Meso-scale modeling of hypervelocity impact on spacecraft foam-core sandwich panels

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1 Introduction

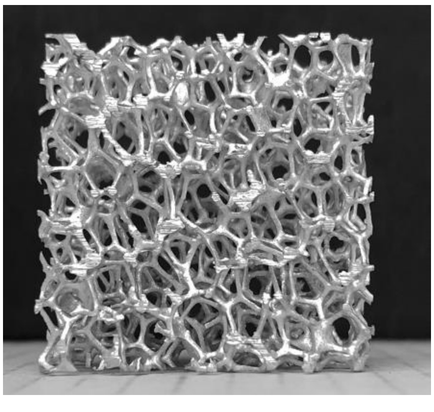
In a typical satellite bus, most impact-sensitive equipment is situated in the enclosure of the structural sandwich panels. Being the most commonly used elements of satellite structures, these panels form the satellite's shape and are primarily designed to resist launching loads and provide attachment points for satellite subsystems [1]. With low additional weight penalties, their intrinsic ballistic performance can often be upgraded to the level required for orbital debris protection [2]. Consequently, assessing the orbital debris impact survivability of satellites requires the availability of predictive techniques and hypervelocity impact (HVI) simulation models for sandwich panels, which are capable of accounting for various impact conditions and design parameters.

*Open cell foam-cor*e sandwich panels (FCSP) offer some significant advantages if used in satellite shielding. In particular, they provide secondary interaction of projectile fragments (initial projectile fragmentation happens upon its collision with the front facesheet of the sandwich panel) with individual ligaments of an open-cell foam, which results in a significant reduction in the fragments' damaging potential (so-called "multishock effect" of foam [3,4]). Therefore, this projectile–foam interaction requires adequate representation in numerical modeling of HVI on FCSP, including replication of geometric features of different commercially available foam grades, stochastic variation of pore sizes, true cross-sectional topology of ligaments, and the complex geometrical shapes of ligaments' junction regions.

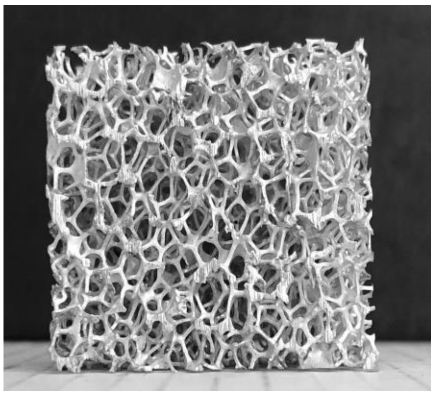
This paper describes LS-DYNA simulation models developed for hypervelocity impact on open-cell aluminum foam-core sandwich panels, in which the foam geometries were obtained using the X-ray Computed Tomography of real foam samples, thus eliminating any simplifications inherent to techniques based on foam idealization. The capability of the developed simulation models to predict ballistic limits of the foam-core sandwich panels is evaluated through comparison of the LS-DYNA simulations with experimental data provided by NASA.

2 Geometric models of open-cell foams

Two grades of open cell aluminum foam were used for this study. Both grades were a nominal 8% density, relative to their base material (Al6101-T6), however they were different in terms of pore sizes. The sample with larger cells contained ten pores per inch (10 ppi) on average, while the sample with smaller cells averaged at twenty pores per inch (20 ppi), as shown in Fig. 1.



10 pores per inch (ppi)

