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# SPH evaluation of out-of-plane peak force transmitted during a hypervelocity impact

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## Abstract

Smooth Particle Hydrodynamics (SPH) technique is applied to simulate a hypervelocity impact of an aluminum sphere on a simple aluminum target and on a honeycomb structure sandwich panel in order to provide a useful input to Finite element Model or Statistical Energy Model on evaluating the vibration environment induced by the projectile on the target. The impact velocity range lays between 4 and 5 km/s. Different approaches have been analyzed. At first, the application of SPH technique for direct calculation of the vibration environment is described. Then the calculation of equivalent force impulse is evaluated. Two strategies have been applied: shear stress analysis and momentum calculation using drift velocity measurement. Momentum approach revealed to be the most convenient and reliable method. Results for an aluminum plate and a honeycomb sandwich panel are reported and compared to results of experiments and Finite Element Analysis.

*Keywords:* Smooth Particle Hydrodynamics, hypervelocity, impact, momentum, drift velocity

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## 1. Introduction

Although smoothed particle hydrodynamics (SPH) technique was invented in 1977 to simulate some astrophysical phenomena (cf.[1], [2], [3], [4]), this method has been applied also to problems involving high and hypervelocity impacts. It provides the capability to perform high distortion impact computations in a Lagrangian framework [5]. Since SPH is a gridless Lagrangian technique (cf.[6]), the discretization of mass is realized using free movable points of fixed mass and particles interact to each other via an interpolation function based on the conservation laws of mass, momentum and energy.

## Nomenclature

SPH Smooth Particle Hydrodynamics

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HVI	Hyper Velocity Impact
GOCE	Gravity Field and Steady-State Ocean Circulation Explorer
FEA	Finite Element Analysis
SEA	Statistical Energy Analysis
SRS	Shock Response Spectrum
EOS	Shock equation of state

This makes SPH an ideal candidate for modelling hypervelocity impact due to space debris and meteoroids that may occur on a spacecraft. In this paper we present the results of some applications of SPH technique aimed at analyzing the propagation of vibration induced by HVI (Hyper Velocity Impact) on the external envelope of the GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) spacecraft. Numerical simulations have been conducted, in support and in parallel of hypervelocity experimental tests performed with CISAS two-stage light-gas gun.

The aim of these numerical tests was to investigate physics phenomena, and to predict numerically the vibration environment induced by a defined impacting particle. The numerical approach is based on a combination of three codes: SPH (Smooth particle Hydrodynamics), FEA (Finite Element Analysis) and SEA (Statistical Energy Analysis). SPH is used to analyze the interaction between target and projectile. FEA is applied to calculate the vibration environment on small target, performing fine modal analysis. SEA is used to calculate the vibration environment on large satellite structure through calculation of transmission of mechanical power.

In this paper only SPH approach will be described. This analysis is focused on the use of SPH codes to simulate the equivalent force impulse applied to the not-perforated part of the structure during a hypervelocity impact. The aim of this study is to provide input force impulse data to FEA and SEA model for the vibration environment analysis. The first section of this paper reports on SPH initial application to directly calculate the vibration environment induced by a hypervelocity impact on a simple aluminum target. This approach gave encouraging results. However, the huge computational time required even for small target and the difficulty of interfacing SPH results with FEA and SEA, which are much more suitable to simulate complex structure, makes this procedure not very interesting for the application considered hereafter.

The force impulse applied by the projectile to the undamaged structure has been considered the most suitable mean for interfacing different codes. The force impulse analysis is described in the second section. Two approaches have been studied: the analysis of the shear stress on a not damaged zone near the impact point, and the calculation of the total momentum applied to the target. Calculations on simple aluminum plate and honeycomb structure panels are the considered test cases. The results, reported in the last two sections, are compared to results obtained through a direct measurement of momentum transfer done using a ballistic pendulum, and indirect measurement of momentum transfer obtained fitting experimental SRS (Shock Response Spectrum) with FEA simulations.

## **2. SPH Simulation of The Vibration Environment on Simple Al Plates**

The target considered was a 500 x 500 mm, 2 mm thick aluminum (Al2024-T81) plate. SPH

calculation has been performed on two cases:

- non-perforating shot: 0.8 mm diameter aluminum projectile at 4 km/s;
- perforating shot: 2.3 mm diameter aluminum projectile at 4 km/s.

