WHIPPLE BUMPER SHIELD TESTS AT OVER 10 KM/S

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A series of experiments has been performed on the Sandia HyperVelocity Launcher (HVL) to evaluate the effectiveness of a thin Whipple bumper shield at impact velocities up to 10.5 km/s by orbital space debris. Upon impact by an 0.67 gm (0.87 mm thick) flier plate the thin aluminum bumper shield completely disintegrates into a debris cloud. The debris cloud front propagates axially at velocities in excess of 14 km/s and expands radially at a velocity of ~ 7 km/s. Subsequent loading on a 3.2 mm thick aluminum substructure by the debris cloud penetrates the substructure completely.

1. INTRODUCTION

It is well known that the principal threat to orbiting space structures results from impact damage caused by space debris[1,2]. Presently, conventional laboratory facilities are not available for evaluating damage mechanisms or the effectiveness of protective structures against this debris. Although analytic methods[3,4] for predicting impact damage and hydrodynamic code[5] simulations of impact events have progressed to the point of providing realistic damage assessments, these analyses or models have not been validated over the velocity range of 7 km/s to 10 km/s, primarily due to lack of experimental capabilities to launch gram-size plates or particles over that velocity range.

A requirement for an effective debris shield is that it must protect the spacecraft from impacts both from the micrometeoroid and orbital debris environment. The micrometeoroid environment is thought to consist of dust-size particles having an average velocity of 20 km/s, while the orbital debris environment is believed to be millimeter or centimeter size particles weighing approximately a gram with average velocities of 10 km/s. It is generally assumed that the average density of the orbital debris environment[1,2] is ~ 2.8 gm/cm^3, and therefore can be fairly represented by the material properties of aluminum. Orbital debris, which is man-made space debris, is more hazardous than the micrometeoroids because of the abundance, and relatively large mass and particle size of the orbital debris.

With the development of a hypervelocity launch[6,7] capability at Sandia, it is now possible to perform impact experiments over the velocity range of 7 km/s to 10.4 km/s, a velocity range not accessible previously for gram-size plates. This meets the requisite mass-velocity criteria established for the orbital debris environment. In this paper, test results performed to evaluate the effectiveness of a simple aluminum Whipple bumper shield located at 114 mm from the space structure at impact velocities of 10.1 km/s are summarized. The mass of the aluminum flier plate which representst the orbital debris particle is 0.67 gm. Numerical simulations of the experiment have been performed using the three dimensional finite-difference code CTH, results of which are summarized in a companion paper[8].

Results of the experiments indicate that in the vicinity of impact, the thin aluminum bumper completely disintegrates into a debris cloud upon impact at 10.1 km/s by the 0.67 gm aluminum flier plate. The debris cloud front propagates at velocities in excess of 14 km/s, and expand radially at a velocity of ~ 7 km/s. Subsequent loading on the hull structure by the debris cloud penetrates the substructure completely. In the next section the experimental technique used to obtain hypervelocity launch is briefly described. The experimental set up used to simulate orbital debris impact condition is described in a subsequent section followed by a discussion and a summary of the results.

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2. EXPERIMENTAL TECHNIQUE

2.1 Sandia's HyperVelocity Launcher (HVL)

This section briefly describes the operation of Sandia's newly developed hypervelocity launcher. It is based on the principle that structured, time-dependent (shockless), megabar driving pressures are needed to launch a plate without inducing melt or fracture in the plate. This is accomplished by using a graded-density material to impact the flier plate. When this graded-density material impacts a stationary flier plate at high velocities on a two-stage light-gas gun, a nearly shockless, structured, and uniform high-pressure pulse is introduced in the flier plate. Since the loading on the flier plate is shockless, excess heating is minimized to avoid melting of the flier plate. The structured pressure pulse prevents the flier plate from fracturing. An impact velocity of 6.4 km/s is used to launch a nominally 1-mm thick aluminum flier plate to a velocity of 10.4 km/s. The mass of the flier plate is controlled by the diameter of the impacting plate. The velocity of the flier plate is measured using radiographic techniques. An x-ray radiograph of the flier plate prior is depicted in Figure 1.

2.2 Debris Shield Configuration

The experimental impact configuration used to simulate orbital debris impact is also indicated in Figure 1. The bumper shield material used in these studies was a 305 mm square 6061-T6 aluminum alloy sheet, 1.27 mm ± 0.025 mm thick. The space station hull structure was represented by a 305 mm square 2219-T87 aluminum alloy panel, 3.20 mm ± 0.03 mm thick. In this experiment, the stand-off distance between the bumper shield and the hull plate was 114 mm. The debris shield and the hull plate assembly was placed at a distance of 700 mm away from the plate launch position. This ensures that a reading time of 70 μs is available for fast framing photography which was used to record the propagation of debris cloud generated upon impact of the bumper shield. Front-lit photography was used to record the structure of the debris cloud. In this experiment, the side view i.e., the view between the bumper shield and the hull plate was monitored; the back surface view of the hull plate was also photographed. The side view and the back surface view of the photographs are shown in Figure 2. The grid markings indicated in the figure have a spacing of 1 cm.

