Numerical Simulations for Spacecraft Catastrophic Disruption Analysis

Executive Summary

Report I-64/18

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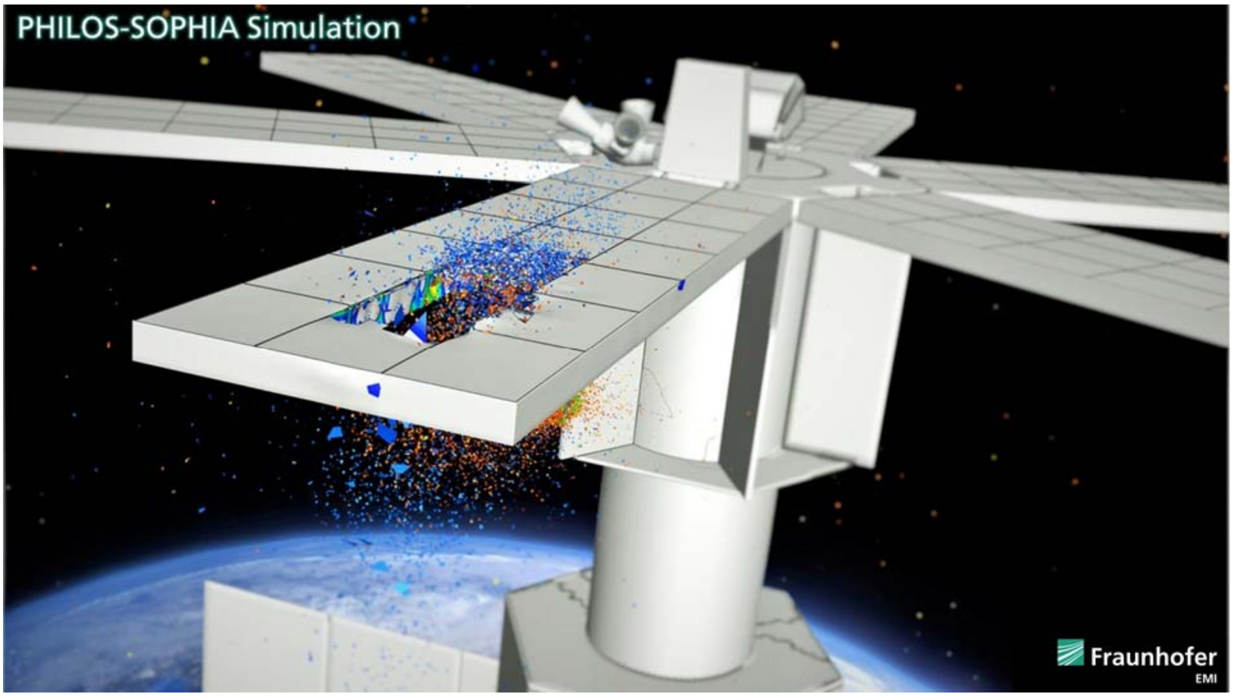
PHILOS-SOPHIA Simulation
Fraunhofer
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1 Numerical Methods for Spacecraft Collision Analysis

While the vast majority of space debris still stems from explosion events of satellites and rocket upper stages, current forecasts state that collisions, such as those of the two satellites Cosmos 2251 and Iridium 33 in 2009, will play a dominant role in the mid-term future when a critical spatial density of satellites has been reached [STA08]. In order to assess the risks emanating from space debris, a deeper understanding of the formation and residence time of breakup debris in orbit is essential for operational activities. It is crucial for the definition and forecast of the space debris environment to characterize satellite disruptions events in terms of resulting

- Fragment number,
- Size distribution,
- Area-to-mass ratio,
- Linear and angular momentum transfer of fragments etc.,

and to understand how these data depend on the

- Collision scenario (orbit parameter),
- Kinematic encounter conditions (orientation, velocity), and
- Involved objects (mass, geometry, materials, configuration).

The characterization of such events is very demanding since the prevailing physical conditions at collision are extreme and the objects are complex, thus, opening a wide parameter space of possible collision scenarios. Ground testing at full scale entails tremendous effort and covers only a small range of the parameter space, thus, making it difficult to generalize and extrapolate experimental findings. Numerical simulations may close this gap in a practical and effective way. A numerical methodology that allows for the studying of the physical processes of a spacecraft disruption in a physically consistent form can pave the way to a general understanding of hypervelocity fragmentations and their effects on the orbit environment.

In the field of impact analysis, mainly three basic methods are being used:

1) Empirical models, which predict an impact damage based on analytical formulae derived from observational or experimental data,

2) Semi-empirical models, which use analytical formulae based on more fundamental physical equations, but still are fitted to empirical data,

3) Sophisticated numerical simulation methods, that solve the fundamental conservation equations for mass, momentum and energy, which are formulated as partial differential equations (involving spatial and temporal derivatives of the physical variables). This set of equations is complemented by constitutive equations describing the material behavior (material laws). Specifically hydrocodes are used for solving highly dynamic processes as hypervelocity impact collisions.