Even if Smoothed Particle Hydrodynamics is a proved suitable technique for high deformation events, it shows to be quite time consuming. Thus a hybrid meshing technique of SPH and Lagrangian mesh has been used. SPH meshing has been applied near the impact site while Lagrangian technique has been used for the remaining part of the plate. In Fig.1 the geometric configuration used for these simulations is reported. The model is axis-symmetric along the projectile axis, being x direction the projectile velocity direction. The target is represented by a plate of 2 mm thick (x-direction) and 250 mm high (y-direction); the lower left corner located on the axis origin point. The projectile is half circle shaped and it is positioned on the x-axis close to the target.

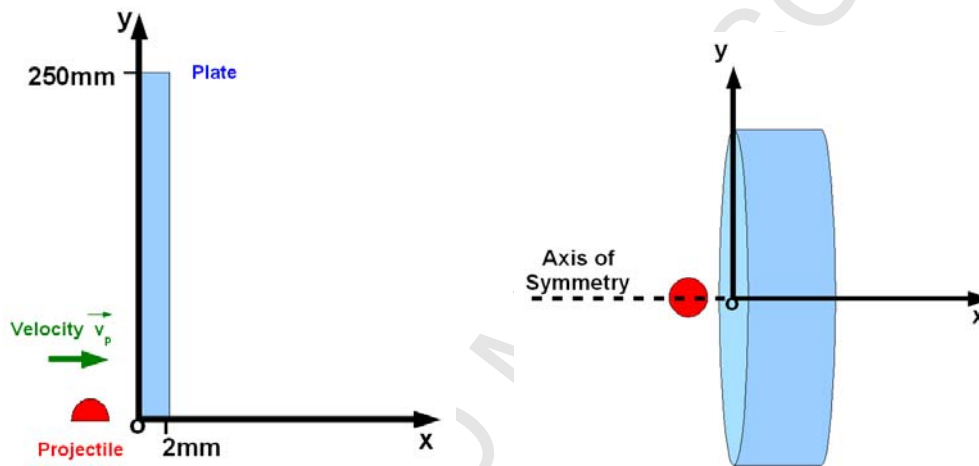


Fig. 1. Reference system assumed for geometrical mode in SPH simulations.

Some cases of different combinations of SPH and Lagrangian meshing have been simulated. Comparison of the obtained acceleration peaks with experimental data showed that the best configuration is reached with 80 mm SPH zone, surrounded by Lagrangian Mesh zone. As a best compromise between numerical convergence and simulation time length, SPH size has been chosen to be 20 times smaller than the smallest between projectile diameter and plate thickness. Lagrangian mesh size is equal to SPH size along join surface between the two different mesh zones, then it degrades towards y direction. About material models, those available from Autodyn libraries had to be adjusted to fit the experimental set up. In the case of projectile, Al2017 ( $\rho = 2.79 \text{ g/cm}^3$ ) was selected, configured for a Shock equation of state (EOS), with a Johnson-Cook strength model and a Principal Stress failure model with a tensile failure stress of  $1.58 \cdot 10^6 \text{ kPa}$ . The plate was modeled with Al2024-T4 using as Shock EOS, a Steinberg-Guinan strength model and a Principal Stress failure model with a tensile failure stress of  $2.1 \cdot 10^6 \text{ kPa}$ .

In order to evaluate several physical parameters, such as forces, velocities, stresses, along the plate, many target points were located along target surfaces and thickness, more abundantly within 10 mm from impact point (1 mm step instead of 5 mm step along y-direction). Numerical simulations of the

vibration environment required large computational time to achieve a good frequency resolution to allow meaningful comparison with experimental and FEA data. To achieve a frequency resolution of 100 Hz (which allow for 100 points in the range 0-10 kHz requested in this study) the simulation need to be stopped at 10 ms, requiring a computational time of 4 weeks with a Pentium IV PC, 2.33 GHZ 1GB RAM. The simulation presented on Fig.2 run up to  $4.4 \cdot 10^{-2}$  ms and required 4 days of CPU time.

