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Using modified ballistic limit equations in spacecraft risk assessments

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ABSTRACT

The fundamental components of any meteoroid/orbital debris (MOD) risk assessment calculation are environment models, damage response predictor equations, and failure criteria. In the case of a spacecraft operating in low earth orbit, the response predictor equation typically takes the form of a ballistic limit equation (BLE) that defines the threshold particle sizes that cause failure of a spacecraft wall or component. Spacecraft risk assessments often call for BLEs for spacecraft components that do not exist. In such cases, it is a common procedure to use an existing BLE after first equivalencing the actual materials and/or wall thicknesses to the materials that were used in the development of the existing BLE. The question naturally arises regarding how close are the predictions of such an 'adapted BLE' to the response characteristics of the actual materials/wall configurations under high speed projectile impacts. This paper presents the results of a study that compared the predictions of a commonly used BLE when adapted to the Soyuz OM wall configuration against those of a new BLE that was developed specifically for that Soyuz wall configuration. It was found that the critical projectile diameters predicted by the new Soyuz OM wall BLE can exceed those predicted by the adapted use of the existing BLE by as much as 50% of the existing BLE values. Thus, using the adapted version of the existing BLE in this particular case would contribute to a more conservative value of assessed risk. If the same trends were to hold true for other spacecraft wall configurations, then it is also possible that using existing BLEs, even after they have been adjusted for differences in materials, etc., may result in predictions of smaller critical diameters (i.e., increased assessed risk) than would using BLEs purposely developed for actual spacecraft configurations of interest.

1. Introduction

The fundamental components of any meteoroid/orbital debris (MOD) risk assessment calculation are the meteoroid and orbital debris environment models, the damage response predictor equations for the various components that comprise the spacecraft, the failure criteria for those spacecraft components, and the spacecraft size and orbital parameters. The response predictor equation typically takes the form of a ballistic limit equation, or BLE, that characterizes the performance of a hypervelocity impact shield. Such an equation defines the threshold particle sizes that cause failure (however that is defined) of the spacecraft component or impact shield. Guidelines for spacecraft protection as well as how to achieve them have been developed for a variety of spacecraft types and structural elements (e.g., [1,2]).

In preparation for a risk assessment calculation during the design of a spacecraft, the need for a BLE often arises for spacecraft components where one does not exist. In such cases, it is a common procedure to use an existing BLE after first equivalencing the materials and/or wall thicknesses to the materials that were used in the development of that BLE. The question naturally arises regarding how close are the predictions of such an 'adapted BLE' to the response characteristics of the actual materials/wall configurations under high speed projectile impacts.

In an attempt to begin addressing this issue, a study was conducted to compare the predictions of a commonly used BLE modified to be applicable to a highly specialized spacecraft wall configuration against those of a new BLE that was developed specifically for that wall configuration. As such, this paper discusses how response predictor equations such as BLEs can be used in situations for which they were not specifically developed and what kinds of discrepancies might develop in such applications.

2. Spacecraft ballistic limit equations

Ballistic limit equations are empirically-based equations that are developed to characterize the response of a spacecraft component, often an impact shield, under the high speed impact of a meteoroid or space debris particle. Such an equation defines the threshold particle size that causes, for example, perforation or

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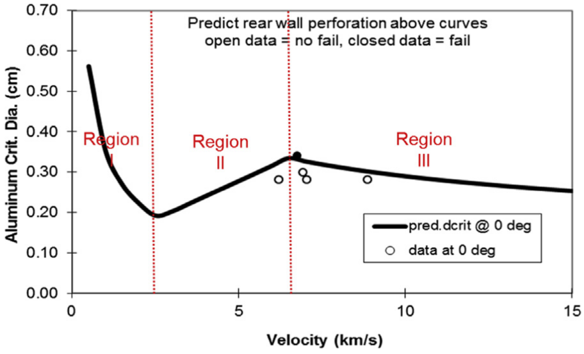

Fig. 1. Typical BLC for a Dual-wall System under Normal Projectile Impact.

detached spall from the inner wall of a multi-wall system as a function of velocity, impact angle, particle density, shield and inner wall thicknesses, and particle shape. BLEs are typically drawn as lines of demarcation between regions of inner-wall failure and no failure in two-dimensional projectile diameter-impact velocity space. When graphically represented they are referred to as ballistic limit curves, or BLCs.

The high-speed impact testing that provides data for the development of BLEs and BLCs typically use spherical projectiles fired in light gas guns at impact velocities between 3 and 7 km/s (although some can reach velocities up to 10 km/s now). These data are then fitted with scaled single-wall equations below approximately 3 km/s, and with theoretical momentum and/or energy-based penetration relationships above approximately 7 km/s to obtain three-part BLCs that cover the full range of impact velocity from approximately 0.5 to 16 km/s. The transitional velocity region (from approximately 3 to 7 km/s for normal aluminum-on-aluminum impacts) takes the form of a linear interpolation between the low and high velocity regions. Fig. 1 shows a typical BLC for a dual-wall system (i.e., Whipple shield) under normal projectile impact. Also included in this figure are some generic data points that are intended to be representative of the test data that would be typically obtained in the development of such a BLE or BLC.

