# Characterization of fragments induced by High Velocity Impacts and additional Satellite shielding protective structures evaluation

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## 1 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 optimized 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 computation's 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 to better protect the satellite equipment and there SPH modelling methodologies. A method has also been developed in order to evaluate the size and density of the fragments ejected from a first impact. The results, as a function of impact velocity and sheet material, will be presented.

## 2 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 and prevent fatal impacts on vital equipment. The purpose is, on one hand to assess some alternative structures and on the other hand high modulus materials in alternative to aluminium under high velocity impacts, such as composite laminates with carbon or zylon fibres, and finally combine them to create a resistant and innovative Whipple shield or sandwich structure. The Whipple structure is composed of a failure sheet, on the impact side, and a containment sheet positioned between the failure sheet and the equipment. The failure sheet is positioned at 25mm from the containment one and is parallel to it. The aim of the failure sheet is to fragment the impacting debris, whereas the aim of the containment sheet is to resist the collisions of the secondary debris cloud coming from the first sheet impact.
Another classical shield structure used on satellites is composed of the same two sheets as the Whipple one and integrates a honeycomb structure between them which cells are perpendicular to the external sheets. Such honeycomb has been added to the initial Whipple for global structure stiffness reasons, and is called "sandwich shield" in further sections of this paper.
The loadings those structures have to endure without failure correspond to the impact of a specific lethal debris which diameter range is around one millimetre. 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 for an impact 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 behaviour of each material subjected to high velocity impacts by performing numerical tests and experimental validations,
- Evaluate the behaviour of various structures, potentially made of those new materials assemblies with or without aluminium by performing numerical tests and experimental validations. Compare them to the behaviour of actual shields (aluminium 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. A second one [2] dealt with the new materials high velocity characterization and their modelling when subjected to high velocity impacts. Using the conclusions of both preliminary studies, the current article focuses on the progress on the modelling of high velocity impacts on alternative structures such as heterogeneous Whipple structures and modified sandwich shields.

# 3 Heterogeneous Whipple structures

## 3.1 Experimental tests

Four tests were made by Thiot Ingénierie on Whipple structures with an impactor of 1mm diameter at ~4km/s. The main observation is made whether or not the containment plate failed after impact. The listing of the 4 tests and the principal results are given in the table below with the failure surfaces pictures:

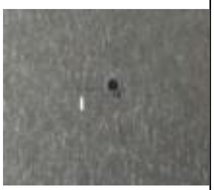
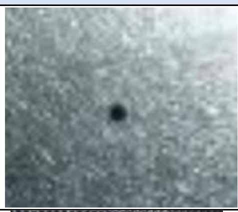
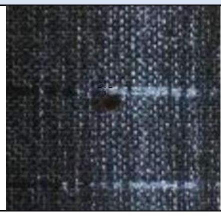
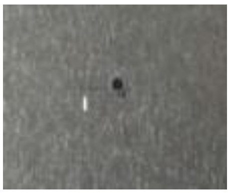
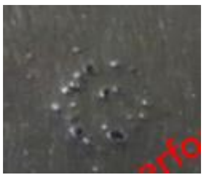
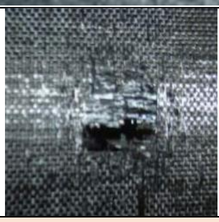
| Case | Alu→Alu 3.9km/s | Alu→Carbon 3.9km/s | Carbon→Alu 3.9km/s | Alu→Zylon 4.0km/s |
|---|---|---|---|---|
| Failure plate after impact – zoom on the impacted area |  |  |  |  |
| Containment plate after impact – zoom on the impacted area |  |  |  |  |
| Containment plate state | Failure | Failure | Failure | No failure – resin spalling at rear face |

*Table 1: Impact results on heterogeneous Whipple shields*

The following table sums up the results obtained by Thiot Ingénierie for two categories of impactor velocity on various heterogeneous structures.

| Case | | Alu →Alu | Alu →Carbon | Carbon →Alu | Alu →Zylon | Zylon →Alu |
|---|---|---|---|---|---|---|
| 4-5.5km/s | Result | Failure | Failure | Failure | No failure, resin spalling | |
| | Cloud velocity (m/s) | 2700 (Impact velocity ~3.9km/s) | 3000 (Impact velocity ~3.9km/s) | 4500 (Impact velocity ~5.4km/s) | 3000 (Impact velocity ~4.0km/s) | |
| | % of initial velocity | ~68% | ~77% | ~80% | ~73% | |
| 6-8km/s | Result | No failure | Failure | Failure | No failure, resin spalling | Failure |
| | Cloud velocity (m/s) | 5800 (Impact velocity ~7.8km/s) | 6700 (Impact velocity ~7.5km/s) | 4000 (Impact velocity ~5.9km/s) | 3700 (Impact velocity ~5.8km/s) | 5100 (Impact velocity ~5.8km/s) |
| | % of initial velocity | ~75% | ~75% | ~68% | ~63% | ~87% |

*Table 2: Experimental results of the ~4km/s and ~6km/s impacts on heterogeneous Whipple structures*

First, the complete aluminium structure seems to resist to an impact at 7.8km/s since the containment plate does not fail under the impacts of generated debris. This behaviour is linked to the impactor high velocity which engenders the interface material sublimation when contacting the first plate. The generated debris are then smaller and lighter than the ones generated at lower impact velocities
Then, all the configurations lead to the failure of the containment sheet except the Aluminium/aluminium (~6km/s) and Aluminium/Zylon (~4km/s & ~6km/s) one. According to [2] the failure of the three first structures subjected to a ~4km/s impact is mainly due to the impactor velocity which is not sufficient to cause its high fragmentation. The generated debris are then too heavy and fast for the containment sheet which cannot resist to all of them.
Moreover, those debris seem to be lethal in both velocity cases for the carbon containment plate which leads to the conclusion that the carbon sheet is not able to resist such impacts.
The zylon prepreg fabric is the only one that succeeded in resisting impact velocities. However, it shows resin spalling and ejecta from the containment sheet rear face, that could be damageable for the satellite equipment located behind. If the problem comes from the resin, a solution to be tested could be to stretch the zylon fabric without resin. This solution should be tested in further experimental tests.
Considering the cloud velocity before the secondary impact, it appears that the material that leads to the most reduced cloud velocity remains aluminium.

## 3.2 Numerical correlations

The numerical result obtained for the following configurations have already been published in [2]:
- Carbon →Alu at 4km/s,
- Alu →Zylon at 6km/s.

Their comparison with the previous experimental results is presented below.