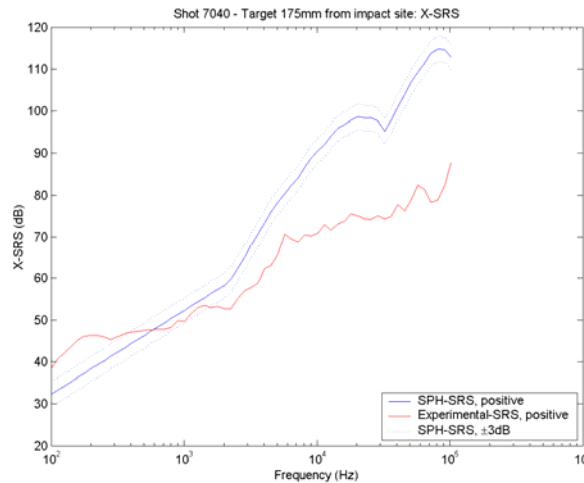


Fig. 2. SRS comparison for shot 7040 between experimental data and numerical data calculated at a distance of about 175 mm from impact site.

The comparison with experimental data showed encouraging results; especially considering the short time of the signal used respect to the time duration of the experiment. However the large computational time required, combined with the low accuracy achieved by FEA on propagating acceleration signals suggested to abandon this way towards calculation of equivalent force impulse applied by the projectile to the target.

### 3. SPH Calculation of Equivalent HVI Force Impulse

In order to calculate the equivalent force impulse applied by the projectile to the target two different strategies have been identified and applied:

- monitoring the shear stresses on a section close to the impact point, but located on an undamaged zone;
- calculation of the total momentum applied to the target, equivalent to the impulse of the applied force.

The first approach provides more detailed information on the HVI phenomena. However, as it will be explained in the following, the complexity of the stress-wave environment makes the determination of an equivalent force impulse very uncertain. Moreover the need of avoiding border reflections (to achieve clear force peak identification) requires large target and thus large computational time. The

second approach provides more macroscopic information (no insight on the real shape of the peak force applied). However, using FEA analysis it has been verified that a fit to experimental out-plane SRS for frequencies below 10 kHz, within 3dB, can be achieved with any force peak of equivalent integral (total momentum transfer) with duration lower than  $5 \cdot 10^{-5}$  s. Thus the determination of total momentum transfer is the only information required to reconstruct an equivalent useful out-of-plane force impulse.

### 3.1.1 Analysis of stresses induced during HVI

Two cases have been considered: 0.8 mm at 4 km/s impacting on a 2 mm thick aluminum plate (CISAS ID ref. 7040) and 2.3 mm at 5 km/s (CISAS ID ref. 7674) resulting in a not penetrating and penetrating impact respectively (see Fig.3).

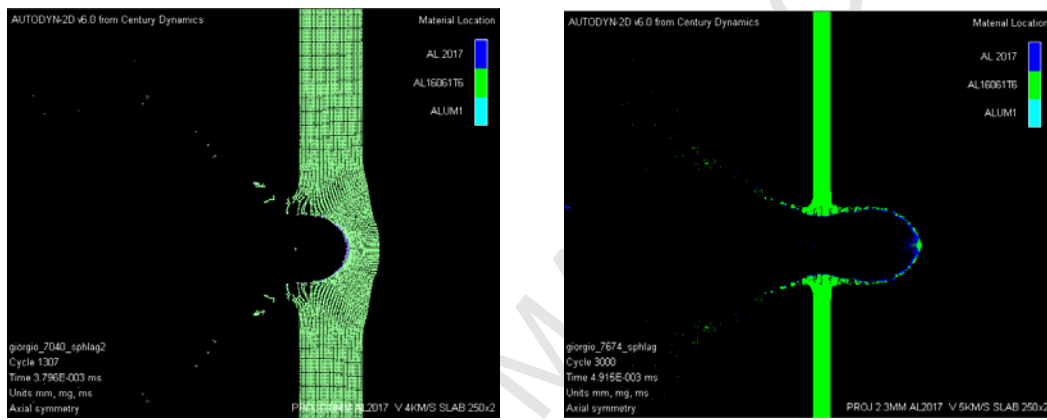


Fig. 3. Results of Autodyn 2D simulations for shot 7040 (left) and shot 7674 (right) configuration set up.

As only  $xy$ -stress components contribute to the transmission of force impulse along out-of-plane direction, the approach adopted was to determine the integral average  $\overline{\sigma_{xy}}$  of the  $xy$ -stress along plate thickness  $h$  at a fixed distance  $d$  from impact site and then to integrate it on the ring surface:

$$\overline{\sigma_{xy}} = \int \sigma_{xy} \frac{dx}{h} \Rightarrow T = 2\pi dh \overline{\sigma_{xy}} \quad (1)$$

Results of this approach, both for shot 7040 and shot 7674 are presented in Fig.4. A detailed analysis of the shear stress behavior along the selected section showed complicate superposition of not-synchronous phenomena (in-plane and out-plane wave) induced on the target during the perforation dynamics. Consequently, shear stress on front face is not in-phase with shear stresses on the rear surface of the target. This makes very difficult to clearly identify the force impulse applied to the structure during the HVI respect to the general stress environment remaining on the target after perforation. Thus, it appeared not feasible to identify a procedure to measure the force impulse from simulated stress profiles, unless making questionable assumptions.

