Experimental and Numerical Study of Submillimeter-Sized Hypervelocity Impacts on Honeycomb Sandwich Structures

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1 Abstract

This paper deals with hypervelocity impacts of submillimer-sized debris on honeycomb sandwich panels. These debris, which are mostly present within the low Earth orbit, indeed represent a real threat for spacecrafts and satellites. In fact, for debris large enough to be tracked, pre-determined debris avoidance manoeuvre is usually conducted to prevent any damage. Submillimer-sized debris, however, are too small to be identified and therefore spatial structures must be protected against such threat. Honeycomb structural panels and whipple shields have been used as primary shielding against orbital debris impact. The protection capability is usually estimated using Ballistic Limit Equations (BLE). These data have been built from experimental tests on whipple shield protection and transposed to honeycomb sandwich panels.
In the case of Whipple shield, the debris cloud generated at the impact on the bumper sheet expands until reaching the rear wall. BLE for Whipple shields only depends on materials properties, protection geometry, angle of incidence and impact velocity. For honeycomb sandwich panels, the debris cloud is partially channelled within honeycomb cells, thus limiting its radial expansion. The channelling effect is thus a function of the honeycomb cell geometry. The honeycomb BLE presented by the Centre d'Etudes de Gramat (CEG) in 2008 has been introduced in order to take into consideration such effect.
The present study proposes to extend the results of the CEG. The main approach is to consider the relative dimensions between the projectile diameter and the honeycomb geometry in order to evaluate the perforation risks of submillimer-sized hypervelocity impacts. The impact process on honeycomb sandwich panel has first been modelled using commercial hydrocode LS-Dyna using hybrid Lagrange and Smooth Particle Hydrodynamics (SPH) solvers. The numerical model has been validated through several hypervelocity impacts experiments carried out at Thiot Ingenierie Shock Physics Laboratory at velocities up to 9.3 km/s. This model has then been used to define a ballistic curve which defines the critical projectile diameter of a specific sandwich panel subjected to submillimer-sized debris impact. The results are finally compared to the ones obtained by the CEG leading to an updated estimation of the protection capability of honeycomb sandwich panels.

2 Introduction

In the beginning of space exploration, meteorite impact constitutes one of the major threat to space vehicles. Currently, due to the increasing number of space debris in the low earth orbit [1], space debris collision has become the main threat to near earth space structures. Space debris are man-made fragments consisting of different materials (plastic, metal …) from the destruction or collision of space launcher, rockets and satellites. The debris size ranges from submillimeter size to a few tens of centimetre with a velocity from a few km/s to 15 km/s.
Avoidance manoeuvre is not feasible for small debris (millimetre size) since they cannot be detected by radars. Thus, protective shield must be installed near to critical area of the spacecraft to withstand such threat. Whipple shield is widely used [2-4] on spacecraft: an aluminium bumper is placed at a specific distance from the wall of the spacecraft to fragment the debris in order to reduce the damage of the rear wall. Such solution is capable to protect from impact of space debris of size below 10 mm. This protection capability is commonly estimated using ballistic limit equation (BLE) (Fig.1) which defines the critical projectile diameter beyond which the shield is not effective. Three main regimes can be considered:

- "A" ballistic regime: projectile is not fragmented, the higher the velocity; the more important is the damage to the rear wall.

- "B" intermediate regime: projectile is fragmented and the debris cloud expands until reaching the rear wall; the higher the velocity, the higher the radial expansion reducing the damage to the rear wall.
- "C" hypervelocity regime: projectile and front plate are potentially vaporised, the critical diameter decreases with the velocity

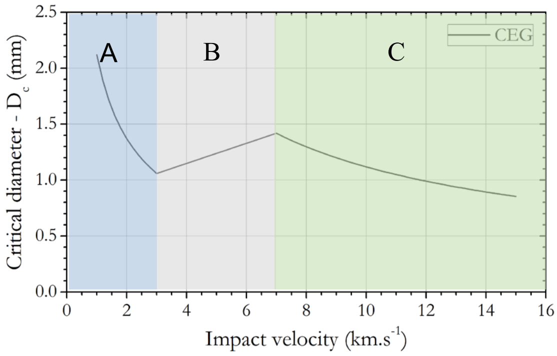


Fig.1: BLE for a typical whipple shield [5]