### *3.2.1 Carbon/Aluminium – impact velocity ~4km/s*

The cloud velocity range measured here is reasonnably of the same order as the one measured experimentally.
Both figures below illustrate the containment sheet failure profiles (rear view).

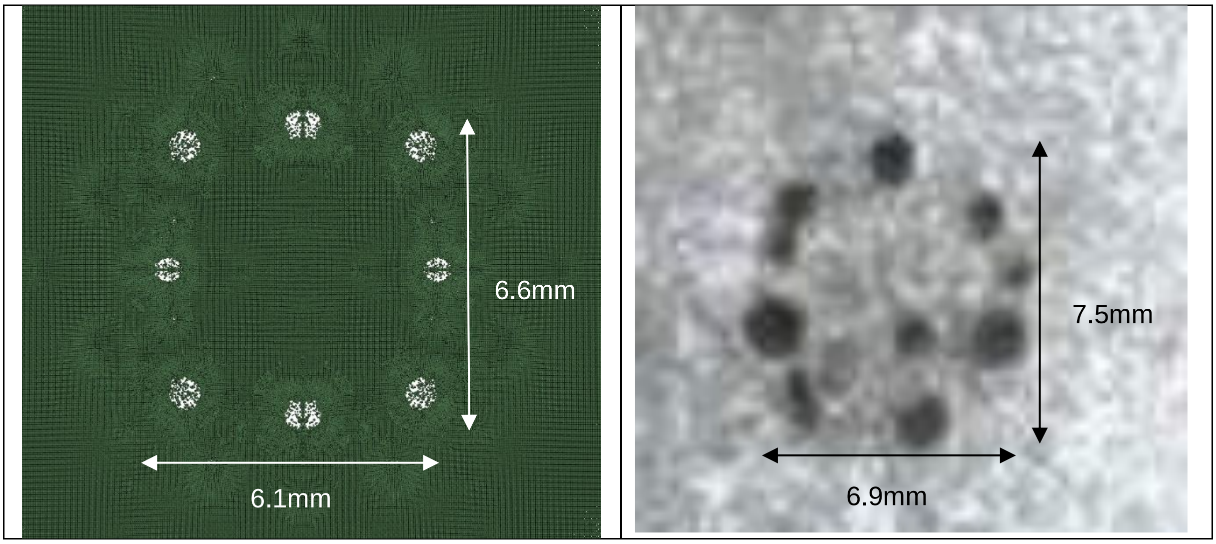



*Fig.1: Sheet profile with post-processing reflections (rear view)*

The failure of the containment plate was expected here (Table 1:). The sheet rear face failure profile shows a good visual agreement with the experimental sheet with the cloud circle imprint (Fig.1:). Moreover, the dimensions of the "cloud imprint" on the containment plate are comparable between numerical and experimental results for the width (11.6% error) and the height (12% error).
In order to better understand how the materials (impactor and first plate ones) behave during the impact and to know what kind of debris generates those holes (heavy "slow" debris or light fast ones, impactor debris or plate ones), a debris sorting software was developed. This software enables to map every debris generated by the impact on the first plate from its position at an instant defined by the user. All collected debris are then projected on a plane positioned at the theoretical containment plate top surface. The projection is made in the direction of the debris displacement at the studied instant. This map is completed with fringes of either the mass, the volume, the velocity or the kinetic energy associated to each projected debris.
The following figures illustrate the theoretical debris repartition after projection of the cloud on the virtual containment plate top surface, and their associated kinetic energy and mass. The Fig.2: right hand side also illustrates the repartition of the debris coming from the impactor (in red) and the ones coming from the impacted plate (in blue).

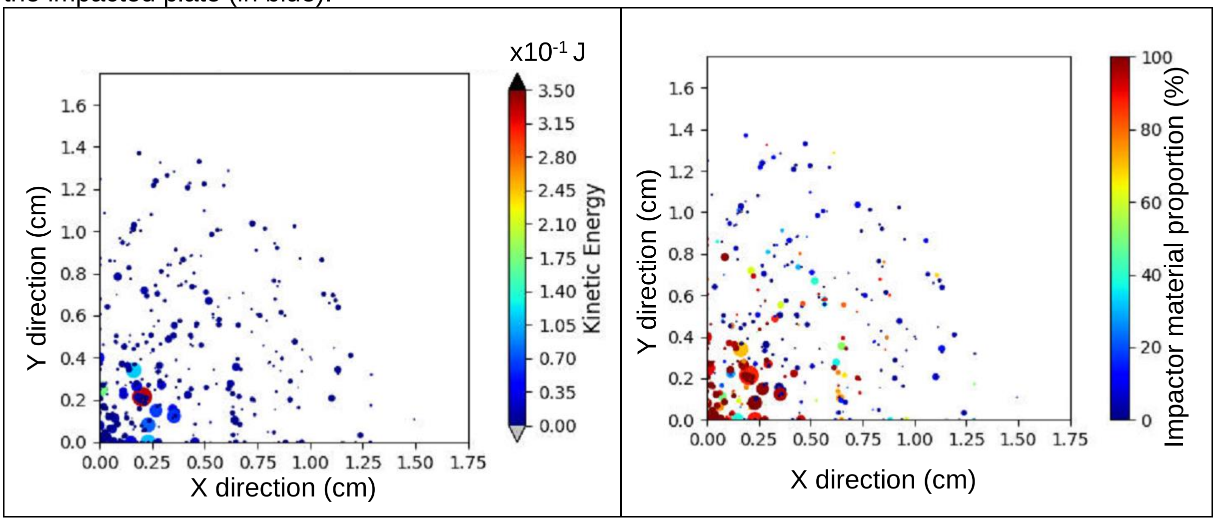



*Fig.2: Visualisation of energy and impactor material proportion of the projected debris cloud - CFRP 4km/s impact (top view of a quarter model)*

This figure shows that the impact on the carbon sheet generates few highly energetic debris and a high number of volumetric ones located at the centre of the cloud (quarter model). According to the right-

hand side figure, the huge debris at the centre mainly come from the impactor. Those post-treatments show that the carbon impacted sheet at 4km/s does not enough slow down the impactor (velocity reduction by 12.5%, see Fig.3:), and does not allow to sufficiently fragment it (133 of the 441 fragments are from the impactor). Thanks to the graphics coming from the post-treatment program (Fig.3:), a precise analysis can be performed on the debris origins, masses, volumes, etc. In this situation, it enabled to compute the impactor debris mass proportion, and it represents 54% of the total generated debris mass. These graphics can directly be compared to the Fig.10: which corresponds to the same impact conditions on an aluminium sheet.
The post-treatment program also provides some distribution graphics of the number of debris as a function of their mass, velocity and volume. The following figure illustrates the debris repartitions as a function of their mass, velocity and volume in order to quantify the information coming from the previous figure.

