

SHAPE EFFECT ANALYSIS OF ALUMINUM PROJECTILE IMPACT ON WHIPPLE SHIELDS

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ABSTRACT

The informed design with respect to hypervelocity collisions involving micrometeoroid and orbital debris (MMOD) is influential to the success of space missions. For an orbit comparable to that of the International Space Station, velocities for MMOD can range from 1 to 15 km/s, with an average velocity around 10 km/s³. The high energy released during collisions at these speeds can result in damage to a spacecraft, or worst-case, loss of the spacecraft, thus outlining the importance of methods to predict the likelihood and extent of damage due to an impact. Through experimental testing and numerical simulations, substantial work has been conducted to better understand the effects of hypervelocity impacts (HVI) on spacecraft systems and shields; however, much of the work has been focused on spherical impacting particles.

To improve environment models for the analysis of MMOD, a large-scale satellite break-up test was performed at the Arnold Engineering and Development Complex to better understand the varied impactor geometries that could be generated from a large impact⁴. As a part of the post-experiment analysis, an undertaking to characterize the irregular fragments generated is currently being performed by the University of Florida under the management of NASA's Orbital Debris Program Office at Johnson Space Center (JSC). DebrisSat was a representative, modern LEO satellite that was catastrophically broken up in a HVI test. The test chamber was lined with a soft-catch system of foam panels that captured the fragments after

impact. Initial predictions put the number of fragments larger than 2mm generated from the HVI at roughly 85,000. The number of fragments thus far extracted from the foam panels has exceeded 100,000, with that number continuously increasing. The shapes of the fragments vary dependent upon the material. Carbon-fiber reinforced polymer pieces, for instance, are abundantly found as thin, flat slivers. The characterization of these fragments with respect to their mass, size, and material composition needs to be summarized in a form that can be used in MMOD analysis.

The mechanism that brings these fragment traits into MMOD analysis is through ballistic limit equations (BLE) that have been developed largely for a few types of materials¹. As a BLE provides the failure threshold for a shield or spacecraft component based on parameters such as the projectile impact velocity and size, and the target's materials, thickness, and configuration, it is used to design protective shields for spacecraft such as Whipple shields (WS) to an acceptable risk level. The majority of experiments and simulations to test shields and validate BLEs have, heretofore, largely used spheres as the impactor, not properly reflecting the irregular shapes of MMOD. This shortfall has motivated a numerical impact analysis study of HVI involving non-spherical geometries to identify key parameters that environment models should provide.

With the objective to expand the WS BLE to the shape of the impactor, the Ernst-Mach Institute (EMI) from Freiburg, Germany, conducted impact tests using spherical and ellipsoid-shaped projectiles on simple aluminum WS. EMI chose rotationally symmetric ellipsoids, where the semi-major axes $a=b \neq c$. This allowed them to describe the shape of the projectile based solely on one parameter- the "shape factor", f , of the projectile. The shape factor is the ratio of the length of the projectile to its diameter, or c/a . Therefore, for a sphere $f = 1$, an oblate ellipsoid $f < 1$, and a prolate ellipsoid $f > 1$. The selected projectiles each had a shape factor of: $f = 0.4$, $f = 1$, or $f = 1.53$.

The impacts tests were conducted using a two-stage light gas gun at velocities ranging from 0.85 km/s to 6.76 km/s. The aluminum projectiles were fired normal to the target at a 0° angle-of-attack. From the experimental data and numerical simulations, EMI modified the WS BLE developed by Christiansen to take into account the projectile shape². Based on their results, EMI validated their modified BLE and concluded that at higher velocities the critical masses for ellipsoids were below the critical masses for spheres, although at low velocities, the WS has a higher protection performance when impacted by an oblate projectile as opposed to a sphere.

