

EXTENDING THE APPLICABILITY OF THERMAL PROTECTION SYSTEM BALLISTIC LIMIT EQUATIONS BEYOND THE TESTABLE REGIME

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Abstract

All spacecraft use some sort of thermal insulation in their design, which is usually placed on the spacecraft's exterior. As such, it is highly susceptible to high-speed impacts by meteoroids and orbital debris. These high-speed impacts can damage the insulation to a point where the protection it offers is below acceptable limits. It is, therefore, important to be able to characterize expected TPS damage levels stemming from such high-speed impacts. In a recent paper, we presented the results of a study that sought to characterize the high-speed impact damage that would be sustained by two thermal protection materials that have recently gained attention for possible use in interplanetary missions. As part of the analyses performed, ballistic limit equations for these materials were developed using recent high-speed impact test data, and then assessed by comparing their predictions against test data. In this paper, we extend the applicability of the ballistic limit equation for one of those thermal materials beyond the testable regime using the results of series of Smooth Particle Hydrodynamics Code (SPHC) impact simulations at velocities in excess of 10 km/s. When the predictions of the updated and expanded BLE were compared against the results of the SPHC runs, the predictions were seen to be

consistent with the data: non-perforation data points were typically below the BLE curves, while perforation data points were typically above them.

Introduction

All spacecraft use some sort of thermal insulation, or thermal protection system (TPS), in their design. TPS materials vary, ranging from ceramic tiles or phenolic ablators for heatshields to lightweight multi-layer insulation (MLI) blankets. Since TPS is usually placed on the spacecraft's exterior, it is susceptible to impacts by meteoroids and orbital debris. These high-speed impacts can damage the TPS to a point where the protection it offers is below acceptable limits. As such, it is important to be able to characterize expected TPS damage levels stemming from such high-speed impacts.

In a recent paper [1], Schonberg and Squire presented the results of a study that sought to characterize the high-speed impact damage that would be sustained by two ablative TPS materials that have recently gained attention for possible use in future interplanetary missions, Phenolic Impregnated Carbon Ablator (PICA) and SLA-561V (hereafter referred to as simply SLA). Using high-speed impact test data, empirical equations were developed for TPS crater depths, as well as maximum and minimum TPS crater mouth dimensions. Where the impacts caused TPS perforations, empirical equations were developed for the maximum and minimum through-hole dimensions. As part of the analyses performed, ballistic limit equations (BLEs) for these TPS materials, with and without a backing substructure, were also developed. The validity of the BLEs developed was also assessed by comparing their predictions against test data. In nearly all cases, the empirical equations developed were seen to adequately capture the magnitudes of the measured damage parameters, as well as whether or not the TPS, or the substructure underlying the TPS, would be perforated by the initial impact.

Figure 1 shows a sketch of a generic TPS layer placed atop a substructure, and a projectile with diameter d_p traveling at velocity V_p is impacting the TPS at an obliquity of θ_p . The substructure could be a single monolithic metallic plate, a honeycomb sandwich panel (HC/SP), or some other configuration depending on the application.

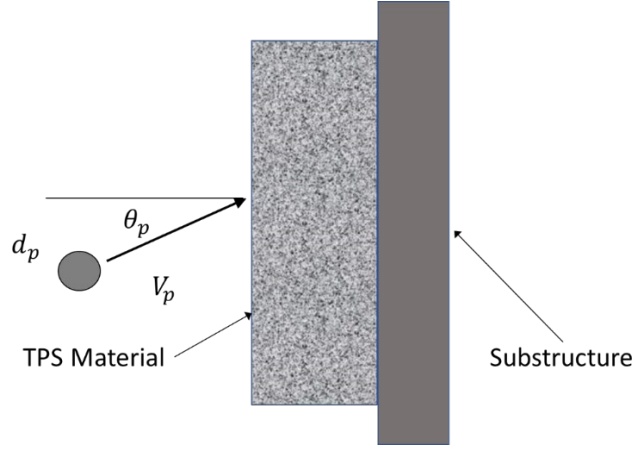


Figure 1. Oblique Impact on TPS Material Backed by a Substructure

In this paper, we extend the applicability of the BLE for one of the TPS materials beyond the testable regime (i.e., above an impact velocity of 7 km/s), namely, the SLA-561V. This is achieved using the results of a series of Smooth Particle Hydrodynamics Code (SPHC) impact simulations at 7, 10, 15, 20, 25, and 35 km/s, and impact obliquities of 30, 45, and 60 degrees [2]. When predictions from this updated BLE were compared graphically against the results of the SPHC runs, the positions of the BLE curves were consistent with the data; non-perforation data points were below the BLE curves, while perforation data points were above the BLE curves.

