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Structural Damage Equivalence of Selected Explosive Materials Based on the Response of Thin Circular Plates Subjected to Blast Loading

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Abstract. Determining explosive equivalence remains a complex problem because it is a function of the effect of interest. The metric of interest in the present work is blast damage to a thin aluminum plate. In order to determine structural damage equivalence of different explosive materials, Sandia National Laboratories developed a circular plate test method. The present work uses this test method to determine explosive equivalence of selected explosive formulations. It is important to conduct this equivalence testing because actual explosive performance may deviate from the optimal performance predicted by thermochemical calculations. Each test was conducted by detonating an explosive charge located at a standoff distance of 20 inches from the center of the target. High speed 3D digital image correlation was used to capture the deformation of the plate as a function of time. Metrics developed from the deformation were then used in order to compare relative damage between the explosive material of interest and C-4 (the reference explosive). These metrics were used to determine explosive equivalence for each explosive material.

Introduction

The present work seeks to provide experimentally-derived equivalence for selected explosive materials. In order to generate baseline information for this method, blast damage was imposed on thin circular aluminum 2024-T3 plates with center-initiated spherical C-4 charges; C-4 serves as the reference explosive. The mass of C-4 was chosen such that the plate experienced significant plastic deformation without leading to plate failure. As such, each test required a new plate.

The mass of the explosive of interest was calculated using that material's mass factor[a], which provides a straightforward method for determining a mass which is equivalent to the mass of the C-4 reference charge based on each material's respective mechanical energy of detonation. These thermochemical calculations were conducted using Cheetah 6.0[b], which takes the density of the formulation into account. Blast damage obtained with these charges of theoretically-equivalent masses was then

[a] Souers and Maienschein, 2009
[b] Bastea *et al.*, 2010

compared to the C-4 baseline data using damage metrics which were developed based on the full-field measurement of the deformation of the plate as a function of time. This comparison was used to update the values of the mass factors in order to calculate structural damage equivalence.

Test Method

Experimental Setup and Procedure

Each test measured the response of a thin aluminum plate to a detonation of the explosive of interest. Each 48" diameter plate was clamped at its boundary between a 2" thick steel plate with a 44" diameter opening and a 2" wide by 2" thick ring. No slippage was observed to have occurred at the metal plate boundary during any test, validating the fixed boundary condition assumption. Figure 1 shows a plan view of the test setup.

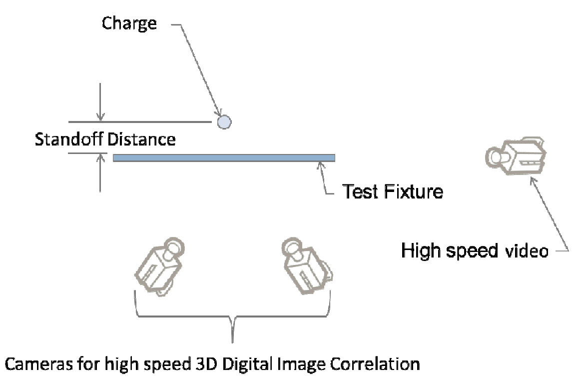

Figure 1. Plan view of test setup.

The charge was detonated at a standoff distance of 20 inches from the center of the circular plate test fixture. The plate was painted with a black and white speckle pattern (Figure 2) on the side opposite from the blast in order to enable non-contacting displacement measurements as a function of time using high speed 3D digital image correlation. The test fixture was also painted with a speckle pattern in order to assess whether displacement of the structure was significant. Results showed fixture deflection to be negligible.

Plate deformation was recorded using two Phantom cameras with a minimum frame rate of 35,000 frames per second and a minimum resolution of ~0.21 in./pixel[c]. The cameras were located approximately 18.6 feet from the center of the plate and approximately 8.6 feet apart with an included angle of about 27°. The software used for digital image correlation was Vic3D produced by Correlated Solutions, Inc.

Figure 2. Test fixture with plate.

Each explosive mixture of interest was tested three times except for HME-02 and HME-12 which were tested twice and HME-10 which was tested once (for security reasons, the explosive formulations are not referred to by name). Each material was placed into a spherical configuration and was center-initiated with either a RISI (Reynolds Industries Systems Inc.) RP-83 detonator or a RISI RP-85 detonator (which is an RP-83 detonator designed for submersion). The C-4 baseline explosive was tested 5 times in a molded spherical configuration and detonated with a RISI RP-83.