Honeycomb structure are recently introduced as a spacecraft shield; their protection capability is initially considered as equivalent to whipple shield. However, for honeycomb sandwich panels, the debris cloud is partially channeled within honeycomb cells [5-8], thus limiting its radial expansion. The ballistic limit equation presented by the Centre d'Etudes de Gramat (CEG) [5] has been introduced in order to take into consideration the presence of honeycomb. This BLE has been defined from simulation with millimeter sized projectiles.
The aim of this work is to study the effect of submillimeter sized projectile with a specific modelling in order to refine the work published by Sibeaud et al. [5] The first part of this paper is dedicated to the development of a numerical model, the second is devoted to the validation of this model through two impact experiments and the third details the simulations performed to predict an updated ballistic curve.

3 Numerical modelling of hypervelocity impacts

Numerical simulations have been carried out with the commercial hydrocode LS-Dyna. The projectile and the honeycomb are meshed with hydride Lagrangian-SPH elements (Fig.2). In this case one Lagrangian element is converted into one or several SPH elements upon reaching the plastic strain to failure. The first advantage of hybrid elements is the conservation of the mass unlike erosion. The second benefit is that they allow to limit the step size drop at the contact interface between the projectile and the target. The mesh density of the projectile sphere was 25 hydride elements per millimetre with one SPH element inside each one.

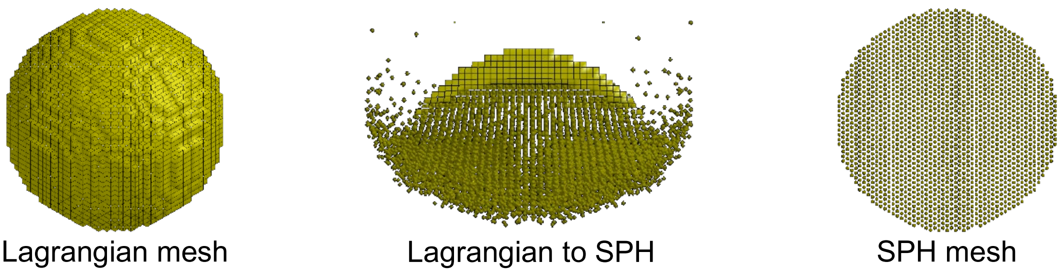


Fig.2: Lagrangian to SPH transformation of the projectile

The meshing of the sandwich panel (honeycomb and skins) is assured with 365000 hybrid elements. This model is then enriched compared to the one presented by the CEG. This 3D mesh reproduces the exact geometry of the honeycomb used in their experimental work. The mesh density of the honeycomb mainly depends on the thickness of the honeycomb foils: 25 µm. These foils are meshed with one hybrid element within their thickness leading to two elements in the thickness of the glued region (Fig.3). Only 12 honeycomb cells are represented and the mesh is extruded (20 mm) in the z direction with 130 hybrid elements. The red dashed lines represent the symmetry plane.

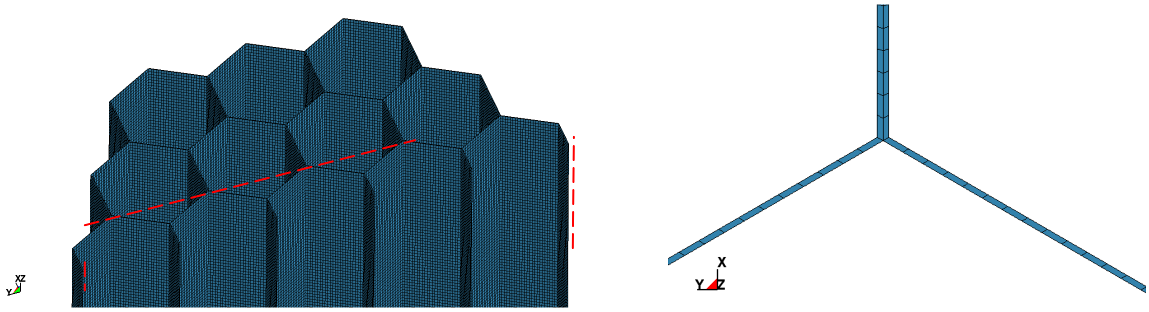


Fig.3: (a) Honeycomb Hybrid mesh (b) Zoom on glued region

The two skins (thickness 0.8 mm) and the honeycomb are stuck together by sharing common nodes within the interface. The target (honeycomb and skins) has a mesh density of 10 elements by millimeter. Eight SPH elements per hybrid element are used into the impact regions and only one elsewhere. The SPH mesh density is then equivalent between the projectile and the impact areas of the target.