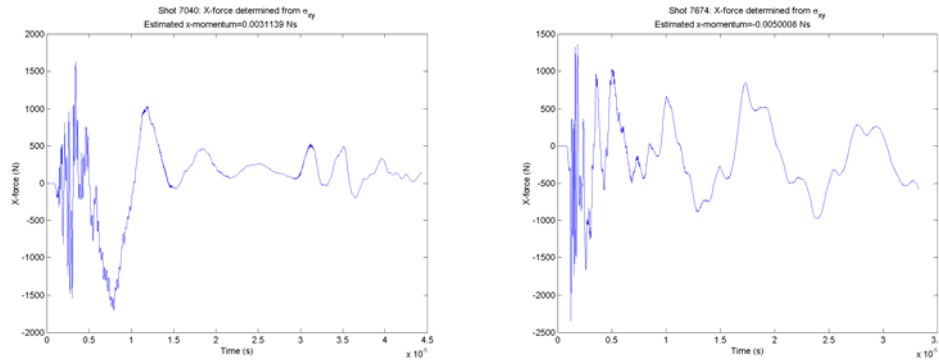


Fig. 4. Results of shear-stress approach for the evaluation of the force impulse for shot 7040 NP (left) and shot 7674 P (right).

The final comment on this approach is that, due to the very complex environment induced by superposition of different type of waves, propagating from the beginning to the end of penetration, it may not be suitable for evaluating an equivalent force impulse.

### 3.1.2 Evaluation of momentum transferred during impact

Hypervelocity impacts induce a rigid motion on an unconstrained target. This approach is based on direct calculation of target momentum by using the drift x-(rigid motion velocity) computed by SPH hydrocode.

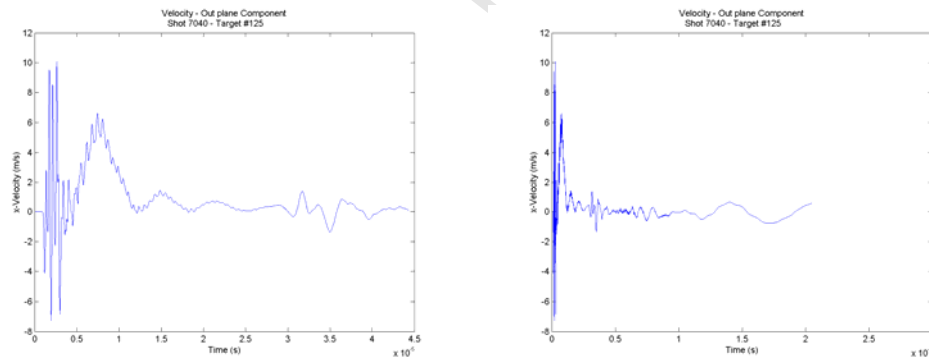


Fig. 5. X-velocity for 7040 NP case, for a simulation lasting  $3.5 \cdot 10^{-5}$  s (left) and  $2 \cdot 10^{-4}$  s (right). In the first case drift velocity can not be analysed since impact first effects are still active.

Since rigid motion velocity can be evaluated only after all other vibration-velocity-components are damped (see Fig.5) large geometry and thus long lasting simulation are needed. Otherwise, momentum transfer is related to the local perforation phenomenon. Hence, to reduce computational time and to increase accuracy, a small model was built up. The numerical model was composed by only SPH zone reduced down to 10 mm from impact point (Fig.6). The computational time became very low and simulation time up to  $1 \cdot 10^{-1}$  s has been achieved in less than one hour of simulation instead of several



days. The momentum transferred is evaluated as:

$$q_T = m_{target} \cdot v_{drift} \quad (2)$$

where  $q_T$  is the momentum transferred to the target,  $m_{target}$  is the mass of the perforated target and  $v_{drift}$  is the rigid-motion-velocity of the target after impact.  $v_{drift}$  is calculated averaging the final velocity of different measurement point placed on the target as described below.

