Use of Prepreg Carbon and Aluminum in Satellite Shielding Submitted to High Velocity Impacts

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Abstract

A substantial number of debris coming from human production gravitates around the Earth. Their size, nature, orbit and velocity can extremely vary, but all these debris represent an increasing collision risk and a threat for the current and future spatial activity. The spatial researchers are looking for solutions to limit this risk, by better controlling the launched objects number and by improving the protection of their structures.

All those debris are classified depending on their size. The ReVuS European project showed that the most dangerous debris, according to the satellite mission failure probability, have a diameter included in the range 1mm to 5mm.

Following this reference, the aim of the ATIHS project, funded by French region Occitanie, is to improve the satellite protection from millimetric debris impacts. Multiple solutions exist in order to do so, ATIHS focuses on the shielding one. The project global aim consists in:

- *Improving the satellites resistance on strategic locations to prevent it from the mission failure,*
- *Working on the secondary debris generation limitation during a non-lethal impact in order to minimize the satellite contribution in the debris increasement.*

The project is composed of three main tasks:

- *Evaluating new material solutions showing an optimised mass/resistance combination,*
- *Evaluating new hypervelocity testing devices which should permit to go further than the currently available devices (goal: 8 to 12 km/s for millimetric to centimetric projectiles),*
- *Setting up numerical methodologies that should permit to increase the capacities and the hypervelocity computations reliability, by accurately modelling the materials behaviour during this kind of extreme solicitations.*

This article focuses on the hypervelocity impact response. It especially deals with the evaluation of new structures composed of carbon prepreg or/and zylon laminates to better protect the satellite equipment and there SPH modelling methodologies. As a first step, some tests have been performed on a unique sheet made of composite (carbon prepreg or zylon). Then, it is used to compose a mixed Whipple shield such as the assembly of two skins using various materials.

Introduction

Because of the surge in spatial debris numbers, satellite shields have to be adapted to resist increased impact risks. Many solutions exist to protect the satellite vital equipment, but the majority of them is too expensive or leads to a large mass increase. As part of the ATIHS project funded by the French Occitanie region, a combined solution is evaluated to protect specific areas of the shielding to prevent fatal impacts on vital equipment. The purpose is to evaluate some high modulus materials in alternative to aluminum under high velocity impacts, such as composite laminates with carbon or zylon fibers, and then to combine them to create a resistant Whipple Shield or sandwich structure. This Whipple structure is composed of a failure sheet, corresponding to the impacted one, and a containment sheet positioned between the failure sheet and the equipment. The aim of the failure sheet is to fragment the impacting debris, whereas the aim of the containment sheet is to resist (avoid failure) the impacts of the secondary debris coming from the cloud generated at the debris impact on the failure sheet.

The loadings those structures should endure without failure correspond to the impact of a debris specific lethal diameter range around one millimeter. The velocity of this kind of debris is equally important since a velocity higher than 8km/s leads to the partial or total vaporization of the debris at the impact on the failure sheet [1]. The containment by the second sheet is then easier than during an impact of a debris against the failure sheet at velocities around 4-6km/s where the debris is only fragmented.
The challenges this project faces are multiple:

- Evaluate the dynamic resistance of new orthotropic materials. To do so, their static and highly dynamic experimental characterizations are needed,
- Evaluate the behavior of each material subjected to high velocity impacts by performing numerical tests and experimental validations,
- Evaluate the behavior of various structures made of those new materials assemblies with or without aluminum by performing numerical tests and experimental validations. Compare it to the behavior of actual shields (aluminum Whipple shields) that also have to be studied numerically and experimentally at various impact velocities.

A first article [1] focused on the numerical methodologies and their robustness to model this kind of impacts on current shields. Using the conclusion of this preliminary study, the current article focuses on the materials' experimental characterization in the first paragraph. The second paragraph deals with the modelling of orthotropic materials under high velocity impact with SPH method and its correlation with experimental results. Finally, the last part recounts the advancements on the modelling of high velocity impacts on heterogeneous Whipple structures made of orthotropic materials assemblies.

1. Materials characterization under shock waves – experimental study

1.1. Material

This characterization has been conducted on composite M55J/RS3M prepreg of 0.25 mm thickness. The study of zylon fiber composite is in progress. Laminated plate of thickness around 0.5 mm [0/90] is available for the project.

1.2. Mechanical characterization

The objective of the material characterization is to determine the parameters for a Mie-Grüneisen Equation Of State (EOS) for the homogeneous composite. It should be noted from the beginning that it does not exactly correspond to the EOS any of the composite constitutive materials because the ratio of bulk modulus of the fiber and the matrix is in the order of magnitude of 100. The proper method should be to characterize individually each material and conduct the simulation by representing the fiber and matrix. However, this method would provide enough data for the modelling of the meso-scale behavior of the composite and reproduce the shock wave propagation inside the material.

1.3. Test configuration

A reverse plate configuration presented in Figure 1 is used: a projectile consisting of an anvil, an aluminum (Table 1) disc and the specimen is accelerated with laboratory Gas Gun. The projectile impacts an aluminum target of the same material.

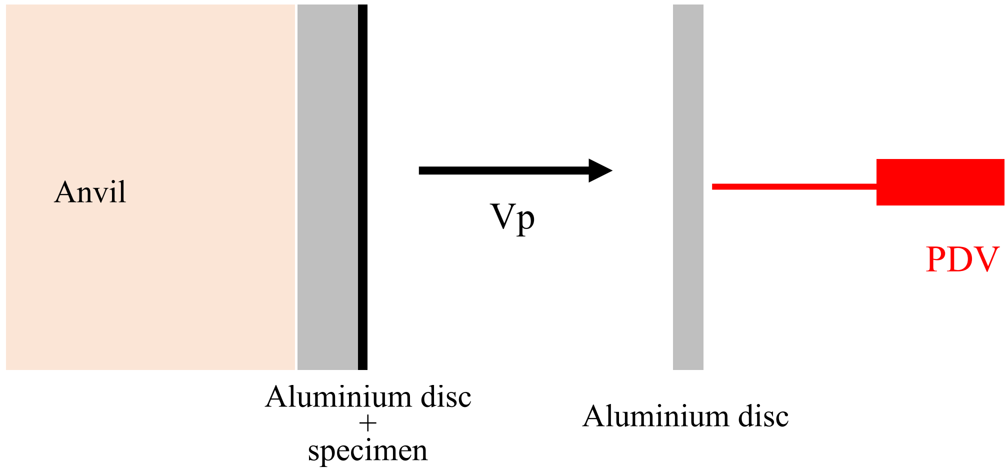


Figure 1 Reverse plate impact configuration

A Particle Displacement Velocimetry (PDV) is used to measure the material velocity at the free surface. For all tests, the impact face is normal to the third direction of the composite, therefore it is only the shock propagation in the o-o-p direction which is considered. The response in the fiber direction can be different due to the orthotropy of the material. The material orthotropic behavior leads to some difficulty in conducing this test; since wave propagates at a higher speed in the fiber direction, radial release waves rapidly reach the center of the specimen and effects the measurement.