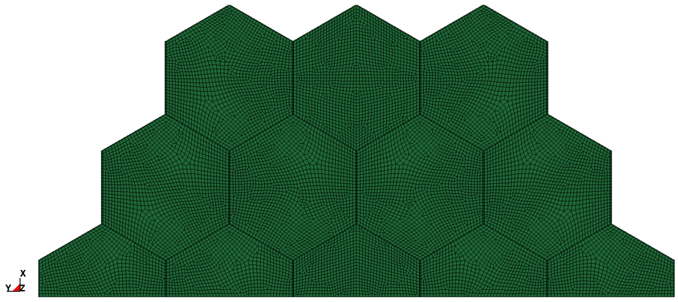
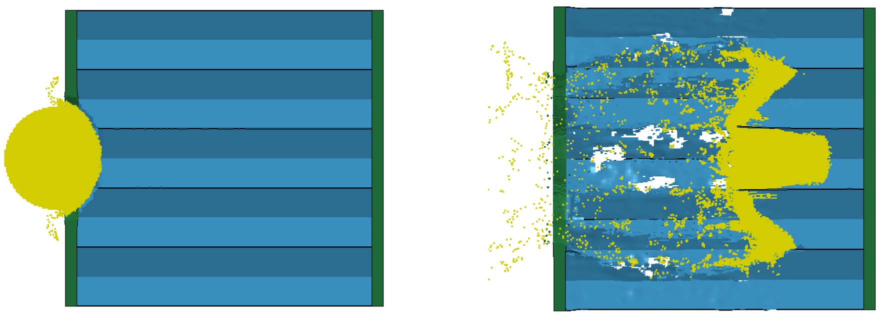


Fig.4: Skin hybrid mesh

The constitutive law used for the Lagrangian elements is an elastic-plastic one. After conversion into SPH element the material behaviour is managed by an elastic-plastic hydrodynamic law coupled to a Mie-Gruneisen equation of state.

This model has been used to simulate the test P259 performed by the CEG. It consists in an aluminium ball of 7 mm impacting this same aluminium sandwich panel at 5818 $m.s^{-1}$. Some pictures of this simulation are depicted in Fig.5 where the SPH elements from hybrid elements of the honeycomb are blanked for clarity purpose. The channelling effect of the honeycomb is highlighted on the second picture (at t = 2.0 µs): most of the debris cloud is guided within three honeycomb cells, therefore limiting its radial expansion.



t = 0.5 µs t = 3.5 µs

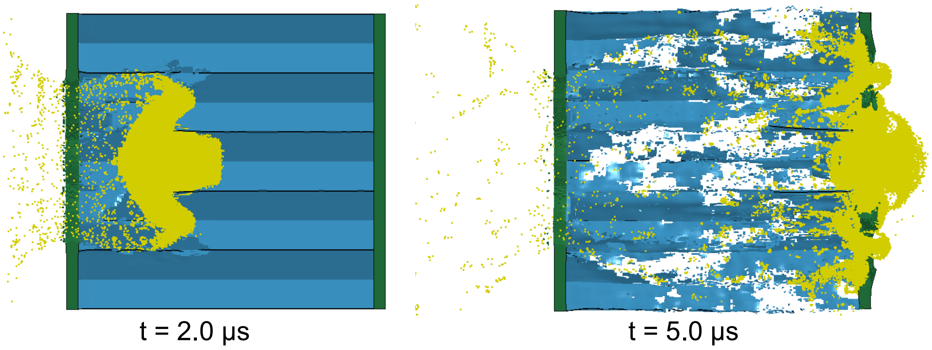


Fig.5: Simulation of the test P259 from the CEG

The velocity profile of the projectile (i.e. at the centre of the debris cloud) has then been compared (Fig.6) with the residual velocity obtained for the test P259 and the associated simulation realized by CEG. The velocity of the debris cloud is experimentally estimated at 4830 m.s^{-1} [1] while the associated simulation results (#2D-27) estimates a residual velocity of 4380 m.s^{-1}. The velocity profile for this simulation is in agreement with the results of the CEG.