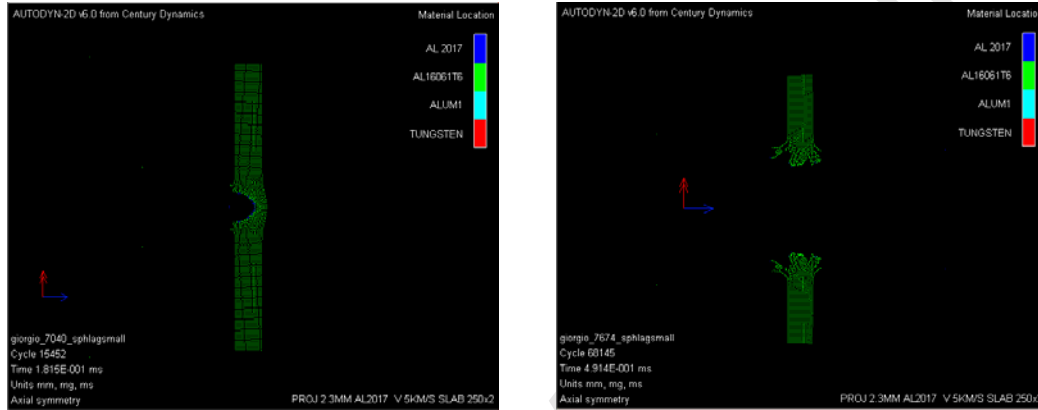


Fig. 6. Plate aspect after impact in the case of shot 7040 (left) and 7674 (right) for small configuration: plate was reduced to 10 mm x 2 mm and discretized only by using SPH technique.

This technique appeared to provide reliable results, thus it was used both for aluminum plates and for honeycomb panels, as described in detail in the next sections.

#### 4. Momentum Measurement on Simple Aluminum Plates

Figure 7 presents velocity numerically measured in an undamaged zone, about 7 mm from impact point along y-direction, in the case of simulation for shot no.7040 (NP) and shot no.7674 (P). As showed on Fig.7 after the impact phenomena is completed, stresses waves move along the target. The velocity on particles located on not damaged zones of the target is a superposition of an oscillating component related to travelling waves and a steady component equal to the drift-velocity of rigid-motion. The drift velocity on a selected target location was calculated as the average velocity in the time interval between 1 ms and 2 ms after the impact. Then the target drift velocity has been calculated averaging the drift velocity calculated on 10 different points. SPH results showed to be dependant on the failure model applied expectably in case of perforation phenomena. Different models applied are reported in Table 1.

Table 1. Strength and Failure models applied to Al targets

<i>Ref.</i>	<i>Material</i>	<i>Strength Model</i>	<i>Failure model</i>
A	Al 2024	Johnson-Cook	Principal stress
B	Al 2024	Steinberg-Guinan	Principal stress

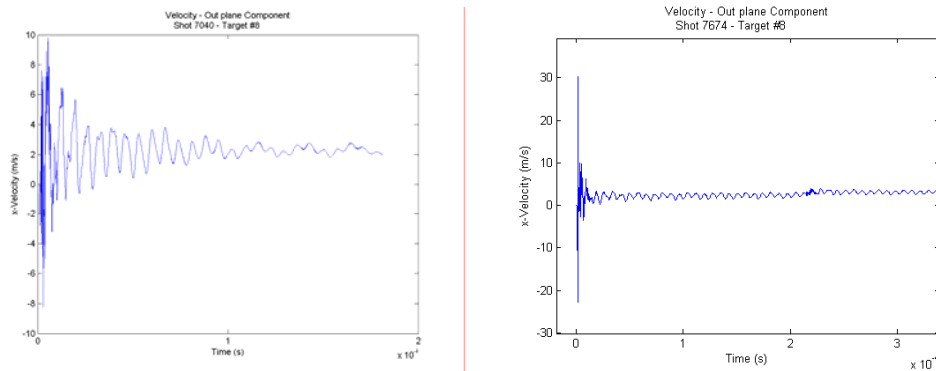


Fig. 7. Velocities in the case of simulated shot 7040 NP (left) and shot 7674 P (right); plate in Al2024.