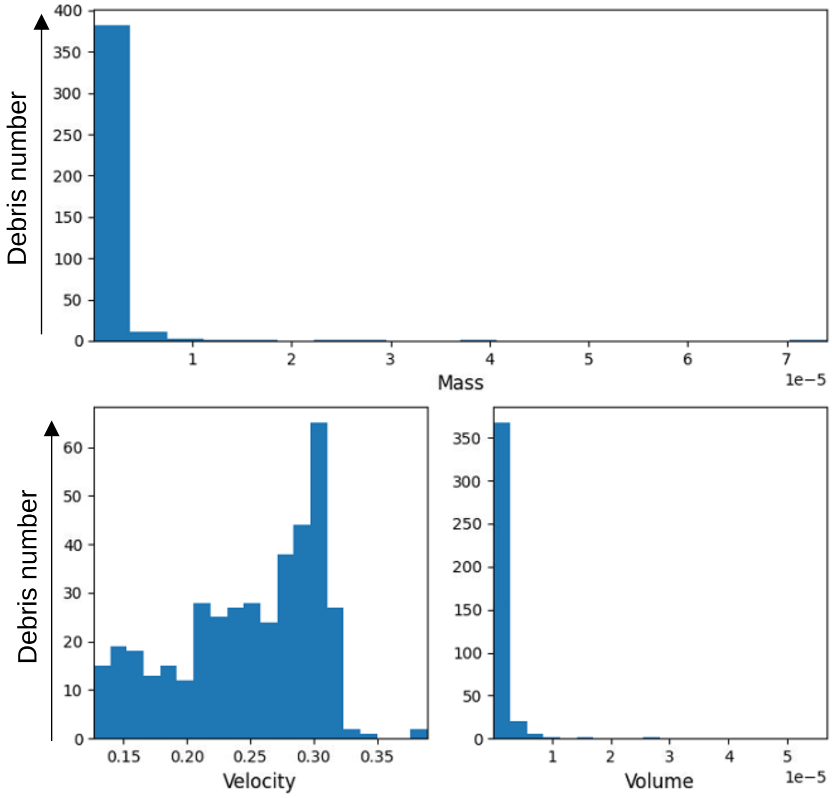



*Fig.3: Mass, velocity and volume debris number repartitions - Aluminium 4km/s impact (quarter model, units: g, cm, µs)*

The debris generated by the impact remain quite heavy compared to the ones obtained with an aluminium failure sheet (around 2 times heavier) and swift. Compared to an aluminium sheet (Fig.10:), the carbon is not sufficiently efficient to slow down the impactor and fragment it. Indeed, the aluminium sheet generates lighter debris with a reduced velocity but yet the impact already breaks the containment sheet. The carbon sheet should then not be used as failure sheet. This conclusion was also made experimentally, and enables to increase our confidence in the performed simulations.

### *3.2.2 Aluminium/Zylon – impact velocity ~6km/s*

According to Table 2:, the containment plate material should not break in this case, except for the rear side resin which should spall. The numerical simulation does not give results in accordance with experimental results (Fig.4:) since all the material (fibres + resin) locally breaks at the debris impacts locations. Indeed, multiple holes are visible on Fig.4:. This result is not so surprising since kevlar properties were used instead of zylon ones because of their unavailability. Moreover, the material phase change is not modelled here. At this impact velocity, liquefaction or sublimation can occur, which generate smaller and lighter debris. The containment plate is then subjected to less dangerous damage than for impact velocities around 4km/s. Since those phenomena are not modelled in the presented simulation, this lack of precision in the material behaviour could explain a part of the differences observed between numerical test and experimental data.

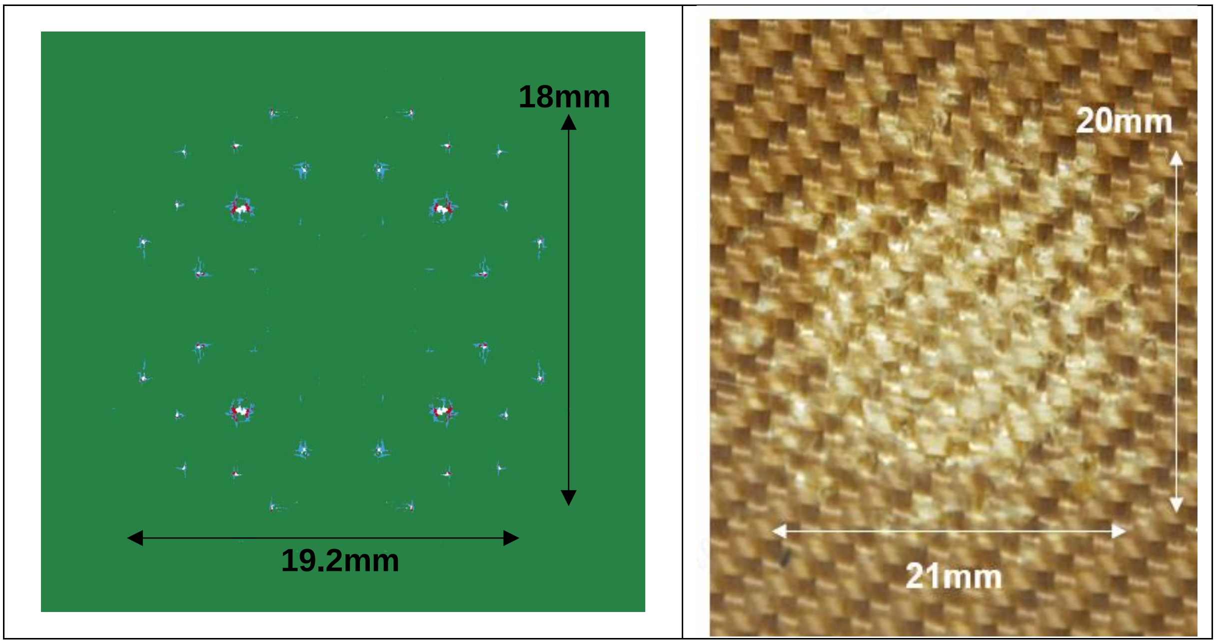



*Fig.4: Zylon sheet profile with reflections of the quarter model (rear view, 6km/s)*

Similarly, as for the previous section, the debris post-treatment program was used to identify the impactor debris proportion in the cloud after such impact, the debris positions, sizes, energies, masses and velocities just before impacting the containment sheet.