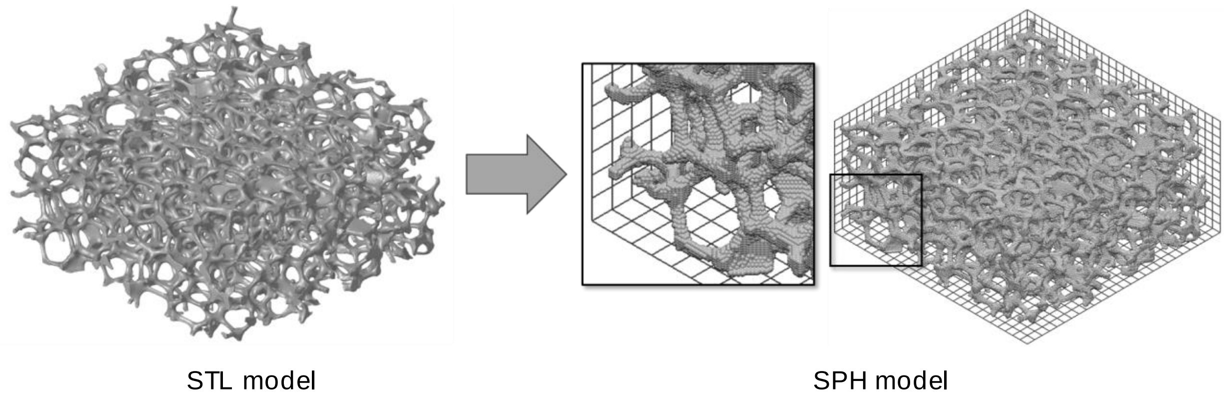


20 pores per inch (ppi)

Fig.1: Samples of 8% open-cell aluminum foams with different pore sizes

For digitizing the geometry of the foam, X-ray Computed Tomography imaging was conducted on a 225 KeV microfocus system. The specimens were placed on an extruded polystyrene (XPS) foam fixture during imaging. The procedure included data reconstruction, advanced surface determination, and STL export.
In order to obtain a representation of the foam suitable for hypervelocity impact modelling, volumes described by triangulated STL surfaces were filled with SPH (smoothed particles hydrodynamics) particles, as illustrated in Figure 2. A particle size of 0.1 mm was employed for the discretization of both types of aluminum foam.

10 PPI 8% ALUMINUM FOAM



20 PPI 8% ALUMINUM FOAM

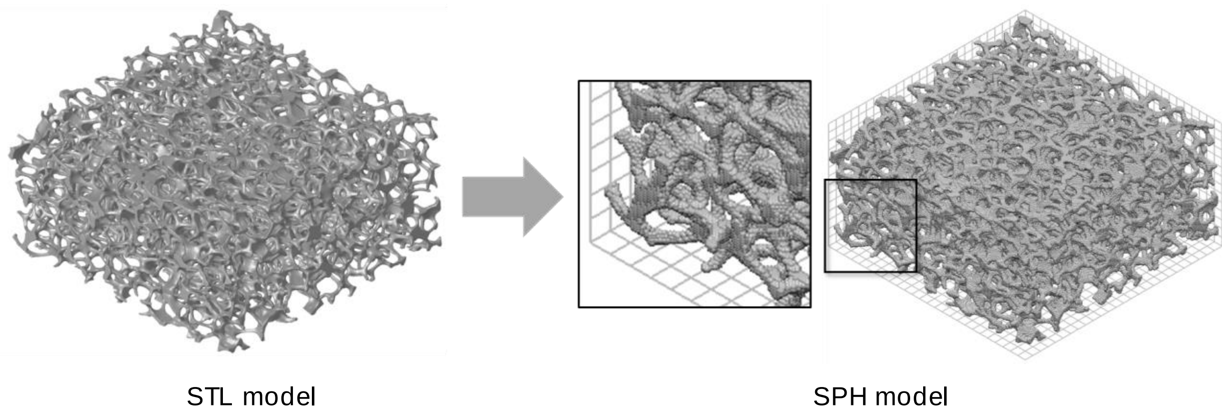


Fig.2: Filling STL geometry with SPH particles

3 LS-DYNA model

The HVI simulation models were developed to replicate the conditions of three physical experiments conducted by NASA using 1.0”-thick open cell foam core panels which were hit by 6.9 km/s aluminum projectiles. The experiments are denoted in Ref. [5] as follows:

- HITF 08261 (10 ppi foam; 2.0 mm projectile);
- HITF 08253 (20 ppi foam; 2.0 mm projectile);
- HITF 08254 (20 ppi foam; 1.9 mm projectile).