The general features of the numerical methods may be compared with each other as follows:

1) Empirical models
2) Semi-empirical models
3) Numerical simulation methods

Increase in

- Flexibility, fidelity and range of applicability
- Ability to model complex scenarios and objects close to reality
- Complexity of the models and effort for model setup
- Computational effort and time needed to perform analyses

We found that sophisticated numerical simulation methods like hydrocodes are the best choice for systematically studying hypervelocity collisions for a wide range of collision scenarios [D1, D2, D3]. Other numerical methods are limited to a narrow validity range. Although their computing time is much faster due to their simplifying nature, they cannot meet the quality and precision of physics-based methods, nor do they allow for complex modelling.

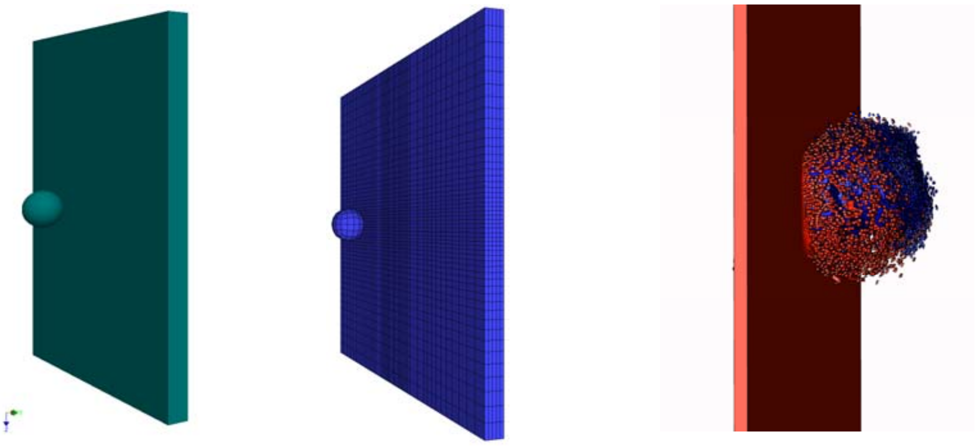


Figure 1: Example of hydrocode simulation. Left: a CAD model defines the setup and the geometry (here sphere on plate). Middle: Corresponding finite element model for numerical simulation. Right: detail of a hydrocode simulation showing the projectile (blue) penetrating through a thin plate (red) at hypervelocity, thereby generating fragment clouds. Due to the explicit spatial discretization, fragments characteristics can be analyzed by post-processing.

2 Software Tool PHILOS-SOPHIA

We developed the software tool “PHILO-SOPHIA” that enables a non-expert user to perform hydrocode simulations of hypervelocity collisions on orbit. It is based on hydrocode simulations using the established EMI-hydrocode SOPHIA as solver. SOPHIA has been developed specifically for studying impact fragmentation in the context of missile defence, thus, making it predestined for the spacecraft disruption application.

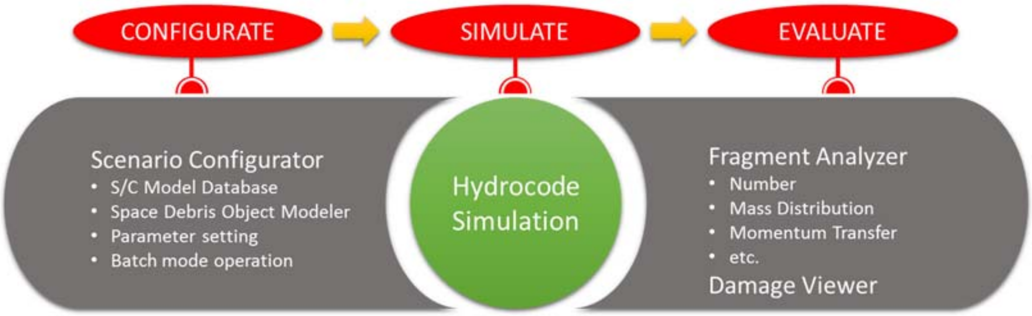
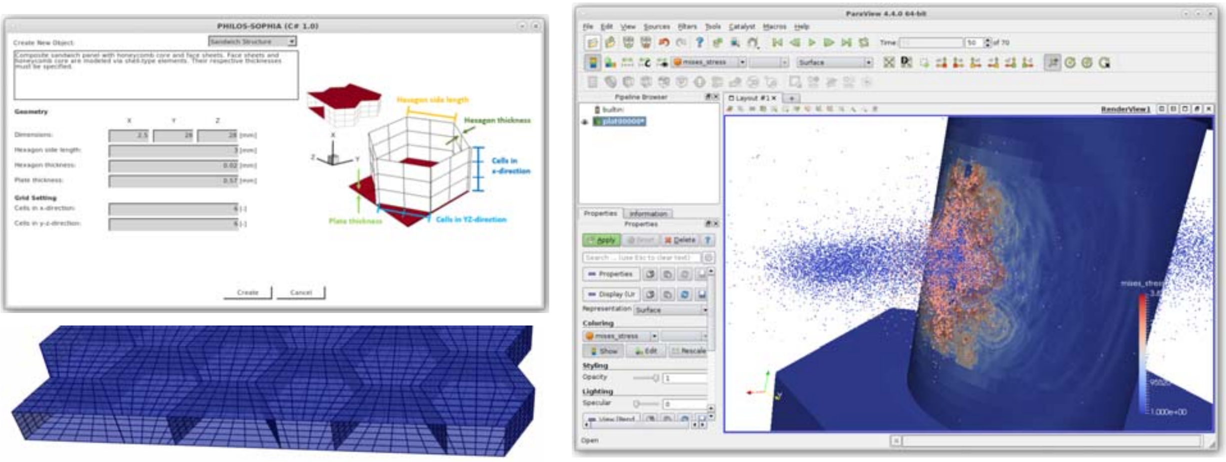