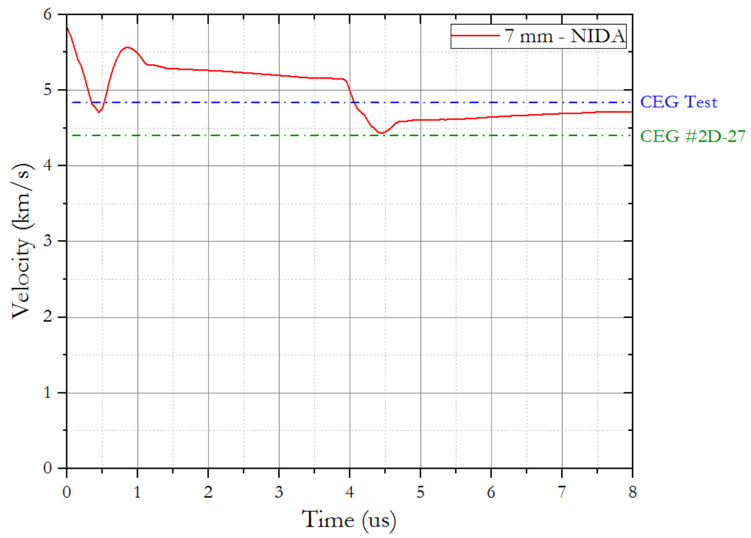


Fig.6: Comparison of the velocity profiles of the projectile

4 Experimental investigation and validation

Two impact tests on sandwich panels are performed to gather experimental data on the response of the honeycomb structure. The results will be used to evaluate ability of the model to reproduce hypervelocity impact on this type of target. the panels are made up with 0.8 mm thick aluminium 2024 skins and 20 mm thick Hexcel® 5056 honeycomb (5/32 cells). The projectile is a 1.0 mm diameter aluminium sphere. Impact velocities are measured with two optical barriers and confirmed with the analysis of the high speed camera frames.

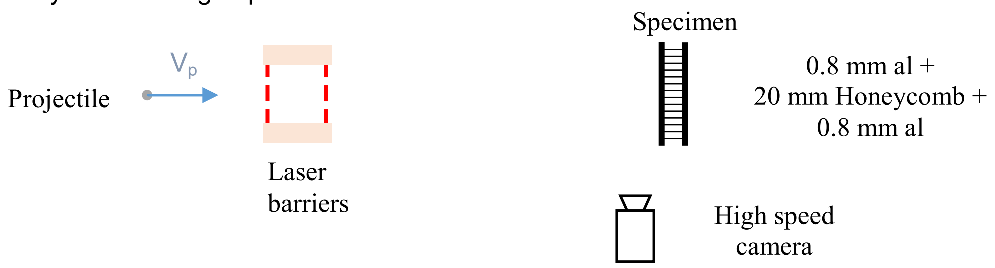


Fig.7: Schematic of the tests condition

This test was carried out at an impact velocity of 9180 m.s-1. Images of the impact have been captured with the help of the framing camera Specialized Imaging SIM16 at 500 000 frames per second (see Fig.8). The projectile (red arrow) is coming from the right side and enters in the camera field at the fourth frame. The following images indicates that the impact occurs between the frame 4 and the frame 5. A reference image was taken before the shot in order to calibrate the pixel / mm ratio. The resulting spatial scale allowed to validate that the projectile seen on frame 4 was the 1 mm aluminum sphere.
A small debris plume is observed on the first image and is developing on the following four images. It corresponds to a residual part of the sabot but is off the depth of field and thus off-axis. This impact on the front face is shown on Fig.9. The main hole is the one made by the projectile sphere and its diameter is 3.62 mm. On the zoomed region one can observe that the impact has been located on a honeycomb wall. The punching on the back face indicates that this test was performed close to the ballistic limit.

