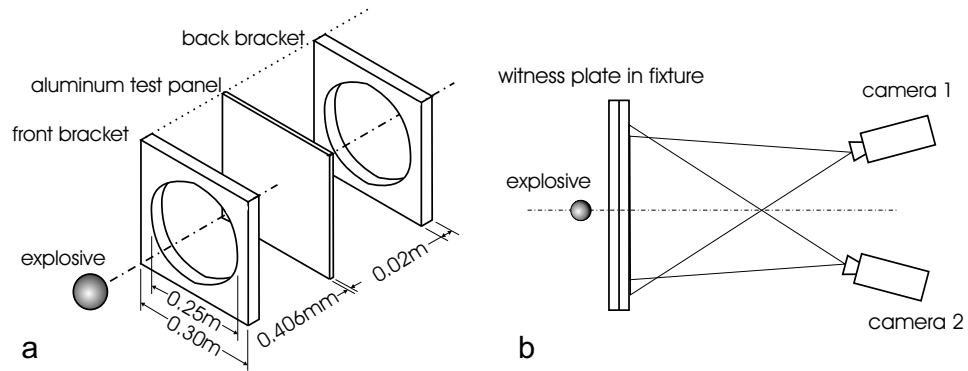
Two explosive compounds are used here to examine a range of blast parameters: Pentaerythritol tetranitrate (PETN) is a common and well-documented secondary explosive [11] and triacetone triperoxide (TATP) is a primary explosive recently linked to terrorist activities [12]. These explosives were previously studied using shadowgraph techniques and high speed digital videography to measure the shock radius as a function of time [4]. Example results are shown in Figure 1a, where the horizontal axis is the shock wave radius scaled to represent a 1g charge. The shock wave profile, from Rankine-Hugoniot theory and piezoelectric pressure-gage data, provides the peak overpressure magnitude and duration as functions of radius from the charge. The positive explosive impulse is calculated as the integral of pressure from the time of shock-wave arrival to the end of the positive pressure duration [13]. Figure 1b shows the explosive impulse versus radius due to 1g charges of PETN and TATP and a 3g charge of TATP.



**Fig. 1.** a shock wave Mach number as a function of scaled radius for PETN and TATP charges b explosive impulse as a function of radius for various PETN and TATP charges

In this research so far, aluminum witness plates are deformed by the gram-range explosions. Aluminum alloy 3003, 0.406mm thick, was selected because it is readily available and its static and low-speed properties are well-documented, making it an ideal material for initial high-speed blast deformation research. The witness plates are 0.3m square, and are bolted into a rigid mounting fixture with a 0.25m circular opening as diagrammed in Figure 2a. The plate fixture is then oriented so that the side of the plate opposite the explosive can be optically recorded to determine its real-time 3-D motion in response to the explosive loading, Figure 2b. Some refer to this as a “shock-hole” test geometry.

3-D witness-plate motion is determined from the stereo camera records using commercial software by Correlated Solutions. The rear of the test panel is spray-painted with a random black dot pattern on a white ground using automotive primer paint. The two high-speed cameras then record images of the plate from different view angles. With a calibration, the software can determine the 3-D location of the dots on the plate surface at every image interval. To achieve the optimum spatial and temporal resolution possible with our twin Photron APX-RS high-speed digital cameras, every test is recorded at 36000 frames/s with a frame resolution of 512x128 pixels. This resolution allows the entire width of the plate and a 0.06m-high “slice” to be tracked throughout the test.

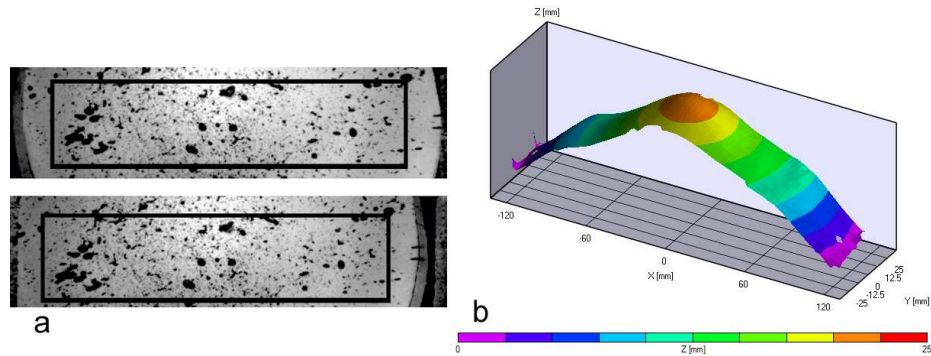


**Fig. 2.** **a** schematic of explosive charge and witness plate setup **b** top view schematic of witness plate and high-speed cameras for 3-D plate deformation measurement

In this manner one can document witness-plate deformation profiles for different explosive blast input parameters. These parameters are varied by changing the explosive compound, the charge mass, and the charge stand-off distance from the witness plate.