The new BLE we present herein is sufficiently general and includes many of the key parameters that would be used to describe the composition of the selected TPS material and its underlying substructure. As such, the BLE can be used to compute critical projectile diameters for impact parameters and target constructions other than those used in their development.

However, such exercises are not to be undertaken lightly—varying parameters too far from the values used in the development of the equation presented herein could yield results inconsistent with the actual TPS impact behavior.

Review of Previous Work

In reference [1], Schonberg and Squire considered the following two TPS materials and configurations: PICA and SLA-561V, both are with and without an underlying substructure.

Empirical equations were developed for the following impact damage response characteristics:

- maximum crater depth (in the event of TPS non-perforation)
- maximum and minimum crater mouth dimensions
- maximum and minimum through-hole dimensions (in the event of TPS perforation)
- critical projectile diameter for the TPS only (i.e., TPS ballistic limit equation)
- critical projectile diameter for the TPS+substructure configuration (i.e., ballistic limit equation for the TPS+substructure)

The equations developed were based on the results of impact tests involving aluminum and nylon projectiles, travelling at speeds between 5 and 9 km/s, and impacting the targets at obliquity angles between 0 and 70 deg. Details regarding the data (for each TPS material and the various substructure configurations considered) that gave rise to these equations as well as the equations themselves can be found in reference [1]. In the end, in nearly all cases, the empirical equations developed were found to adequately capture the magnitudes and trends of the measured damage parameters, as well as the perforation/non-perforation response of the various target configurations considered.

The Present Study

In this study, we update the BLE for the SLA TPS+substructure configuration so that it is also applicable to impact velocities beyond the testable regime, as well as for other TPS+substructure variations. This was accomplished using the results of series of SPHC impact simulations at 7, 10, 15, 20, 25, and 35 km/s, and at impact obliquities of 30, 45, and 60 degrees [2] for the configuration design shown in Figure 2.

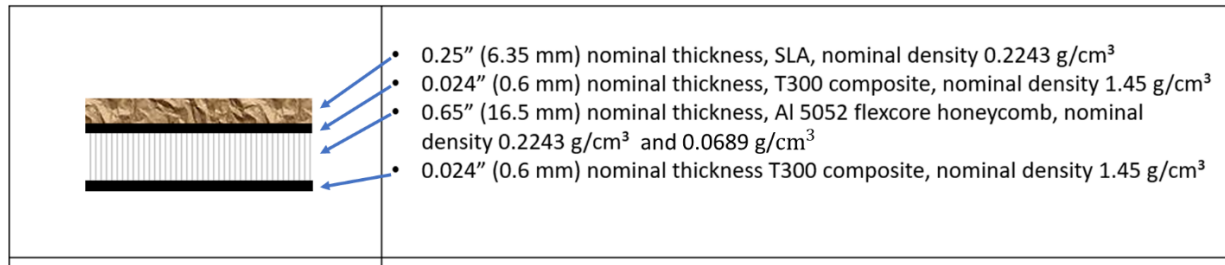


Figure 2. Nominal TPS+Substructure Design Parameters

Although the TPS+substructure BLE developed in [1] showed a good correspondence with the penetration/no penetration data obtained from high-speed impact tests, it did have a major shortcoming—strictly speaking, it was only applicable to configurations using the same substructure design as that used in the impact tests performed to generate the data upon which it was based, that is, a substructure consisting of a 2.5 cm air gap between two 0.5 mm thick titanium plates.

However, the substructure in Figure 2 consists of a honeycomb sandwich plate (HC/SP) with aluminum flexcore sandwiched between two graphite/epoxy plates. As such, the TPS+substructure BLE in [1] had to be modified so that it could take into account the different substructure design shown in Figure 2. This was accomplished by including an equivalent facesheet thickness term and a facesheet spacing term, both of which would include the densities of the facesheet and flexcore materials, respectively.