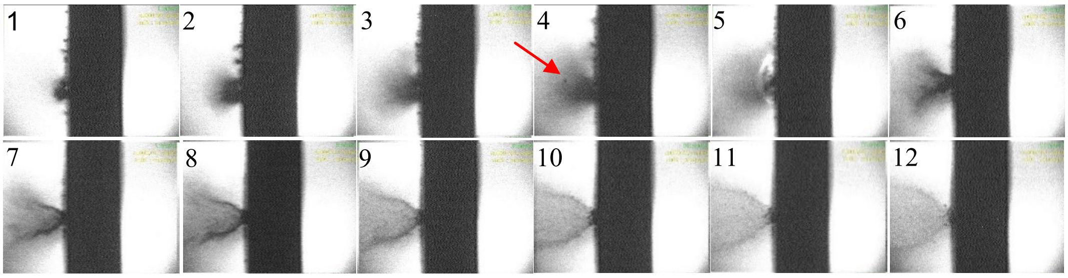


Fig.8: Image taken with the SIM16 camera. 2 µs interframe

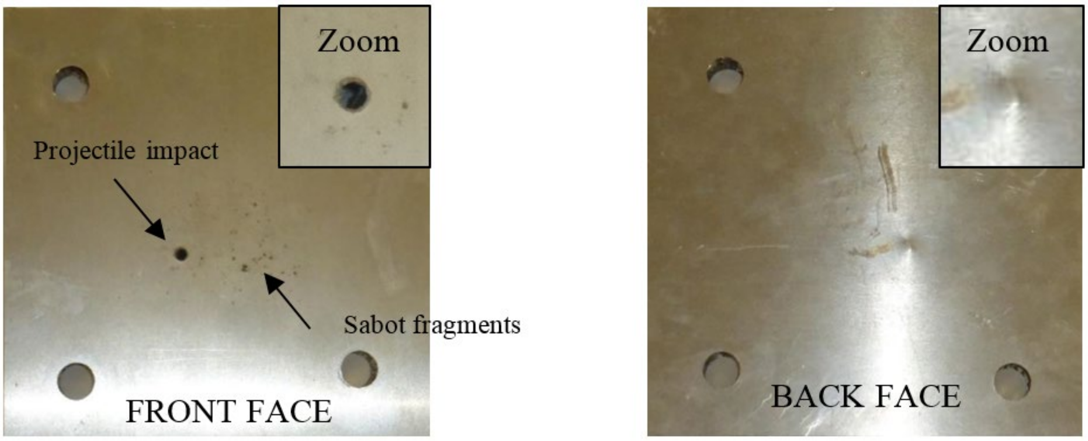


Fig.9: Post-mortem pictures of the front and back faces

This test has then been simulated. For this simulation a part of the mesh had to be deleted for memory allocation purposes. The debris cloud indeed splits in two parts when arriving on the honeycomb wall. The impacted area on the second skin is therefore greater than for an impact centered in a honeycomb cell. The second skin had thus to be entirely meshed with hybrids elements containing 8 SPH elements. The maximum allocating memory has been reach because of this enriched mesh.
Images of this simulation are shown on Fig.10. They show that the debris cloud is developing within two adjacent cells of the impacted honeycomb wall and then running along the external walls of these cells. The result is not perfectly like the test in terms of back face damage since only one punching is experimentally observed. Nevertheless, the end of the simulation indicates a configuration just above the ballistic limit.