In addition to the foam cores, all the panels included AL6061-T6 facesheets of equal thickness (0.254 mm), which were bonded to the core by (nominally) 0.241 mm-thick epoxy structural adhesive film.
The developed hypervelocity impact simulation model with explicit representation of the open-cell foam core is shown in Figure 3. The model is a 30 mm x 30 mm representative element of the larger 150mm x 150 mm panels that were used in the NASA experiments. It should be noted that, as the adhesive film in the experiments had nearly the same thickness as the aluminum facesheets, it was deemed important to include its explicit representation in the numerical model as well. A detailed description of the different parts of the model, as well as the methods used to describe those parts, is provided below.

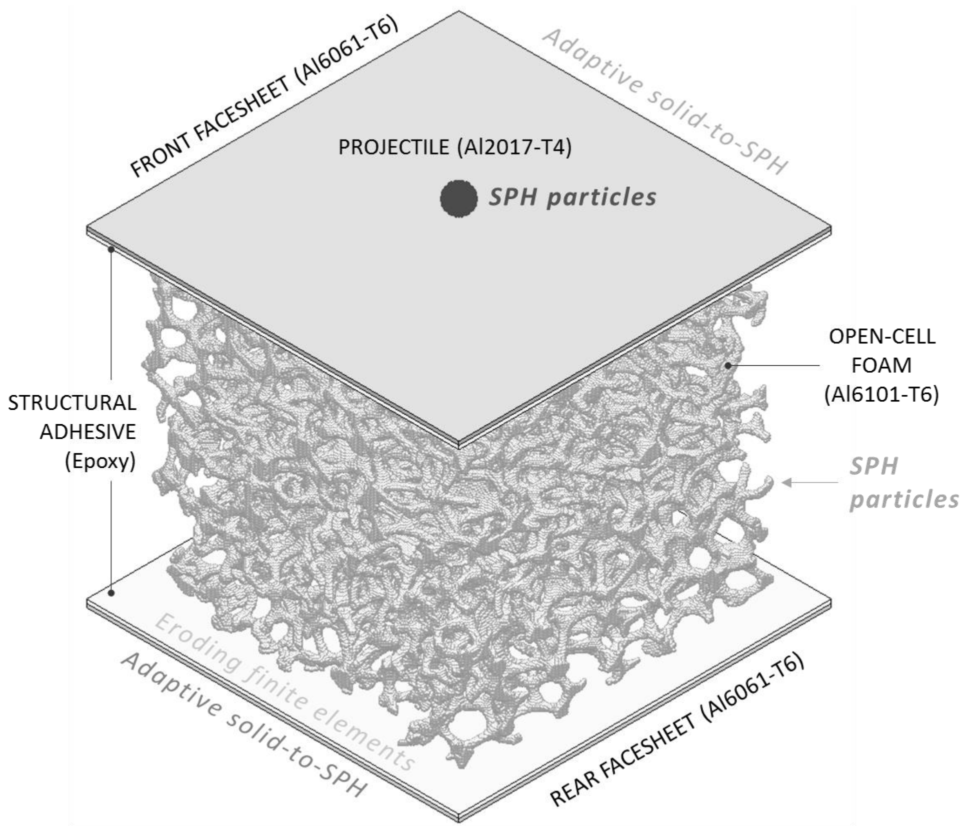


Fig.3: LS-DYNA simulation model for HVI on a 1.0-inch-thick foam-core sandwich panel

Projectile. Due to the fact that a projectile, as a result of hypervelocity collision with a sandwich panel, was expected to experience a complete disintegration, fragmentation, and be subjected to extremely high deformations, a meshless method – smoothed particles hydrodynamics (SPH) – was employed to represent this part of the simulation model. Projectiles of two different diameters (2.0 and 1.9 mm) were modelled in this study, however a common particle size of 0.1 mm was used for the discretization of both considered projectile types.

