Proceedings of the Canadian Society for Mechanical Engineering International Congress 2022
CSME Congress 2022
June 5-8, 2022, Edmonton, AB, Canada

A NEW BALLISTIC LIMIT EQUATION FOR HYPERVELOCITY IMPACT ON HONEYCOMB-CORE SANDWICH PANELS

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Abstract— Parameters of the honeycomb core, such as cell size and foil thickness, as well as the material of the core, influence the ballistic performance of honeycomb-core sandwich panels (HCSP) in the case of hypervelocity impact (HVI) by orbital debris. A dedicated ballistic limit equation (BLE) that accounts for this influence has been developed in this study. BLE fitting was conducted using a database composed of entries resulting from physical and numerical experiments. The new ballistic limit equation was based on the Whipple shield BLE, in which the standoff distance between the facesheets was replaced by a function of the honeycomb cell size, foil thickness, and yield strength of the HC material. The BLE demonstrated excellent accuracy in predicting the ballistic limits of HCSP, when tested against a new set of simulation data, with the discrepancy ranging from 1.13% to 5.58% only. The new BLE can be recommended for use in the design of spacecraft orbital debris shielding involving honeycomb-core sandwich panels.

Keywords-orbital debris shielding; sandwich panels; hypervelocity impact; computational modeling; ballistic limit equation.

I. INTRODUCTION

To ensure mission success, Earth satellites must be analyzed for their ability to survive hypervelocity impacts (HVI) by orbital debris, as a collision of a functional satellite with even a millimeter-sized object, traveling at a typical orbital speed (7 km/s and higher), can be detrimental for both the spacecraft and the Earth's orbit environment [1].

In a typical satellite design, most impact-sensitive equipment is situated in the enclosure of the structural honeycomb-core sandwich panels (HCSP). Being the most commonly used elements of satellite structures, these panels form the satellite's shape and are primarily designed to resist launch loads and provide attachment points for satellite subsystems [2]. With low additional weight penalties, their intrinsic ballistic performance can often be upgraded to the level required for orbital debris protection [3]. On the other hand, perforation of a structural honeycomb panel can be considered as a failure criterion, as otherwise unprotected satellite components (e.g., circuit boards, cables) may be rendered non-functional post-impact or even experience catastrophic failure (e.g. pressurized propellant tanks, gas accumulators). Therefore, assessing the orbital debris impact survivability of unmanned satellites requires HVI testing or reliable predictive models for honeycomb-core sandwich panels, capable of accounting for various impact conditions and panel design parameters.

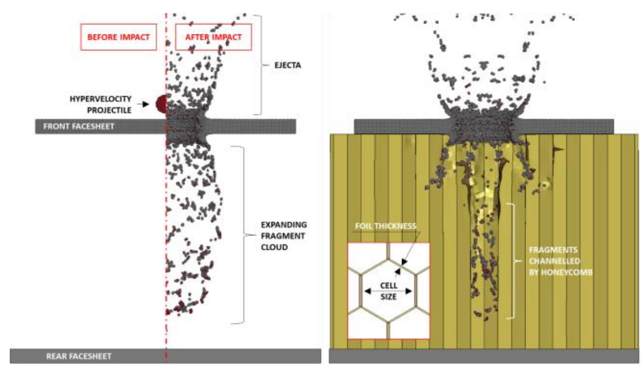

Figure 1. HVI on a Whipple shield (left) and a honeycomb-core sandwich panel (right)

Several such HCSP-specific models (implemented in the form of ballistic limit equations) have been described in the literature. They all stem from the well-known BLE for a Whipple shield. As illustrated in Fig. 1 (left), this commonly used protective system represents a structure consisting of two thin facesheets (walls) separated by some distance, such that the front facesheet fragments the hypervelocity projectile. The empty spacing between the facesheets allow the formed fragment cloud to expand while travelling between the facesheets and, thus, distribute energy and momentum on a wider area of the rear facesheet. The function of the rear facesheet is to collect and stop the shattered projectile fragments.