Figure 2 PHILOS-SOPHIA process chain. EMI’s hydrocode SOPHIA is used as solver. SOPHIA couples smooth particle hydrodynamics (SPH) and finite element (FE) methods and includes a robust 3D contact algorithm. We developed a graphical user interface as well as modules for configuring and evaluating collision scenarios within this study.

The “PHILO-SOPHIA” includes a graphical user interface (GUI) that can be used to 1) define the collision scenarios, 2) analyze the fragmentation, and 3) visualize the simulation results [D5, D6, D7].



Create New Object: Sandwich Structure

Composite sandwich panel with honeycomb core and face sheets. Face sheets and honeycomb core are modeled via shell-type elements. Their respective thicknesses must be specified.

Geometry

	X	Y	Z	
Dimensions:	2.5	28	28	[mm]
Hexagon side length:	3			[mm]
Hexagon thickness:	0.02			[mm]
Plate thickness:	0.57			[mm]

Grid Setting

Cells in x-direction: 6 [-]
Cells in y-z-direction: 6 [-]

Figure 3: Screenshots of the PHILO-SOPHIA GUI. Left: set-up of a sandwich panel structure. Right: 3D visualization during a collision calculation (hit on central tube of the LOFT spacecraft). Colors indicate von Mises stress distribution.

3 Evaluation of Numerical Results

We performed comprehensive numerical simulations using “PHILO-SOPHIA”. The objectives of the evaluation of numerical results were to

1) Show the capabilities of the PHILO-SOPHIA software tool for studying hypervelocity fragmentation analysis in spacecraft shielding analysis,

2) Validate the PHILO-SOPHIA tool with available experimental results, and

3) Demonstrate the numerical simulation of complex collisions using ESA LOFT spacecraft as an example and compare it to predictions of the semi-empirical NASA Standard Satellite Breakup Model [JOH01].

3.1 Validation

The spacecraft shielding analysis demonstrated the tool’s capability for studying specific hypervelocity features [D8]. The scenarios included multilayered targets and composite sandwich structures. It showed the demand for adequate material models when new materials like Kevlar and CFRP structures come into play. This includes experimental material characterizations and the development of analogous material models for complex structures for full-scale simulations. We proposed simple models for the materials involved in the shielding analysis. Nevertheless, specific material models can be developed and implemented into PHILOS-SOPHIA, as required. Fraunhofer EMI creates and experimentally validates material models for numerical simulations as for example in previous ESA activities [HIE99, RIE03, WIC07].

We performed the tool validation for PHILO-SOPHIA in comparison with experimental high-speed recordings of hypervelocity impact experiments at Fraunhofer EMI. In addition to the extensive validation of the SOPHIA-solver in the context of missile defence, we also proved that the PHILO-SOPHIA tool is able to reproduce experiments with non-spherical impacts and oblique impact configurations as shown for example in Figure 4.

The validation also showed the need to carefully choose the modeling and the numerical parameters with respect to the study objective. As an example, the selection of the eroded nodes method involves lower computation time compared to FE/SPH coupling, which, however, may better describe specific features of the fragment cloud expansion. Figure 4 presents the results of both methods.

We also cross-checked the PHILOS-SOPHIA code with a commercial hydrocode, i.e. the general purpose hydrocode ANSYS AUTODYN (R18.1). Both codes yield similar results for the mass distributions of fragments, but PHILO-SOPHIA better matched the experimental measured velocity of the cloud. In addition, PHILO-SOPHIA needed less computation time than the commercial tool (9 hours compared to 27 hours for 20 µs simulated physical time).

