CONF-950846--38

SAND95-0890 C

PROJECTILE SHAPE INFLUENCE ON BALLISTIC LIMIT CURVES AS DETERMINED BY COMPUTATIONAL SIMULATION

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A requirement for an effective debris shield is that it must protect a spacecraft from impacts by irregularly shaped particles. A series of numerical simulations has been performed using the multi-dimensional shock physics code CTH to numerically determine the ballistic limit curve for a Whipple bumper shield. Two different projectile shapes are considered for the numerical simulations, flat plates of varying diameters with a constant thickness and spheres of varying diameters. The critical diameter or ballistic limit was determined over a velocity range from 4 km/s to 15 km/s. We have found both experimentally and numerically that the particle shape has a significant effect on the debris cloud distribution, ballistic limit curve, and penetration capability.

INTRODUCTION

A requirement for an effective debris shield is that it must protect a spacecraft from impacts, both from the meteoroid and orbital space debris environments. The micrometeoroid environment is thought to consist of dust size particles with an average impact velocity of 20 km/s, while the orbital debris environment is believed to be millimeter to centimeter size particles with an average velocity of 10 km/s. The orbital debris environment (1) is thought to be more hazardous because of the relatively large mass. The Whipple bumper (2) is a space shield designed to protect a spacecraft from the more hazardous orbital space debris environment. Design of these bumper shields is currently done by a combination of experiments at accessible velocities and analytical models developed from scaling theories (3).

In this paper, calculated ballistic limit curves and experimental and computational debris cloud distributions will be presented and discussed in detail. The use of simulation tools allows us to perform numerical experiments that are not tractable in the laboratory. Even though we do not consider CTH (4) to be fully validated for the class of problems discussed here, it has been shown to replicate many important features of high velocity impacts.

COMPUTATIONAL SCHEME

Since only normal impacts were considered, the computational geometry was two-dimensional axis-symmetric. The computational scheme represents a simple Whipple bumper shield with a sheet of 1.27 mm 6061-T6 aluminum. The rear sheet consists of 3.175 mm 2219-T87 aluminum with a void space of 101.6 mm between the bumper and rear sheet. The projectile was modelled as 6061-T6 aluminum.

Our experience with CTH has shown that four computational zones across the thickness of a material is the minimum number necessary to resolve the shock structure in that material. For these simulations, we chose to increase the computational resolution to ~8 zones across the thickness of the bumper shield. In the region of initial impact, the zones are square (0.015 cm x 0.015 cm). The zones are gradually increased in size radially. Longitudinally, the zones are first increased in size and then decreased, so that in the region of the secondary impact (where the debris cloud impacts the rear sheet), the zones are again square (0.015 cm x 0.015 cm).

The different types of aluminium modelled in this simulation were treated using an elastic-plastic approximation for material strength with a Von Mises

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yield surface. Failure in tension was modelled by a simple cutoff scheme that relieves tension by introducing void into a computational cell when the mean principal stress exceeds the tensile strength. Identical equations-of-state were used for the three types of aluminum, namely, the SESAME table developed by Kerley (5). This table was scaled to take into account the higher density of the 2219-T87 aluminum (2.851 gm/cm^3 versus 2.7 gm/cm^3 for 6061-T6).

For each velocity, the diameter of the plate or sphere was varied until penetration of the rear sheet occurred, with the minimum change in diameter being 0.025 cm and 0.02 cm for the plate and sphere, respectively. For all simulations, computational penetration was characterized as an intact rear sheet, that is, one with no perforations. This definition allows a rear sheet to have detached spall and still be characterized as not penetrated computationally. This definition may result in some systematic differences between the current ballistic limit curves as developed from experiments at accessible velocities and analytical models (3) that are velocity dependent. Computationally, spall is a major component to rear sheet damage at velocities below $\sim 7 \text{ km/s}$. If the computational no-penetration condition did not allow for detached spall, the computational ballistic limit would be lowered below 7 km/s , but would not change significantly at high velocities.