Front facesheet. It is well known that while the SPH technique is often advantageous in modelling scenarios involving extreme deformations and fragmentation, the finite element method (FEM) in its Lagrangian implementation is well-suited for tracking the materials' interfaces. To use the advantages of both techniques simultaneously, a hybrid FEM/SPH approach was implemented for the facesheets using the LS-DYNA's **`*DEFINE_ADAPTIVE_SOLID_TO_SPH`** keyword, which allowed local and adaptive transformation of Lagrangian solid elements to SPH particles when the solid elements became highly distorted and inefficient. Such a conversion was triggered by the erosion of solid elements which happened when the effective plastic strain in the element reached the level of 30%. The SPH particles replacing the eroded solid elements inherited all the nodal and integration point quantities of the original solids and initiated being attached to the neighboring solid elements. Using this approach prevented numerical instabilities that could have happened if both facesheet and adhesive were modelled using SPH particles (SPH interpolation between particles of materials with different densities can result in unphysical behavior, see [6]) and allowed modelling of the debonding between facesheets and epoxy adhesive, as described below.

Adhesive film. Assuming that the damaging potential ("lethality") of epoxy fragments will be rather low as compared to the aluminum facesheet and the aluminum projectile fragments (both density and strength of epoxy are significantly lower than that of aluminum), the adhesive was simply modelled using eroding Lagrangian finite elements without further conversion into meshless particles. The erosion was allowed to happen in a particular finite element when the effective plastic strain in it reached the level of 35%. As extensive debonding was observed between the adhesive and the facesheets in the physical experiments, the corresponding contact interfaces were represented using LS-DYNA's **`*CONTACT_AUTOMATIC_ONE_WAY_SURFACE_TO_SURFACE_TIEBREAK`** with OPTION 9. This contact algorithm is equivalent to using zero-thickness cohesive zone elements and is based on the fracture model with bilinear traction-separation law, mixed-mode delamination criterion, and damage formulation. A detailed description of this approach can be found elsewhere, including the author's previous work [7].

Open-cell foam core. As has been described in Section 2, the open-cell foam cores of the sandwich panels were represented in the simulations explicitly using the SPH models derived from the CT-scan imaging of the real foam samples.

Rear facesheet. Similar to the front facesheet, the technique based on the adaptive transformation of finite elements into SPH particles was employed for modelling of the rear facesheet. This approach makes it possible to accurately capture different levels of rear wall damage: from small deformations (using solid elements) to very large deformations, converting, if needed, distorted solid elements to SPH particles.

In addition to the above, a "non-reflecting boundaries" condition was applied to the representative element of the sandwich panel using the corresponding LS-DYNA keyword card (**`*BOUNDARY_NON_REFLECTING`**) to prevent reflection of stress waves from the sides of the facesheets and the attached adhesive layers.

A combination of **`*EOS_GRUNEISEN (*EOS_004)`** and **`*MAT_JOHNSON_COOK (*MAT_015)`** was used to represent the behavior of the Al2017-T4, Al6061-T6 and Al6101-T6 alloys. For the epoxy layers, **`*EOS_004`** was combined with **`*MAT_ELASTIC_PLASTIC_HYDRO (*MAT_010)`**. Parameters of the material cards used are provided in Ref. [8].

4 Results of HVI simulations

All hypervelocity impact simulations were conducted using a massively parallel processing (MPP) solver of LS-DYNA on a computer with eight Intel Core i7-7700HQ CPUs and 32 GB of RAM. With these computational resources and for simulations involving 20 μs after impact initiation, an average simulation runtime was around 21 hours.

