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Sacrificial bumpers with high-impedance ceramic coating for orbital debris shielding: A preliminary experimental and numerical study

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ABSTRACT

This study investigates the potential of layered ceramo-aluminum sacrificial bumpers as external elements for spacecraft orbital debris shielding. The bumpers are tailored based on the principle of matching shock impedance of ceramic and metallic layers. They consist of aluminum substrate coated from both sides with silicon carbide. The investigation of the bumpers' performance included both hydrocode modeling and physical hypervelocity impact (HVI) experiments. Obtained results indicate that coated ceramo-aluminum bumpers provide better fragmentation of hypervelocity projectiles and can be considered as a substitute for all-aluminum bumpers in the design of orbital debris shielding.

1. Introduction

Traveling at hypersonic speeds (7 km/s and higher), orbital debris represents a major threat to satellites in Low Earth Orbit. Protection of satellites from collisions with orbital debris is typically implemented in terms of passive shielding. The common design of such shields, also known as Whipple shields [1], represents a system consisting of two walls separated from one another by a standoff distance (Fig. 1). In this design, the first wall is often referred to as a sacrificial bumper. Its major function is to break up a hypervelocity projectile into a cloud of small dispersed fragments. The subsequent expansion of the fragment cloud, while it propagates to the rear wall, provides distribution of impactor energy and momentum over a large area, thus reducing damage to the rear wall and the overall weight of the shielding system required to defeat the projectile [2].

Fragmentation of hypervelocity projectiles on sacrificial bumpers and the typically observed liquid-like behavior of solid materials are provided by high-amplitude shockwaves generated in both bumper and projectile upon collision. It is quite common for hypervelocity impacts that the amplitudes of induced shock waves' orders of magnitude exceed the strength of the colliding materials [3].

In its "conventional" design, the bumper of a Whipple shield is monolithic and made of an isotropic material, usually aluminum, known for its ability to efficiently break up medium-density projectiles. Other possible designs of the shielding systems are continuously being sought with the ultimate purpose of increasing their structural weight efficiency. In this regard, a stuffed Whipple shield concept has been found beneficial [4]. This shield represents a combination of aluminum outer bumper and intermediate layers of advanced flexible materials. Recent studies, aimed at evaluating the efficiency of other types of outer bumpers for orbital debris shielding, such as, for example, dry fabrics, have established the superiority of monolithic aluminum bumpers over all considered alternatives [5].

In this work, instead of looking for a complete substitute for the aluminum bumper, we preliminarily investigate the possibility of enhancing its performance by adding to it thin layers of high-impedance ceramic material, such as silicon carbide. Such a laminated bumper is tailored based on the principle of impedance matching [6,7]. Both numerical modeling and physical experiments were used to investigate the performance of the ceramo-aluminum plates as sacrificial bumpers for orbital debris shielding.

The study has been conducted as part of a contract with Magellan Aerospace and the Canadian Space Agency (CSA) on the development of an orbital debris protection system for a satellite in an 800 km altitude Sun-synchronous orbit [8]. According to the contract requirements, the orbital debris was represented by a 1 mm aluminum projectile that corresponds to the medium-density class prevailing in the overall orbital debris population [9].

2. The concept of a sacrificial bumper with high-impedance coating

An important property used in the design of the laminated ceramo-aluminum bumpers is the shock impedance *(I)* of a material, which can be defined as a product of initial density and shock wave velocity. It represents a measure of the material's ability to generate pressure under

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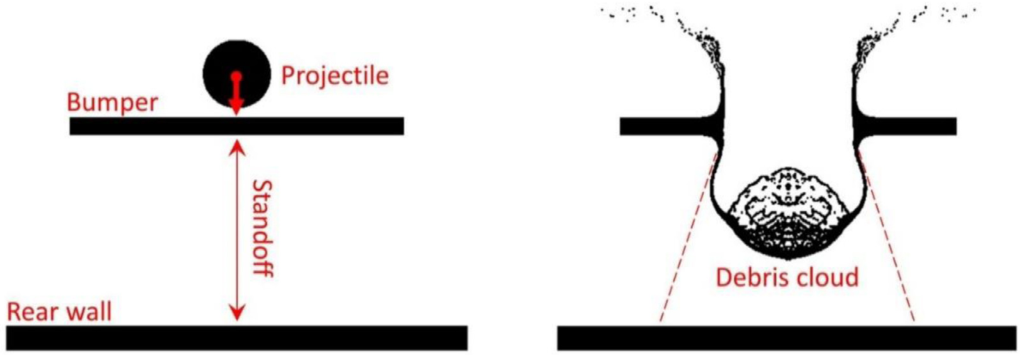

Fig. 1. Schematic of a Whipple shield: before impact (left) and after perforation of the bumper (right).

