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Application of the NASA/JSC Whipple shield ballistic limit equations to dual-wall targets under hypervelocity impact

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ABSTRACT

All Earth-orbiting spacecraft are susceptible to damage that can be caused by high-speed impacts with pieces of man-made debris or naturally-occurring meteoroids, and spacecraft at locations other than near Earth are subject to similar naturally-occurring hazards. Traditional protective shield design consists of a "bumper" that is placed at a relatively small distance away from the main "inner wall" of the spacecraft component, the performance of which is typically characterized by its ballistic limit equation (BLE). This paper addresses the question of how well the NASA/JSC dual-wall BLE performs when it is used to predict inner wall response in applications other than those used for its development. The major conclusions reached as a result of the analyses performed are that (1) to be truly conservative the critical projectile diameter value as calculated by the NASA/JSC dual-wall BLE needs to be multiplied by 0.75 to accommodate results from other test databases, (2) the NASA/JSC dual-wall BLE is not as conservative for impact obliquities exceeding 60° as it is for obliquities of 45° or less, and (3) the NASA/JSC dual-wall BLE is not as conservative for impact tests with MLI between the bumper and inner wall as it is for tests without the MLI.

1. Introduction

The space environment about Earth in which satellites, the Shuttle, and the International Space Station orbit is cluttered with naturally-occurring micrometeoroids and pieces of man-made orbital debris. These objects range in size from microscopic particles to spent rocket boosters still in orbit. All Earth-orbiting spacecrafts are therefore susceptible to impacts by these meteoroids and pieces of debris. In addition, spacecraft at locations other than in Earth orbit are subject to similar naturally-occurring hazards. Orbital debris and meteoroid impacts can occur at extremely high speeds and can damage flight- and mission-critical systems. Therefore, the design of all spacecraft must take into account the possibility of such impacts and their effects on the spacecraft and on all of its exposed system components. For this reason, extensive studies continue to be performed devoted to investigating and assessing these threats, as well as protecting spacecraft through a variety of shielding techniques.

Traditional protective shield design consists of a "bumper" that is placed at a relatively small distance away from the main "inner wall" of the spacecraft component. This concept was first proposed in the 1940s and is referred to as the "Whipple Shield" [1]. It has been studied extensively in the last four decades as a means of reducing the perforation threat of hypervelocity projectiles. A sketch of a typical dual-wall Whipple Shield with optional multi-layer insulation (MLI) is shown in Fig. 1. Such a dual-wall configuration had been repeatedly shown to provide significant increases in protection against perforation by relatively small high-speed projectiles over equivalent single-wall structures.

The performance of a hypervelocity impact shield is typically characterized by its ballistic limit equation (BLE), which defines the threshold particle diameter that causes perforation or spall of the inner-most wall of the system as a function of variables known to affect the ballistic limit (e.g., impact velocity, angle, particle density and shape, shield and inner wall separation distance, shield and inner wall thicknesses and material properties). Over the last 30 years, BLEs have been developed for a number of spacecraft applications, including the modules and elements of the International Space Station, the various structural and thermal components of the Space Shuttle, and interplanetary spacecraft. These BLEs are typically drawn as ballistic limit curves (BLCs) that define lines of demarcation between regions of rear-wall perforation and no perforation in two-dimensional spherical projectile diameter and impact velocity space. Most BLEs in use are primarily based on hypervelocity impact tests, and their empirical nature subjects them to potential inaccuracy, in particular when applied to shield configurations that have not been well tested.

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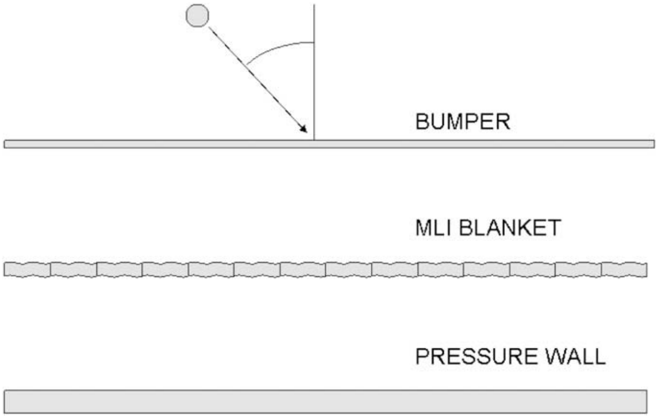

Fig. 1. Illustration of a typical dual-wall Whipple Shield with optional MLI.

2. Research objective

BLEs are also used to optimize the design of spacecraft wall parameters (material, thickness, etc.) so that the walls can withstand high-speed impacts by meteoroids and pieces of orbital debris. Existing BLEs are often used as part of the spacecraft design process either to model dual-wall systems that are outside of the parameters of the test database that was used to develop the BLEs, or to model spacecraft wall systems that, at best, bear only a passing resemblance to a Whipple Shield (e.g. a Shuttle ceramic heat resistant tile that is backed by an aluminum plate). The question naturally arises regarding how well an existing Whipple Shield BLE performs in both of these non-standard applications.

