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Ballistic limit equations for non-aluminum projectiles impacting dual-wall spacecraft systems

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Abstract

One of the primary design considerations of earth-orbiting spacecraft is the mitigation of the damage that might occur from an on-orbit MMOD impact. Traditional damage-resistant design consists of a 'bumper' that is placed a small distance away from a spacecraft component or from the wall of the element in which it is housed. The performance of such a multi-wall structural element is typically characterized by its ballistic limit equation (BLE), which defines the threshold particle size that results in a failure of the spacecraft element. BLEs are also key components of any micro-meteoroid/orbital debris (MMOD) risk assessment calculations. However, these assessments often call for BLEs to predict impact response for projectiles made of materials not used in the development of those BLEs. The question naturally arises regarding how close are the predictions of such BLEs when used in impact scenarios involving projectiles made of materials not necessarily considered in their development. In an effort to address this issue, a study was performed with the objective of assessing the validity of the NNO BLE for non-aluminum particles. Particle materials considered included steel, copper, and Al_2O_3 (i.e. particles that are made of materials that are more dense than aluminum). Comparisons are made between actual test results involving these non-aluminum projectiles and the predictions of the NNO BLE. In nearly all cases, the NNO BLE was found not to work very well in the predicting failure / no failure response of these non-aluminum projectiles. A new NNO-type BLE is then developed that can be used to more reliably predict the response of dual-wall systems under the hypervelocity impact of such "heavier" non-aluminum projectiles.

Keywords: ballistic limit equation; non-aluminum projectiles; dual-wall structure; orbital debris; risk assessment

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1. Introduction

One of the primary considerations of earth-orbiting spacecraft is the anticipation and mitigation of the possible damage that might occur from an on-orbit MMOD impact. Traditional damage-resistant wall design consists of a 'bumper' plate that is placed at a small distance away from a spacecraft component or from the wall of the compartment or element in which it is housed. The bumper protects the spacecraft component by disintegrating the impacting particle to create one or more diffuse debris clouds that travel towards and eventually impact it or its main or inner protective element. The area over which the impulsive loading of these debris clouds is distributed is governed by the manner in which the projectile and bumper fragment, melt, or vaporize, and by the spacing between the bumper and the inner wall or protected element.

The performance of the multi-wall structural element is typically characterized by its ballistic limit equation (BLE), which defines the threshold particle size that would result in its failure as a function of velocity, impact angle, particle density, particle shape, as well as the composition and geometry of the structural element. This failure can be in the form of a perforation (i.e. a hole) in the main or inner wall of the system. BLEs for multi-wall systems are typically drawn as lines of demarcation between regions of inner-wall failure and non-failure in two-dimensional projectile diameter-impact velocity space; when graphically represented, they are often referred to, in this form, as ballistic limit curves (BLCs).

Ballistic limit equations are one of the key components of any micro-meteoroid/orbital debris (MMOD) risk assessment calculations. However, these assessments often call for the BLEs to be used to predict the response of spacecraft components under the impact of projectiles made of materials that were not used in the development of those BLEs. The question naturally arises regarding how close are the predictions of such BLEs when used in impact scenarios involving projectiles made of materials not necessarily considered in their development.

In an effort to address this issue, a study was performed with the objective of assessing the validity of the primarily-aluminum-projectile-based NNO BLE [1] for non-aluminum particles. Particle materials considered included steel, copper, and Al_2O_3 (i.e. particles that are made of materials that are more dense than aluminum). Debris populations having particles with densities approximating these materials are specifically called out in the NASA debris environment model, ORDEM-3 [2].

In this paper we present comparisons between actual test results involving these “heavier” non-aluminum projectiles and the predictions of the NNO BLE. In nearly all cases, the NNO BLE was found not to work sufficiently well in predicting failure / no failure response of these non-aluminum projectiles. Suggestions are then made regarding how the NNO BLE could be adjusted to accommodate the impact of such more dense non-aluminum projectiles. The end product is a new NNO-type BLE that can be used to more reliably predict the response of dual-wall systems under the hypervelocity impact of “heavier” non-aluminum projectiles.

2. Original dual-wall ballistic limit equations

The BLE for a dual-wall structure is known for its characteristic “bucket shape”, which is a direct result of the phenomenological changes in response that occur at different impact velocities, from (nearly) complete projectile fragmentation (near 3 km/s for aluminum-on-aluminum impacts) to complete projectile melt (near 7 km/s for aluminum-on-aluminum impacts). The space between the dual-wall BLE and that of an equal-eight single-wall BLE is a measure of the increase in protection provided by a dual-wall system over that provided by its equal-weight single-wall counterpart.

The dual-wall BLE used by NASA and others to characterize the response of many dual-wall structural configurations is frequently referred to by the spacecraft design community as the New Non-Optimum, or “NNO”, BLE [1]. The equations for the low velocity and high velocity regions of the NNO BLE are written, respectively, as follows:

$$V_n = V_p\cos\theta_p < 3 \text{ km/s}: \qquad d_{c,L} = f_L(t_b,t_w,\rho_p,\sigma_w)C_L[(V_p\cos\theta_p)^{-2/3}]^{18/19} \tag{1}$$

$$V_n = V_p\cos\theta_p > 7 \text{ km/s}: \qquad d_{c,H} = f_H(t_w,\rho_p,\rho_b,\sigma_w,S)C_H(V_p\cos\theta_p)^{-2/3} \tag{2}$$

In equations (3) and (4), f_L and f_H are functions that contain information regarding the geometry of the particular dual-wall system under consideration, and $C_L=(1/0.6)^{18/19}$ and $C_H=3.918$ are parameters that seek to place the BLE in the most appropriate place on the plot of empirical failure / non-failure data points.