SPH MODELING OF ADVANCED MATERIALS IN HYPERVELOCITY IMPACT SIMULATIONS

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1 INTRODUCTION

Spacecraft must be analyzed for their ability to survive hypervelocity impacts (HVI) by orbital debris, as collision of a space vehicle 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 orbital environment. Due to the high cost of the physical HVI experiments, numerical modeling plays a significant role in conducting such analyses. In particular, the smoothed particles hydrodynamics technique (SPH) was previously found applicable for simulating scenarios involving extreme deformations and fragmentation, including hypervelocity impact. With the extensive use of advanced lightweight materials in space structures, it is important to find a rational way of representing them using the SPH framework. This study reports the results of SPH modeling of two distinct types of lightweight materials often employed in space structures: open-cell foams and fiber-reinforced composites. For foams, explicit representation of their complex mesoscopic architecture was achieved by filling the STL exteriors (generated using X-ray computed tomography) with SPH particles. For laminated composites, ply-wise representation was obtained using finite elements that could locally and adaptively transform to SPH particles when the elements become highly distorted and inefficient. Results of HVI simulations involving foams and composites were compared with available experimental data. The advantages and limitations of the modeling techniques are discussed.

2 MODELING OF HYPERVELOCITY IMPACTS ON CARBON FIBER REINFORCED POLYMERS

2.1 Background

Carbon fiber reinforced polymers (CFRPs) are used in the design of satellites due to their high strength-to-weight ratio (specific strength): since 2012, the number of active satellites has increased by a factor of 2.4, due to increasing demand [1]. This introduces the need for accurate numerical models that can predict composites' damage resulting from impacts at velocities exceeding 7 km/s. Experimental studies have been reported in the literature (see Ref. [2-4]), with a limited number of experiments at or exceeding 7 km/s. The impetus of this study was to replicate some of these experiments using an adaptive finite element/SPH particles approach. The FEM method captures minor deformations around the impact and delamination between the adjacent ply layers, while the SPH method models the extreme deformation and fragmentation due to the impact.

2.2 Numerical model

Three experiments reported in [2] for 16-ply AS4/PEEK composites were used as a basis for validation in this study. The experiments labeled Rice #61, Rice #62, and Rice #63 in [2] contained identical set-ups, apart from the impact velocity and projectile composition (all – normal incidence w.r.t the target). The details of the projectiles are as follows:

- Rice #61 - 1 mm 440C Stainless Steel projectile-impacting at 7060 m/s.
- Rice #62 - 1 mm. Aluminum (Al) 2017 T4 projectile-impacting at 7140 m/s.
- Rice #63 - 1 mm Nylon projectile-impact at 6950 m/s.

Hypervelocity shots with three different projectile materials were selected from the database reported in [2] to diversify the range of this numerical study. The face sheets comprised a 16-layer laminate with plies in a $[0°,45°,-45°,90°]_s$ orientation [2]. The thickness of the face sheets were 1.84 mm, 1.84 mm, and 1.73 mm, for the Rice #61, Rice #62, and Rice #63 experiments, respectively. A secondary witness plate comprised of Al 2024 was situated 100mm away from the rear surface of the face sheet to capture ejected debris.

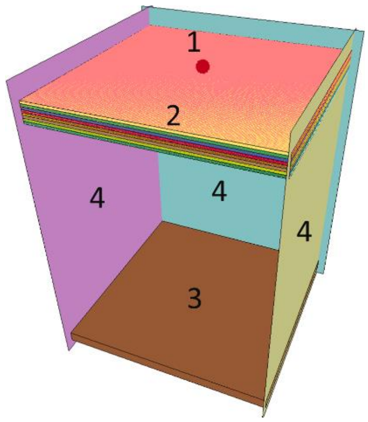


Figure 1: Hypervelocity impact simulation model of 16-ply laminates subjected to micrometeorites.