The Whipple shield BLE for projectile speeds $v_p \geqslant 7$ km/s is given by the following expression [4]:

$$D_{cr} = 3.918 \cdot \sqrt[3]{\frac{\bar{S}}{\rho_p \sqrt[3]{\rho_b}} \cdot \left(\frac{t_{FC}}{v_p \cdot \cos\theta}\right)^2 \cdot \left(\frac{\sigma_{Y,FC}}{70}\right)} \qquad (1)$$

Here: ρ_p and ρ_b are the projectile and front facesheet ('bumper') densities in g/cm^3; t_{FC} – thickness of the rear facesheet in mm; v_p – projectile speed in km/s; θ – impact angle measured from target normal, deg ($\theta = 0$ for normal impact); $\sigma_{Y,FC}$ – facesheet yield strength in ksi; and $\bar{S}$ is a standoff distance between the facesheets, in mm when t_{FC} is also in mm.

For the HCSP, the presence of honeycomb between facesheets has a two-fold effect on the ballistic performance. In the case of oblique impacts, honeycomb walls serve as additional layers that can contribute to the fragmentation of the hypervelocity projectile, thus reducing damage to the rear wall. However, in the case of a normal impact, honeycomb is known to constrain the radial expansion of the fragment cloud, channeling the fragments through its cells [5]. In turn, this results in focusing the impact energy and momentum of the fragments onto a small area of the rear facesheet, as shown in Fig. 1 (right), and facilitates its perforation [6-8]. This most conservative scenario (impact at normal incidence) is usually considered as the design case for orbital debris shielding involving HCSP.

It follows from the above that the ballistic performance of HCSP in case of HVI will be influenced by the parameters of the honeycomb core, such as cell size and foil thickness (see Fig. 1), as well as the material of the core [4, 9]. Together, these affect the severity of fragment channeling. This is in line with the findings of Kang et al. [10] who, through a series of numerical simulations, concluded that the HC core cell size is the most influential parameter for the damage of the rear facesheet due to the channeling effect. The same conclusions, regarding the HC cell size effect, were reached by Ilescu et al. [11] and Schubert et al. [12].

Sennett and Lathrop [13] proposed a method to account for the cell size effect by replacing standoff distance $\bar{S}$ in (1) by either the product of twice the honeycomb cell size (A_{cell}) or by the core depth (t_{HC}), whichever is less:

$$\bar{S} = \min(2 \cdot A_{cell}, t_{HC}) \tag{2}$$

This approach, however, is considered to be a 'rough estimate' [4] and does not include other influential parameters, such as foil thickness and material of the core.

The purpose of this study was to develop and validate honeycomb core parameters sensitive BLE for spacecraft sandwich panels subjected to HVI. The development of such a BLE relied on the availability of a database for HVI on HCSP. Such a database was constructed by combining the results of new numerical simulations conducted in this study with the experimental data already available in the literature. The developed BLE was focused on the most conservative scenario of HVI at the normal incidence and limited to aluminum HCSP.

II. COMPUTATIONAL MODEL

To facilitate the creation of a database needed for the development of predictive models, this study adopted the LS-DYNA simulation model that was developed and thoroughly validated in [14]. The model employed SPH particles to represent a hypervelocity projectile and a front facesheet of a HCSP; shell finite elements (FE) for the representation of a honeycomb core; and adaptive SPH-FE technique for modeling of a rear facesheet, as illustrated in Fig. 2.

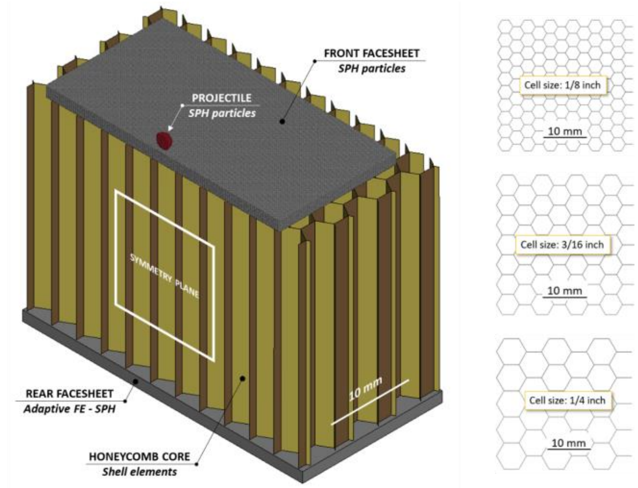

Figure 2. The LS-DYNA model used to simulate HVI on HCSP

A detailed description of the computational model and its validation can be found in [14].

III. NEW BALLISTIC LIMIT EQUATION

While a significant amount of experimental data is available for HVI on HCSP [9], the following criteria were used when selecting the experiments suitable for the development of new BLE:

- the projectile impacts the panel at a normal incidence;
- the projectile, the facesheets and the honeycomb core are made of aluminum alloys;
- the data set contains full information about the honeycomb core used, including the cell size and the foil thickness;
- no additional protective elements, such as multilayer insulation (MLI), are involved.