COMPUTATIONAL RESULTS

Figure 1 shows the ballistic limit as determined by CTH for normally impacting plates and spheres in the velocity range of 4 to 15 km/s. The ballistic limit curve is drawn halfway between the penetration/no-penetration locations as determined by CTH. The differences between the two curves are striking. The ballistic limit for flat plate impacts shows little variation as a function of velocity. An inspection of the debris clouds from flat plate impacts shows amazing consistency over the range of impact velocities. The debris clouds due to a flat plate impacting normally are collimated with minimal lateral dispersion (see Fig. 2 for a typical debris cloud). Even though the total momentum of the debris

FIGURE 1. Computational ballistic limit for plate and spheres

cloud increases with increasing velocity, Fig. 1 implies that the impulse is relatively constant over the range of impact velocities. The converse of this statement is true for spherical normal impacts (see Fig. 3 for a typical debris cloud). The lateral dispersion for the spherical projectiles depends significantly on the impact velocity. At low velocities ($< 7 \text{ km/s}$), the projectile and bumper fracture and exhibit little lateral dispersion. At impact velocities near 8 km/s , the projectile and bumper start to melt and lateral dispersion increases. At higher impact velocities ($> 10 \text{ km/s}$), vaporization of the projectile and bumper occur and lateral dispersion increases.

The ballistic limit for spherical projectiles shows reasonable agreement with experimental data (6) over the 4-7 km/s velocity range accessible by light gas gun technology. CTH tends to over-predict rear sheet damage in this range, most likely due to the relatively simple material strength model. A strain hardening strength model would decrease predicted damage and may improve the correlation with experiment. The current extrapolations (3) beyond the experimental regime rely on analytic scaling assumptions. It is in this velocity regime that the curve determined using CTH and the analytic extrapolation techniques differ significantly. In this velocity range, CTH is predicting that the amount of shock induced vaporization increases as the velocity increases. The increased

vaporization results in increased lateral dispersion and a reduction in damage due to the initial impulse.

FIGURE 2. CTH debris cloud for a plate impact.

FIGURE 3. CTH debris cloud for a spherical impact.

Figure 4 displays a radiograph taken when a thin plate impacts a sheet similar to that of a Whipple bumper shield. Figure 5 displays a similar radiograph taken when a sphere impacts the same sheet. Experimentally, significant differences between the two debris clouds can be seen. The plate impacts results in a collimated debris structure with a high density remnant at the leading edge of the cloud. The

FIGURE 4. Experimental debris cloud for a disk impacting a thin sheet.

FIGURE 5. Experimental debris cloud for a sphere impacting a thin sheet.

sphere impact results in a diffuse debris structure with a higher density leading edge.

The CTH simulations similar to these are seen in Figures 2 and 3. The right and left side of the figures represent different information from CTH. The right side of each figure displays a grey scale that is proportional to the density integrated along the line of sight, similar to the data collected by a radiograph. The left side of each figure displays the material locations by color, where light grey represents the target contribution to the debris cloud and dark grey represents the projectile contribution. Due to a limited computational domain used in these simulations, some portion of the trailing debris structure is lost.

In Fig. 2, the results from right side of the image indicate a collimated debris cloud and a closed tulip shape of the lower density debris that is similar to the data from Fig. 4. Although not visible in the figure a closer examination of the results indicates a high density structure at the leading edge of the predicted debris cloud also similar to the radiograph. In Fig. 3, the results from left side of the image indicate a shell-like leading edge of the cloud and a higher density structure in the front third of the cloud that is also similar to the data from Fig. 5.

SUMMARY

CTH has been utilized extensively for a wide variety of impact and high explosive related applications (7). In recent years, work has also been done with CTH related to debris generation and secondary impacts (8,9) similar to those that are in this paper. This Whipple bumper shield simulation may be the most difficult problem to confront in an Eulerian hydrocode. The wide range of impact velocities entails a wide range of physics that controls the secondary penetration. For all velocities, the wide range of dimensions (from ~1 mm bumper thicknesses to ~300 mm bumper to rear sheet separations) inherent in these simulations can cause significant numerical difficulties. At low velocities, the fracture dynamics and material strength models are important, but at high velocities, the equation-of-state dominates the predictions. Phase change

phenomena and phase separation may need to be included in hydrocodes before better agreement with experiment can be expected.

Below ~7 km/s impact velocities, the CTH results for spherical projectiles agree with available experimental data. At higher velocities, CTH can predict the differences in debris structure and secondary penetration due to projectile shape (8) as noted in the previous section. The difference in penetrating ability of plates and spheres as predicted here by CTH is significant. At higher velocities, the lack of experimental data to develop equation-of-state information limits the confidence that can be placed on these simulations. Even with these limitations, the difference in penetrating ability of plates and spheres as predicted by CTH is significant and should be investigated further. In addition, the deviation between the CTH predictions for spherical projectiles and the analytic extrapolations is substantial in the high velocity regime.

ACKNOWLEDGMENTS

This work performed at Sandia National Laboratories supported by the U.S. Department of Energy under contract DE-AC04-94AL85000.

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