		Alu 2024
Density (kg.m^{-3})	$\rho_{0\text{-al}}$	2700
Sound speed (m.s^{-1})	$C_{0\text{-al}}$	5330
Hugoniot coefficient (-)	S_{al}	1.34

Table 1 Aluminum discs' material properties

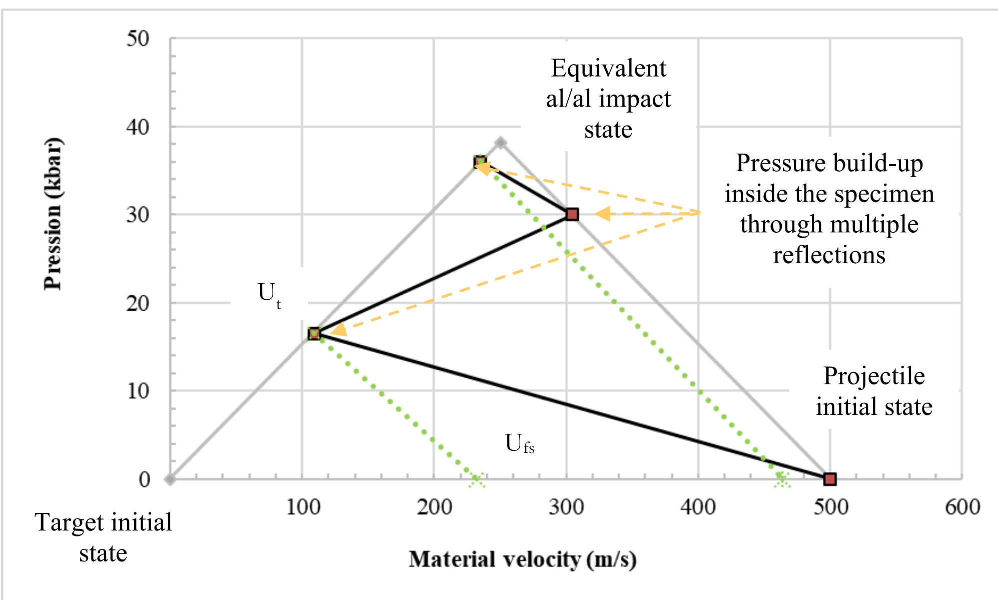


Figure 2 Representation of multiple shock wave reflections inside the specimen

The first shock wave is generated at the interface of the composite and the target aluminum. Then, multiple reflections of shock waves at the interface of specimen and the projectile aluminum results in pressure building inside the composite. This pressure will increase until the pressure of aluminum/aluminum impact is reached (Figure 2) or the release wave reaches the center of the specimen. Similar configurations have been used in the literature to characterize shock wave propagation inside composite laminate material [2], [3].

1.4. Test results and analysis

	Projectile			Target	
Tests	*Material*	*Thickness (mm)*	*Impact Velocity (m/s)*	*Material*	*Thickness (mm)*
TI1705	Al 2024 + M55J/RS3M	5.01 + 0.52	194.4	Al 2024	2.53
TI1706	Al 2024 + M55J/RS3M	4.97 + 0.52	382.6	Al 2024	2.61
TI1707	Al 2024 + M55J/RS3M	5.07 + 0.53	610.0	Al 2024	2.52
TI1708	Al 2024 + M55J/RS3M	5.04 + 0.53	838.0	Al 2024	2.63

Table 2 Tests results for material characterization

Figure 3 shows the profile of free surface velocities of the aluminum target of each test.

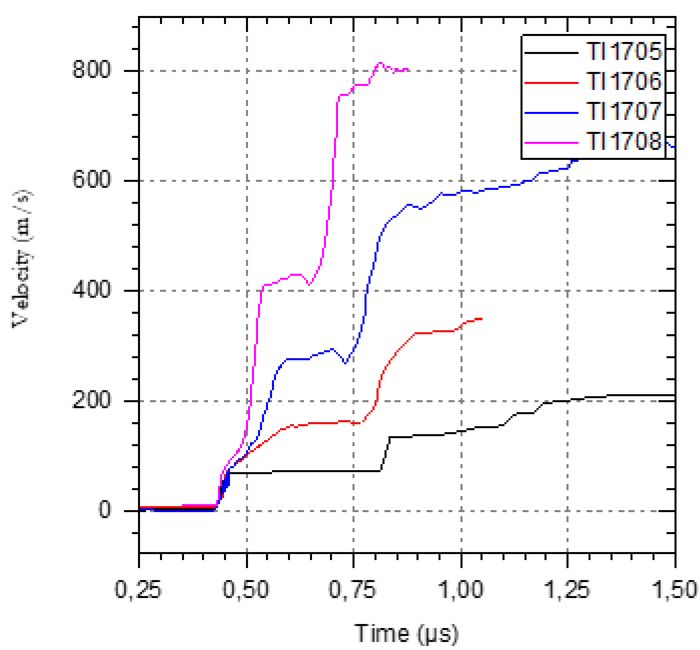


Figure 3 Aluminum target free surface velocity profile

Material velocity and pressure inside the composite are computed using the following equations:

$$P_{comp} = P_t = \rho_{0-al}\ D_t\ U_t$$

$$U_t = \frac{U_{fs}}{2}$$

Where P_x is the pressure, D_x the shock wave speed and U_x is the material velocity. Regarding the subscripts, "comp" is for composite laminate, "t" represents the target and "fs" is the aluminum target free surface. The data gathered and computed from the tests are summarized in Table 3. In this table, the free surface velocity is relative to the first plateau value identified ono the velocity profile in Figure 3.

Tests	**V_p** *(m/s)*	**U_{fs}** *(m/s)*	**U_t** *(m/s)*	**P** *(MPa)*	**u_{comp}** *(m/s)*	**D_{comp}** *(m/s)*
TI1705	194.4	70.9	35.5	514.5	159	2071
TI1706	382.6	160.8	80.4	1179.5	302.2	2497
TI1707	610	281	140.5	2092	469.5	2851
TI1708	838	415	207.5	3141	630.5	3187

Table 3 Data computed from tests

The Mie-Grüneisen EOS parameters for this material are computed using a least mean square method to fit the evolution of D in function of U. The values are given in
Table 4:

Sound speed ($m.s^{-1}$)	$C_{0\text{-}comp}$	1740
Hugoniot coefficient (-)	s_{comp}	2.33

Table 4 Mie-Grüneisen parameters for composite M55J/RS3M laminate

2. Hypervelocity impact study – experimental tests and modelling

As mentioned in previous paragraphs, one of the tested materials is prepreg carbon. One of the aims of the project is to evaluate the structural strength of new orthotropic materials under a large range of high velocity impacts. Some experimental tests were made and constitute the numerical model references.