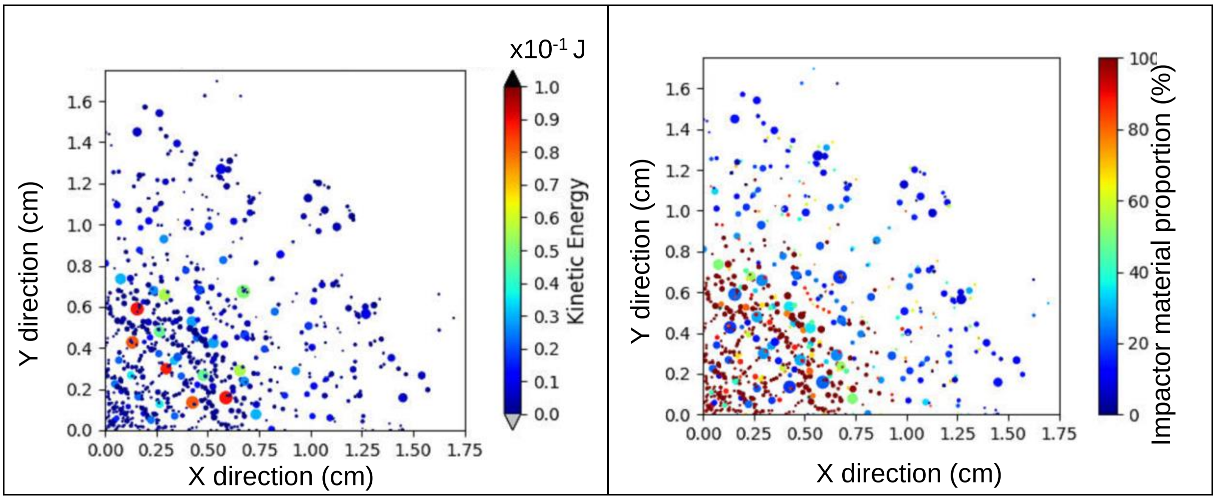



*Fig.5: Visualisation of energy and impactor material proportion of the projected debris cloud - Aluminium 6km/s impact (top view of a quarter model)*

This figure shows that the impact on the aluminium sheet at 6km/s generates some energetic debris and a high number of small ones located at the centre of the cloud but also distributed beyond it (quarter model). According to the right-hand side figure, the high number of small debris at the centre mainly comes from the impactor. Those two figures show that the aluminium impacted sheet at 6km/s slows down the impactor by 22% (considering the quickest of the generated debris, see Fig.6:), and highly fragments it (437 of the 738 fragments are from the impactor). The impactor debris mass represents 54% of the total generated debris mass. These graphics can directly be compared to the Table 3: which corresponds to the same impact conditions on an aluminium sheet at 4km/s.

The following figure illustrates the debris repartitions as a function of their mass, velocity and volume in order to quantify the information coming for the previous figure.

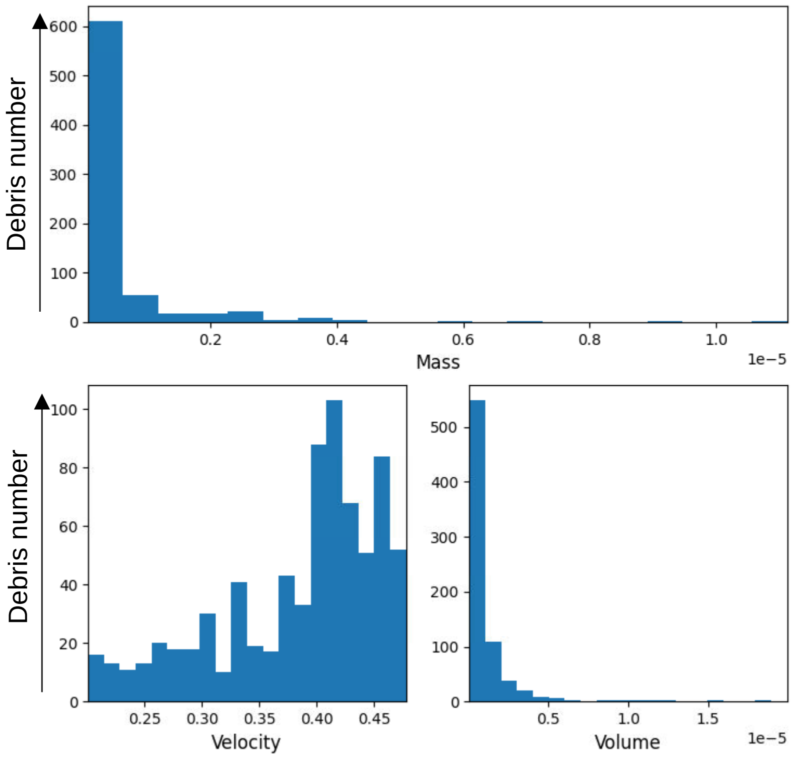



*Fig.6: Mass, velocity and volume debris number repartitions - Aluminium 6km/s impact (quarter model, units: g, cm, µs)*

## 4 Alternative aluminium structures

In parallel with the study performed on heterogeneous Whipple shields, a structural investigation has been performed to replace or modify the honeycomb in the sandwich shield. According to [3], the honeycomb causes dramatic damage on the containment sheet due to a tunnelling effect. The following section deals with the introduction of an intermediate sheet positioned at the middle of the honeycomb height. The sheets are modelled with SPH elements using formulation 5 and follow the recommendation issued from [1]. The honeycomb geometry is also given in [1] and is modelled with shell elements using formulation 16, and ***MAT_PIECEWISE_LINEAR_PLASTICITY** [4] material law with aluminium classical elastic characteristics associated to a tangent modulus of 10% of the elastic modulus and a plastic strain failure criterion fixed at 20%. These characteristics are quite simple and could be complicated in a second time. However, in a first time considering the impact velocity, these characteristics were considered sufficient.

### 4.1 Intermediate sheet

The idea is to break or slow the lethal debris cloud formed by the impact of the projectile against the shield structure first sheet. To do so, an intermediate sheet having the same geometrical and material characteristics as the external ones is added at the middle distance between the impacted sheet and the containment one.
The following figure illustrates the cloud velocity repartition at 25ms as a sectional view obtained for an impact at 4km/s.