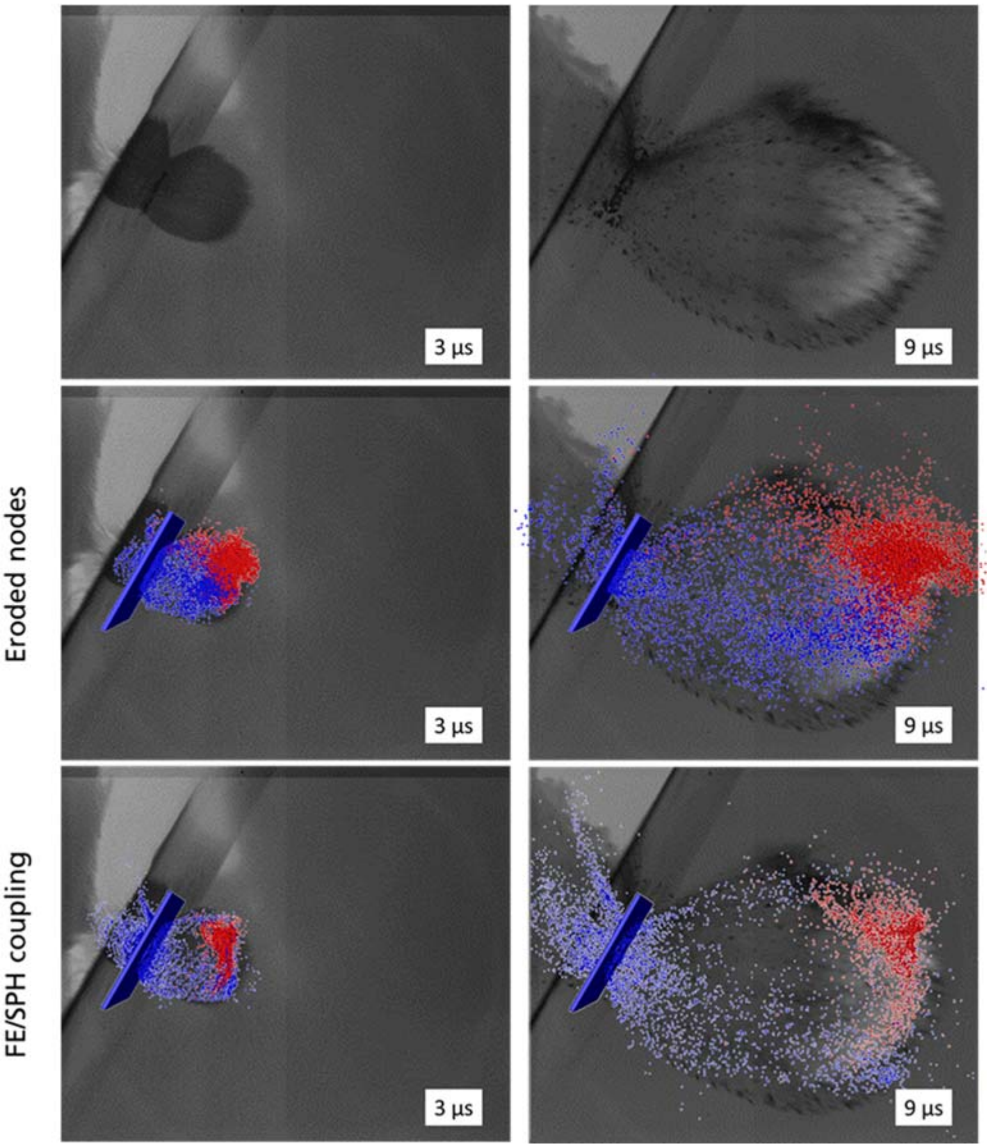


Figure 4: Tool validation: Comparison of the debris cloud at two instants of time between experimental recordings and PHILO-SOPHIA simulations. Two different numerical simulation methods have been used: Eroded nodes (second row) versus FE/SPH coupling (third row). The simulation results are superimposed on the high-speed video extracts, which are displayed in the first row. Projectile fragments are indicated in red. Target plate fragments are indicated blue.

3.2 Complex collision simulations

We performed detailed fragmentation analyses for the collision of the LOFT spacecraft, the geometry of which was provided by ESA in CAD file format. Six complex collision scenarios were agreed upon with ESA for simulation. The background of the collision scenario definition is to shed light on the transition between local damage effects and a so-called catastrophic disruption upon impact. The defined scenarios represent different cases with varied energy-to-mass ratio (EMR, between different sized impactors and the LOFT target satellite) and with varied collision geometry. The latter includes central impacts, central impacts with offset ("graze"), and impacts on outer parts with and without the collision velocity vector pointing to the center of the target. Figure 5 shows an example scenario.