2.1. Experimental setup

Hypervelocity impacts were performed on HERMES two-stage light-gas gun. The configuration of the target is presented in Figure 4 and is composed of (from impact to back sides):

- failure sheet,
- stand-off distance "s" around 25 mm,
- containment sheet,
- aluminum witness plate to evaluate the debris spreading in case of perforation of the containment sheet.

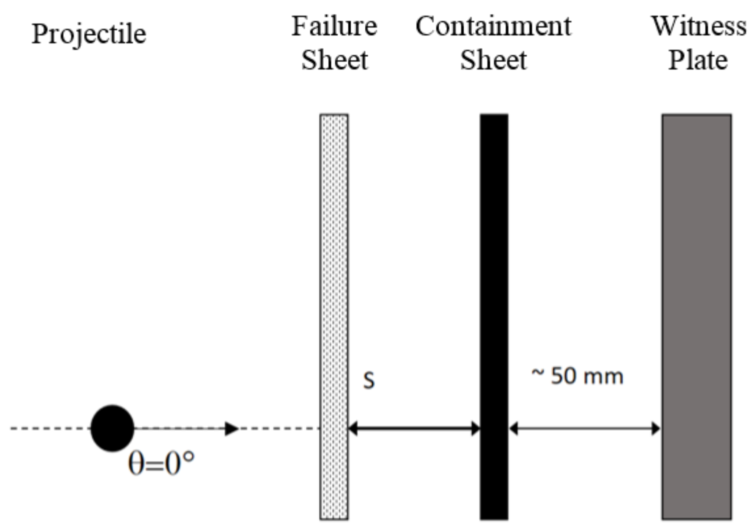


Figure 4. Initial configuration of the target

All three plates have a dimension of 15 x 15 cm² and are maintained together as illustrated Figure 5. A high-speed camera is used to record the impact of target using shadow photography with a laser driven light source. Projectiles are 1 mm diameter aluminum 2017 sphere. The impact velocity is measured with laser barriers and the high-speed camera images. The tests are conducted inside a chamber where a partial vacuum is achieved (below 500 mbar).

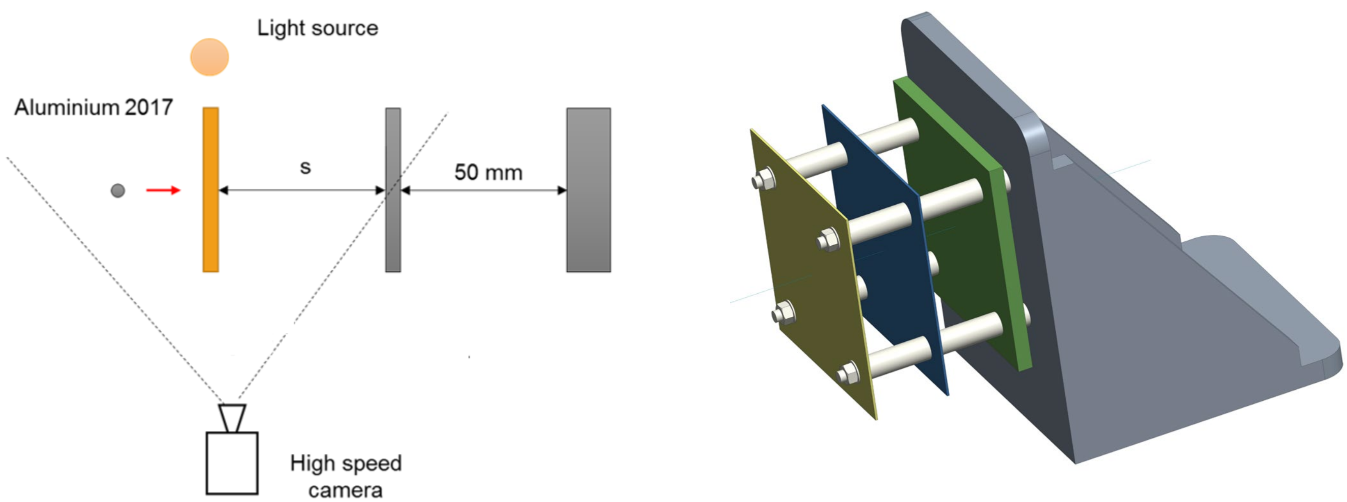


Figure 5. Experimental setup

2.2. Hypervelocity impact modelling of a laminated composite

The main numerical issue is to properly model large deformations and volumetric behavior due to high velocity impact in orthotropic material.

To do so, the SPH method was chosen because of its ability to model large deformations as mentioned in [1], and the *MAT_COMPOSITE_FAILURE (059) combined to a Mie-Gruneisen equation of state (EOS) was used. The deviatoric characteristics of prepreg carbon and the failure criteria used in this study are taken from [4] and are listed below:

Density (g/cm^3)	E_a (Mbar)	E_b (Mbar)	E_c (Mbar)	ν_{ba}	ν_{ca}	ν_{cb}	G_{ab} (Mbar)	G_{bc} (Mbar)	G_{ca} (Mbar)
1.562	1.5	0.082	0.082	0.0186	0.0186	0.53	0.0434	0.027	0.0434

S_{ba} (Mbar)	S_{ca} (Mbar)	S_{cb} (Mbar)	XX_t (Mbar)	YY_t (Mbar)	ZZ_t (Mbar)
0.0014	0.0014	0.00112	0.0276	$6.37e^{-4}$	$6.37e^{-4}$

Table 5 Deviatoric data used for prepreg carbon composite

As shown in the table above, no compression failure criteria have been used in the model, because the failure in pure compression on the material without previous damage is not expected in this kind of study. Using compression failure criteria as expected by the code should lead to premature material failure.
The volumetric characteristics used for the EOS are those determined experimentally thanks to the procedure described in §1.