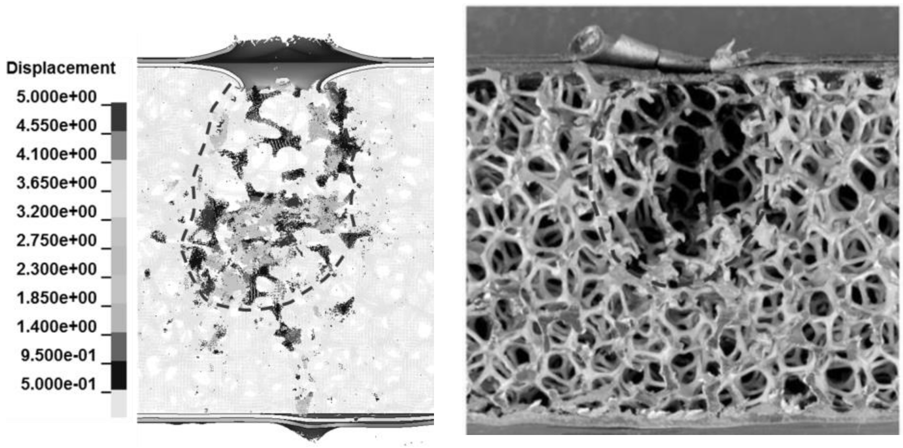


Fig.4: Post-impact damage of 10 ppi foam-core sandwich panel (model vs. HITF 08261 experiment)

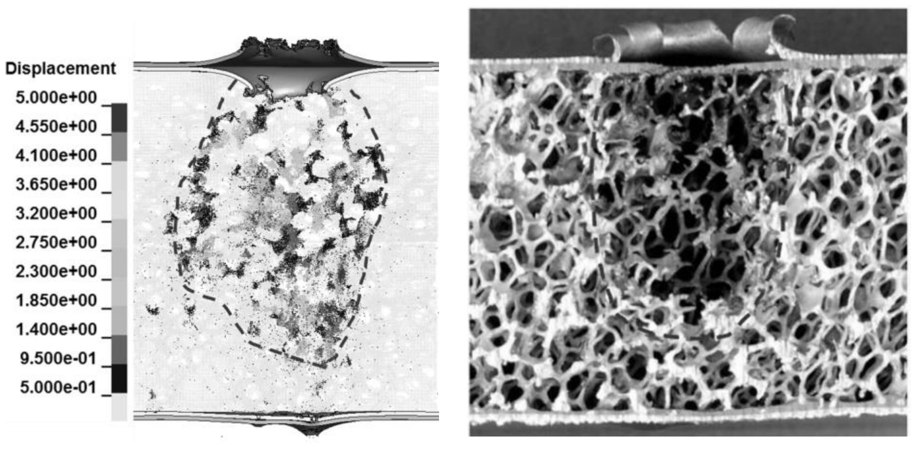
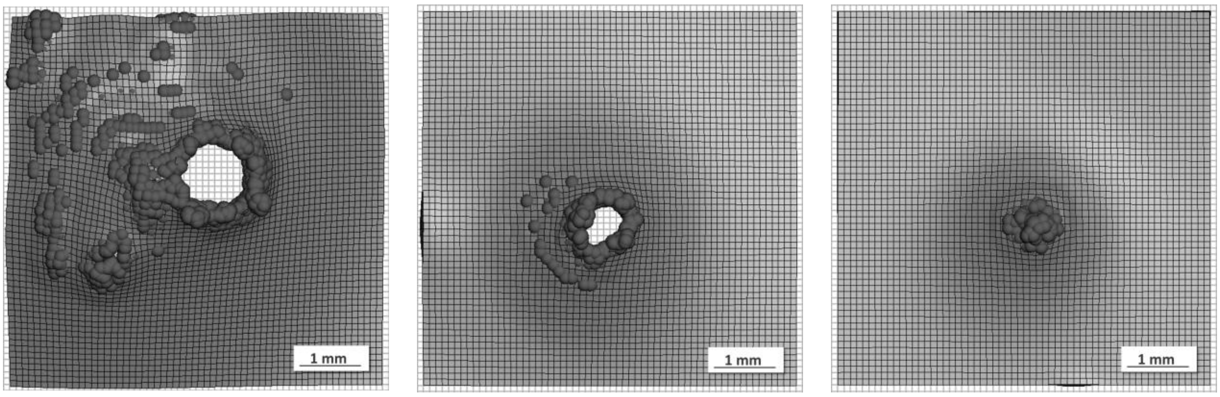