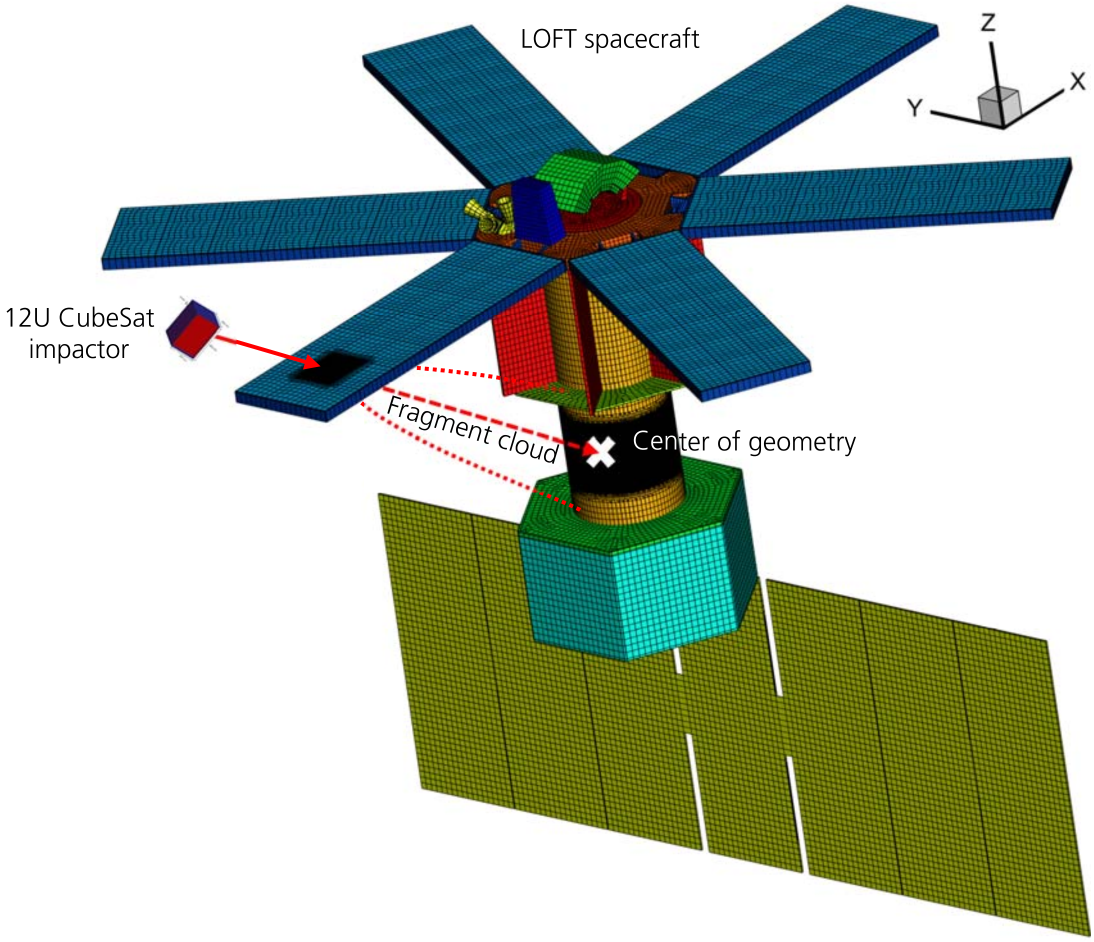


Figure 5: Mesh model for a complex collision simulation.scenario. A 12U nanosatellite, having 10 kg mass and 200 × 200 × 300 mm^3 dimension, impacts on a Large Aperture Detector of the LOFT spacecraft in such a way that the spacecraft center is hit by the generated fragment cloud. The mesh is locally refined in the affected zones (appearing darker).

We created different finite element models for the complex collision scenarios, including the LOFT spacecraft, rectangular plates and 1U to 12U nanosatellites. The FE models are included in the PHILOS-SOPHIA software and can be selected via the graphical user interface. Figure 6 and Figure 7 exemplarily show results of the simulations for the scenario shown in Figure 5

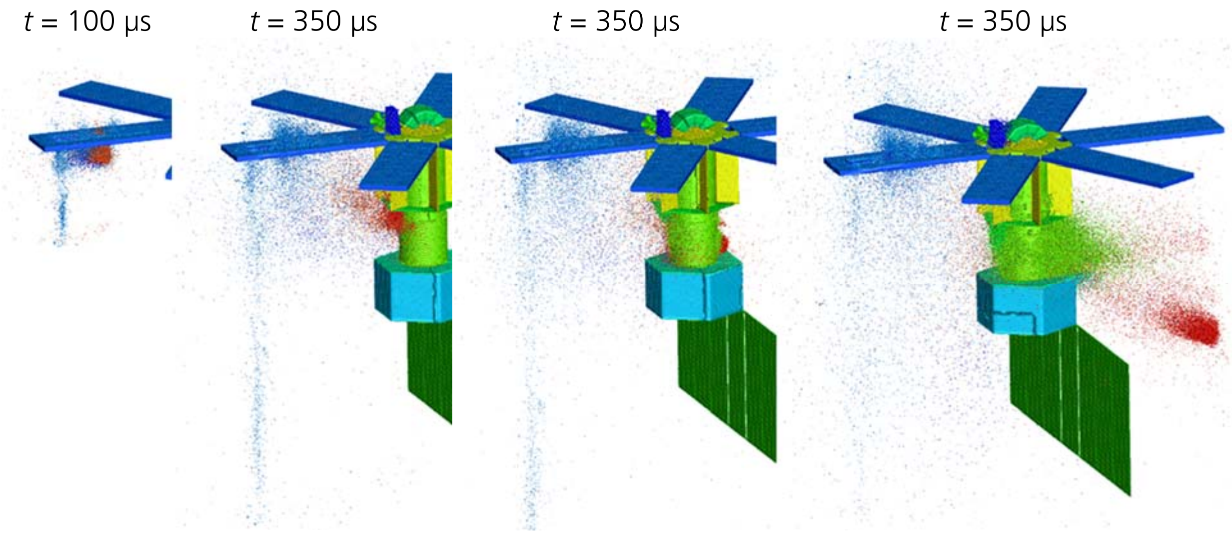


Figure 6: Oblique impact of a 12U CubeSat near the free end of the LAD panel. The trajectory of the resulting fragment clouds points to the center of geometry of the LOFT satellite. Impactor fragments are indicated in red, target fragments are indicated according to the component color. Different fragment clouds propagate from the impact locations.