High velocity impacts on prepreg carbon at velocities higher than 4km/s lead to partial or total vaporization of the resin (Figure 8). Which means that the behavior of the prepreg carbon can be described by two parts: the carbon fibers immerged in the resin on one side, and the resin, especially the layers between fiber plies on the other side. For this reason, two models have been established and will be compared to an experimental reference:

- The first one corresponds to 4 plies with similar properties oriented at $[0, 90]_s$,
- The second one corresponds to the previous one except that an intermediate thin resin layer is modelled between each ply. In order to ensure computation stability and physical coherence because of the reduced section of resin between plies, the same density and volumetric behavior as prepreg carbon ones are applied to those intermediate layers. However, the deviatoric part is modelled with the *MAT_ELASTIC_PLASTIC_HYDRO (010) law with the following parameters:

Shear modulus (Mbar)	Yield stress (Mbar)	Tangent modulus (Mbar)
0.174	2.33	0.78

Table 6 Deviatoric data used for expoy resin

Using MAT_10 with a tangent modulus is not the most accurate choice, but it enables to simply model intermediate resin layers before having better experimental resin characterization data.
The figure below illustrates both quarter models:

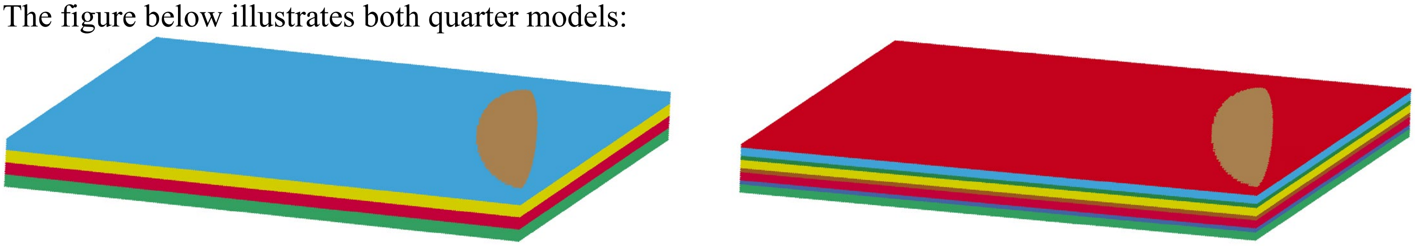


Figure 6 Models of prepreg carbon composite: four homogeneous plies in the plate (left) and modelling of resin intermediate layers (right)

The plate thickness is 0.5mm represented by 24 particles. Both plate models count the same particle number. The sphere is in aluminum, its diameter is 1mm and its initial velocity is 4.535km/s.
Measures made on the model are compared to the experimental observations at 4.5µs on:

- The debris cloud length,
- The debris velocity at the cloud front,

- The debris velocity in front of the sheet,
- The cloud maximal diameter,
- The crater diameter in the plate.

The figure below illustrates the various measures listed above and the Table 7 summarizes the experimental data extracted from the tests:

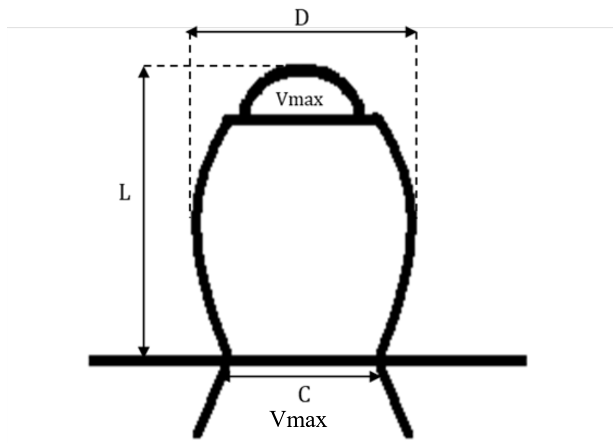


Figure 7: Illustration of the profile measurments

The measured results are listed in the following table:

	Debris velocity sheet front (m/s)	Debris velocity cloud (m/s)	Crater diameter (cm)	Cloud diameter (cm)	Cloud length (cm)
Experimental	3700	[1500, 2000]	0.29±0.06	1.18±0.06	1.6±0.06
Numerical	[170, 3100]	[2080, 3830]	0.48	1.1	1.58
			$e_{measure}$=-66% e∈[-108%, -37%]	$e_{measure}$=6.8% e∈[2%, 11%]	$e_{mesaure}$=1.3% e∈[-2.6%, 5%]
Numerical with resin layers	[3200-4200]	[810, 2250]	0.36	1.04	1.58
			$e_{measure}$=-24% e∈[-56%, -3%]	$e_{measure}$=11.9% e∈[7%, 16%]	$e_{mesaure}$=1.3% e∈[-2.6%, 5%]

Table 7 Comparison between experimental and numerical measures on the prepreg carbon composite impacted at ~4km/s

The experimental measurements are performed on the high-speed camera videos, so the available data are not sufficient to strictly conclude on the model accuracy. However, the collected results shown above demonstrate a relatively accurate agreement between experience and simulation, considering the experimental measurements accuracy. However, the model without resin intermediate layers does not correctly reproduce velocities. Indeed, this model results show high particle dispersion which skews the numerical velocity measurements.
Moreover, the cloud and back stream debris shapes are properly reproduced by the numerical model (see picture below):

- The ejected debris in front of the sheet show the same line inflections,
- The cloud shows an oval global shape with flat front.

However, the material behavior at the cloud front is not correctly represented. Indeed, the lighter-shaded area that can be observed resembles a material phase change. It probably means that the resin or aluminum changes phase, which can not be represented with a Mie-Gruneisen EOS. Current work is done on the development of an EOS that should be able to take into account this kind of behavior.
As the model with 4 plies without intermediate resin layers is not stable enough and gives unrealistic velocities, the accurate model with the resin layers between plies is chosen as the reference one. Moreover, this model will be more adapted to future works with the integration of potential resin vaporization.

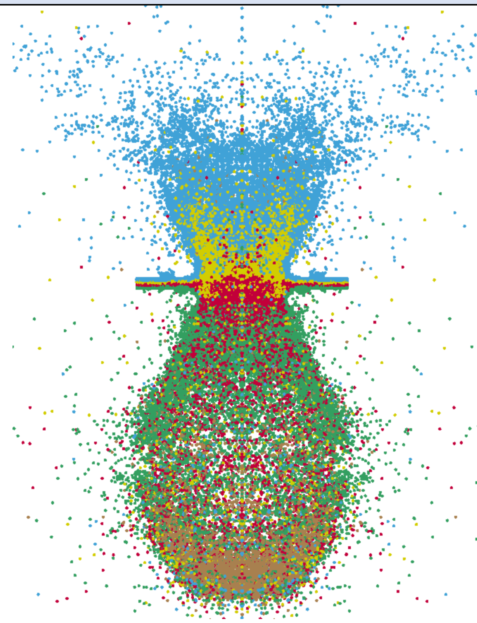
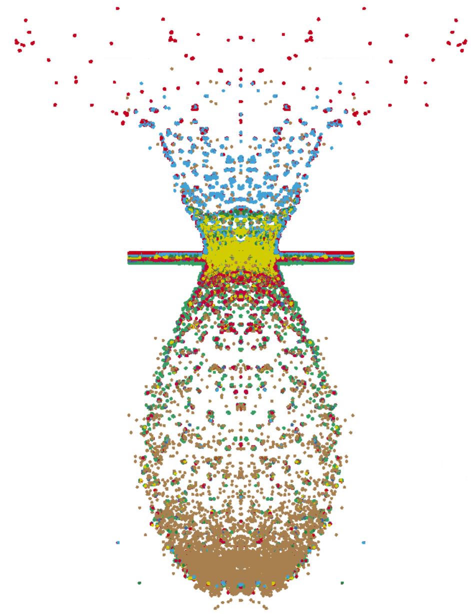
Experimental	Numerical with 4 layers	Numerical with 4 layers and intermdiate resin layers
		