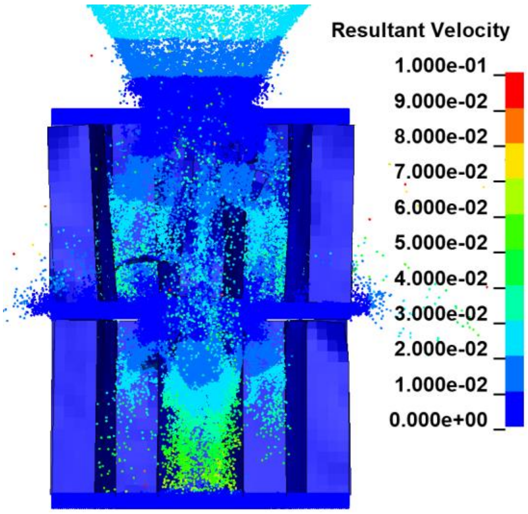



*Fig.7: Sandwich shield behaviour with a 0.4mm intermediate sheet impacted by a 1mm diameter debris at 4km/s (sectional view). Velocities in cm/µs*

The initial velocity is reduced by 88% which corresponds to an improvement of 40% compared to the classical sandwich shield velocity reduction [1]. Moreover, the containment sheet does not break in this case. This solution seems highly efficient to protect the containment sheet from failure. However, the percentage of added mass due to the intermediate sheet is 39%. A such important mass addition seems not acceptable for the space industry even if it concerns local patches.

Another intermediate sheet has been tested. It has the same geometrical and material characteristics as the honeycomb constitutive sheets (aluminium sheets of 25µm thickness) and has the same modelling as honeycomb (shell elements instead of SPH ones). It corresponds to 6.25% of the previously tested intermediate sheet in terms of mass and so to a percentage of global added mass of 2.4% instead of 39% compared to the classical sandwich shield. The following figure illustrates the cloud velocity repartition at 25ms for an impact at 4km/s and considering such intermediate sheet.
The added mass is much more acceptable in this case. However, according to the Fig.8:, a such thin intermediate sheet is not sufficient to efficiently slow down the generated debris cloud since the containment sheet fails. Indeed, this intermediate sheet slows down the debris velocity by 45% which corresponds to a sandwich shield velocity reduction capacity improvement of 10%, which is not sufficient in this case.
This study concerning an added intermediate sheet was closed at this step. However, to go further, multiple computations with various intermediate sheet thicknesses and materials (like CFRP for example) should be performed in order to establish a kind of ballistic limit curve.

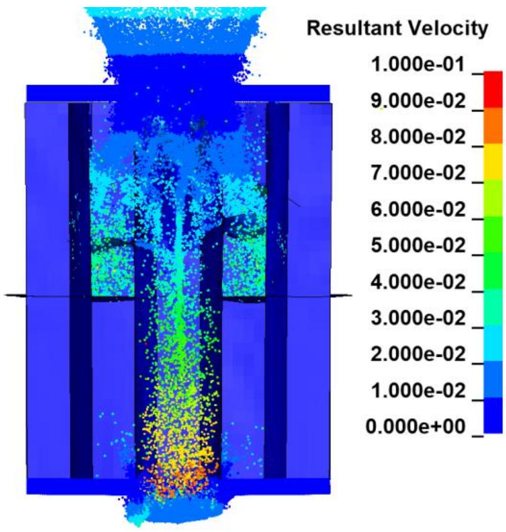



*Fig.8: Sandwich shield behaviour with a 25µm intermediate sheet impacted by a 1mm diameter debris at 4km/s (sectional view). Velocities in cm/µs*

The addition of an intermediate sheet is not completely a success. Another alternative that has been studied consists in replacing the honeycomb, which channels a major part of the debris cloud on a containment sheet restricted area, by a structure which spreads the debris in directions orthogonal to the impact one. This is the topic of the following section.

### 4.2 Innovative sandwich structure

For confidentiality reasons, the structure cannot be shown or geometrically described in this paper. This structure conserves the two external sheets and their initial distance from each other. The honeycomb is replaced by another aluminium structure. The total mass of the initial sandwich shield is reduced by 52,1% thanks to the innovative internal structure. The following figure illustrates the shape of the cloud at t=7.5µs for a Whipple shield, a sandwich one and the innovative sandwich one (sectional views). The considered impact velocity is 4km/s.