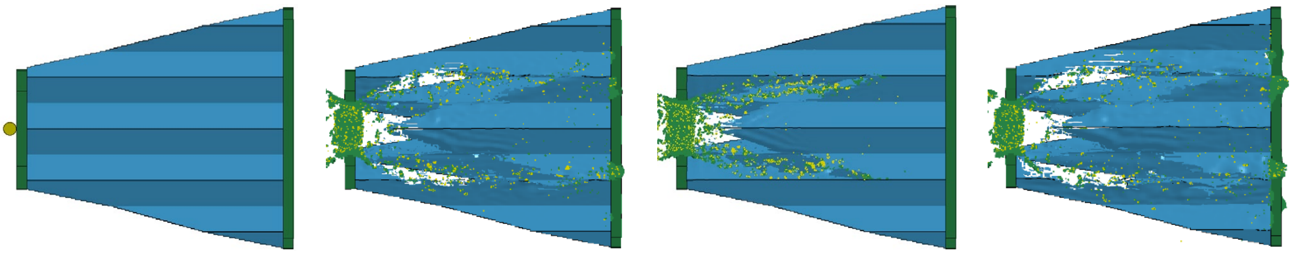


Fig.10: Simulation results of the test

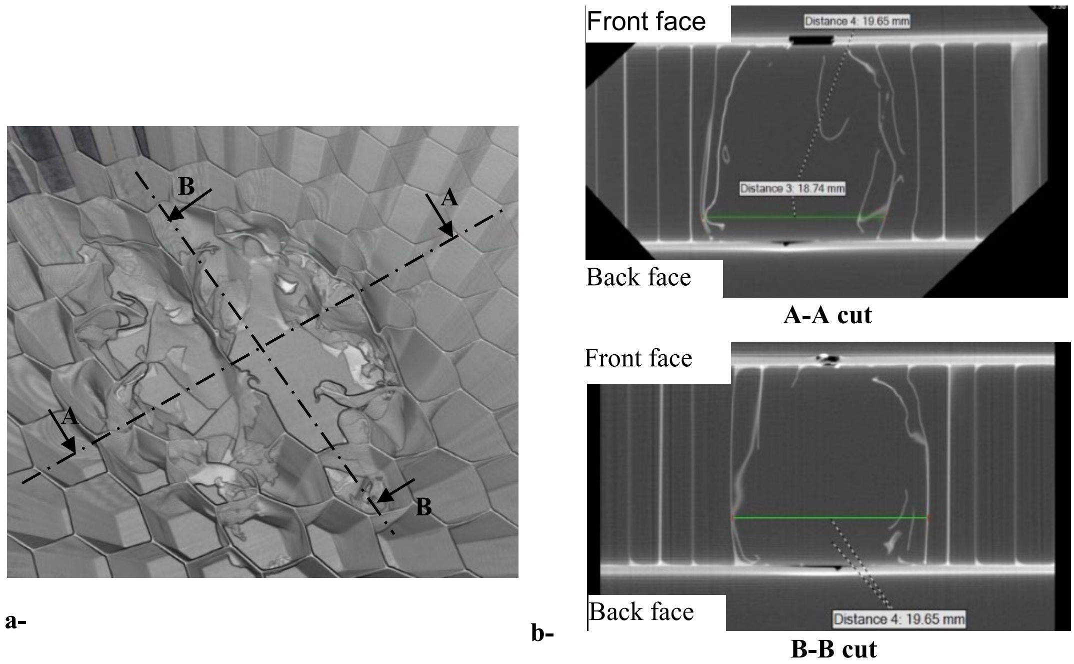


Fig.11: Post-mortem tomography of the specimen, (a-) isometric view, (b-) cuts A-A and B-B

Fig.11 shows post-mortem images obtained from 3D-tomography of the specimen. The isometric view (Fig.11-a) confirms that the impact point is at the wall of the honeycomb. The debris of the front face impact split into two main parts creating two holes in the honeycomb. The cuts view Fig.11-b, highlights the cone shape of the hole along the z-direction which reflect the debris direction of projection.

5 Prediction of ballistic limit curves for the honeycomb structure

The results presented hereafter were obtained with the numerical model developed and validated in this paper.

5.1 Methodology

The CEG's BLE [5] is based on the one developed by Christiansen [2] and is expressed as follow :

$$D_c = \left[\frac{K_3(t_{HC}+t_w+K_2 t_b^{\mu} \rho_s^{v_2})}{K_1 \rho_p^{\beta} \rho_w^{\kappa} V_p^{\gamma} t_s^{\delta} [\cos\theta]^{\xi} \rho_b^{v_1}}\right]^{1/\lambda} \quad (1)$$

where K_1, K_2, K_3, λ, β, γ, δ, κ, ξ, μ, v_1 and v_2 are parameters taking different values depending on the velocity regime. Subscript s corresponds to the honeycomb, b to the bumper (first skin) and w to the back wall (second skin). t refers to thicknesses and ρ to densities. V_p is the impact velocity and θ is the projectile incidence.
The Eq. 1 has been developed by Christiansen for configuration without honeycomb. The CEG has added two correcting parameters to take into account the presence of honeycomb:

- t_{HC} : is a function of the cumulative thickness of honeycomb wall laterally crossed in the case of an oblique impact. This parameter is equal to 0 for an incidence below 10°.

