TARGET RESPONSE TO DEBRIS CLOUD INCIDENCE

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The extent of penetration and/or perforation of a target layer by a debris cloud, whose particle mass distribution and velocities were calculated from a previous impact, was determined with two computational approaches. First, the size of single or paired particles required for target perforation was calculated and compared with the largest particle expected based on the fragment size distribution in the debris cloud. A second approach used a three-dimensional shock-wave code to calculate the explicit interaction of individual particles in the debris cloud with the target. The cloud was represented by randomly locating the particles within an envelope, maintaining the mass and size distribution of the particles. This interaction of the cloud of particles produced target surface craters and penetration comparable to recovered witness plates from impact experiments.

INTRODUCTION

When a projectile perforates the initial layer of a spaced target array, fragmented projectile and target material combine to form an expanding debris cloud. Analysis of the damage to a subsequent target caused by this debris has been the subject of considerable study (*e.g.* [1]). If the targets are relatively close, the numerical analysis has typically connected the ejecta from the first impact to the second target, and computed the impact effects of this expanding, rarified material. This provides insight into the damage to the primary target, expansion characteristics of the debris cloud, and some information about the integrity of secondary targets.

In order to capture the details characterizing the ejected fragments and their interaction with subsequent targets, additional computational refinement is required. This is particularly necessary if the target separation is large enough for the fragments to form a dispersed cloud. Under these conditions, the fragments impact a secondary target as discrete particles, and the cloud cannot be represented as a distributed mass of low mean density.

A quantitative definition of the particle size and mass distribution of the debris cloud that results from the initial target impact can be determined from current fragmentation theories, using material state information calculated at the time of fracture (*e.g.*

[2],[3]). An estimate of the envelope of the cloud can be obtained using the residual axial and radial expansion velocities of the material ejecta, and extrapolating to the position of incidence with the next target plate; guidance is also provided by radiographic and holographic diagnostics of debris clouds ([2],[4]).

Two computational paths were pursued for evaluating the extent of penetration and/or perforation this debris cloud would have on a subsequent target layer. The first method calculated the size of single or paired particles required to perforate the target, and compared it with the largest expected size determined by the fragment distribution. A second approach used a three-dimensional shock-wave code to calculate the explicit interaction of individual particles in the cloud with the target.

DEBRIS CLOUD DEFINITION

The specific configuration chosen to illustrate these computational techniques is that of a 6.35 mm hard steel sphere of mass $M = 1.05$ g and initial velocity of 4570 m/s impacting a 3.38 mm PMMA (polymethylmethacrylate) primary target at normal incidence, with an aluminum witness plate to intercept the debris cloud [2]. The 12.7 mm aluminum witness plate is 470 mm directly behind and parallel to the PMMA target. The steel sphere is shattered during impact with the PMMA, and the debris prop-

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agates to the aluminum witness plate, diverging both radially and axially during the time of transit to form a clearly defined disk-like cloud [2]. The residual axial velocity was 4300 m/s, and the radial expansion velocity of the cloud was 270 m/s. The statistics of the particle sizes were calculated and found to compare favorably with radiographic data. The calculated particle size distribution can be represented analytically as an exponential function, N_m , of the particle mass, m ,

$$N_m = A \frac{N_0 m^2}{\mu^3} e^{-3m/\mu}, \quad (1)$$

where A is a constant, N_0 is the number of particles in the cloud, and μ is the average particle mass, defined by $\mu = M/N_0$. The coefficient A is 13.5, which normalizes the distribution to the correct total mass. In this experiment, the number of particles is about 300, the average particle mass is 3.5 mg, and the largest mass is about 7 mg; assuming spherical fragments, the average particle diameter is 0.95 mm. The largest number of particles have a diameter of about 0.7 mm (Figure 1).

Figure 1. Fragment number vs. size distribution for 300 steel particles, formed by impact with a PMMA target.

The dimensions of the debris cloud envelope at the location of the aluminum witness plate were determined from the calculated expansion and transit velocities of the debris, and adjusted with radiograph

data. This cloud is defined by a circular disk of diameter about 55 mm and thickness about 10 mm.

The coordinate positions of each particle were assigned in the envelope of the cloud with a random number generator. The particles are then fairly uniformly distributed within the cloud. No attempt was made to represent the preferential spatial positions or shapes of particular particle sizes that are observed in the radiographs of these events. The axial velocity of the particles at impact with the witness plate is 4300 m/s; each particle was also assigned a radial expansion velocity scaled to the outer expansion velocity of 270 m/s.