For the failure model the Principal stress was chosen but for this kind of material no tensile failure stress is available, probably because of lack of data for dynamic test in hypervelocity regime. Then the tensile failure stress value of similar alloys were taken into account, of Al2007 of  $1.58 \cdot 10^6$  kPa and that of Al6061 of  $2.1 \cdot 10^6$  kPa. Strong differences between models appeared in simulating the penetrating case. Model A applied to 7674 case provided not-physical drift velocity increment during the entire simulation as showed in Fig.8-right. This anomalous behavior of drift velocity could be due to numerical instabilities obtained combining test settings to this material model.

Model B provided better results Fig.9 both for non perforation and perforation. The best fit with FEA and experimental data has been obtained with model B using  $1.58 \cdot 10^6$  kPa as failure stress. A small no physical drift is anyway present as showed in Fig. 9 in case of not perforation. SPH simulation results together with FEA and experimental data are presented in Table 2. Momentum calculation obtained applying SPH technique is in good agreement with the other two approaches, particularly in the case of perforating impact.

Table 2. Comparison between SPH simulation, FEA and Experimental results on momentum

Test ID	P/NP	Momentum [N s]		
		SPH	FEA	Experimental
7040	NP	$5.38 \cdot 10^{-3}$	$3.40 \cdot 10^{-3} \pm 0.5 \cdot 10^{-3}$	$1.06 \cdot 10^{-3} \pm 6.77 \cdot 10^{-3}$
7674	P	$2.02 \cdot 10^{-3}$	$1.59 \cdot 10^{-3} \pm 0.5 \cdot 10^{-3}$	$2.90 \cdot 10^{-3} \pm 6.77 \cdot 10^{-3}$

As SPH simulations presented in some case some anomalous, not physic, drift velocity increment, a test using Lagrangian technique was also done. Both projectile and plate have been modeled using Lagrangian technique. The instantaneous geometric strain erosion model with an erosion coefficient of 300%, was applied. This approach resulted in numerical convergence problems revealing that Lagrangian technique is not suitable for this kind of analysis.

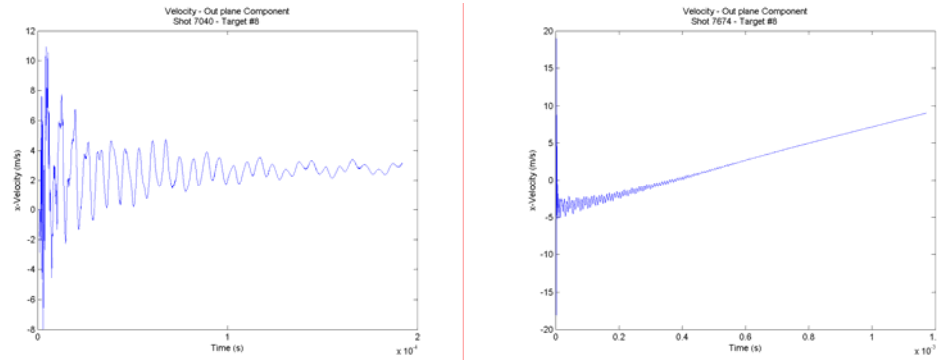


Fig. 8. Drift velocities for case 7040 (left) and 7674 (right). Plate in Al2024-T351 with Johnson-Cook strength model. 7674 curve presents an anomalous behavior.

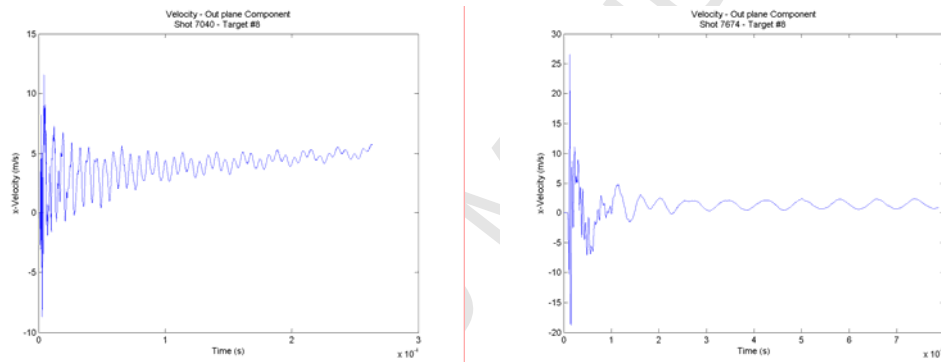


Fig. 9. Drift velocities for case 7040 NP (left) and 7674 P (right). Plate in Al2024 with Steinberg-Guinan strength model.