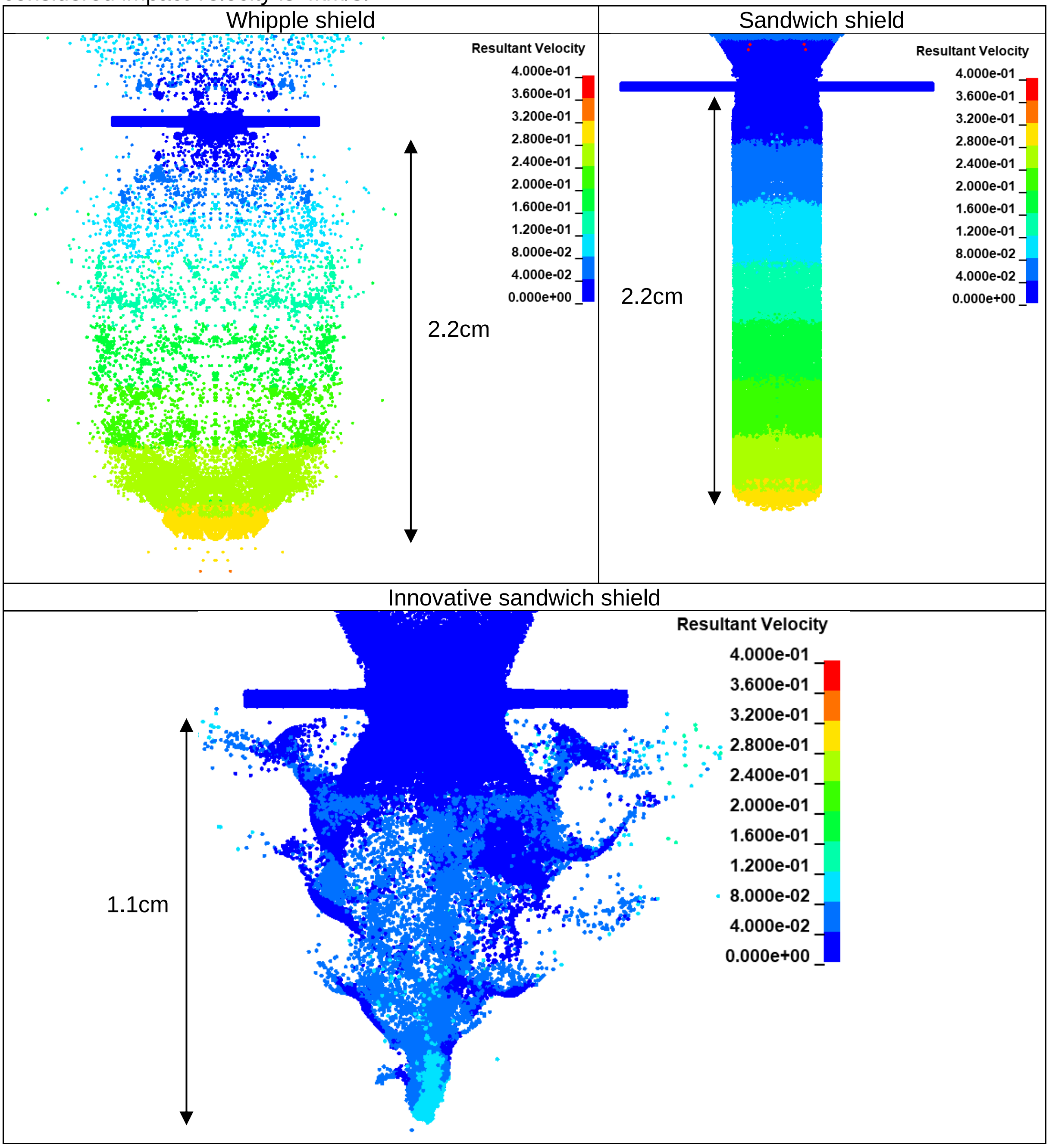



*Fig.9: Debris clouds generated by a 1mm diameter impactor at 4km/s against a Whipple shield, a sandwich one and the innovative one*

Considering the same impact conditions and the same observation instant (16µs, which corresponds to the simulation final time of the innovative structure case), the innovative sandwich structure enables to divide the cloud length by two and the cloud front velocity by 15. In these conditions, even if the computation final time is premature compared to the non-null debris velocity, it is easy to affirm that the cloud front will never reach the containment sheet surface.

The debris post-treatment program was used to identify the proportion of debris from the impactor in the cloud, the debris positions, sizes, energies, masses and velocities just before impacting the containment sheet. The following figures illustrate the debris repartitions for the three previous shielding structures.

It is important to know that the innovative structure computation reached its user-defined final time when the debris cloud reached the middle distance between the two sheets, because of the structure efficient velocity reduction capacity. This computation took 6 days on 28 CPU MPP and is the reason why it could not be launched on a longer duration. Since the innovative structure is present in the total depth between the two sheets, the projections made by the user post-treatment program on the second sheet surface is not completely realistic. In addition, because of the premature computation end time, the debris generated are not totally distinctly shaped compared to the other cases, especially the ones situated at the centre of the top view because of the structure geometry. This aspect can compromise the debris accounting and the mass and volume balances illustrated in the Fig.12: for the innovative structure.

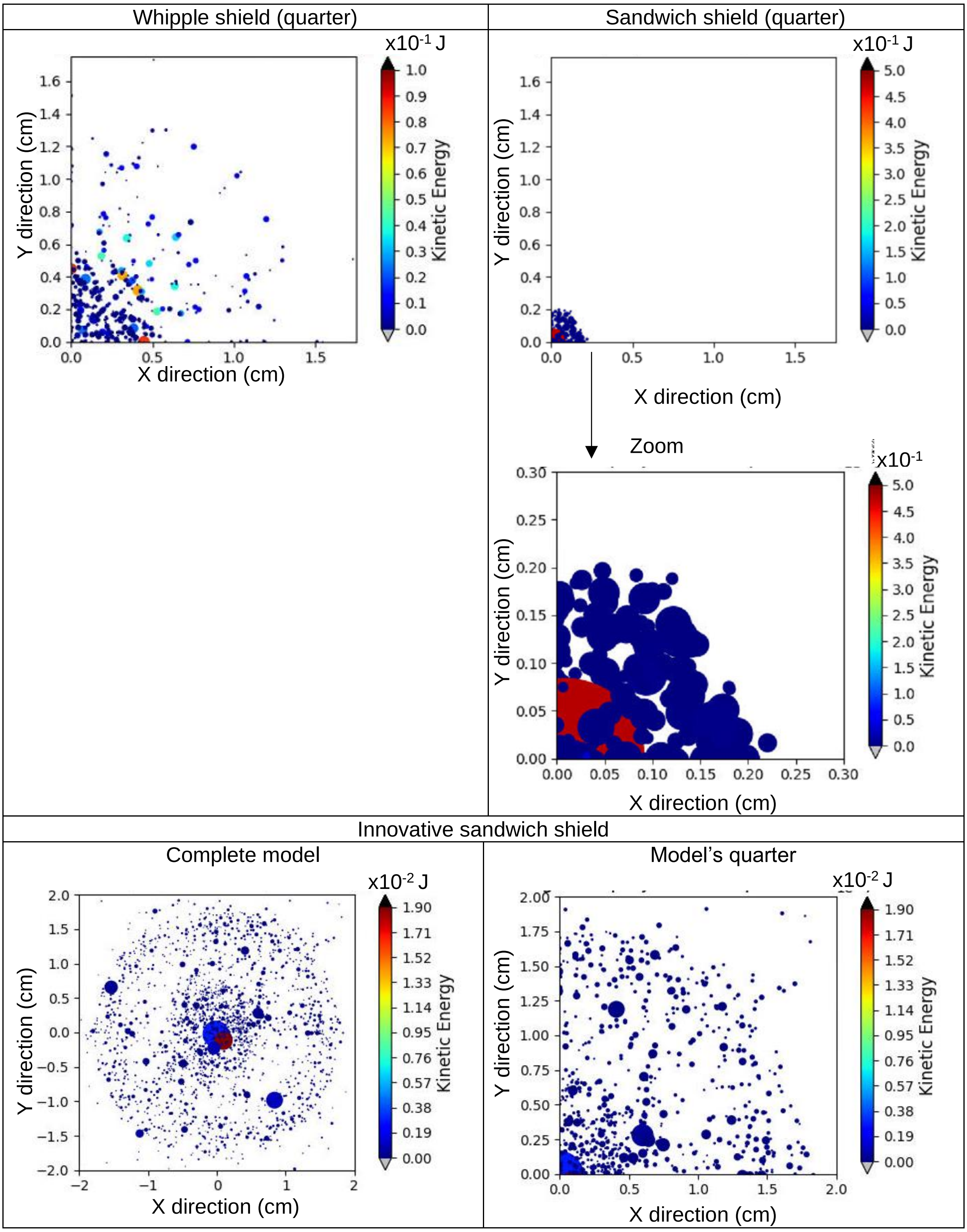



*Fig.10: Visualisation of the kinetic energy of the projected debris cloud for the Whipple shield, the sandwich shield and the innovative structure - 4km/s impact (top view)*