This resulted in a database only containing the ten entries. Among them, only two pairs of tests clearly defined the ballistic limit of the panels used in those experiments. Apparently, although the availability of these experimental results is extremely useful, the database requires a significant extension to be suitable for the derivation of a BLE capable of accounting for the influence of honeycomb core parameters.

To support these developments, the computational model described in the previous section was used to extend the existing experimental database and supplement it with HVI results corresponding to different

- honeycomb cell sizes (3.18 mm [1/8 in], 4.76 mm [3/16 in], and 6.35 mm [1/4 in]),
- honeycomb foil thicknesses (0.025 mm [0.001 in], and 0.075 mm [0.003 in]),

Table 1 - Ballistic limits of HCSP configurations considered in physical experiments and numerical simulations

	PROJECTILE		FACESHEETS		HONEYCOMB		BALLISTIC LIMIT
Designation	Speed, km/s	Material	Material	Thickness, mm	Grade*	Depth, mm	D_{cr}, mm
HITF03145	6.80	Al2017-T4	Al6061-T6	0.41	1/8-5052-0.003	12.7	0.90
A	6.75	Al2017-T4	Al7075-T6	1.60	3/16-5056-0.001	50.0	1.71
SIM01	7.00	Al2017-T4	Al6061-T6	1.60	1/8-5052-0.001	25.0	1.70
SIM02	7.00	Al2017-T4	Al6061-T6	1.60	3/16-5052-0.001	25.0	2.50
SIM03	7.00	Al2017-T4	Al6061-T6	1.60	1/4-5052-0.001	25.0	2.50
SIM04	7.00	Al2017-T4	Al6061-T6	1.60	1/8-5052-0.003	25.0	1.50
SIM05	7.00	Al2017-T4	Al6061-T6	1.60	3/16-5052-0.003	25.0	1.90
SIM06	7.00	Al2017-T4	Al6061-T6	1.60	1/4-5052-0.003	25.0	2.10
SIM07	7.00	Al2017-T4	Al6061-T6	1.00	1/8-5052-0.001	50.0	1.10
SIM08	7.00	Al2017-T4	Al6061-T6	1.00	3/16-5052-0.001	50.0	1.30
SIM09	7.00	Al2017-T4	Al6061-T6	1.00	1/4-5052-0.001	50.0	1.50
SIM10	7.00	Al2017-T4	Al6061-T6	1.00	1/8-5052-0.003	50.0	1.10
SIM11	7.00	Al2017-T4	Al6061-T6	1.00	3/16-5052-0.003	50.0	1.10
SIM12	7.00	Al2017-T4	Al6061-T6	1.00	1/4-5052-0.003	50.0	1.30
SIM13	7.00	Al2017-T4	Al6061-T6	1.60	1/8-5052-0.001	50.0	1.50
SIM14	7.00	Al2017-T4	Al6061-T6	1.60	3/16-5052-0.001	50.0	1.90
SIM15	7.00	Al2017-T4	Al6061-T6	1.60	1/4-5052-0.001	50.0	2.30
SIM16	7.00	Al2017-T4	Al6061-T6	1.60	1/8-5052-0.003	50.0	1.50
SIM17	7.00	Al2017-T4	Al6061-T6	1.60	3/16-5052-0.003	50.0	1.70
SIM18	7.00	Al2017-T4	Al6061-T6	1.60	1/4-5052-0.003	50.0	2.10

- front and rear facesheet thicknesses (1.0 mm and 1.6 mm), and
- honeycomb depths (25 mm and 50 mm).

A set of 46 simulations was conducted to expand the database available for the new BLE development to 56 entries – experimental and numerical results combined. Different panel configurations and their respective ballistic limits, derived from this database, are summarized in Table 1.