Mass Factor and Equivalence

The mass factor (α) is defined as[d]:

[c] Larsen *et al.*, 2012
[d] Souers and Maienschein, 2009

$$\alpha = \frac{E^D_{0C4}}{E^D_{0Explosive}}$$

where E^D_0 is the mechanical energy of detonation per unit mass in kJ/g. Inspection of this relationship shows that an explosive with a mass factor greater than unity is less energetic than C-4 while an explosive with a mass factor smaller than unity is more energetic than C-4. Note that the inverse of the mass factor may be used to provide explosive equivalence to C-4.

The mechanical energy of detonation can be calculated using a thermochemical code given the density and chemical composition of the explosive in question. In order to obtain the equivalent mass, this mass factor is multiplied by the reference mass of C-4 as follows:

$$mass_{Explosive} = \alpha \cdot mass_{C4}$$

For example, if the mass of C-4 used in baseline testing is 1 kg and the explosive of interest has a mass factor of 1.5, the required mass of the explosive of interest would be 1.5 kg. Further, since the example material has a mass factor of 1.5, its C-4 equivalence would be 0.67 (i.e. the inverse of 1.5).

Test Results

Data from 3D digital image correlation provided detailed deformation time history of the test plate. Circumferential averages of the measured displacement components with respect to time were used to calculate two quantities in order to compare explosive material performance: 1) area percent change of the plate surface and 2) volume contained by the concave side of the deformed plate[e]. The analyzed region included a 50 cm radius about the geometric center of the plate because areas near the edge of the plate were shaded by the fixture and did not contain good data. The area and volume are calculated from:

$$Area = 2\pi \int_0^R (r+u)\sqrt{\left(1+\frac{du}{dr}\right)^2 + \left(\frac{dw}{dr}\right)^2}\, dr$$

and

$$Volume = 2\pi \int_0^R (r+u) w \left(1+\frac{du}{dr}\right) dr$$

where R is 50 cm, r is the undeformed radial coordinate, u is the radial displacement, and w is the out-of-plane displacement.

Figure 3 and Figure 4 show representative plots of these values for C-4 and a selected explosive formulation. Data from all tests appeared qualitatively similar to that shown in the representative plots. Inspection of these figures shows that the plates exposed to detonations from C4 respond faster than those exposed to the test explosive due to a faster moving shock wave. The maximum values for percent area change and for volume (indicated with symbols in Figure 3 and Figure 4) were then used to determine damage equivalence. Average values, along with standard deviations are given for each material in Table 1.

Table 1. Averages and Standard Deviations for Maximum Area Increase and Maximum Volume.

		Max. Area Increase (%)		Max. Volume (liters)	
Explosive	# Tests	Avg.	Std. Dev.	Avg.	Std. Dev.
C-4	5	1.87	0.13	34.1	0.78
HME01	3	1.10	0.23	25.2	2.43
HME02	2	1.81	0.06	32.5	0.53
HME03	3	1.48	0.05	29.5	1.09
HME04	3	1.73	0.09	31.5	1.00
HME05	3	1.86	0.12	32.5	1.26
HME06	3	2.37	0.01	37.3	0.24
HME07	3	1.89	0.05	32.7	0.47
HME08	3	1.73	0.09	32.3	0.26
HME09	3	1.55	0.08	29.7	0.14
HME10	1	1.79	-	32.2	-
HME11	3	1.71	0.17	32.3	1.74
HME12	2	1.88	0.03	34.2	0.24