Figure 8 Picture of the impact result on the experimental plate (left), on the 4 homogeneous plies model (middle) and on the resin intermediate layer modelling model (right) taken at the same time

2.3. Aluminum VS orthotropic materials

In order to improve understanding of the specificities of prepreg carbon and zylon fabric behaviors under high velocity impact compared to aluminum, some experimental tests were done on aluminum sheets, prepreg carbon composite and prepreg zylon fabric at similar velocities. Figure 9 illustrates the comparison between the impact on an aluminum sheet (left), a prepreg carbon composite one (middle) and a prepreg zylon fabric one (right) by an aluminum sphere of 1mm diameter. The sheets thicknesses are 0.5mm each and the pictures scales are approximately the same for an easier qualitative comparison.

The table below summarizes the measures performed on each material:

	Debris velocity sheet front (m/s)	Debris velocity cloud (m/s)	Crater diameter (cm)	Cloud diameter (cm)	Cloud length (cm)
Aluminum	[2000, 2700]	5000	0.83±0.06	2.0±0.06	3.1±0.06
Prepreg carbon composite	[900, 1600]	4700	0.23±0.06	2.4±0.06	3.1±0.06
Prepreg zylon fabric	[1200, 1500]	3900	0.47±0.06	1.6±0.06	2.2±0.06

Table 8 Comparison between experimental meaures on the aluminum, prepreg carbon composite and prepreg zylon fabric impacted at ~6km/s

The pictures and the measurements show large differences between the three material behaviors. The pictures show that the cloud length is nearly the same for aluminum and carbon sheets, which is validated by the measurement. The zylon fabric nonetheless shows a reduced cloud length. Those differences in the measures probably come from different measurement timings, since the pictures are not extracted exactly at the same time.

However, the carbon composite shows a larger lighter-shaded area, which is in accordance with the hypothesis that this bright area corresponds to sublimation, since the resin vaporization point is at lower pressure/temperature state than the aluminum one. The zylon case shows a brightening ranging between the aluminum case and the carbon composite one. One of the plausible explanations to this observation could be that the prepreg zylon fabric contains less resin than the prepreg carbon composite since the zylon yarns are thicker than carbon fibers. This hypothesis has to be verified.
The crater is only two times the impactor diameter in the carbon composite sheet but the cloud is five times more flared than in the aluminum case, whereas the crater in the aluminum sheet is nine times the impactor initial diameter. The prepreg zylon fabric crater is five times the impactor initial diameter, and the cloud shape is 1.6 times more flared than the aluminum one.
Then, the cloud velocity corresponds to the impactor velocity reduction of around 8% in the aluminum case, against 16% in the carbon case and 21% in the zylon case.

Finally, the carbon composite and the zylon fabric do not show large debris in the cloud, on the contrary to aluminum. This aspect added to the bigger sublimated area and reduced cloud velocities are really encouraging for both new materials study in the failure sheet.

Aluminum sheet – 5440m/s t=6.31µs	Prepreg carbon composite – 5609m/s t=5.68µs	Zylon fabric – 4932m/s t=5.11µs