3. RESULTS

3.1 Side View

In this experiment, an intact flier plate 19 mm in diameter, 0.868 mm thick impacted the bumper shield at 10.1 km/s. It appears that the flier plate is bowed prior to impact, and the bowing appears to be relatively symmetric in this experiment. As indicated in the figure, the expansion of the debris cloud appears to be very nearly spherical as it propagates towards the hull plate. The axial debris front velocity is calculated to be approximately 14.1 km/s, while the radial expansion velocity of the debris cloud is estimated to be ~ 7.3 km/s. However, this does not mean that the entire debris cloud is propagating at a velocity of 14.1 km/s. The structure of the debris cloud at 7 μs suggest an approximate dispersion of 50 mm, indicating a velocity distribution from a maximum of over 14 km/s to ~ 7 km/s. Impact of the hull plate is evidenced by the impact flash observed in the photographic frame at 8 μs. The debris cloud is over 120 mm in diameter prior to impacting the hull plate.

3.2 Back Surface View

The set of framing photographs shown in Figure 3 displays the back surface view of the hull plate. The first frame is taken at 8 μs, which is approximately the time at which the leading edge of the debris cloud impacts the hull plate. No deformation of the hull plate is observed until the subsequent frame at 13 μs in which a deformation bulge ~15 mm in diameter is observed. Penetration/rupture is observed in the subsequent frame at 18 μs. The exact size of the rupture of the hull plate cannot be estimated, since it is obstructed by the penetrating debris. The radial expansion of the penetrating debris as determined from the framing photographs propagates at a velocity of 2 km/s.

4. DISCUSSION

In this study, impact of the bumper shield with the flier plate occurs at velocities over 10 km/s. This generates stresses in excess of 160 GPa both in the flier plate and in the bumper shield. Aluminum melts at ~ 120 GPa in the shocked state. Therefore, upon release from 160 GPa the entire plate and the bumper shield will be molten with the final release temperatures to be about 3000 K. Since the boiling point for aluminum is 2700 K, partial vaporization is also anticipated. The debris cloud generated upon impact is therefore expected to be completely molten with partial vaporization.

As mentioned above, the debris cloud expands almost spherically as it propagates longitudinally. The leading edge of the debris cloud is presumed to be low-density material, presumably vapor, travelling at velocities of 14 km/s; there appears to be a density gradient across the debris cloud in that the higher density material is travelling slower at velocities of 6 to 7 km/s. The debris cloud expands radially at a rate of ~ 7 km/s. This implies a spray angle of ~45 ^{o}. This is indicated schematically in Figure 4. Locations A and B in the figure are areas where there is evidence of instability growth. The subsequent loading on the hull sub-structure is both spatial and time-dependent in that it is distributed over a considerable portion of the hull plate, and spans over a time interval of ~ 8 µs. This is consistent with the experimental observation that the hull plate usually ruptures ~ 5 µs after initial loading.

The total mass in the debris cloud is composed of the mass of the flier plate and the fraction of the mass of the bumper shield that was penetrated upon impact. If we assume that the flier plate punches an equivalent diameter hole in the bumper shield upon impact, then for a 19 mm diameter plate impact, the contributing mass to the debris cloud from the bumper shield will be approximately 0.96 gm. Specifically, the total mass in the debris cloud will be 1.61 gm neglecting any mass due to back splatter. If the entire mass is distributed uniformly in a sphere of ~ 12 cm diameter prior to impact (see Figure 2) of the hull plate, then the density of the debris cloud is calculated to be ~ 0.001 gm/cm^3. (However, as indicated in Figure 2, the mass appears to be distributed towards the "front" of the cloud within a finite shell thickness. On an average the density of the cloud should then be larger than 0.001 gm/cm^3. X-ray diagnostics will be useful in estimating the density distribution in the debris cloud.

5. SUMMARY

In this paper, we have described results of first experiments performed to characterize the design of a simple Whipple bumper shield at velocities in excess of 10 km/s. The mass and velocity of the impacting plate very nearly approximate the average orbital debris characterization[1]. An orbital debris mass of 0.67 gm represented by an aluminum flier plate at 10 km/s completely disintegrates the thin bumper shield located 114 mm from a witness plate. The debris cloud generated upon impact expands spherically as it propagates in the longitudinal direction. The low density material in the debris cloud front, presumably vapor, propagates at velocities in excess of 14 km/s, while the higher density molten material travels slower at velocities of 6 km/s to 7 km/s. Subsequent loading of the representative hull plate by the debris cloud leads to perforation.

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FIGURE 1

Experimental impact cofiguration to simulate orbital debris impact.