[e] Larsen *et al.*, 2012

Damage Equivalence

This section assesses damage equivalence derived from experimental data. The method for performing this calculation is based on the trend observed in previous research[f] which indicates that if one plots maximum percent area increase or maximum volume with respect to normalized mass (defined as the mass of the explosive being tested divided by the product of its mass factor and the mass of the C-4 reference charge), the slope of these lines are nearly independent of the material being plotted. The lines were obtained computationally by simulating the blast and calculating the plate deflections. The material which supplied the equation of state to provide the slope for the line is C-4. Using the slope of this line, one translates the metric of interest (maximum percent area increase or maximum volume) from the average measured value for that material to the average measured value for C-4, giving the normalized mass of that material which would be required to produce the same response as that produced by C-4. The experimentally-derived mass factor is the product of the experimentally-derived normalized mass and the mass factor of that material as used in the experiment. The experimentally-derived C-4 equivalence is simply the inverse of the experimentally-derived mass factor, as noted in the Test Method section. This technique is shown graphically in Figure 5 and Figure 6 with the dotted lines representing the slope given from the C-4 equation of state[g]. The figure includes error bars with a magnitude of ±3 standard deviations (representing 99% confidence) from that material's mean value, allowing visual comparison between the magnitude of a material's standard deviation to that of C-4 (which is presented as horizontal lines in the figures). Table 2 lists the area-based and volume-based equivalence for each material along with the uncertainty of the experimentally-determined equivalence based on +/- 3 standard deviations. Additionally, this table includes the value for C-4 equivalence which is calculated from Cheetah.

General observations can be made from inspection of the information in Table 1. First, the experimentally-derived damage equivalence is generally (but not always) less than the value which is predicted by the mass factor. This means that most of the explosive materials included here impose even less damage to a structure than one would expect. Additionally, they generally impose less damage than C-4. Also, the area-based equivalence and volume-based equivalence appear to be reasonably close to each other, indicating that the experimental data is self-consistent.

In summary, the general method for determining damage equivalence for a given material is 1) get the mass factor for the material using Cheetah, 2) conduct circular plate testing using the correct material mass, 3) calculate required area and volume metrics based on 3D digital image correlation data, 4) determine experimental equivalence based on material data and C-4 data.

Table 2. Experimentally-derived equivalences.

Material	C-4 Equiv	Experimental Equivalence [Area Metric] (uncertainty)	Experimental Equivalence [Volume Metric] (uncertainty)
HME01	0.30	0.23 (+0.07/-0.04)	0.21 (+0.07/-0.04)
HME02	0.48	0.44 (+0.04/-0.03)	0.42 (+/-0.03)
HME03	0.61	0.52 (+/-0.03)	0.49 (+0.08/-0.06)
HME04	0.56	0.53 (+0.07/-0.06)	0.50 (+0.08/-0.06)
HME05	0.48	0.48 (+0.09/-0.06)	0.44 (+0.10/-0.07)
HME06	0.34	0.43 (+/-0.01)	0.41(+/-0.02)
HME07	0.62	0.62 (+0.04/-0.07)	0.58 (+/-0.04)
HME08	0.64	0.61 (+0.07/-0.06)	0.59 (+/-0.02)
HME09	0.63	0.55 (+0.06/-0.05)	0.52 (+/-0.01)
HME10	0.91	0.88 (-)	0.83 (-)
HME11	0.79	0.78 (+0.22/-0.14)	0.76 (+0.27/-0.16)
HME12	1.16	1.17 (+/-0.04)	1.17 (+0.05/-0.04)