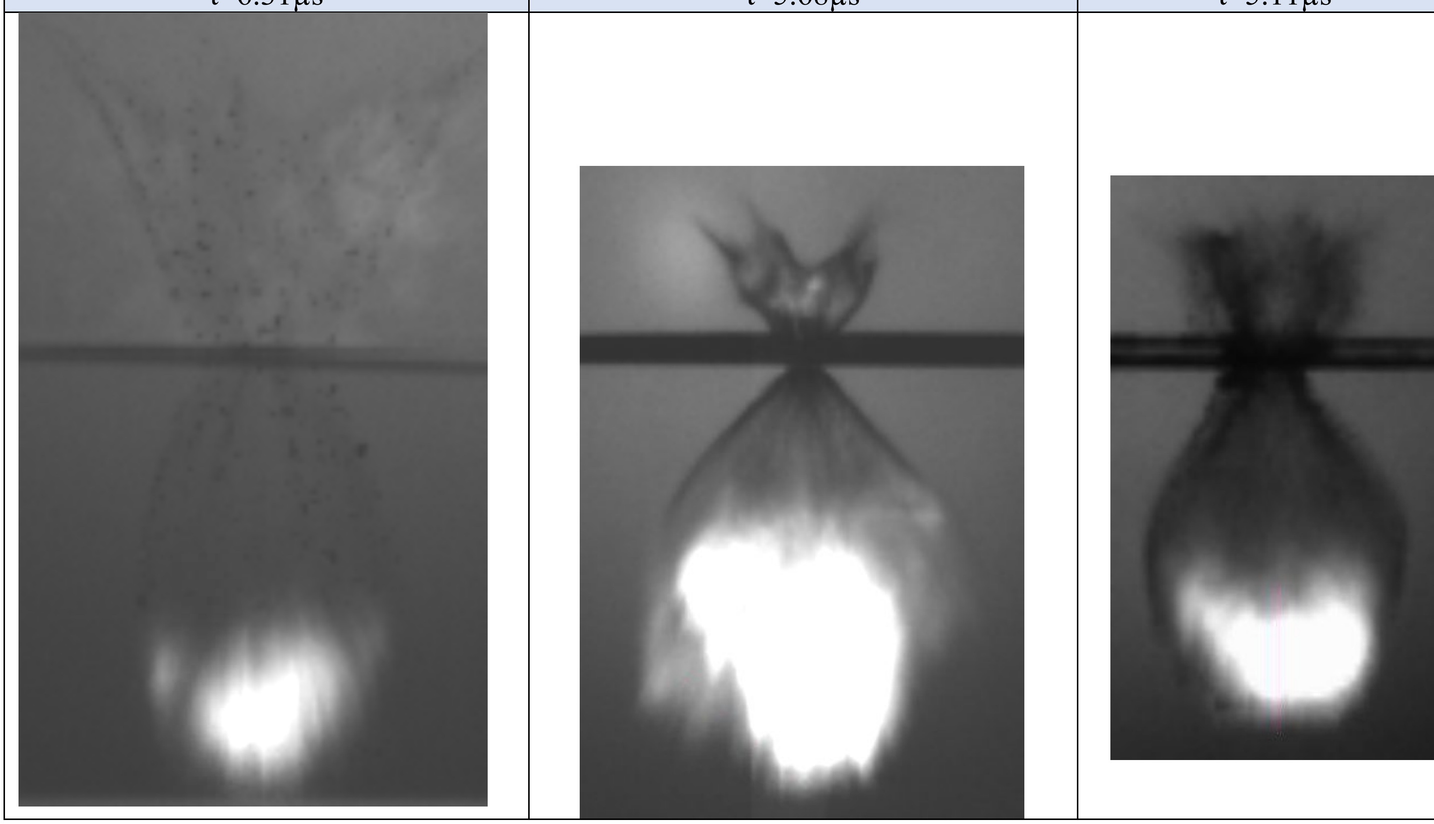


Figure 9 Qualitattive behaviour comparison between experimental aluminum, prepreg carbon and zylon fabric under HVI at ~6km/s

The following pictures illustrate numerical results obtained in those three configurations. Since the material data for zylon fabric were not available for the present article, computations were performed with Kevlar data, which seems to have quite similar fiber behavior to zylon. This aspect will be improved in future work when the zylon experimental static characterization will be achieved.

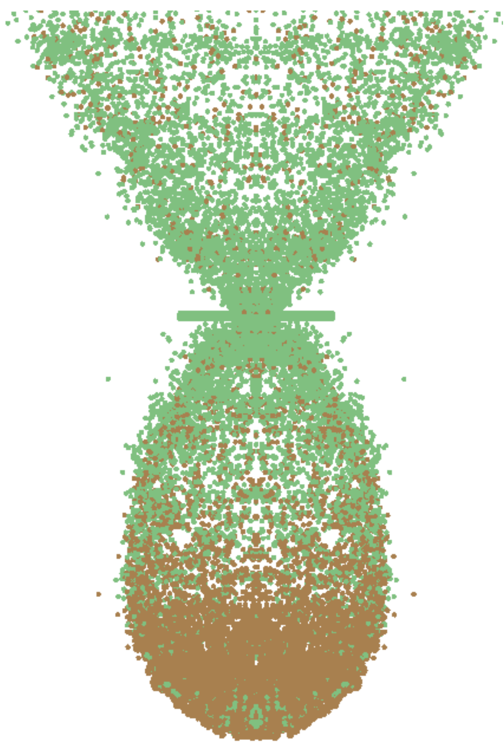
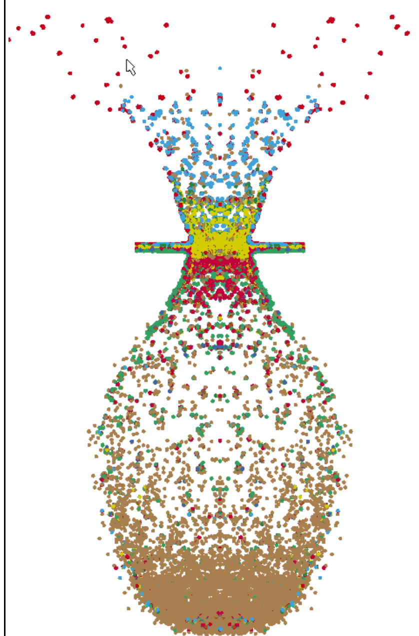
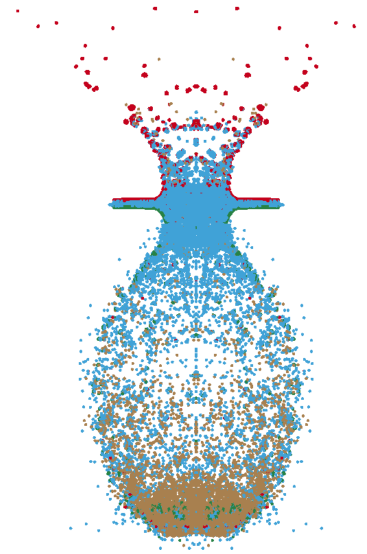
Aluminum sheet – 5440m/s t=6.31µs	Prepreg carbon composite – 5609m/s t=5.5µs	Zylon fabric – 4932m/s t=5.11µs
		

Figure 10 Qualitative behaviour comparison between numerical aluminum, prepreg carbon and zylon fabric under HVI at ~6km/s

The table below summarizes the measures performed on those results:

	Debris velocity sheet front (m/s)	Debris velocity cloud (m/s)	Crater diameter (cm)	Cloud diameter (cm)	Cloud length (cm)
Aluminum	[2600, 3700]	4300	0.31	1.9	3.0
			$e_{measure}=62\%$ $e \in [60\%, 65\%]$	$e_{measure}=5\%$ $e \in [2\%, 8\%]$	$e_{measure}=3\%$ $e \in [1\%, 5\%]$
Prepreg carbon composite	[1300, 2100]	[4200, 5300]	0.29	1.6	2.5
			$e_{measure}=-26\%$ $e \in [-71\%, 0\%]$	$e_{measure}=33\%$ $e \in [31\%, 35\%]$	$e_{measure}=19\%$ $e \in [18\%, 21\%]$
Prepreg zylon fabric	[900, 1300]	[3800, 4500]	0.33	1.3	2.0
			$e_{measure}=30\%$ $e \in [20\%, 38\%]$	$e_{measure}=19\%$ $e \in [16\%, 22\%]$	$e_{measure}=9\%$ $e \in [7\%, 12\%]$

Table 9 Comparison between numerical meaures on the aluminum, prepreg carbon composite and prepreg zylon fabric impacted at ~6km/s

First of all, the numerical cloud shape differences between aluminum and orthotropic materials are well represented, compared to the ones observed on the experimental pictures. Thus, the numerical models established during this project are then able to reproduce the principal shape characteristics of the clouds for isotropic materials and orthotropic ones subjected to high strain rates.

The aluminum simulation gives good agreement with experimental measures regarding cloud diameter, cloud length and debris velocities. However, the numerical model does not correctly reproduce the crater diameter.