SECONDARY TARGET RESPONSE

The debris cloud of steel fragments defined in the previous section - particle location and velocity - was used as the initial condition to evaluate the extent of penetration and/or perforation resulting from impact with the aluminum witness plate. All of the calculations were made with the Eulerian shock-wave propagation code, CTH [5]. The materials were modeled with a Mie-Gruneisen equation of state, with elastic perfectly plastic deviatoric behavior (see Table 1). The primary focus of these numerical approaches is on the integrity of the aluminum witness plate when impacted by debris.

Table 1: Material Parameters for CTH Calculations

Property / Material	Aluminum	Steel
Density, ρ_0 (kg/m ³)	2785	7850
Bulk Sound Speed, C_0 (m/s)	5238	4610
Slope of $U_s - U_p$ Hugoniot, s	1.338	1.73
Gruneisen Coefficient, γ_0	2.00	1.67
Specific Heat, C_v (J/kg-K)	948	464
Yield Stress, Y_0 (GPa)	0.3	2.0
Poisson Ratio, ν	0.333	0.2897
Fracture Stress, σ_f (GPa)	1.5	4.0

Single and Paired Particle Analyses

Two-dimensional axisymmetric analyses of spherical particle impacts on a 12.7 mm aluminum target were made to determine the threshold particle size for perforation of the target, and to compare that

size with the sizes available in the distribution. This study was done numerically, since directly applicable penetration data or verified analytic formulae for the target perforation limits were not available. The particle impacts were assumed to be events uncoupled from other regions of the debris impact on the target. Of the many possible impact configurations of particles in a debris cloud, two were considered: (1) a single particle, and (2) two identical particles on the same trajectory, separated by the cloud thickness of 10 mm (the largest separation that can occur). For a single spherical particle, a diameter greater than 2.5 mm is required to perforate this target; for two spherical particles, a diameter greater than 1.6 mm is required to perforate the same target (Figure 2). In either case the particle size required for perforation is larger than the maximum fragment size defined by the debris cloud distribution (1.2 mm, Figure 1). A 1.2 mm spherical particle penetrates only one-half the thickness of the aluminum target.

Figure 2. Calculated residual velocity after penetration, for one and two spheres impacting 12.7 mm aluminum at 4300 m/s.

One variation on particle shape is that of a splinter, or long rod. The longest possible fragment from the original spherical projectile is 6.35 mm. The largest mass allowed by the distribution, 7 mg, limits the rod diameter to 0.42 mm. Normal impact of this particle at 4300 m/s is calculated to be at the threshold for perforation of the aluminum witness plate.

Full Debris Cloud Analysis

The second approach is a three-dimensional numerical simulation of the complete cloud of particles impacting the aluminum target. The physical space of the debris cloud and 12.7 mm aluminum witness plate was defined by uniform 0.3 mm cubical cells, resulting in about 6.25 million cells in the calculation. The resolution of the calculation provides about 2 cell widths to define the diameter of the particles of average size in the distribution. Consequently, some of the particles will be shapeless masses impacting the target rather than well-defined spheres. Views of the initial conditions are shown in Figure 3.

Figure 3. Debris cloud of 300 steel particles, randomly placed within the envelope of a disk (10 mm x 55 mm), prior to impact with an aluminum target (edge and top views).

By 10 μ s after impact the craters have all been formed and the steel particles have transferred their momentum to the aluminum witness plate. Edge and surface views of the target at this time are shown in Figure 4, in which both the jagged impact crater lips and the significant rear surface bulge are evident. No perforation of the aluminum target has occurred, although there are crater depths to within 1 mm of the rear surface, suggesting that perforation is imminent. An estimate of the computed excavation (crater) volume of aluminum is 3 cm³.

Figure 4. Views of the calculated aluminum target plate at 10 μ s: an edge view of the target (upper), and a perspective view of the target (lower).

Computational and Experimental Observations

Both numerical analyses indicate that the particles in this debris cloud will not perforate the aluminum target; however the calculated single rod and debris cloud results suggest that the threshold for perforation has nearly been reached. This principal conclusion is verified by experimental results. Two nearly identical experiments indicate that the impact conditions are at the threshold for perforation: the witness plate in one was not perforated, and in the other was perforated with a single small hole [2]. Other aspects, such as the crater surface features and rear surface bulge calculated for the full debris cloud, are consistent with the recovered witness plates reported for these particular experiments [2].

CONCLUSIONS

The techniques described here provide two levels of analysis to determine the effects of debris on secondary targets, both leading to correct assessment of the extent of protection offered by the secondary target. Analysis with the full debris cloud present is the more accurate approach. Coupling the debris characterized from an initial impact event to the numerical simulation of the resulting debris cloud of discrete particles impacting a secondary target provides a view of the entire impact process in unparalleled detail. Addition of particle shape variations in the full debris cloud analyses would lend support to the proximity to threshold that has been calculated here.

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