[f] Larsen *et al.*, 2012
[g] Larsen *et al.*, 2012

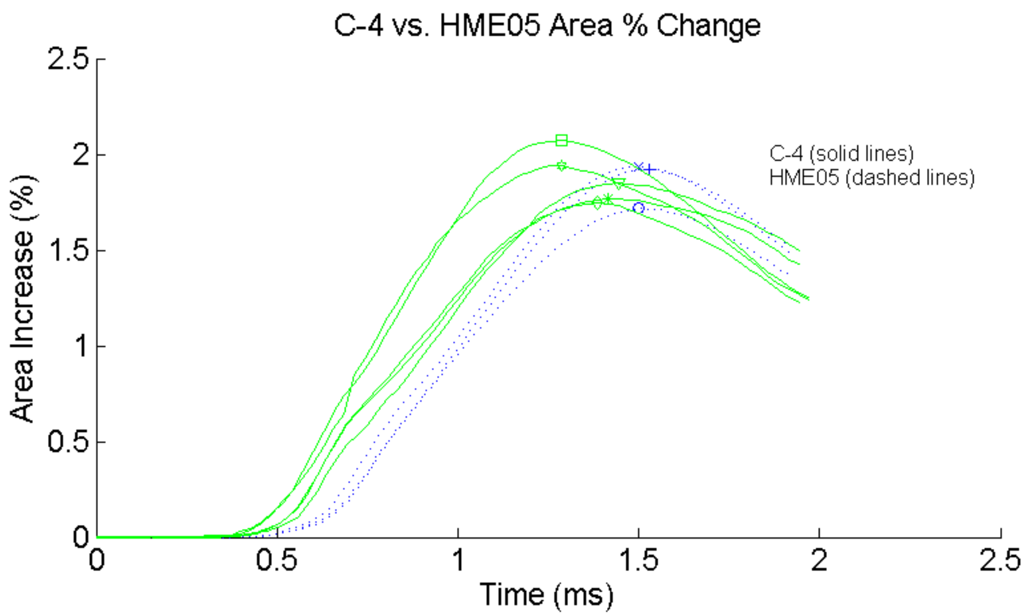

Figure 3. Representative area change (%) with respect to time.

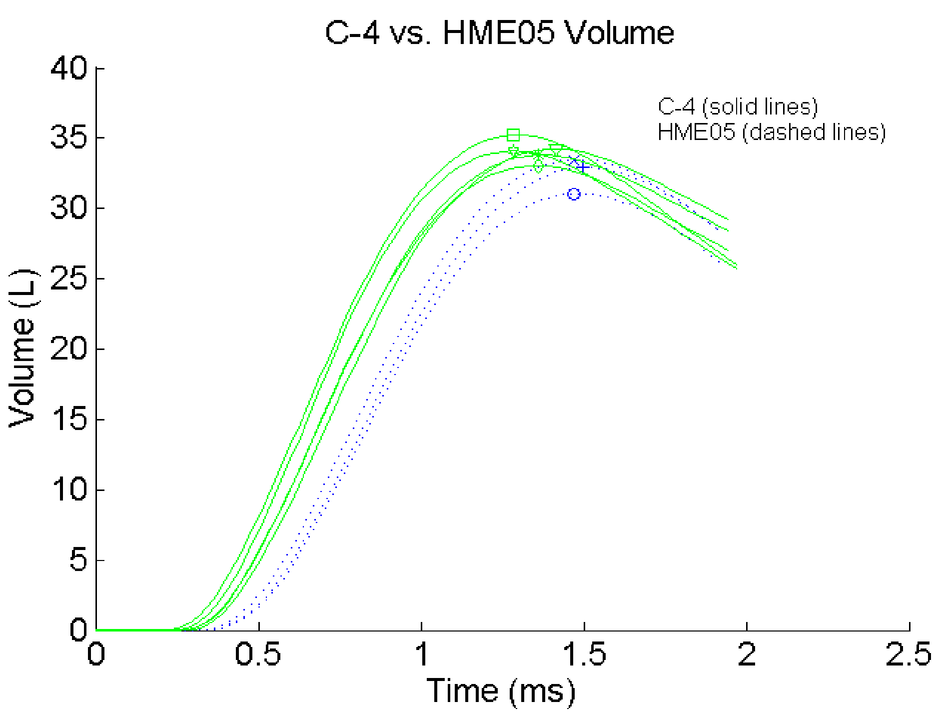

Figure 4. Representative volume (liters) with respect to time.