LS-DYNA was used for creating and solving these numerical models. Since the SPH method was implemented, an explicit single-precision MPP solver (R13.0) was utilized to increase simulation efficiency. The simulation setup consisted of four main parts, namely, the projectile, the face sheet, and the witness plate (see Figure 1). The projectile (labeled 1) was created with SPH elements to simplify the modeling procedure, as fragmentation was guaranteed. The face sheet and the witness plate (2 and 3, respectively) were created initially with solid elements, with characteristic element lengths of 0.1 mm, which would transition into SPH elements upon reaching a specified erosion criterion (adaptive technique, ADT). A one-to-one ratio was implemented so that each solid element would transition into only one SPH element. Finally, for the sake of simplifying the simulation parameters further, the complete length of the face sheet and the witness plate were not modeled. A smaller section in the vicinity of the impact zone was captured and the boundary keywords *NON_REFLECTING and *SPH_NON_REFLECTING were implemented to ensure that no adverse effects would be incurred from reflected shockwaves.

Each of the projectiles were modelled through a Johnson-Cook material model (*MAT_015) in LS-DYNA. A Mie-Gruneisen equation of state (EOS) was used for each of the projectiles to describe their volumetric expansion due to the impacts. Similarly, the witness plate was also modelled with the Johnson-Cook material model, with a Mie-Gruneisen EOS. The face sheet was modeled with the solid/SPH, composite failure material model (*MAT_59), and no EOS was implemented for this material, due to lack of availability. Finally, an add erosion (*MAT_ADD_EROSION) keyword was implemented with an effective strain-based failure criterion. Upon failure, the eroded solid elements converted into SPH particles, retaining the material properties, and continued to partake in any contact interactions. This erosion keyword was implemented for the 16-ply face sheet and the witness plate. Due to erosion, contact was set up in four steps:

- An eroding surface-to-surface contact was used to maintain contact between the solid elements of each ply layer upon the onset of erosion, through segment sets.
- An eroding nodes-to-surface contact was implemented to maintain contact between the SPH elements and the solid elements, through part sets.
- An automatic one-way tiebreak surface-to-surface contact, with option 9, was used to model the adhesion between the adjacent ply layers, through segment sets.
- Finally, a contact interior keyword was implemented to prevent negative volume errors within the solid elements in the simulations. This was implemented with part sets.

2.3 Results of simulations

The simulations were compared against the experimental observations and the parameters used as comparison include the size of the front-side, entry crater, and the size of the rear-side, exit crater as illustrated in Figure 2. The area of the front-side and rear-side craters were computed and normalized to determine equivalent diameters.

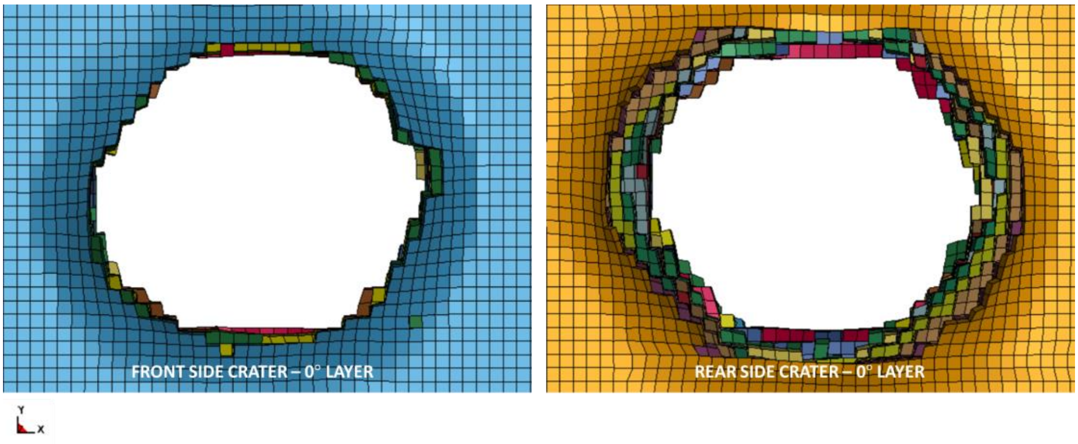


Figure 2: Front and rear side craters within numerical simulations.