To address the first of these issues, a study was performed to determine how well the current NASA/JSC Whipple Shield BLE (a set of three equations) models the response of dual-wall systems under hypervelocity projectile impact. The latest version of this BLE (and the one used in this study) includes the effects of MLI placed between the bumper and the inner wall, and can be found in Ref. [2]. The focus of the study was on the tests performed at other facilities and ostensibly not used in the development of the NASA/JSC Whipple Shield BLE. The potential issues addressed were as follows.

- Effectiveness in predicting inner wall failure/non-failure.
- Effectiveness variability with respect to impact obliquity.
- Effectiveness variability with respect to the presence of MLI within the dual-wall system.

Table 1
Overview of hypervelocity impact test databases

Database	Year	No. of tests	
NASA/JSC [3]	1990s	161	Normal impact
		42	Oblique impact
GM-DRL [4]	1963	135	Normal impact
		0	Oblique impact
Lundeberg [5]	1965	67	Normal impact
		0	Oblique impact
Burch [6]	1967	5	Normal impact
		42	Oblique impact
CR-915 [7]	1968	165	Normal impact
		37	Oblique impact
NASA/MSFC [8,9]	1980s	322	Normal impact
		366	Oblique impact
		(See note)	

Note: 124 normal; 104 oblique tests w/o MLI; 198 normal; 262 oblique tests w/ MLI; 16 normal tests w/ uniaxial stress in a hoop direction; 23 normal, 7 oblique tests w/ biaxial stress in hoop/longitudinal dir.

Table 2
Impact conditions modeled in test databases

Database	Impact velocity range (km/s)	Projectile diameters (cm)	Trajectory obliquities (deg)
NASA/JSC [3]	2.50–8.06	0.02–1.91	0–85
GM-DRL [4]	1.37–8.06	0.32, 0.48, 0.64	0
Lundeberg [5]	1.40–7.83	0.16, 0.32, 0.64	0
Burch [6]	3.23–5.82	0.32, 0.64	0, 30, 45, 60
CR-915 [7]	0.72–8.08	0.16–0.48	0, 30, 45, 60
NASA/MSFC [8,9]	1.62–8.04	0.32–1.27	0, 30, 45, 60, 65, 75

With respect to the first issue, it is important to note that in the development of the NASA/JSC BLE inner wall failure is defined as either a through hole in the inner wall (with or without detached inner wall rear side spall) or detached inner wall rear side spall (*even in the absence of a through hole*). This could be considered a very conservative definition of failure, since it was planned to be used with BLEs to be applied to design the International Space Station, where human lives are at stake. However, most spacecraft functionalities (e.g. electronics, power and signal cables, pressurized lines and containers, etc.) can be damaged by spall fragments, and the definition could be considered relevant to the design of unmanned spacecraft as well. It is with this definition in mind that this study was performed, and with which the answers to the above questions are provided. These answers could change if the definition of inner wall failure were relaxed somewhat for some applications, e.g., to include only a complete through hole perforation.

Table 1 lists the test databases consulted and some overall general characteristics of the tests performed. Tables 2–4 present specific information regarding the test programs, including impact conditions, geometric parameters, materials tested, etc. It is important to note that, with the exception of the NASA/MSFC tests, these databases typically did not provide information regarding detached spall, only inner wall perforation (which is a more severe failure type). As such, one would expect that the ostensibly highly conservative NASA/JSC BLE would predict nearly all inner wall failures as failures. As will be seen later, this was not always the case. Additional comments regarding the types and information presented in the various databases and possible difficulties in the interpretation of this information are also presented later as they arise.

3. Research program results

3.1. Predicting inner wall failure/no failure

3.1.1. The NASA/JSC test database

The effectiveness of the NASA/JSC BLE in predicting inner wall failure or non-failure was studied by noting, on a test-by-test basis, whether or not the prediction of the BLE was correct. As a starting point, Fig. 2 demonstrates the ability of the NASA/JSC BLE to predict failure or non-failure for the tests used in its development as a function of velocity based on information published in the open literature. Solid markers indicate inner wall failure, while hollow

Table 3
Geometric parameters considered in test databases

Database	Spacing(s) (cm)	Bumper thickness(es) (cm)	Inner wall thickness(es) (cm)
NASA/JSC [3]	1.18–76.2	0.0025–0.813	0.0102–2.858
GM-DRL [4]	2.54, 5.08, 10.16	0.0075–0.254	0.635
Lundeberg [5]	3.2–17.8	0.0125–0.160	0.0254, 0.0508
Burch [6]	2.54–22.9	0.0508–0.406	0.0254, 0.0508, 0.1016
CR-915 [7]	1.27–10.16	0.0305–1.570	0.0406–1.27
NASA/MSFC [8,9]	10.16, 15.24, 20.32, 30.48	0.0813–0.480	0.16, 0.32, 0.41, 0.48, 0.64