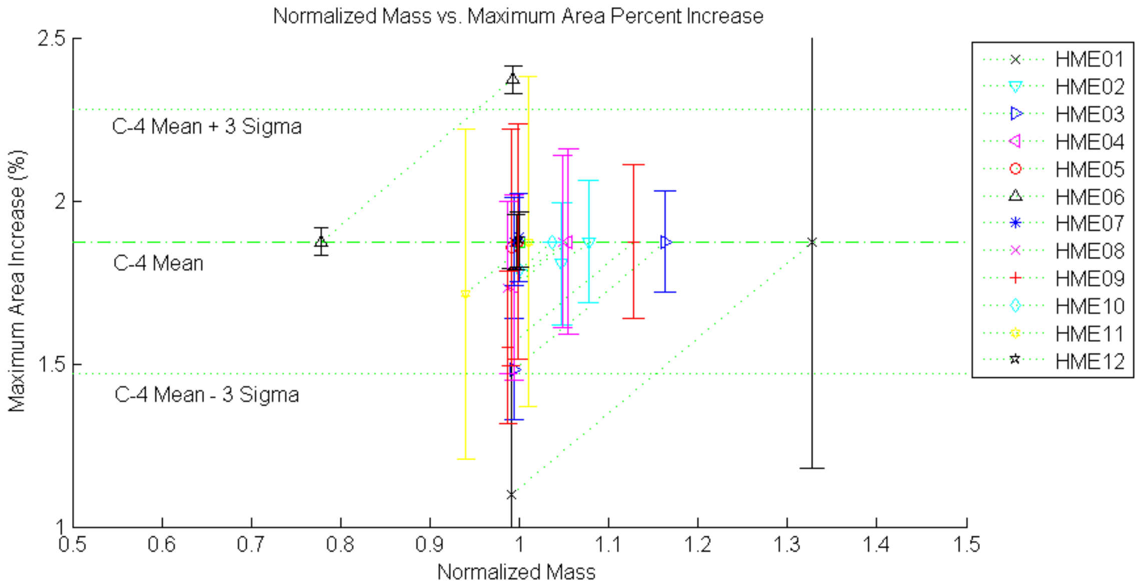

Figure 5. Calculated normalized mass for explosive materials based on area criterion.

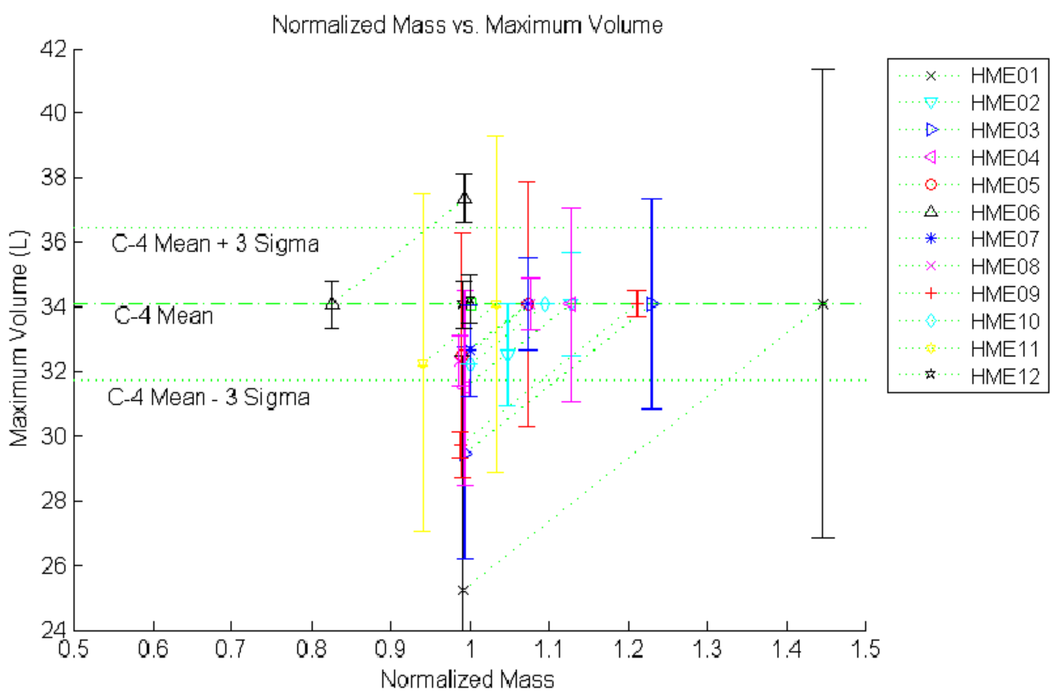

Figure 6. Calculated normalized mass for materials based on volume criterion.

Conclusions

Mass factors provide a conservative estimate to calculating amounts of material which will cause equivalent damage. This method can be implemented inexpensively using thermochemical calculations. However, since this research shows that the mass factor tends to over-predict damage, it is important to conduct circular plate testing in order to obtain a realistic estimate of damage equivalence.

References

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3. Larsen, M., Haulenbeek, K., Corona, E., Rath, J., Reu, P., Gruda, J., Phelan, J. and Gwinn, K.; *Assessment of Mass Factors Based on Structural Damage Equivalence of Thin Circular Plates*; Sandia National Laboratories, Albuquerque, NM; NEXESS Center Report 2010-0104; August 2012.