Furthermore, the plot of the TPS+substructure BLE developed in [1] is akin to that of a single-wall BLE, that is, it monotonically decreases as velocity increases. At some point, as velocity continues to increase, one might expect that the two substructure facesheets would begin to act as a Whipple Shield and that the configuration shown in Figure 2 would exhibit similar response phenomenologies. As such, in addition to adding facesheet thickness and facesheet spacing terms, the TPS+substructure BLE was modified to include an updated velocity-based term to bring out a Whipple Shield-like response. Equation (1) shows the final form of this BLE.

$$d_{crit} = \left[\left(\frac{C_1}{3.398} \right) t_{SLA} \left(\frac{\rho_p}{\rho_{SLA}} \right)^{-1/2} V_p^{-f(\rho_{HC})} \cos^{-g(t_{eff,Ti})} \theta_p \right]^{\frac{1}{1.46}} (C * t_{eff,Ti}^A * S_{HC}^B) * K(\theta_p) \quad (1)$$

where

$$C_1 = 1.6061 t_{SLA}^{1.8712} \cos^{-0.3657} \theta_p \quad (2a)$$

$$t_{eff,Ti} = (t_{fs} \rho_{fs} + 0.5 S_{HC} \rho_{HC}) / \rho_{Ti} \quad (2b)$$

where ρ_{SLA} and t_{SLA} are the density (in g/cm³) and the thickness (in cm) of the SLA TPS, respectively, and ρ_p is the density of the projectile materials (in g/cm³). Also, in Eqn (1), the impact velocity (V_p) and impact obliquity (θ_p) exponents are now given by:

$$f(\rho_{HC}) = 1.4862 \rho_{HC} + 0.667 \quad (3a)$$

$$g(t_{eff,Ti}) = 0.906 \{1 - [1 - \exp(0.39 t_{eff,Ti}^{0.040})]\} \quad (3b)$$

The additional obliquity effects term, $K(\theta_p)$, is given as:

$$K(\theta_p) = F_1(\theta_p) * [1 - h(\theta_p)] + F_2(\theta_p) * h(\theta_p) \quad (4)$$

$$\text{with } F_1(\theta_p) = 0.970 \cos^{-0.435} \theta_p \quad (5a)$$

$$F_2(\theta_p) = 0.744 \sin^{-1.2} \theta_p \quad (5b)$$

$$h(\theta_p) = 1 - \exp(-10^6 * \theta_p^{50}), \theta_p \text{ in radians} \quad (5c)$$

In Eqns (1-5), $t_{eff,Ti}$ is an effective facesheet thickness (in cm), t_{fs} is the actual facesheet

thickness (in cm), S_{HC} is the flexcore thickness or facesheet spacing (in cm), ρ_{fs} is the density of the actual facesheet material (in g/cm³), ρ_{HC} is the flexcore density (in g/cm³), and ρ_{Ti} is the density of titanium (equal to 4.43 g/cm³). The coefficients A, B, and C introduce a Whipple Shield-type formulation into the BLE; the values depend on whether the impact velocity is below the low-to-intermediate velocity transition value, V_L , or above the intermediate-to-high velocity transition value, V_H . These transition velocities depend on the impact obliquity, and are given as follows:

$$V_L(\theta_p) = 6 * \cos^{-0.518} \theta_p \text{ (in km/s)} \quad (6)$$

$$V_H(\theta_p) = 14 * \cos^{-0.518} \theta_p \text{ (in km/s)} \quad (7)$$

Then, depending on whether $V_P \leq V_L(\theta_p)$ or $V_P \geq V_H(\theta_p)$, the constants A, B, and C are as follows:

Table 1. Values of A, B, and C as a Function of Impact Velocity

	A	B	C
$V_p \leq V_L(\theta_p)$ km/s	0.4969	-3.7751	148.4
$V_p \geq V_H(\theta_p)$ km/s	0.6782	-5.0625	845.5

If the impact velocity is between V_L and V_H , the BLE is the interpolation between the d_{crit} values when $V_p = V_L$ and when $V_p = V_H$.

Results and Discussion

Figure 3 shows plots of the BLE given by Eqn (1) for impact obliquities of 30°, 45°, and 60° and SPHC results for whether the rear facesheet of the substructure having a low density flexcore (LDFC) was (solid data points) or was not (hollow data points) perforated, or just on the verge of being perforated (gray data points).

As can be seen from Figure 3, the BLE does a reasonable job in predicting whether or not

there will be a rear facesheet perforation for each obliquity angle. Namely, for the most part, the hollow data points, which signify non-perforation impact events, are below the BLEs, while the solid data points, which signify perforation events, are above the BLEs. It is also worthwhile to note that this revised and updated BLE does, in fact, reduce to the BLE in [1] when the parameters of the Ti-Air Gap-Ti substructure in [1] are used as input.