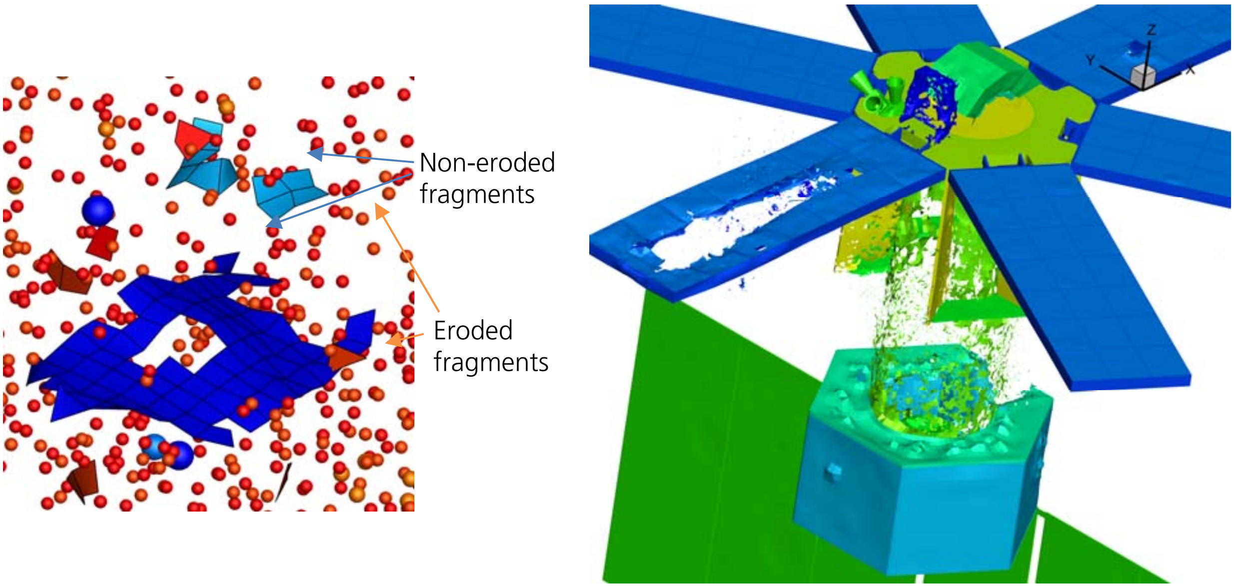


Figure 7: Post-impact damage analysis: Left: scheme showing the difference between eroded nodes and non-eroded fragments. Right: global damage of the LOFT for the above shown spacecraft disruption (at 1.38 milliseconds after impact). Here, only the non-eroded fragments are shown to better display the damage of the spacecraft.

Besides the qualitative evaluation of the impact processes as shown in the snapshots, we performed quantitative analyses of the fragmentation caused by the impacts. We thoroughly investigated the generated fragments in terms of number of fragments, size distributions, velocity distributions, and area-to-mass ratios. Figure 8 shows the velocity distribution for the presented scenario (left diagram). The velocities are measured relative to the LOFT satellite. The small peak at 11 km/s corresponds to the impact velocity of the original CubeSat collision. Fast fragments in the cloud, which resulted from the perforation of the LAD panel, collided again with the LOFT main body, causing extensive damage and creating many new fragments with lower, but much broader distribution of, velocities.