The hypothesis is that the material behavior laws used in this model are not able to represent phase changes. At ~6km/s, aluminum begins to melt, which should explain the larger crater measured experimentally than the one reproduced numerically. In future works, phase changes should be taken into account using a user defined EOS. This hypothesis will then be evaluated.
Laminated carbon composite numerical model shows a worse correlation with experimental results than in the study performed in section 2.1. This could be explained by the same hypothesis as the one exposed for aluminum differences. The phenomenon in the prepreg carbon composite is exacerbated, since resin properties are weaker than aluminum ones, which leads to earlier phase changes (visible thanks to the illuminated area).
Prepreg zylon fabric shows a qualitative acceptable correlation with the experimental results: the shape seems to globally be reproduced but the quantitative measures are perfectible, since the zylon deviatoric characteristics are approximated by Kevlar ones in this study. The same discrepancy as for the carbon model on crater diameter appears, which suggests once again that the resin phase change hypothesis in this region is true. This aspect will be studied with a user EOS in future works.

This section dealt with the characterization of new orthotropic materials, the comparison of their behavior with classical aluminum under high velocity impact and the models' ability to reproduce those specific behaviors. It appears that the numerical simulations give reasonably good and reliable results even for orthotropic materials under impacts of ~4km/s. At impact velocities higher than 5km/s, it appears that melting and vaporization have to be taken into account in the model to improve the correlation with experiments.
Some tests on a Whipple configuration have been performed with various materials in both sheets. The following section deals with this study, which aim is to evaluate the ability of orthotropic materials to prevent the failure of the containment sheet.

3. Correlation between experimental tests and computations on a Whipple structure

3.1. Experimental tests

The heterogeneous Whipple configurations made of two plates of different constitutive materials are currently in process. In order to evaluate the most interesting configuration in terms of equipment protection, a first study is performed on the failure plate ability to slow down the impactor velocity before the debris cloud impact on the containment plate.
The table below shows the cloud debris velocities experimentally measured on a unique sheet at various impact velocities (impactor diameter 1mm).

Case		Alu	Carbon	Zylon
4-5.5km/s	Cloud velocity (m/s)	3000 (Impact velocity ~4.0km/s)	4500 (Impact velocity ~5.4km/s)	3900 (Impact velocity ~4.9km/s)
	% of initial velocity	~73%	~80%	~80%
6km/s	Cloud velocity (m/s)	3700 (Impact velocity ~5.8km/s)	4000 (Impact velocity ~5.9km/s)	5100 (Impact velocity ~5.8km/s)
	% of initial velocity	~63%	~68%	~87%

Table 10 Experimental results of 4-6km/s impact on various constitutive materials

Considering the cloud velocity before the secondary impact, it appears that the material that leads to the most reduced cloud velocity remains aluminum.

Another important information concerns the debris sizes and their ability to perforate the containment sheet. This information is quite hard to obtain experimentally, and some tests are performed to get those debris back after a test. Numerical post-processing should be an easier way to obtain this information. A post-processing program is currently in validation to evaluate the size of the debris in the cloud, their velocity and their distribution.

3.2. Numerical correlations

In order to perform fewer experimental tests and to be able to accurately predict experimental behaviors, some numerical models have been realized. The following two cases are presented here:

- Carbon (failure plate) →Alu (containment plate) at 4km/s,
- Alu (failure plate) →Zylon (containment plate) at 6km/s.

Both cases are presented in the sections below.

3.3. Carbon/Aluminum – impact velocity ~4km/s

The computation characteristics and associated cloud velocities are given in the table below:

Total number of particles (1/4 model)	Computation duration (28MPP CPU)	Cloud velocity (m/s)
6 759 558	278 hours to reach 11µs	[2000, 4600]

Table 11 Computation characteristics

The computation duration on 28 MPP processors is extremely binding. Some solutions that should enable more flexible computations like full restarts, dynamic load balancing or homogeneised pressure are currently studied. The cloud velocity range measured here is reasonnably the same order as the one measured experimentally. Both figures below illustrate the containment sheet failure profiles (lateral section and rear view).

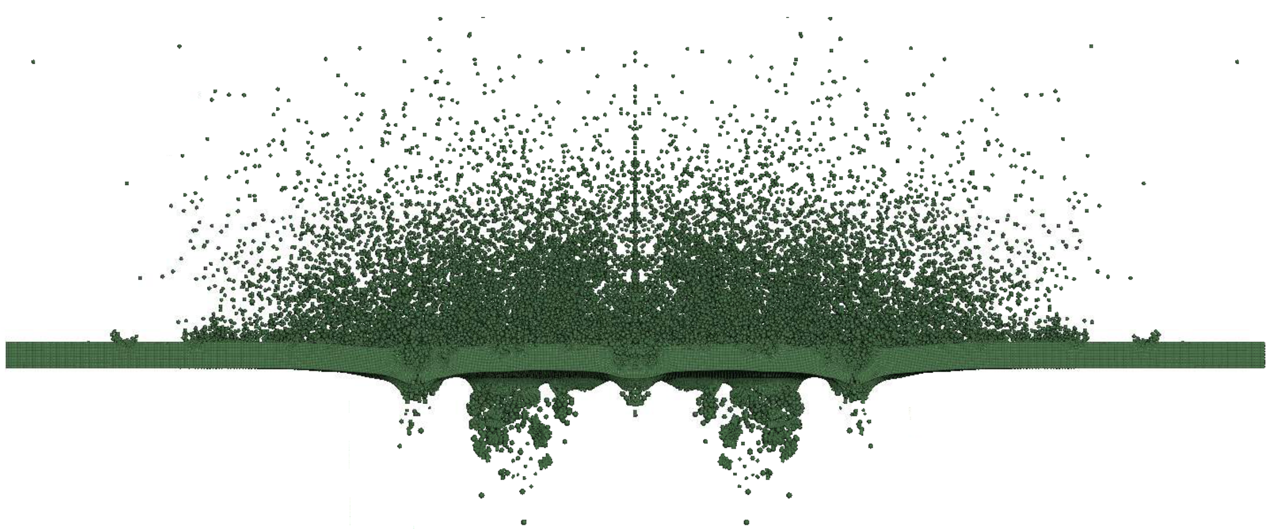


Figure 11 Sheet profile with post-processing reflection (lateral section)

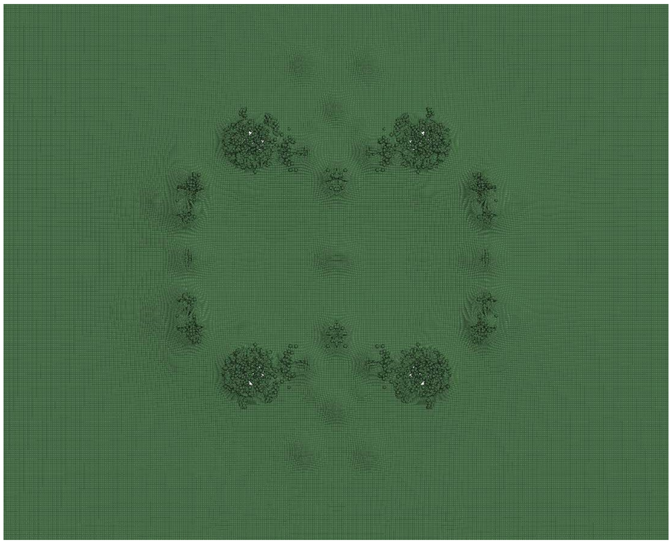


Figure 12 Sheet profile with post-processing reflections (rear view)

The failure of the containment plate was expected here since the projectile velocity is not enough to lead to a sufficient impactor fragmentation. The sheet rear face failure profile shows a cloud circle imprint. This phenomenon has to be validated with future experimental results.