Fig.5: Post-impact damage of 20 ppi foam-core sandwich panel (model vs. HITF 08253 experiment)

Comparison of foam core damage – as predicted by the developed numerical models and obtained in NASA experiments HITF 08261 and HITF 08253 (Ref. [5]) under the same impact conditions – is shown in Figures 4 and 5. For the simulation results in these figures, the “damaged” portion of the foams was visualized by highlighting the ligaments that, as a result of HVI, experienced a displacement that was anything larger than 0.5 mm (damage of the ligaments with a resultant displacement in the range from 0 to 0.5 mm was deemed to be either lacking, or barely visible, and such parts are grayed in the Figures 4 and 5, representing the “intact” material). As can be deduced from Figures 4 and 5, there is a good correlation between the numerical and experimental results in terms of the extent of the developed cavities. Also, both numerical and physical experiments predict more foam damage for the panel with the smaller pore size (20 ppi), which is an indication of the more extensive interaction of the fragment cloud and the foam in this case.



10 ppi, 2.0 mm, 6.85 km/s **20 ppi, 2.0 mm, 6.87 km/s** **20 ppi, 1.9 mm, 6.87 km/s**

Fig.6: Rear facesheet damage of a 1.0 inch-thick FCSP as a function of projectile diameter and foam pore size (shown: 6 mm x 6 mm area around perforation/largest bulge)

#	NASA code	Target	Projectile, mm	Speed, km/s	Experiment (NASA)	Simulation (UWindsor)	D_{hole}, mm (experiment)	D_{hole}, mm (simulation)
1	HITF 08261	1.0” Al F10	2.0	6.87	Perforation	Perforation	1.00	0.94
2	HITF 08253	1.0” Al F20	2.0	6.85	Perforation	Perforation	< 1	0.53
3	HITF 08254	1.0” Al F20	1.9	6.87	Pass	Pass	N/A	N/A

Table 1: Summary of simulations conducted to verify the developed LS-DYNA model and their correlation with available experimental data

While the results shown in the previous figures confirm the adequacy of the developed model and show good qualitative correlation with the available experimental data, the main validation metric for the numerical model is its ability to accurately predict the ballistic limit of a panel subjected to HVI. The latter is usually linked to the rear facesheet damage resulting from the impact. For the three impact scenarios considered in this study, the corresponding modes of rear wall damage (close-up views with all parts other than rear wall hidden) are shown in Figure 6. They are represented by full perforation of the rear wall in the case of 2 mm projectile impacts (both cores), and no perforation in the case of the smaller 1.9 mm projectile impact on the sandwich panel with 20 ppi foam core. This is in line with the experimental observations reported by NASA for the same impact conditions. Furthermore, as shown in Table 1, hole size estimations obtained using the numerical models correlate well with the post-impact measurements conducted in the physical experiments.

5 Summary

This study investigated the possibility of developing high-precision numerical simulation models for orbital debris impact on structural elements that are often used for the protection of unmanned spacecraft – sandwich panels with open cell foam core. The proposed modelling technique features a relatively simple two-step procedure that includes

1. obtaining a realistic foam geometry model using X-ray Computed Tomography imaging, and

2. its conversion to a LS-DYNA meshless SPH model suitable for hypervelocity impact simulations.

An important advantage of the method is that it does not involve any significant simplifications of the complex foam structure, which is important for an adequate representation of the multishock effect (numerous collisions of projectile and front facesheet fragments with foam ligaments) during the HVI process. In spite of the high level of realism in representing the foam structure, the proposed modelling approach did not impose any significant requirements on the computational resources, which may also have a significant practical importance: all the simulations conducted in this study for a typical sandwich panel were completed on a desktop computer within a 24-hour window. The simulation models developed in this study demonstrated a good correlation with the available experimental data in terms of their ability to predict the ballistic performance of foam-core sandwich panels subjected to impacts by hypervelocity projectiles. The proposed modeling technique is recommended for implementation in the shielding design process, when accurate evaluations of spacecraft vulnerability to orbital debris is required.

6 Acknowledgements

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7 Literature

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