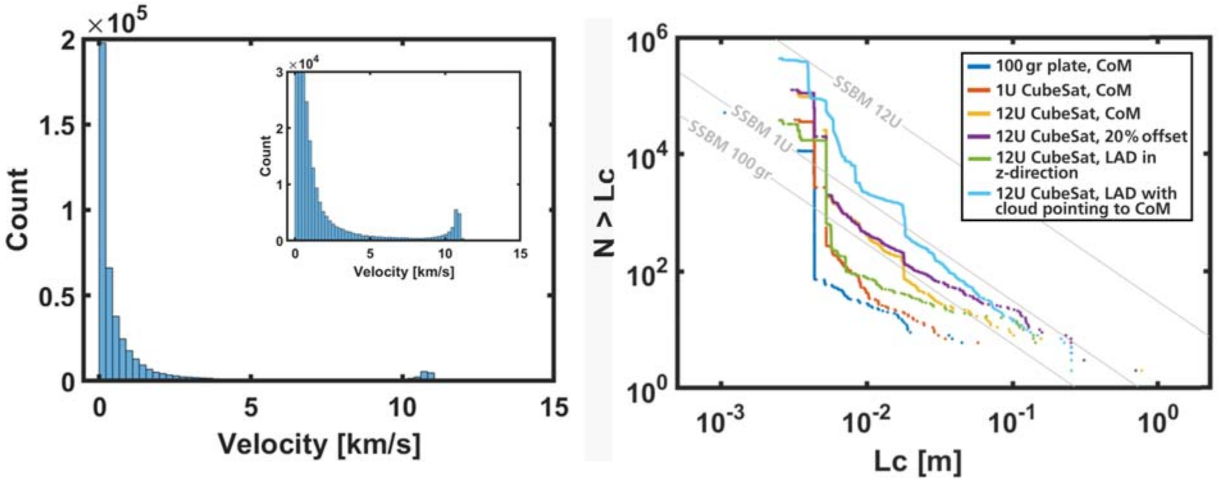


Figure 8: Fragmentation analysis at 940 µs after impact. Left: Histogram of fragment velocities (of eroded and non-eroded fragments) from the scenario shown in Figure 5 through Figure 7. The insert to the figure allows the small number of fragments between the two peaks to be seen. Right: Comparison of the cumulative number of fragments over the characteristic length over six different scenarios. The example scenario (12U CubeSat on LAD panel with secondary impacts on the LOFT main body) created the most fragments of the compared scenarios. Also shown are power curves predicted by the NASA Standard Satellite Breakup Model (SSBM) for the different impactor masses.

Figure 8 also shows the number of generated fragments having a characteristic length *Lc* for different scenarios in comparison to the semi-empirical NASA Standard Satellite Breakup Model (SSBM) on the right [D9]. The characteristic length is defined as $Lc = (x+y+z)/3$, where x, y and z are the length, width, and thickness of a minimum box containing the entire fragment. We see less fragments but similar slopes predicted by the numerical simulation results compared to the SSBM in the large fragment range. In the small fragment range, the number of fragments show better agreement, but the slope is different on the log-log scale. The large vertical spikes at the lower size end in some scenarios are due to the discretization of the models. Here, the material completely fragmented to eroded nodes. The eroded nodes, mass points representing single elements from the finite element mesh, are not able to divide any further, so they represent the smallest resolution possible in this simulation. These effects can be minimized by an even finer discretization (simultaneously increasing the computing effort). What is apparent is that the empirical breakup model does not reflect the variations in the impact scenarios. The best example is the comparison between a vertical impact on the LAD panel (in Z-direction, green line in Figure 8) with the oblique impact on the LAD panel with a high number of secondary impacts by the fragment cloud as shown in our example before (light blue line in Figure 8). While the number of generated fragments differs significantly, the empirical model does not include these effects of the impact geometry.

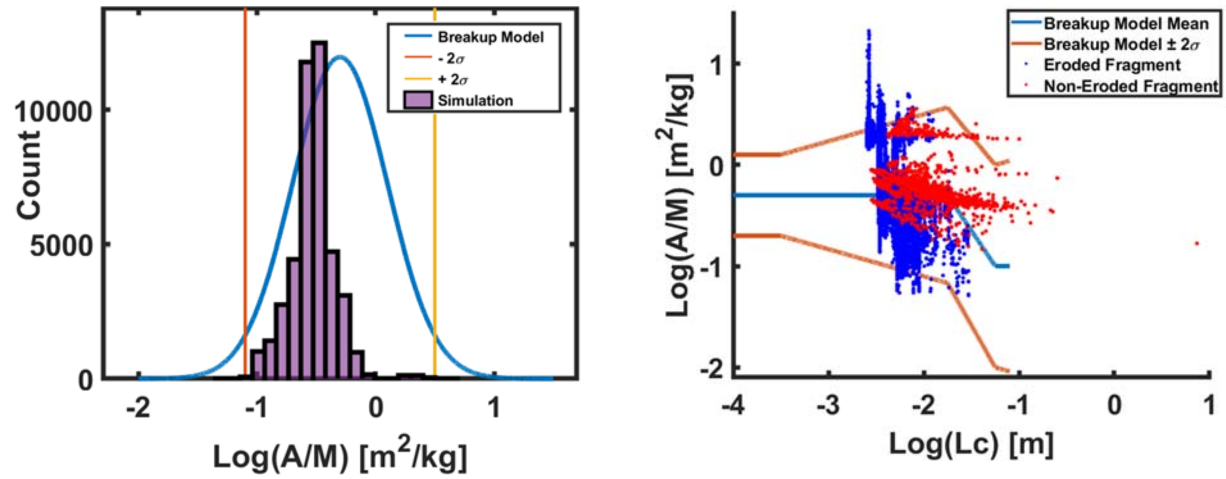


Figure 9: Fragments area-to-mass ratio A/M. Left: histogram of A/M of fragments with characteristic length between 5.6 mm and 17.8 mm ($-2.25 < \lambda_c < -1.75$). Blue curve is the distribution predicted by the NASA breakup model, with ± 2σ positions marked with vertical lines. Right: A/M vs characteristic length L_c. Since predicted mean and standard deviations of the area-to-mass ratio distribution are a function of L_c in the NASA breakup model, only the mean and 2σ values are plotted from the distribution. Fragment area-to-mass ratios from the simulation are plotted as individual dots.