impact loading, such that pressure (P) is given as

$$P = \rho \cdot U_s \cdot U_p = I \cdot U_p,$$

where: ρ is the material's density; U_s is the shock wave speed; and U_p is the particle speed [6]. For the sake of simplicity, in further considerations we use the acoustic approximation of shock impedance, i.e. reduce it to acoustic impedance $I = \rho_0 C_0$, where ρ_0 and C_0 are material density and bulk sound velocity, respectively. The following simple expression for a longitudinal wave, passing through material “A” and reflecting from the boundary between materials “A” and “B”, is derived in [6]:

$$\sigma_R = \frac{\frac{I_B}{I_A} - 1}{\frac{I_B}{I_A} + 1} \cdot \sigma_I,$$

where: σ_R and σ_I are the amplitudes of the reflected and incident waves, correspondingly. It can be deduced from this expression, that:

a. If $I_B > I_A$, then $sign(\sigma_R) = sign(\sigma_I)$, i.e. a pulse of the same sign as the incident pulse is reflected from a boundary with material of higher impedance;
b. If $I_B = 0$, then $sign(\sigma_R) = -sign(\sigma_I)$, i.e. a pulse of the opposite sign as the incident pulse is reflected from a free surface;
c. For any $I_B > I_A$, increase of I_B will result in increase of reflected wave amplitude.

Fig. 2 (left) schematically represents a composite bumper consisting of three layers: intermediate aluminum layer and two outer layers made of a material with impedance higher than that of aluminum. Upon impact of an aluminum projectile on the front layer ($t = t_1$), a pair of compressive shock waves of the same initial amplitude (as it follows from the Newton's 3rd law) will originate on the impedance boundary and propagate in the opposite directions: one towards the projectile and another towards the bumper. This process is schematically illustrated in Fig. 2 (right). Owing to the higher impedance of the outer layer, the amplitude (pressure) of these shock waves will be higher than it would be in the case of the impact of an aluminum projectile on the aluminum bumper.

Such a compressive wave propagating into the projectile will eventually reflect from the rear free side of the projectile as a higher-amplitude (as compared to aluminum-aluminum impact) tensile wave, which will enhance fracturing of the projectile material and its fragmentation.

Furthermore, as at $t = t_2$ shock wave in the front layer of the bumper will reach interface with the intermediate aluminum layer, the tensile release pulse will be sent through the front layer while compression pulse (P_2) enters aluminum. The tensile pulse will enter the projectile and, if not dissipated quickly, can interact with the tensile wave reflected from the projectile free side, adding to its amplitude and promoting better fragmentation.

The compressive wave propagating into the bumper will reach the aluminum/rear layer interface (C/D) at $t = t_3$, and reflect from it as a compressive wave ($P = P_3$) owing to the impedance difference. This compressive wave will propagate in the aluminum layer *towards* the approaching projectile, suppressing spalling of the intermediate layer material (which may be important for non-perforating impacts) and, potentially, increasing the degree of projectile fragmentation, as this additional compressive pulse will enter the projectile and reflect from its free surfaces as a tensile wave.

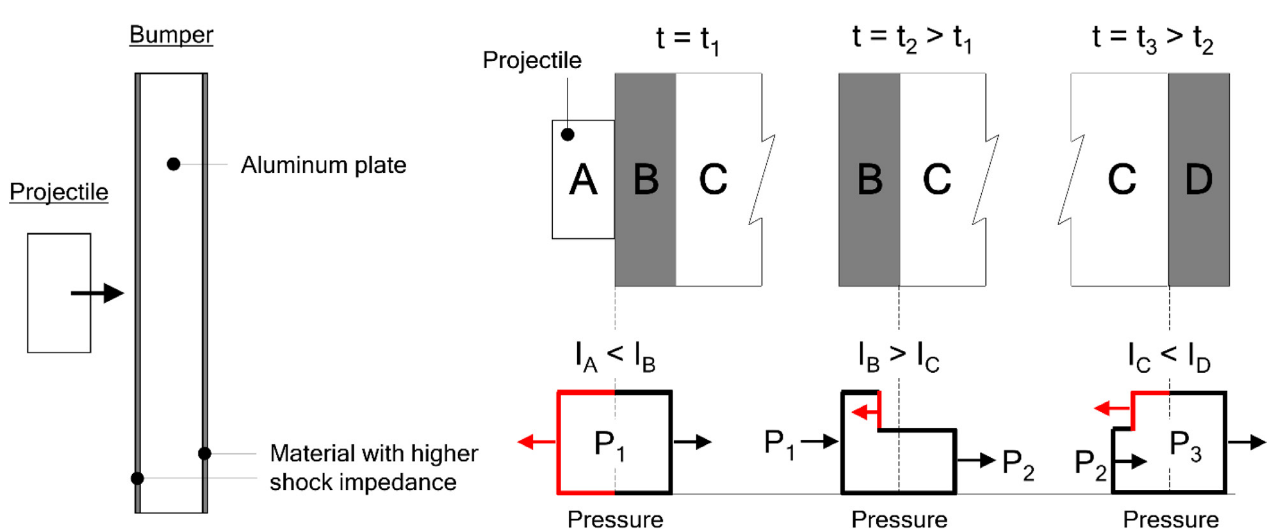

Fig. 2. Laminated bumper with outer layers of high shock impedance (left) and interaction of shock wave with impedance boundaries of the bumper (right).