### 3 Experimental results

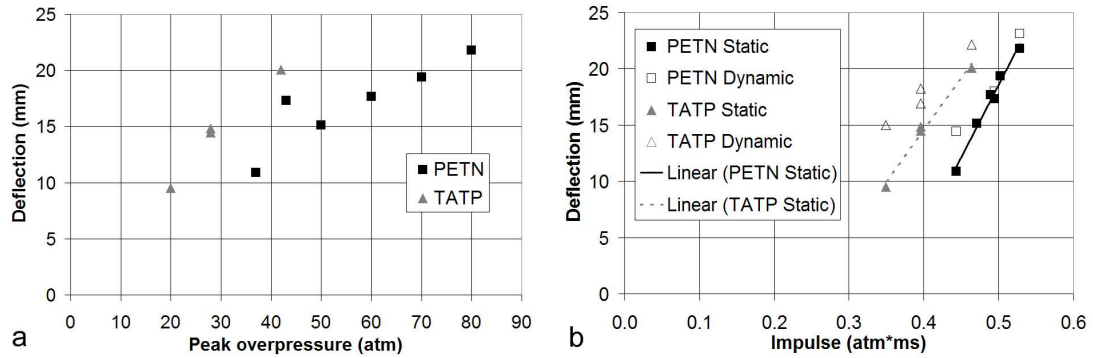
The explosive shock-loading input parameters are determined from previous work [4] and are known to have small variability from charge-to-charge. The recorded data are the dynamic motion and permanent deformation of the witness plate. The input parameters are selected to compare similar PETN and TATP charges, and to cause permanent deformation but not rupture of the witness plate. Table 1 gives a summary of tests performed to date. (Dynamic deflection data are missing from some tests due to data acquisition problems.) The tests with 1.71 and 1.75g TATP charges were performed to evaluate repeatability; resulting plate deflections show 7% and 2% differences in dynamic and static deflections, respectively, which are considered to be within the repeatability error expected in materials testing.



**Fig. 3.** **a** sample stereo image pair with area of witness plate deflection measurement boxed **b** xyz plot of the witness plate deflection as extracted from the stereo images

**Table 1.** Summary of witness-plate tests to date

explosive	mass <i>g</i>	standoff <i>m</i>	overpressure <i>atm</i>	duration <i>ms</i>	impulse <i>atm * ms</i>	final defl. <i>mm</i>	dynamic defl. <i>mm</i>
PETN	0.80	0.057	37	0.024	0.443	10.9	14.4
	0.87	0.046	50	0.019	0.471	15.1	-
	0.88	0.040	60	0.016	0.489	17.7	-
	0.88	0.035	70	0.014	0.502	19.4	-
	0.94	0.032	80	0.013	0.528	21.8	23.1
	1.00	0.055	43	0.023	0.494	17.3	18.0
TATP	1.36	0.052	20	0.035	0.349	9.5	15.0
	1.71	0.042	28	0.028	0.396	14.8	16.9
	1.75	0.042	28	0.028	0.396	14.5	18.2
	1.77	0.032	42	0.022	0.464	20.1	22.2

**Fig. 4.** **a** maximum witness plate deflection as a function of peak overpressure **b** maximum witness plate deflection as a function of impulse

Each test results in a series of stereo image pairs that is processed by the Correlated Solutions software. A sample pair of images and the resulting 3-D surface of the witness plate at that instant are given in Figure 3. The approximate area of analysis is boxed in Figure 3a. The circular edge of the mounting bracket can also be seen in the images.

Each image-pair dataset is processed through the end of the first plate oscillation. The maximum deformation is seen to occur within  $0.4ms$  of the beginning of plate deformation. Subsequent plate motion is merely elastic oscillation. The final deformation is measured after all plate motion has stopped.

To evaluate the parameters affecting plate deformation, the deformation is plotted as a function of peak overpressure, overpressure duration, and explosive impulse. For purposes of this calculation, the pressure decay is approximated to be linear from the peak overpressure to atmospheric pressure over the duration interval. Figure 4 shows the witness-plate deformation as a function of a) peak overpressure and b) impulse. Figure 4b also shows the difference between dynamic and static deflection: Each plate dynamically deforms about 3mm beyond its eventual final deformation. This could be due to elastic deformation at the edges of the plate, which adds to dynamic deformation but contributes nothing to the permanent deformation profile.

The graph of deflection versus peak overpressure, Figure 4a, shows that most of the data for a given explosive compound lie along a single line, with the exception of one PETN test. This outlying point, however, collapses with the other data when deflection is plotted as a function of impulse, Figure 4b. This single test, conducted with a 15% larger charge mass than the others, reveals the importance of mass scaling and the use of explosive impulse as the controlling blast parameter.

## 4 Conclusions and future work

Laboratory-scale gram-range blast testing of materials can be safely and successfully performed. The experiments are highly repeatable and are amenable to instrumentation yielding blast overpressure loading and resulting witness-plate deflection. The dynamic and permanent deformation of a witness plate can be estimated, based on these results, if the explosive blast parameters are known. Before performing materials tests, however, the explosives being used require optical characterization in terms of their shock wave Mach number versus radius profiles in order to understand the variation of overpressure, duration, and impulse that they produce.

The most important parameter for gram-range blast testing appears to be the explosive impulse. The assumption of a triangular overpressure profile is a first approximation, but it is insufficient to accurately estimate and model the explosive blast loading of different explosive compounds.

Future work needs to reconcile the deflection vs. impulse curves of PETN and TATP, which currently do not collapse upon a single line. The difference between these curves could potentially be eliminated by computing the impulse from the actual pressure decay profile instead of the linear-decay assumption [14]. The decay parameter varies with distance from the charge center and initial attempts to scale using it have failed.

Once a better scaling approach has been identified, more testing is planned using the same explosive compounds over a wider range of charge masses. Future work will also include other explosive compounds in order to improve the understanding of blast parameters and to confirm scaling laws. The ultimate goal is to fully understand the deformation of simple aluminum witness plates in order to predict the final and dynamic deflections for a given explosive over a broad range of impulse and overpressure loading.

Another research direction should examine how the blast scaling is affected by witness-plate thickness and dimensions. The strain rate experienced by the witness plates can also be examined in order to estimate material properties which could then be used to validate numerical models of simple materials like aluminum subjected to blast loading. Ultimately, the techniques being developed in this research should be extended to other, more exotic blast-resistant materials and to the development of a comprehensive understanding of material blast response.

## 5 Acknowledgment

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