## 5. Momentum Measurement on Equivalent Honeycomb Panels

Momentum has been evaluated also in case of aluminum honeycomb H/C structure. A close to ballistic limit impact on an H/C panel (CISAS ID ref. 7553) has been simulated. The projectile is an aluminum sphere of 1.9 mm diameter and a velocity of 5 km/s. The target is an aluminum honeycomb sandwich panel in Al2024 52.8 mm thick (Al HC SP Al2024-T81 1 mm 3.1 3/16 5056 10P, panel height 52.8 mm).

The same materials models employed for Shot 7674 were used for this study. The 3-D honeycomb structure, was simulated with axis-symmetric a 2-D SPH simulation, through two plates separated by concentric cylinders. Thickness of cylinder has been calculated assigning 50% of the mass of real honeycomb between two cylinders (due to the core) to the internal one and 50% to the external one.

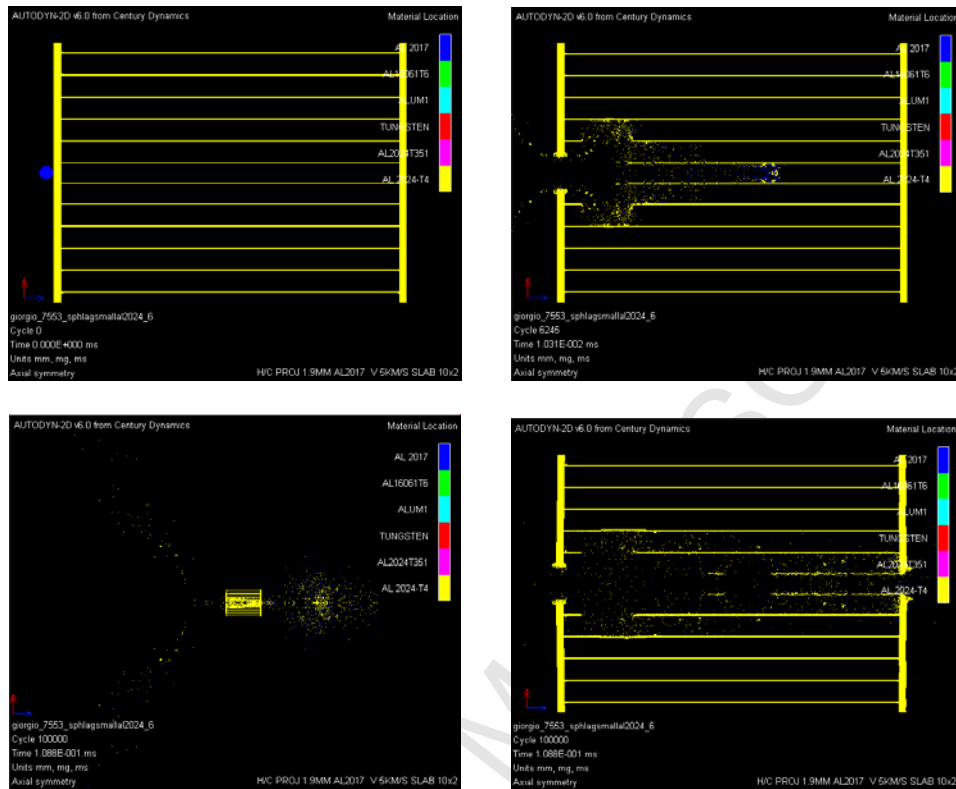


Fig. 10. Simulation results for the case of shot 7553 on a honeycomb panel. Pictures represent respectively: initial configuration (upper left), impact results after  $1 \cdot 10^{-2}$  ms (upper right), complete system and panel hole after  $1 \cdot 10^{-1}$  ms (lower left and right).

In Fig.10 four frames of the simulated impact on a H/C panel are presented. The upper left picture represents the system at the beginning of the simulation. The upper right reports the system after  $1 \cdot 10^{-2}$  ms; at this time ejecta are still tunneling along sandwich internal pipes, close to projectile direction and the H/C last skin is not yet perforated. The lower figures represent the complete and zoomed system after  $1 \cdot 10^{-1}$  ms. Large ejecta clouds formed out of both H/C skins and the damage internal to the panel are confined to the first pipes closest to impact direction.

The momentum transferred to the honeycomb structure has been estimated with the same approach used for the simple Aluminum plates, using drift velocity calculated at several points on the H/C skins (see, i.e. Fig.11).