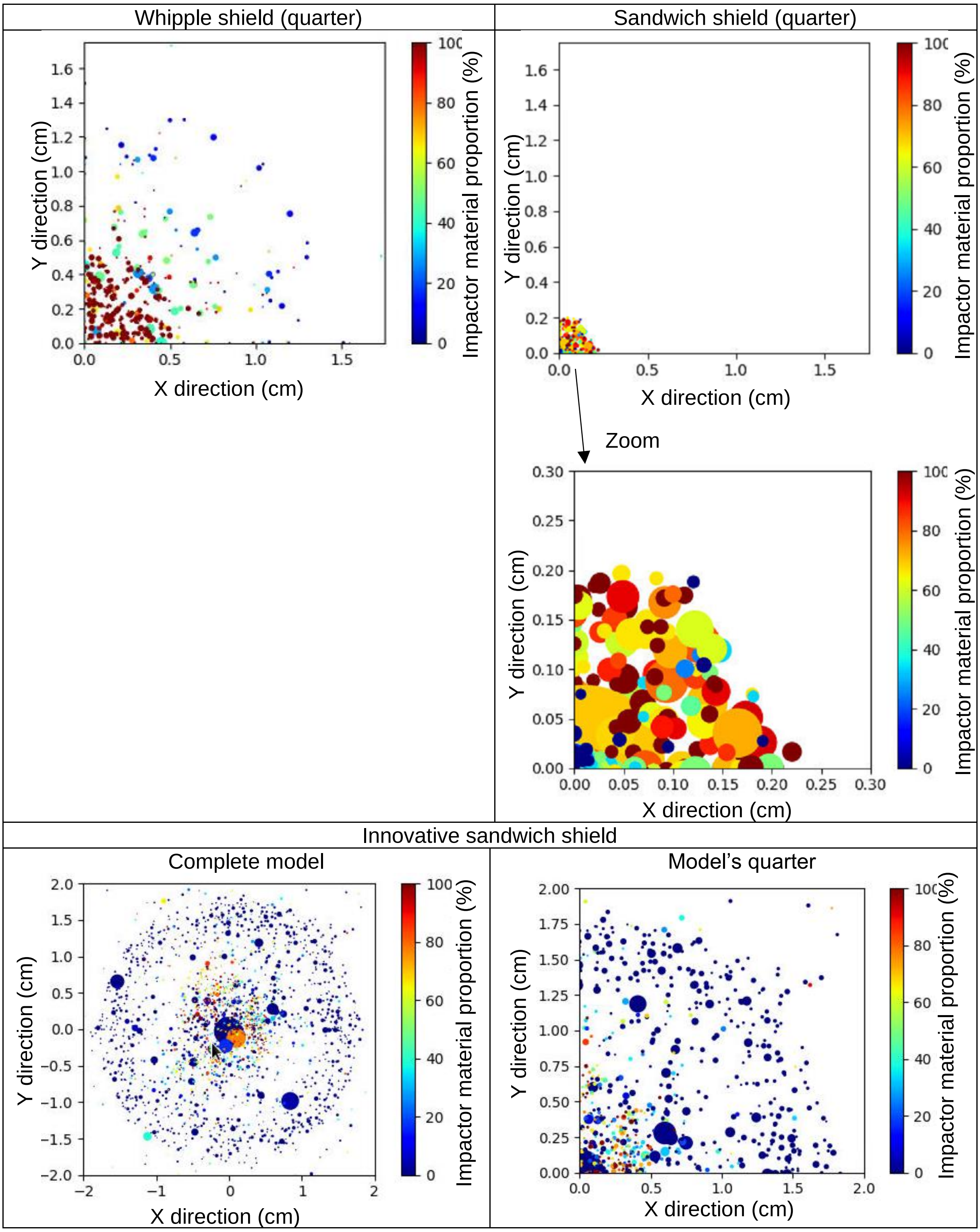



*Fig.11: Visualisation of the impactor material proportion of the projected debris cloud for the Whipple shield, the sandwich shield and the innovative structure - 4km/s impact (top view)*

The post-treatment program debris identification method is based on the distance of the SPH particles between each other's. Consequently, a high number of particles in a restricted volume can wrongly lead to the identification of one huge debris.
The following table sums-up the velocity reduction ratio between the initial impact velocity and the fastest debris one for each case, the ratio of the impactor debris compared to the total debris number and the second sheet impact zone area.

| | Whipple shield | Sandwich shield | Innovative shield (model's quarter) [1] |
|---|---|---|---|
| Fastest debris velocity reduction ratio | 25% | 25% | 85% |
| Second sheet area submitted to the debris cloud (cm²) | 7.07 | 0.15 | 10.18 |

*Table 3: Debris velocity reduction ratio, impactor debris number and second sheet area submitted to the debris cloud for the Whipple shield, the sandwich shield and the innovative structure - 4km/s impact*

The first conclusion coming from the previous figures and table is that the innovative structure highly reduces the debris cloud velocity compared to the current structures, which is a quite encouraging result.

The second important information concerns the impact zone area of the second sheet. In comparison to both current shield structures, the innovative one enables to increase the radial spread of the debris in order to limit the risks of failure for the second sheet.

The following figure illustrates the mass and velocity balances for each case. It is important to remember that the fragment masses and volumes of the innovative structure are not so much relevant because of the premature computation end time and the post-treatment program debris identification method. These data are given for information.

[1] All the data concerning the projection of the debris on the innovative structure containment sheet top surface have to be cautiously interpreted. Indeed, since the debris only reached half the distance from the containment sheet at the computation end time, the user program will not take into account the innovative structure second half and the results will be as if the debris had met no more obstacles until the containment sheet, which is false here. However, the velocity and spatial distribution results are already highly encouraging in such a case, and they should be even better with the innovative structure "missing part" which would increase the structure spreading effects.