In Region I, the projectile is deformed following its impact on and passage through the outer (i.e., bumper) plate, but remains mainly intact as it travels towards and eventually strikes the inner wall of the dual-wall system. For aluminum projectiles impacting aluminum bumpers, Region I is typically impact velocities below 3 km/s. In Region II, the projectile is fragmented and the energy of the impacting projectile and ejected shield material is dispersed over an increasingly larger area of the inner wall. As a result, the ability of the dual-wall system to resist inner-wall failure (whether defined as a perforation or detached rear-side spall) increases as reflected in the curve. This gives rise to the well-known “bucket” shape of the BLC for a dual-wall system. In Region III (which typically starts at 7 km/s for aluminum-on-aluminum impacts), the projectile is completely melted and the impulse delivered to the rear wall is increasingly more difficult to resist.

The BLE sketched in Fig. 1 is frequently referred to by the spacecraft design community as the New Non-Optimum, or “NNO”, BLE [3]. This BLE was developed primarily for aluminum-on-aluminum impacts and for dual-wall configurations with bumpers or shields that are sufficiently thick so as to cause significant fragmentation of an incoming projectile. This BLE has been adapted to other target types and applied to various other materials, including lightweight multi-layer thermal insulation blankets, by equivalencing those materials and wall thicknesses to aluminum on a mass density basis. For example, in the event of a non-aluminum bumper of a specified thickness and having a certain density (ρ), the thickness (t) of an equivalent aluminum shield can be calculated as follows:

$$\rho_{\text{alum}}\, t_{\text{bumper}}^{\text{equiv alum}} = \rho_{\text{bumper}}^{\text{actual}}\, t_{\text{bumper}}^{\text{actual}} \tag{1}$$

so that

$$t_{\text{bumper}}^{\text{equiv alum}} = \left(\rho_{\text{bumper}}^{\text{actual}} / \rho_{\text{alum}}\right) t_{\text{bumper}}^{\text{actual}} \tag{2}$$

Eqs. (1) and (2) are usually applied to lightweight multilayer thermal blankets and other heavier materials to allow wall configurations with those materials to be part of a risk assessment exercise performed by Bumper. The exception is the case of a Kevlar MMOD blanket for which NASA has developed a more complicated equivalencing procedure as described in [4].

3. Transition velocities

The high-end transition velocity in the BLE for a dual-wall system (i.e., the velocity as the BLE transitions from Region II to Region III) is the impact velocity beyond which the projectile is believed to be substantially melted. For normal aluminum-on-aluminum impacts, this transition velocity is approximately 7 km/s. However, for non-aluminum projectiles impacting aluminum plates, this value can be expected to be something other than 7 km/s.

In order to be able to use a BLE in a risk assessments that also uses NASA's latest MMOD environment description (which includes environment parameters – such as particle density variation with respect to altitude – for high density projectiles, including steel – see Reference [5]), it needs to be modified to include a higher high-end transition velocity option. This option would then engage whenever a risk assessment run called for a calculation involving the impact of a high density particle, such as steel.

Initial attempts at modifying the high-end transition velocity for dual-wall BLEs subjected to high density projectile impact were undertaken in the 2003–2004 time period [6]. Based on an analysis of data from tests involving steel projectiles impacting traditional Whipple shields and stuffed Whipple shields, a high-end transition velocity of 9.5 km/s was proposed.

As noted in [7], a recent study by the NASA Johnson Space Center Hypervelocity Impact Technology (HVIT) group found that a value of 9.1 km/s would be an appropriate high-end transition velocity for steel (or particles with a material density close to steel) particles impacting aluminum plates. This value was obtained using the SESAME equation of state (EOS) to determine the impact pressure (and then the corresponding impact velocity) that would be required for an iron projectile to be substantially melted following an impact on an aluminum plate. The SESAME EOS is a computer-based tabular library of the thermodynamic properties of more than 150 materials [8].

In this study, the Mie-Gruneisen EOS was used as part of an analytical 1-D shock physics-based calculation to determine the fractions of solid, molten, and vaporous material remaining in steel and aluminum projectiles impacting thin aluminum plates (%S, %L, and %V, respectively). The Mie-Gruneisen EOS relates internal energy to pressure and density for impact conditions that result in adiabatic material response (see, e.g. [9]). The results of these calculations are presented in Table 1; the procedure used to arrive at these values is described in detail in [10].

For aluminum-on-aluminum impact, projectile melt begins at impact velocities near 5.5 km/s with the projectile being completely melted at approximately 6.9–7.0 km/s. For steel-on-aluminum impacts, projectile melt likely begins at impact speeds between 7.0 and 7.5 km/s, with the projectile being substantially melted at an impact velocity of approximately 8.5 km/s. The difference between this value and the value indicated in Reference