This approach led up to momentum value of  $4.95 \cdot 10^{-2}$  Ns, quite in good agreement with FEA results that gave a momentum of  $4.4 \cdot 10^{-2} \pm 0.5 \cdot 10^{-3}$  Ns. This good agreement could be explained with the consideration that the low target to projectile dimensions ratio caused low ejecta on the first bumper. Thus most of the momentum carried by the projectile is trapped inside the panels reducing level of uncertainty related to debris cloud and ejecta behavior on SPH simulation.

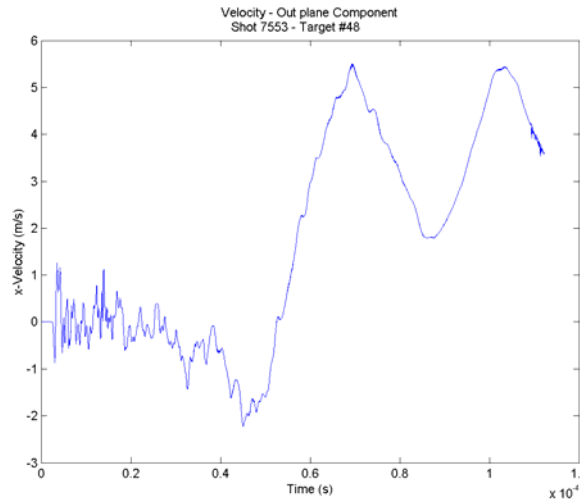


Fig. 11. Drift velocity calculated at 18 mm from impact site after  $1.1 \cdot 10^{-2}$  ms (left).

## 6. Conclusions

Smooth Particle Hydrodynamics technique has been used in order to simulate the vibration environment induced during a hypervelocity impact. The aim of this work was to estimate the force impulse transferred during the impact as input for FEA and SEA models to propagate vibration on the spacecraft external envelope. First analyses conducted on SPH showed that the determination of an equivalent force impulse is very complicate due to superposition of different types of waves following the impact phenomena. To overcome this problem an equivalence was set-up between SPH and FEA models, based on the momentum transferred to the target: it was found from FEA that below a defined time duration of the force pulse ( $1 \cdot 10^{-5}$  s) different force inputs provide the same SRS below 10 kHz if they transfer the same total momentum to the structure. This means that the total momentum transfer can be used as a key parameter on SPH to evaluate the equivalent force impulse to be propagated through FEM in the mid-field and SEA in the far-field. Two main strategies have been analyzed and implemented to identify the equivalent force impulse:

1. monitoring of the shear stresses on a section close to the impact point, but located on undamaged zone;
2. calculation of the total momentum applied to the target, equivalent to the impulse of the applied force.

The computation of force impulse by integration of stress along a cross section provides unreliable results due to complex superposition of stress states. This technique requires large computational time since large plate need to be simulated in order to avoid border reflections. On the other hand the momentum analysis allows determination of equivalent force impulse perfectly applicable to FEA simulation and allows fast simulations on small targets.

The momentum analysis on simple aluminum plates showed an agreement with FEA within in the

worst case 50%, but revealed a code unsteady behavior with Johnson-Cook model application; while analysis results on honeycomb panels agree with FEA within 5%. In conclusion SPH application showed to be reliable as impulse generator for FEA and SEA models for vibration propagation on large structure. Furthermore, momentum analysis revealed to be the faster method for the force impulse calculation showing a good agreement with experimental and FEA results.

## References

- [1] Anderson CE Jr. An overview of the theory of hydrocodes. *Int. J. Impact Engng.*, 1987; **5**: 35-59.
- [2] Johnson WE, Anderson CE Jr. History and application of hydrocodes in hypervelocity impact. *Int. J. Impact Engng.*, 1987; **5**: 423-439.
- [3] O'Donoghue PE, Bodner SR, Anderson CE Jr. Ravid, M. Comparison of a high velocity impact model with numerical simulation. *Int. J. Impact Engng.*, 1989; **8**: 289-301.
- [4] Monaghan JJ. Smoothed particle hydrodynamics. *Ann. Rev. Astron. Astrophys.*, 1992; **30**: 543-574.
- [5] Johnson GR, Stryk RA, Beissel SR. SPH for high velocity impact computations, *Computer Methods in applied mechanics and engineering*, 1996; **139**: 347-373.
- [6] Hayhurst CJ, Clegg RA. Cylindrically symmetric SPH simulations of hypervelocity impacts on thin plates. *Int. J. Impact Engng.*, 1997; **20**: 337-348.