Although delamination was modeled in these numerical simulations, the experiments presented within this study did not present any sufficient pictures of C-scans that could be used to visually validate the delaminated zones. In all cases, the projectile perforated through the face sheet, and the corresponding debris cloud collided with the witness plate. The evolution of the debris cloud can be observed in Figure 3. A summary of the results is presented in Table 1 and Table 2. The letter 'E' is used to represent the experimental observations and the letter 'N' represents the numerical simulations observation.

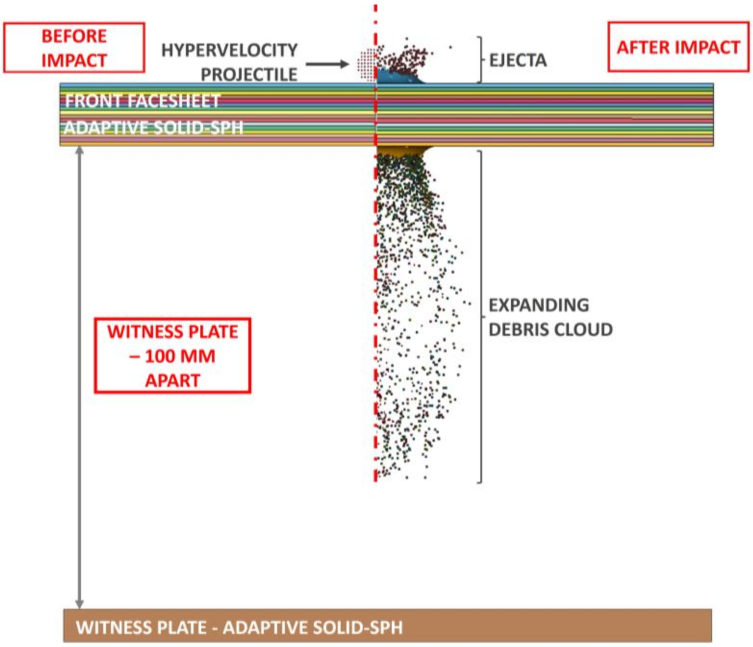


Figure 3: Debris cloud evolution in adaptive numerical model.

Table 1: Summary of results, experimental observations (E) vs. numerical simulations (N).

Test	**Impact speed (m/s)**	**Front-side crater (mm)**		**Rear-side crater (mm)**	
		E	**N**	**E**	**N**
Rice #61	7060	3.98	2.61	3.27	3.01
Rice #62	7140	3.47	2.94	3.62	3.25
Rice #63	6950	2.81	3.39	2.83	3.27

Table 2: Summary of results, experimental observations vs. numerical simulations.

Test	**Impact speed (m/s)**	**Front-side crater (mm)**	**Rear-side crater (mm)**
		Relative Error (%)	**Relative Error (%)**
Rice #61	7060	34.67	7.95
Rice #62	7140	15.30	10.22
Rice #63	6950	21.0	15.55

2.4 Summary for modeling of HVI on CFRPs

The representative area of the crater was computed to determine an equivalent diameter for both the front and rear-side craters. The prediction capabilities of the current simulations leave room for improvement and it can be observed that the relative errors for the prediction of the rear-side crater size are consistently lower than for the front-side crater, with values as low as 7.95% and a maximum of 15.55%. For the front-side crater, the lowest error measured between experimental observations and numerical simulations was 15.30%, with a maximum error of 34.67%. Further, the relative errors in terms of the delaminated area ranged between 14.71% up to 41.71%. An area for improvement in simulation accuracy could be achieved through the implementation of an EOS for the 16-ply face sheet. This could aid with improved accuracy in predicting the response of the face sheet and any temperature effects upon impact.