The new BLE for HVI on HCSP proposed in this study is a modification of the Whipple shield BLE, given by (1). The latter can be re-written for the case of normal impacts (the only incidence considered in this study, as discussed earlier) in the following form:

$$D_{cr} = 3.918 \cdot \sqrt[3]{\frac{\bar{S}}{\rho_p \sqrt[3]{\rho_b}} \cdot \left(\frac{t_{FC}}{v_p}\right)^2 \cdot \left(\frac{\sigma_{Y,FC}}{70}\right)} \quad (3)$$

Here: ρ_p and ρ_b are the projectile and front facesheet ('bumper') densities in g/cm^3; t_{FC} – thickness of the rear facesheet in mm; v_p – projectile speed in km/s; $\sigma_{Y,FC}$ – facesheet yield strength in ksi; and $\bar{S}$ is a standoff distance between the facesheets in the original Whipple shield BLE (in mm when t_{FC} is in mm) and, as proposed by Lathrop and Sennett [13], can be replaced in the case of HCSP by twice the honeycomb cell size (A_{cell}) if it is larger than the distance between facesheets, i.e. $\bar{S} = K \cdot A_{cell}$, where $K = 2.00$.

The BLE proposed in this study does not alter the general expression provided by (3), however the expression for $\bar{S}$ in our BLE was supplemented by additional terms, such that

$$\bar{S} = K \cdot A_{cell} \cdot \left(\frac{t_{HC}}{t_{FC} + \alpha}\right)^{\beta} \cdot \left(\frac{t_{HC}}{t_{foil}}\right)^{\gamma} \cdot \left(\frac{30}{\sigma_{Y,HC}}\right)^{\delta} \qquad (4)$$

where t_{HC} – honeycomb depth in mm; t_{FC} – thickness of a facesheet in mm; t_{foil} – thickness of the honeycomb foil in mm; $\sigma_{Y,HC}$ – yield strength of the honeycomb material in ksi (e.g. 30 ksi for Al5052 and 50 ksi for Al5056 honeycomb); and K, α, β, γ, δ are parameters with the values given in Table 2 below.

Table 2 – Parameters of the new HCSP BLE

BLE parameter	K	α	β	γ	δ
Value	2.63	1.893	-0.804	0.304	1.915

To conduct verification of the developed BLE, additional numerical simulations were performed, and their results were compared with the BLE predictions. It should be noted that these new datapoints have not been used in BLE fitting and, thus, were 'unfamiliar' to the predictive model. Also, panel configurations in these additional numerical simulations featured one or multiple design parameters which have not been represented in the database used for BLE fitting. For example, simulations VER04 were conducted with HCSP that had facesheet thicknesses, honeycomb depths, cell and foil sizes that were different from those possessed by the HCSP configurations included in the BLE fitting database.

Table 3 compares the ballistic limit predictions of the new BLE and the verified LS-DYNA model. As can be deduced from the table, in all cases, the BLE demonstrated an excellent