3.3.1. Aluminum/Zylon – impact velocity ~6km/s

The computation characteristics and associated cloud velocities are given in the table below:

Total number of particles (1/4 model)	Computation duration (28MPP CPU)	Cloud velocity (m/s)
7 469 038	94 hours to reach 8.3µs	[4300, 4800]

Table 12 Computation characteristics

The computation duration on 28 MPP processors is extremely binding in this case too. Some solutions that should enable more flexible computations like full restarts, dynamic load balancing or homogeneised pressure are currently studied.
The cloud velocity range measured here is quite higher than the cloud velocity measured experimentally. First, the experimental measures are not as accurate as the numerical ones since the measure is performed manually by the user on high-speed videos with finite precisions. Then, it is possible that phase change influences the debris velocity. This hypothesis will be studied further during the project.

Both figures below illustrate the containment sheet failure profiles (lateral section and rear view).

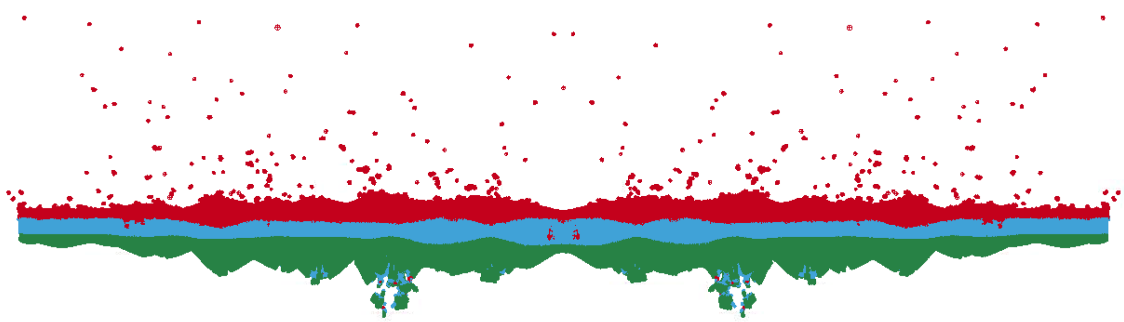


Figure 13 Sheet profile with post-processing reflection (lateral section)

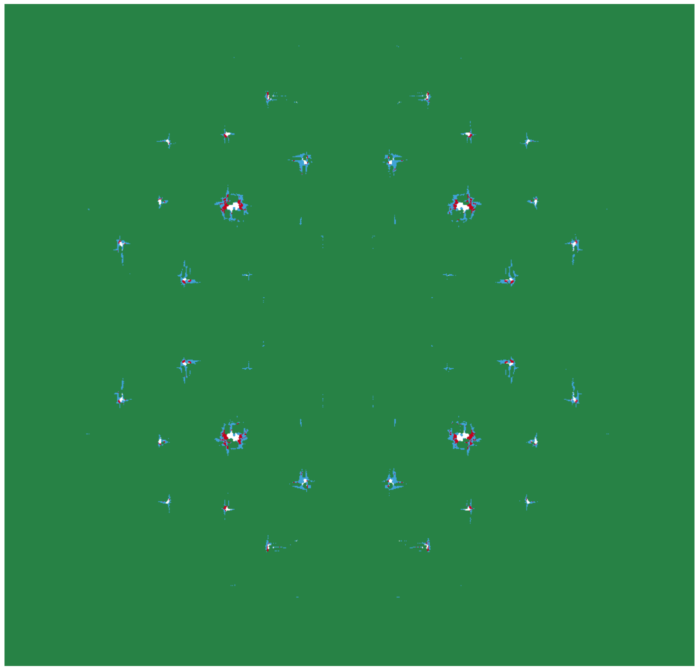


Figure 14 Sheet profile with post-processing reflections (rear view)

Zylon fibers are extremely high modulus ones. Subject to this kind of fragment sizes and velocities, a better behavior avoiding failure was expected. As a reminder, the zylon prepreg fabric deviatoric data have not been characterized yet, so the material data used in this simulation are kevlar's one, which has not as high modulus fibers as zylon. The conclusion is not obvious on this material interest in the containment plate.
A new computation will be launched with more adapted characteristics in further works, and a comparison with experimental tests will enable to conclude on the real material ability to contain this kind of debris cloud and on the model reliability.

Conclusion

This confrontation between experimental and numerical studies significantly enables to progress in the study of new materials application in satellite shielding. Indeed, the experimental characterization results provided reliable material data that have been used in the numerical models to better take into account the volumetric material behavior.
Some experimental tests have been realized at impact velocities of range [~4km/s, ~6km/s] and enable to validate the hypothesis that the most critical damage on the containment plate are caused by impacts that do not lead to a sufficient impactor fragmentation. Two orthotropic materials were tested in failure plate first, and it globally appears that the better solution should come from an aluminum failure plate, which slows down the debris cloud. However, this kind of configuration is not perfect since the aluminum seems to lead to less fragmentation of the impactor than other failure plate materials. Some post-processing is currently performed in order to evaluate the debris sizes, velocities and repartitions in the cloud with the purpose to numerically evaluate the advantages of each failure plate material.

In order to save cost and time, the objective is mostly to perform tests numerically. This is why important research is performed to make simulations more and more robust and reliable. The results obtained numerically are encouraging since the models with fewest phase changes shows errors of 24% on measurements compared to the experimental results. This error seems to be unacceptable, but the information has to be balanced by the experimental measurement error. Those latter can be important regarding the measurement method and the camera orientation. Regarding the numerical results obtained at higher velocities, the error grows up since the models are currently not able to take phase changes and material failure direction dependencies into account.
Knowing this, the aim of future work is to create some user material and equation of state to avoid those approximations. After performing experimental reference tests in Whipple configuration in succeeding in bringing all this reliability, the model should be able to accurately reproduce the materials behavior under a large range of impact velocities and impactor size. A satellite equipment protection should then be easier to find, provided that solutions have to be found to reduce computation times like full restart, with the support of experiments.

Acknowledgments

The authors would like to thank all the partners of the ATIHS research project and region Occitanie for funding.

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