One of the advantages of utilizing this hybrid FEM-SPH technique was that it allowed for the modeling of delamination between the ply layers, as illustrated in **Error! Reference source not found.**. The INTFOR command was invoked in conjunction with equating SPR and MPR to 1 within the one-way tiebreak cards. Delamination was measured through a contact gap, with values of 1 corresponding to complete delamination and values closer to 0 indicating complete adhesion. Although delamination occurred within the simulation and was observed, the visualization of the delaminated area through the ply layers was not accurately shown, while using *MAT_59. Additional work is currently underway to identify the reason for this occurrence. Due to this and the presence of no experimental evidence (C-Scans) for the three experiments explored within this study, the delamination pattern and area could not be validated. Validating this data against experiments can further bolster the viability of this hybridized modeling technique.

3 MODELING OF HYPERVELOCITY IMPACT ON OPEN-CELL FOAMS

3.1 Background

Sandwich panels are widely used in the design of unmanned satellites and in addition to having a structural function, can often serve as orbital debris shielding. In this application, sandwich panels with open-cell foam cores have a significant advantage, enabling intensive interaction between the impactor fragments and the foam ligaments which enhances the fragments' breakdown and reduces their damaging potential.

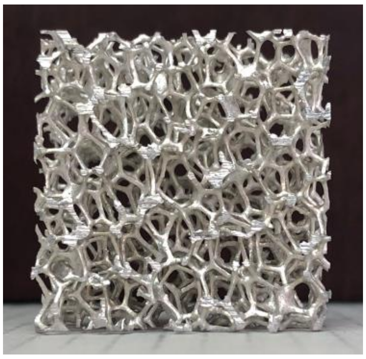


Figure 5: Open-cell aluminum foam – material used as a core in spacecraft sandwich panels

Assessing the orbital debris impact survivability of unmanned satellites requires the availability of predictive techniques and HVI simulation models for sandwich panels, which are capable of accounting for various impact conditions and design parameters. The complexity of the foam meso-structure requires its representation using a meshless method, such as the SPH technique.

3.2 Numerical model

A simulation model was 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 pores-per-inch [ppi] foam; 2.0 mm projectile); HITF 08253 (20 ppi foam; 2.0 mm projectile); HITF 08254 (20 ppi foam; 1.9 mm projectile). All panels included Al6061-T6 facesheets of 0.254 mm thickness, which were bonded to the core by (nominally) 0.241 mm-thick epoxy structural adhesive film. Different parts of the model are described below.

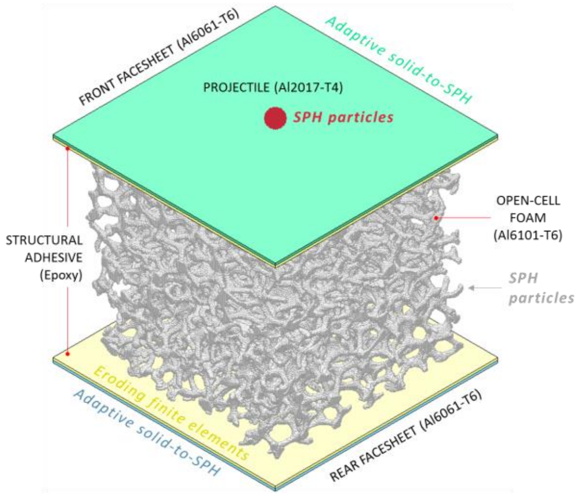


Figure 6: Hypervelocity impact simulation model of 1.0-inch-thick foam-core sandwich panel

Projectile. Due to the fact that a projectile, as a result of hypervelocity collision with a sandwich panel, was expected to experience fragmentation, SPH method was employed to represent this part of the simulation model.

Front facesheet was modeled using the adaptive FEM/SPH technique described in Section 2.

Adhesive film was modelled using eroding Lagrangian finite elements without further conversion into meshless particles. Cohesive-zone modeling approach was used to simulate debonding between the facesheets and the adhesive layers that was observed experimentally using the same approach as the one used for layers of CFRP laminates in Section 2.