An independent analysis of the results obtained by EMI has been conducted as an internship project at JSC Hypervelocity Impact Technology (HVIT) lab. The HVI have been simulated via the three-dimensional, nonlinear-structural-dynamics, simulation tool, CTH, which has been developed by Sandia National Laboratories to treat shock-wave propagation and large-deformation phenomena. The same projectile shapes from the EMI tests have been modeled, in addition to, simulations outside of EMI's published data for BLE development. To validate the CTH model, an initial calibration to adequately select the appropriate constitutive models such that the simulation results were in accordance with the EMI impact tests has been performed. In order to leverage computation time and accuracy of the simulations, the Mie-Grüneisen EOS and Johnson-Cook strength model, both native to CTH, were implemented. The Johnson-Cook fracture model was also selected.

The simulation results of the shield rear-wall, in terms of rear-wall pass-fail and the projectile mass and impact velocity, are described in the paper and plotted against the modified BLE from EMI. The spherical and prolate projectile CTH simulation results matched the EMI impact tests adequately and the BLE curves reasonably predicted the performance of the Whipple shield. Conversely, the simulations for the oblate projectile are not in agreement with the EMI impact test results. The simulations for the oblate impact tended to over-predict

the shield performance relative to the published EMI test results. This mismatch is still being investigated. Next steps of the research include repeating the analysis for oblique impact angles as well as investigating effects of orientation for oblate and prolate ellipsoids on the shield ballistic limits.

References

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3. Stansbery, E. G., et al., NASA/TP-2015-218592, "NASA Orbital Debris Engineering Model ORDEM 3.0 – Verification and Validation", NASA Johnson Space Center, 2015.
4. Clark, S., et al., "Design and Fabrication of DebrisSat - A Representative LEO Satellite for Improvements to Standard Satellite Breakup Models," 63rd International Astronautical Congress, Naples, Italy 2012.

APPENDIX

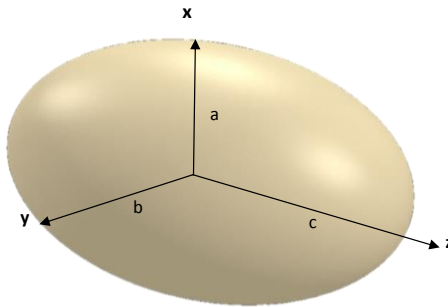


Fig. 1 Axes of a rotationally symmetric ellipsoid, $a=b \neq c$. Impact axis along the z-direction.

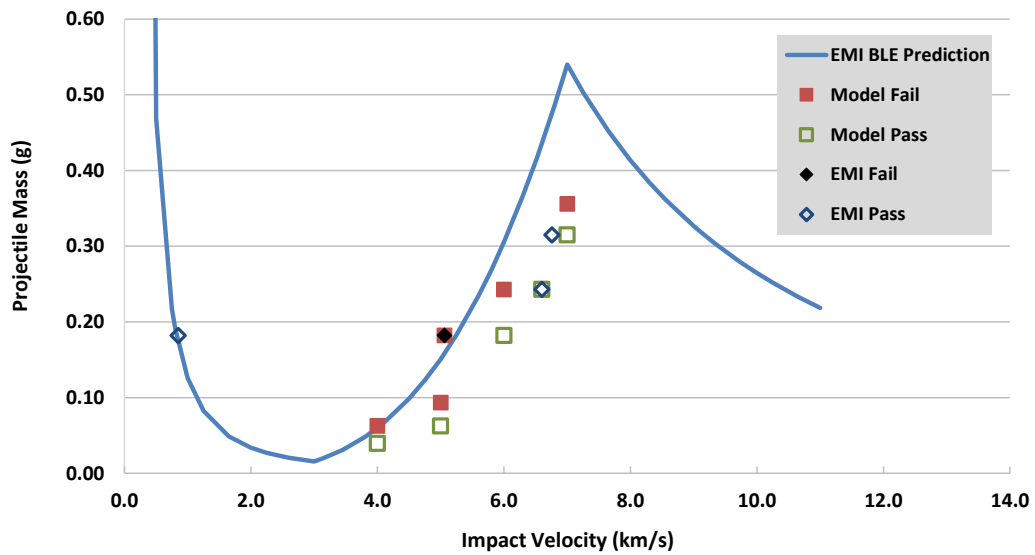


Fig. 2 Simulation results plotted against the BLE for a sphere, $f = 1$.