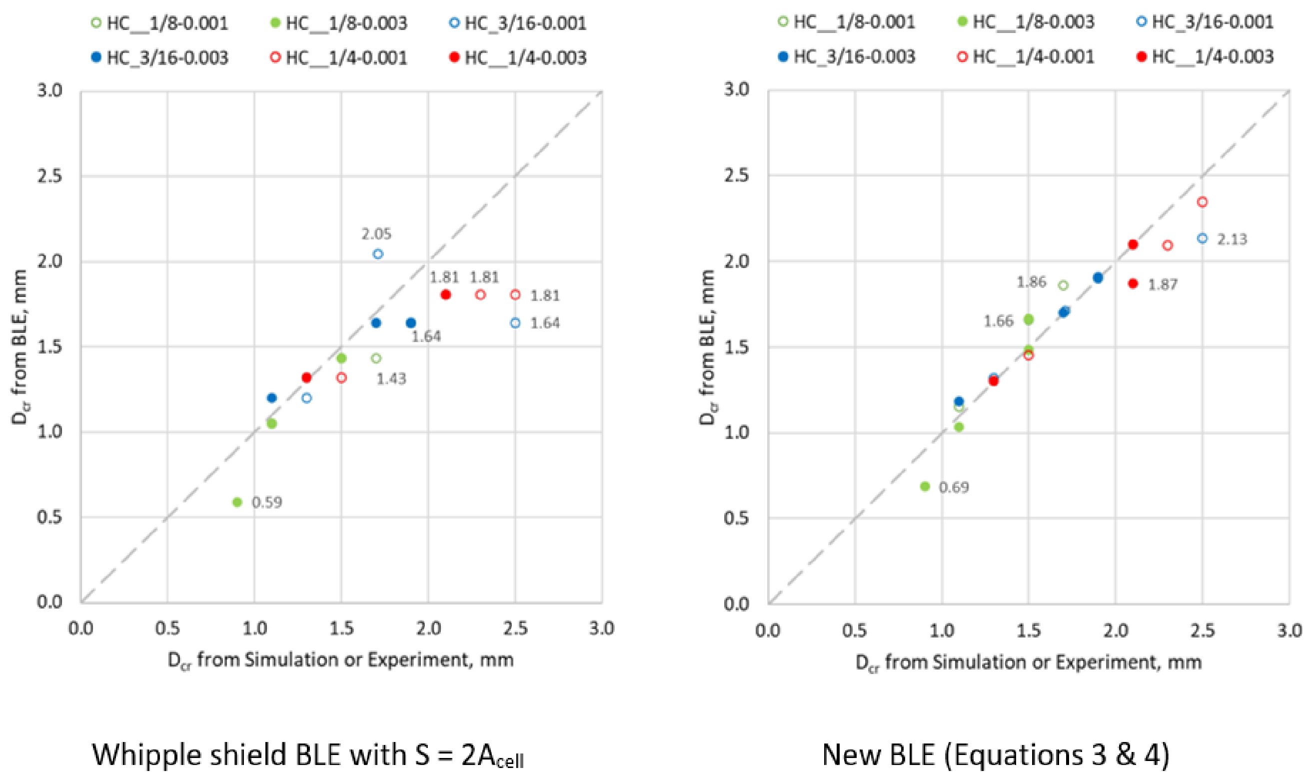

Figure 3 - Goodness of fit diagrams for the Whipple shield (with Sennett-Lathrop correction for HCSP) and the new BLE

The new BLE fit factors presented in Table 2 were determined by minimizing the discrepancy (expressed in terms of the sum of squared errors, SSE) between the BLE predictions and the experimental or simulation data provided in Table 1 (ballistic limits summary).

The goodness-of-fit diagrams for the Whipple shield BLE with the Lathrop and Sennett correction for the honeycomb core effect ($S = 2A_{cell}$) and the BLE proposed in this study, are shown in Fig. 3. BLE predictions for the outliers are added as data labels on the goodness-of-fit diagrams. As can be deduced from Fig. 3, the new BLE provides a significant improvement in terms of the predictive accuracy, compared to the Whipple shield BLE with the Lathrop and Sennett correction.

correlation with the predictions of the sophisticated numerical model, with the discrepancy ranging from 1.13% to 5.58% only.

IV. CONCLUSIONS

Parameters of the honeycomb core (such as cell size and foil thickness), as well as the material of the core, influence the ballistic performance of honeycomb-core sandwich panels in cases of hypervelocity impact by orbital debris. A dedicated ballistic limit equation capable of accounting for this influence has been developed in this study. BLE fitting was conducted using a database composed of 46 numerical experiments, performed with a validated numerical model and ten physical tests derived from the literature.

Table 3 – Verification of BLE predictions

	PROJECTILE		FACESHEETS		HONEYCOMB		BALLISTIC LIMIT		
Designation	Speed, km/s	Material	Material	Thickness, mm	Grade*	Depth, mm	D_{cr}, mm		Error, %
							SIM	BLE	
VER01	7.00	Al2017-T4	Al6061-T6	1.30	1/8-5052-0.001	25.0	1.50	1.58	**5.58**
VER02	7.00	Al2017-T4	Al6061-T6	1.60	3/16-5052-0.003	38.0	1.70	1.78	**4.68**
VER03	7.00	Al2017-T4	Al6061-T6	1.00	5/32-5052-0.002	50.0	1.10	1.16	**5.31**
VER04	7.00	Al2017-T4	Al6061-T6	1.30	5/32-5052-0.002	38.0	1.50	1.48	**-1.13**
VER05	7.00	Al2017-T4	Al7075-T6	1.00	1/4-5056-0.001	50.0	1.30	1.26	**-3.15**

The new ballistic limit equation is based on the Whipple shield BLE, in which the standoff distance between the facesheets was replaced by a function of the honeycomb cell size, foil thickness, and yield strength of the HC material. The corresponding fit factors were determined by minimizing the sum of squared errors between the BLE predictions and the results of HVI tests listed in the database. The BLE was then tested against a new set of simulation data and demonstrated an excellent predictive accuracy, with the discrepancy ranging from 1.13% to 5.58% only. The BLE is recommended for use in the design of orbital debris shielding for spacecraft, involving honeycomb-core sandwich panels.

ACKNOWLEDGEMENTS

This work was financially supported by the Natural Sciences and Engineering Research Council of Canada through Discovery Grant No. RGPIN-2019-03922.

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