Concerning the area-to-mass ratio of fragments, we found that the majority of fragments lie close to the predicted mean A/M (Figure 9). The distinct vertical lines in the eroded fragments are due to the way in which eroded element areas and chararcteristic lengths are calculated. Above, we described how the characteristic length of eroded fragments is calculated based on its mass, and since mass is conserved in each finite element, this value stays constant throughout the simulation. The area, on the other hand, changes depending on the loads and strains experienced by the element before it is eroded.

We have demonstrated the capabilities of the »PHILOS-SOPHIA« software tool to numerically simulate complex spacecraft collisions and analyze the fragmentation behavior. We found both good agreements and clear deviations when compared to the standard empirical breakup model. Due to the strong influence of the collision geometry, we did not find a strongly noticeable breakup limit depending only on the energy-to-mass ratio. More research is needed to define generalized criteria for catastrophic collision conditions.

4 Experimental Techniques for Validation

The established PHILO-SOPHIA tool is a powerful method to study collisional fragmentation in a wide parameter range. However, like all numerical methods, it requires thorough backing by experimental data for fidelity. While experiments are limited in scope and complexity, they can provide precise data for carefully verifying numerical simulations for fidelity. One aspect is the description of the mechanical (and thermodynamic) properties of involved materials in a wide range of dynamic loading conditions. Another aspect is the direct validation of collision scenarios in experiments.

We have used typical experimental data to validate the numerical method qualitatively. Advances in high-speed imaging and new methods in particle tracking now allow for gaining more quantitative data on fragments from hypervelocity impact experiments. We have developed new methods for identifying and tracking individual fragments in experiments [Wat17b]. Further developing the technique has led to the extension of the method into 3D as shown in as illustrated in Figure 10.

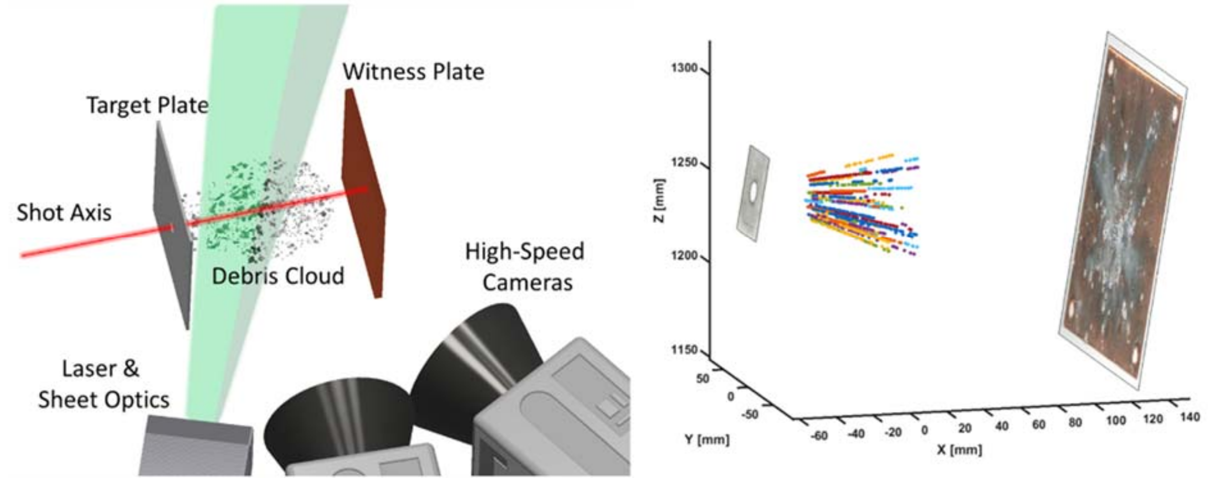


Figure 10: Laser sheet method with stereoscopic camera setup. Left: schematic of experimental setup showing the laser sheet illuminating debris fragments, which are recorded by two high-speed cameras. Right: measured fragment locations shown in three-dimensional coordinates along with target and witness plates.

This means that measurements are no longer constrained to radially symmetric cases, allowing for quantitative investigations of more complex geometries. Such experimental data allows for directly validating fragmentation simulations with experimental outcomes and, thus, paving the way for systematically studying spacecraft breakup behavior.

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6 Abbreviated terms

CAD	Computer-Aided Design
CFRP	Carbon-Fiber-Reinforced Plastic
EMI	Ernst-Mach-Institut
EMR	Energy-to-Mass-Ratio
GUI	Graphical User Interface
HVI	Hypervelocity Impact
ISO	International Organization for Standardization
LAD	Large Aperture Detector
LOFT	Large Observatory for X-ray Timing
SPH	Smoothed Particle Hydrodynamics
SSBM	Standard Satellite Breakup Model

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