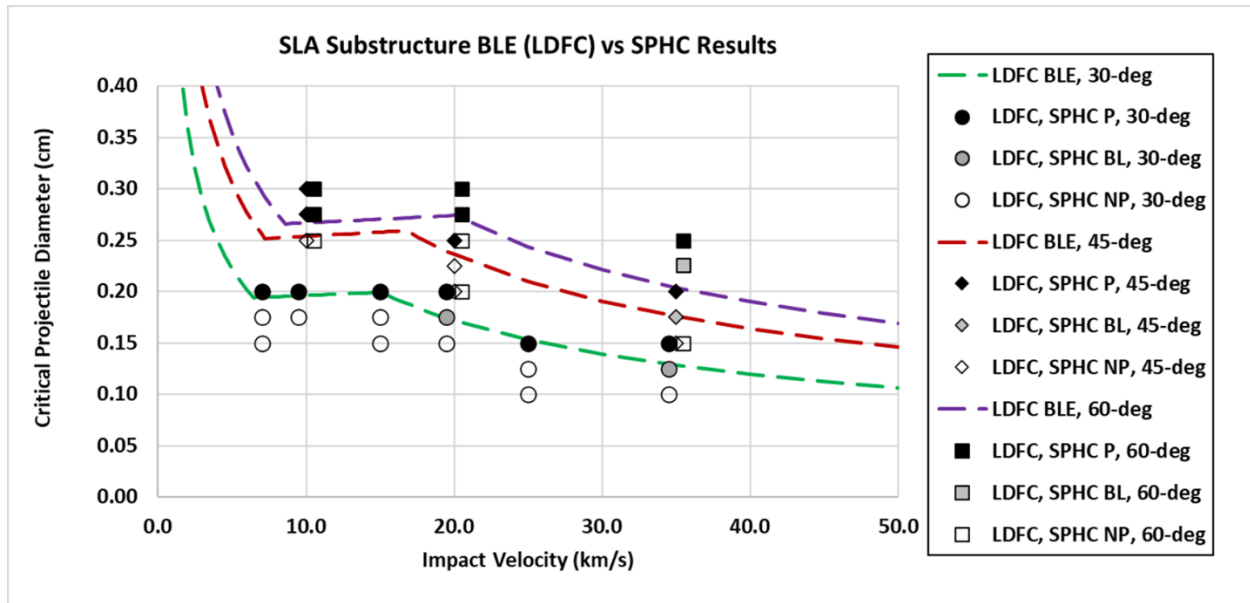


Figure 3. Plots of Ballistic Limit Equations and SPHC Data Points

Finally, it must be noted that the transition velocities as functions of impact obliquity were determined for this BLE using SPHC results for aluminum projectiles only. The question that naturally arises is, then, what should the transition velocities be for other projectile materials? Unfortunately, we do not yet have any high-velocity results for other projectile materials. While it might be reasonable to assume, at least for now, that the transition velocity functions are the same for all projectile materials, this is clearly a point that needs further investigation.

Concluding Comments

A study was successfully completed that sought to extend the applicability of the ballistic limit equation for an SLA TPS+substructure system. The validity of the equation developed was assessed by comparing its predictions against SPHC impact simulation results. In nearly all cases, the ballistic limit equation developed herein were seen to adequately capture whether or not the rear facesheet of the substructure was perforated as a result of the initial impact event. The constants in this equation are easily adjustable as new simulation results become available for different impact velocities, trajectory obliquities, and projectile materials.

Acknowledgements

The authors wish to acknowledge the support provided by the NASA Engineering and Safety Center that made this study possible. The authors are also grateful to Joel Williamsen and Bob Stellingwerf for performing the SPHC simulations that generated the results that were used in the development of the ballistic limit equation presented in this paper.

References

- [1] Schonberg, W.P., and Squire, M.D., “Predicting High-Speed Particle Impact Damage in Spacecraft Thermal Protection Systems”, *Journal of Space Safety Engineering*, Vol. 11, No. 1, 2024, pp. 87-101.
- [2] Corbett, B., Williamsen, J., Stellingwerf, R., and Squire, M.D., “Smooth Particle Hydrodynamic Code Predictions for Meteoroid Damage in Thermal Protection Systems Shielded by Composite Structures”, Proceedings of the 2024 Hypervelocity Impact Symposium, Osaka, Japan, October, 2024.