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Shape Effect Analysis of Aluminum Projectile Impact on Whipple Shields

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Abstract

This report presents a numerical analysis study on the shape effects of prolate and oblate ellipsoid projectiles on the performance of spacecraft shields conducted in support of the Orbital Debris Program Office at the NASA Johnson Space Center with the Hypervelocity Impact Technology (HVIT) group [1]. The study served as an independent analysis of the experimental results obtained by the Ernst-Mach Institute, who conducted hypervelocity impact (HVI) tests using shaped-projectiles against a dual-wall Whipple shield to develop ballistic limit equations (BLE) with shape effects. 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 results from the numerical simulations for the sphere and prolate ellipsoid projectiles indicate numerical simulations are a viable tool for conducting HVI analyses, however, significant differences between the CTH models and published EMI test data for the oblate projectiles point to issues in modeling the impact physics of oblate ellipsoid geometries [2]. Consequently, further analysis should be performed to solve the problem in modeling these oblate projectile impacts. The unmodified BLE for spheres and modified BLE for prolate ellipsoids reasonably predict failure of a Whipple shield at low impact velocities, but based on the obtained data may need to be adjusted for velocities between 4 and 8 km/s.

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Keywords: hypervelocity; DebriSat; ellipsoid; projectile; simulation

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Nomenclature

d	projectile diameter (cm)
d_{bl}	critical projectile diameter (cm)
f	shape factor of ellipsoid with semi-major axis a=b≠c
l	projectile length (cm)
S	standoff length of bumper and rear-wall (cm)
t_b	bumper thickness (cm)
t_w	rear-wall thickness (cm)
v	impact velocity (km/s)
v_{G1},v_{G2}	transition velocities for ballistic limit equations (km/s)
v_n	normal component of the impact velocity (km/s)
ρ_p	projectile material density (g/cm^3)
ρ_t	target material density (g/cm^3)
σ	yield stress of the rear-wall (ksi)
θ	impact angle of the projectile on the target surface

1. Introduction

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/s [3]. The high energy released during collisions at these speeds can result in damage to a spacecraft or even loss, 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 impacting spheres [1].

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 impact [4]. 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 the Johnson Space Center (JSC). DebriSat [5] 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. For instance, Carbon-fiber reinforced polymer pieces are abundantly found as thin, flat slivers and plates, metals as asymmetrical nuggets; therefore, 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 materials [1]. 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. Heretofore, the majority of experiments and simulations to evaluate shields and validate BLEs have largely used spheres as the impactor, which are not properly reflecting the irregular shapes of DebriSat. 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 [1]. EMI chose rotationally symmetric ellipsoids, where the semi-major axes a=b≠c. This allowed them to describe

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