Open-cell foam core was represented in the simulations explicitly using the SPH models derived from the CT-scan imaging of the real foam samples. Data reconstruction, advanced surface determination, and STL export were completed using Volume Graphics Studio Max software. The resulting STL geometry files contained sets of triangles defining the facial geometries of the foam specimens. Volumes described by triangulated STL surfaces were filled with SPH particles.

Rear facesheet. The ADT technique was employed for modelling of the rear facesheet.

3.3 Results of simulations

Comparison of foam core damage – as predicted by the developed numerical model and obtained in NASA experiment HITF 08253 under the same impact conditions – is shown in Figure 7, from which it can be deduced that there is a good correlation between the numerical and experimental results in terms of the extent of the developed cavity in the foam.

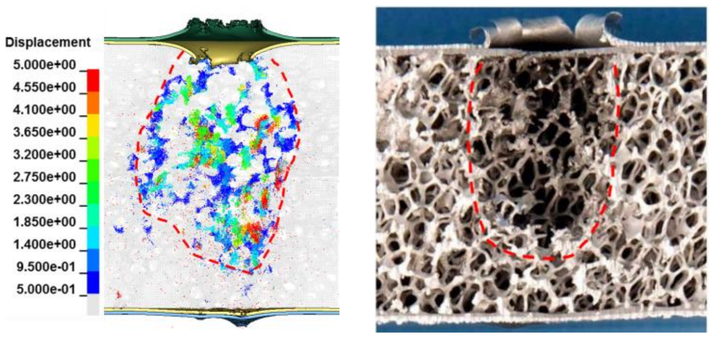
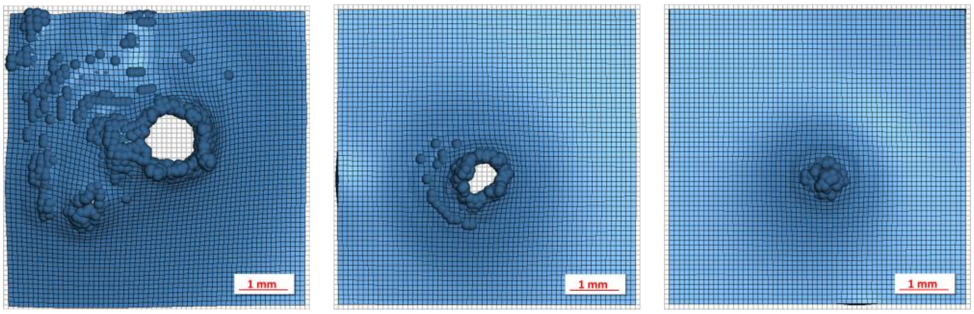


Figure 7: Impact damage of 20 ppi foam-core sandwich panel (model vs. experiment)

The main validation metric for the numerical model is its ability to accurately predict the ballistic limit of a panel subjected to hypervelocity impact. 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 8. 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 (see Table 3).



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**

Figure 8: Rear facesheet damage as a function of projectile diameter and foam pore size

Table 3: Summary of simulations conducted to verify the developed numerical model and their correlation with available experimental data

#	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

3.4 Summary for modeling of HVI on open-cell foams

The simulation model developed in this study, featuring the explicit SPH-based representation of the open-cell foam core, demonstrated a good correlation with the available experimental data in terms of its ability to predict the ballistic performance of foam-core sandwich panels subjected to impacts by hypervelocity projectiles. SPH model development for the open-cell foams was conducted using a two-step procedure that involved: (1) obtaining a realistic foam geometry model using X-ray Computed Tomography imaging, and (2) its conversion to a meshless SPH model suitable for hypervelocity impact simulations.

4 CONCLUSIONS

The two problems considered in this paper demonstrate that particle-based methods can be effective in modeling hypervelocity impact on advanced lightweight materials, such as CFRP composites and open-cell foams. Further improvement of simulation accuracy would require the development and implementation of a dedicated equation of state for carbon fiber plastics.

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