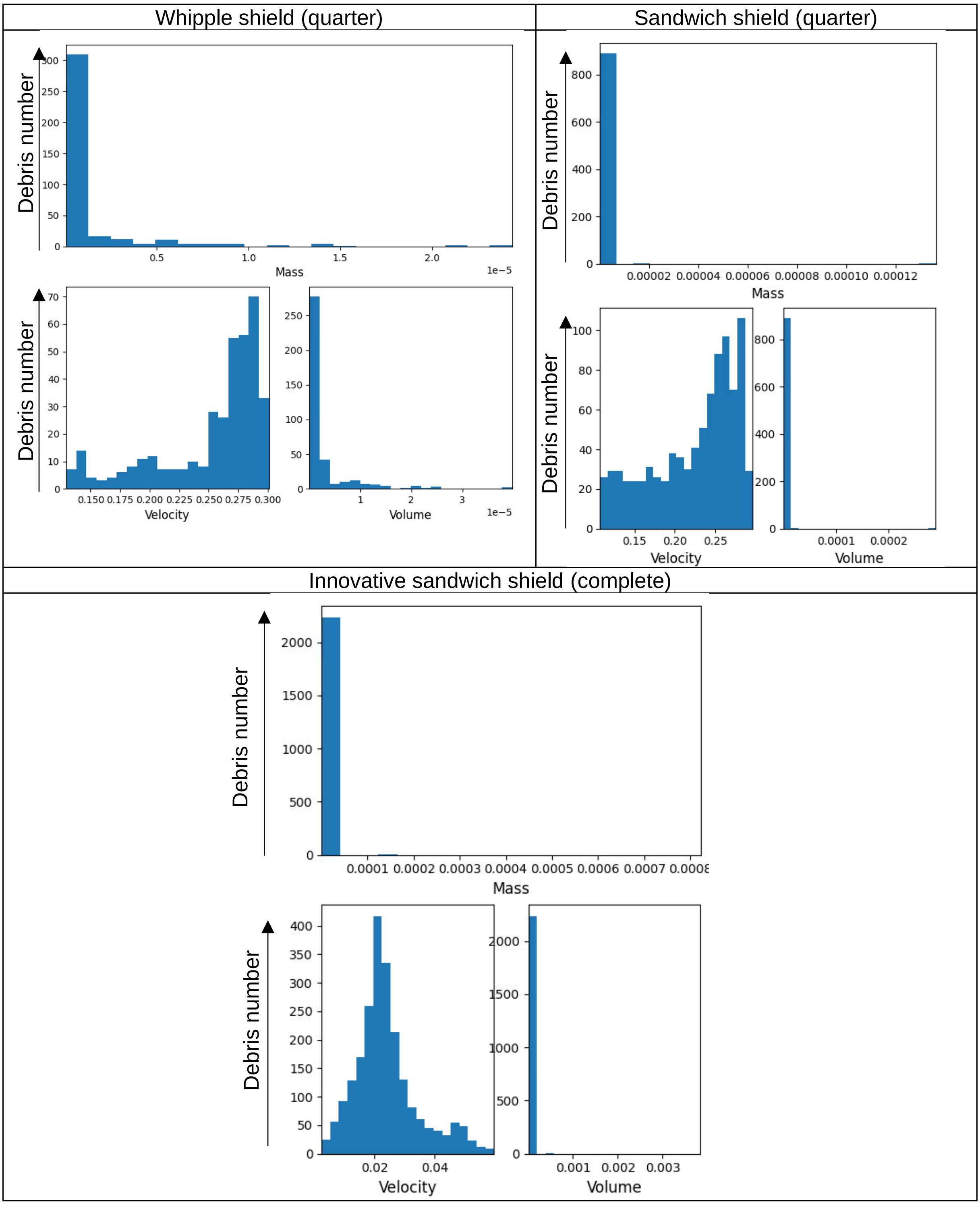



*Fig.12: Mass, velocity and volume repartitions for the Whipple shield, the sandwich shield and the innovative structure - 4km/s impact (units: g, cm, µs)*

According to the previous results, the innovative solution is 52% lighter than classical shielding structures and is highly efficient to reduce the cloud velocity. However, honeycomb is necessary to add stiffness to the shield structure. The innovative one does not enable to add as much stiffness as with the honeycomb. A complementary study dealing with the stiffening of the innovative structure could be performed later as a new project. Moreover, some manufacturing studies should be done in order to evaluate the feasibility of such structure and the associated costs.

## 5 Conclusion

Some experimental tests have been realized at impact velocities of range from ~4km/s to~6km/s and enable to validate the hypothesis that the most critical damages on the containment plate are caused by impacts that do not lead to a sufficient impactor fragmentation. Two orthotropic materials were tested for both plates (failure and containment), and it globally appears that the better hybrid solution should come from an aluminium failure plate, which slows down the debris cloud, and a prepreg zylon fabric which does not fail during the debris cloud impact. Indeed, according to the debris post-treatments, the CFRP composite only slows down the impactor velocity by 12.5% which corresponds to half the aluminium sheet capacity. Moreover, only 30% of the debris cloud comes from the impactor, instead of 70% with an aluminium sheet. This means that aluminium highly fragments the impactor compared to CFRP.
Concerning the containment sheet, however it does not break, the zylon fabric generates a rear face new debris cloud because of the resin spalling that could damage the satellite equipment. Because of this, this solution cannot be retained as it stands. Moreover, in future works, some tests should be performed on heterogeneous structures including honeycomb, since the conclusion could be different mainly because of the channelling effect [3].

In parallel with this material study, a structural one enabled to identify two potential solutions. The first studied one consists in adding an intermediate sheet between the two external ones, in order to slow down the channelled cloud debris inside the honeycomb. This method is efficient but seems to need a quite thick intermediate sheet to be useful, which is not in accordance with the restriction of mass relative to the spatial domain. A solution to be tested could consist in inserting a non-aluminium intermediate sheet, like a CFRP one, or a Zylon fibre fabric one. This solution would enable to insert a lighter intermediate sheet, but could also produce more lethal debris for the containment sheet.
The second structural study dealt with a new innovative structure designed by DynaS+. This structure keeps the classical two external sheets and integrates an aluminium structure between them which replaces the honeycomb. This structure is highly efficient in terms of mass savings and enables to significantly slow down the debris cloud (by 85% instead of 25% for current structures). Indeed, the technology consists in spreading the debris in planes parallel to the external sheets. This aspect is well observed using the post-treatment program and the area measurement is significantly increased compared to the one associated to the Whipple shield according to the projection results.
Knowing this, the aim of a potential future work could be to improve the geometry of the innovative technology in order to stiffen its global structural behaviour. Some other impact tests should be made at various velocities to globally validate the containment structure. Then a manufacturing study should be realized in order to ensure that this structure can be produced with classical manufacturing methods.
Many ideas have been explored but some questions remain and could be addressed as part of a future new project. Some directives for further researches have already been indicated and could already be used by the space researchers to go further on the debris protection problematic.

## 6 Acknowledgments

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

## 7 Literature

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