- K_3 : multiplicative coefficient to correlate CEG's BLE to their simulations.

The values of all other parameters are identical for both equations and take different values within each velocity regime (v < 3 km.s^{-1} and v > 7 km.s^{-1}). These equations are plotted in Fig.12 for a normal impact on a sandwich panel with the associated simulation results. In this case t_{HC} is equal to zero and only K_3 differs from the Christiansen equation. According to the results at 5818 m.s^{-1} the BLE proposed by the CEG does not perfectly fit the simulation results. The multiplying parameter K_3 may not be sufficient to take into consideration the presence of the honeycomb.

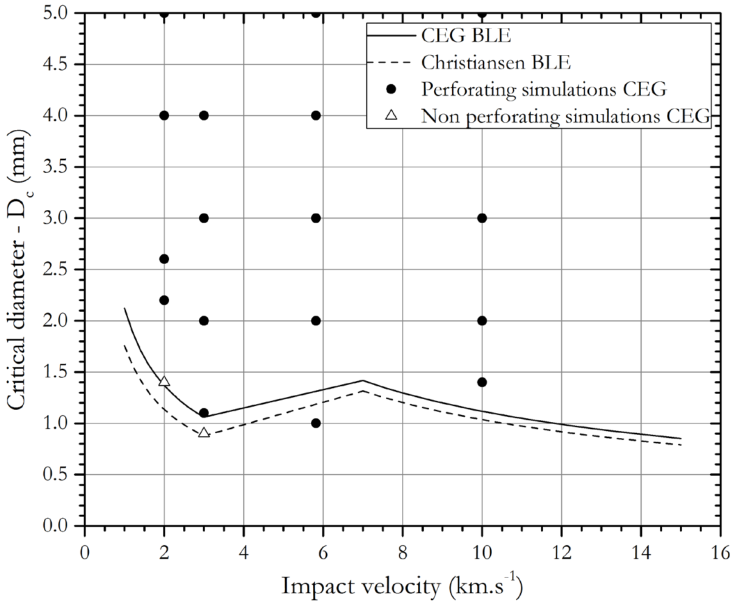


Fig.12: Simulation results of the CEG (from [5])

5.2 Computational results

This section presents simulation results of hypervelocity impact on 0.8/20/0.8 aluminum sandwich panels. Velocities range from 2 to 13 km.s^{-1}. Several simulations were performed for each velocity in order to estimate the critical diameter to perforation within a 0.2 mm interval. These results are plotted in Fig.13.

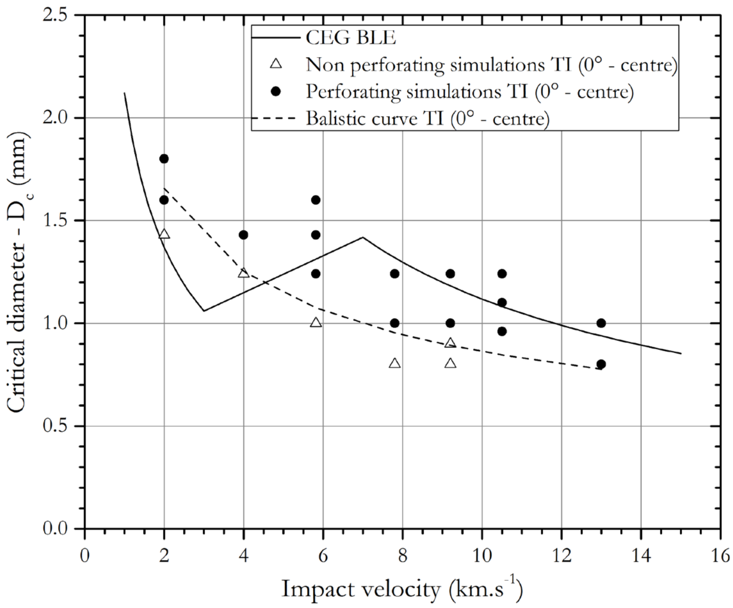


Fig.13: Critical diameter vs Impact velocity for Thiot Ingenierie (TI) centred simulations