FIGURE 2

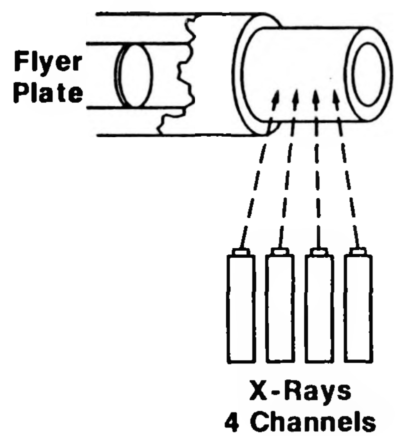
View of debris cloud propagation between the bumper shield and the hull plate

FIGURE 3

Back surface view of the hull plate indicates rupture as a result of subsequent loading by the debris cloud

FIGURE 4

Geometric features of debris cloud propagation suggest a very nearly spherical propagation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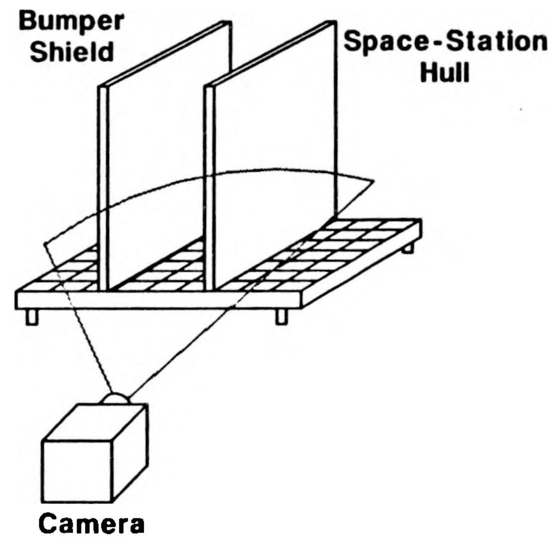
4 Channels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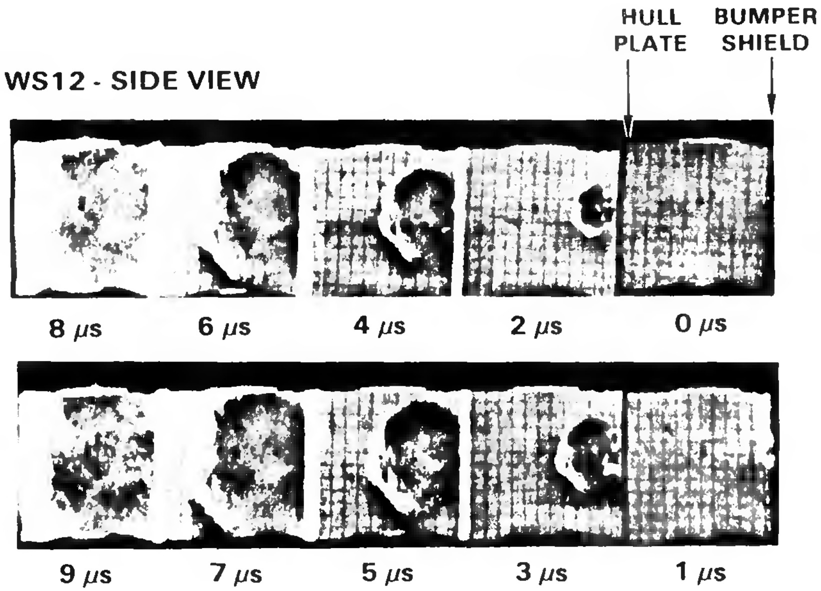
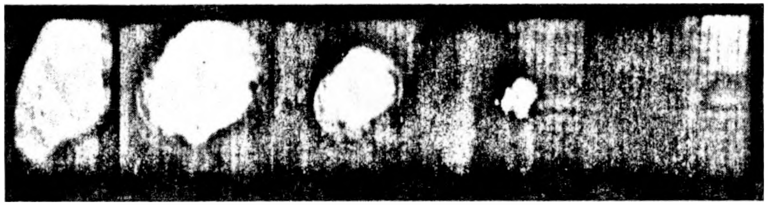
Shield
Space-Station
Hull
Camera

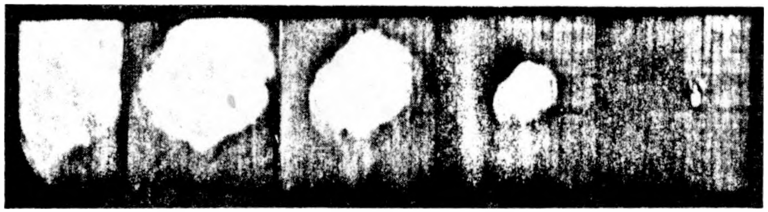
WS12 - SIDE VIEW



WS12 - BACK SURFACE VIEW



48 μs 38 μs 28 μs 18 μs 8 μs



53 μs 43 μs 33 μs 23 μs 13 μs

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