5.3 Analysis

The results presented suggest new elements for which the BLE is not defined on three different regimes for this particular configuration. The values of 3 and 7 km.s^{-1} for v_1 and v_2 had been presented by Christiansen for hypervelocity impacts on Whipple shield. Ryan [9] showed that for specific honeycomb geometry (i.e. cell size) and materials, these regimes could not be differentiable. This trend is observed in this work and in this case for all simulated velocities the debris cloud expansion is considerably limited by the honeycomb. This phenomenon called channelling effect leads to a much higher impulsion on the second skin. The critical diameter to perforation of a sandwich structure is thus lower than for a Whipple shield.
This is the reason why the three regimes are not observed in this study. This is the result of an agreement between the skin thickness and the honeycomb cell size. Two scenario could lead to the apparition of these three regimes:

- A thicker skin: the critical diameter to perforation would be higher and thus the debris cloud more important. It would expand on much more honeycomb cells and would generate lower local impulsions on the second skin.
- Greater honeycomb cells: this would help the debris cloud to expand with the same result. This effect has been observed by Kang et al. [10].

For the honeycomb used in this study, the expression of the critical diameter does not depend on any velocity regimes. This would suggest that the expression established by the CEG (and based on the one by Christiansen) may not be suitable to this honeycomb. This is mainly due to the specific geometry of this sandwich panel.

6 Summary

In this study, a numerical model has first been developed in LS-Dyna. The whole structure was modelled using hybrid elements (Lagrangian and SPH). The model has first been evaluated with the experimental and numerical results of the CEG, and then validated with two hypervelocity impacts performed at THIOT INGENIERIE Shock Physics Laboratory. Its ability to reproduce residual velocities and holes diameter has been highlighted.

The model has at the end been used to draw a ballistic curve for this particular sandwich panel. The critical diameter to perforation has been identified in the range of 2-13 km.s^{-1}. The results showed that the typical three regimes observed on a whipple shield could not be differentiated for this configuration of honeycomb, which is mainly due to the channelling effect. There then could be an underestimation of the risk by using established BLEs on honeycomb sandwich panels.

7 Acknowledgements

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8 Literature

[1] N.N. Smirnov, A.B. Kiselev & A.I. Nazarenko, Mathematical Modeling of Space debris evolution in the Near Orth Orbits 4, Moscow University Mechanics Bulletin, Allerton Press, New-York, 2002, pp.33-41.
[2] E.L. Christiansen, Design and performance equations for advances meteoroid and debris shields, International Journal of Impact Engineering, vol. 14, 1993, pp. 145-156.
[3] H.G. Reimerdes, D. Nölke, & F. Schäfer, Ballistic Limit Equation for spacecraft shielding, International Journal of Impact Engineering, vol. 33, 2001, pp. 645-654.
[4] K.R. Housen & R.M. Schmidt, Whipple shields characterized by a nondimensional geometry parameter, J. spacecr. Rockets, vol. 32 (1), 1995 pp. 162-168.
[5] J.M. Sibeaud, L. Thamié, & C. Puillet, Hypervelocity impact on honeycomb target structures: Experiment and modeling, International Journal of Impact Engineering, vol. 35, 2008, pp. 1799-1807.
[6] S. Ryan, T. Hedman, & E.L. Christiansen, Evaluating potential upgrades to ISS module shielding, Acta Astronaut, vol. 67 (7-8), 2010, pp. 818-825.
[7] W.P. Schonberg, F. Schäfer, R. Destefanis et al., Hypervelocity impact response of honeycomb sandwich panels, Acta Astronaut, vol. 66 (3-4), 2010, 455-466.

[8] K. Nitta, M. Higashide, Y. Kitazawa et al., Response of a Aluminum Honeycomb Subjected to Hypervelocity Impacts, Procedia Engineering, vol. 58, 2013, 709-714.
[9] S. Ryan, Hypervelocity impact induced disturbances on composite sandwich panel spacecraft structures, PhD Thesis, 2007
P. Kang, S.K. Youn, & J.H. Lim, Modification of the critical projectile diameter of honeycomb sandwich panel considering the channeling effect in hypervelocity impact, Aerospace Science and Technology, vol. 29, 2013, pp. 413-425.