Hypervelocity impact damage prediction in composites: Part II—experimental investigations and simulations

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Abstract

The extension of damage in composites during hypervelocity impact (HVI) of space debris is controlled by failure thresholds and subsequent energy consumption during damage growth. Characterisation and modelling of the material under partially and fully damaged states is essential for the prediction of HVI effects on fibre-composite structures. Improved experimental and numerical analysis techniques have been developed and are summarised in an accompanying paper. The present paper deals with the establishment of two precise damage experiments under HVI conditions as a validation basis for numerical simulations: The first type consists of space debris impact configurations optimised for damage evaluation and the second experiments reproduce HVI strain rates and compressions in plate impact. Coupling of damage analysis techniques (visual, ultrasonic, residual strength) to quantify different aspects of failure has been achieved. Numerical simulations using the commercial hydrocode AUTODYN in mesh-based and SPH formulations are presented using the material model and data described in the accompanying paper.

Keywords: Delamination; Composite; Damage modelling; Residual strength; Plate impact

1. Introduction

Model approaches for dynamic behaviour and damage in composite structures caused by hypervelocity transverse shock loading need to replicate several key aspects of mechanical behaviour: Non-linear equation of state properties must describe the shock impedances for accurate prediction of compression and release states with phase changes and spallation [1]. Orthotropic strength is a key aspect of composite in-plane behaviour to be coupled to equation of state properties. Characterisation and modelling methods coupling these aspects of directional non-linear mechanical properties have been developed recently [2] and are described in an accompanying paper [1].

In Ref. [1], application of the numerical technique is demonstrated on the examples of the space debris protection shield of the International Space Station (ISS) Columbus module involving aramid fibre-reinforced plastics (AFRP) as an intermediate bumper. The aim of the present study was to enlarge the validation basis...
by adding controlled damage experiments and loading conditions relevant for hypervelocity impact (HVI) applications. Combinations of non-destructive and destructive testings of the damaged samples should enable in-depth analysis of the aspects of ‘damage’ and couple different evaluation techniques. Two types of HVI damage experiments have been developed and used for validation of the new model approach (Table 1).

All tested composite material consisted of 18 layers of $0^\circ/90^\circ$ woven Kevlar 129/812 fabric (aramid) with 38% mass content of epoxy resin Ciba 914 (Hexcel® prepreg: 914/38%/812). The slightly cylindrical panels, curved to an external radius of 2163.2 mm, correspond to the intermediate composite bumper configuration of the European ‘Columbus’ module of ISS.

### 2. Debris cloud damage

#### 2.1. Impact conditions

Whipple shield configurations consisting of an aluminium bumper layer and a composite plate impacted by an aluminium projectile have been optimised in view of validation of computational damage models. Experimental knowledge in HVI testing and predictive simulations were used (see Fig. 1) for pre-test optimisation of the design with respect to

- **Ballistic limit:** Only a small central perforation should occur.
- **Shatter region:** Smooth transition of hit densities from the central impact region to the outer damage area should be reached by avoiding a large central fragment.
- **Cloud extension:** By maximising this parameter a large damage transition area should be produced but fully contained in intact surroundings of the sample plate.

<table>
<thead>
<tr>
<th>Overview and damage experiment types</th>
<th>Discussion</th>
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<tbody>
<tr>
<td><strong>Damage generated by</strong></td>
<td></td>
</tr>
<tr>
<td>HVI debris cloud</td>
<td>+ Very close to applications</td>
</tr>
<tr>
<td></td>
<td>+ Damage gradient adapted for validation</td>
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<tr>
<td></td>
<td>- Locally statistical impact conditions</td>
</tr>
<tr>
<td>Plate impact</td>
<td>+ Precise and recorded impact conditions</td>
</tr>
<tr>
<td></td>
<td>+ Relevant strain rates and pressures</td>
</tr>
<tr>
<td></td>
<td>- Mainly plane compression and release waves</td>
</tr>
</tbody>
</table>

*Note:* + advantages, – limitations.

Fig. 1. Left: Predictive simulation using base line model [3]. Right: High-speed shadowgraphs (28 vs, 55 µs; exposure 100 ns) of fragment cloud impact onto composite plate (experiment 4355).
The resulting three configurations consisted of an aluminium sphere (diameter 7.0–8.2 mm) fragmented during perforation of a 2 mm aluminium plate at 4.7 km/s (Table 2). A clear distance of 150 mm to the 5.7 mm composite plate permitted the fragment cloud to expand to a lateral extension of about 360 mm diameter. High-speed shadowgraphs (exposure time 100 ns) are shown in Fig. 1, right. It can be seen that only a small central area is fully perforated. The rest of the plate is impacted and damaged by a wide range of fragment densities.

2.2. Visual damage inspection

Visual inspection of the samples proved good pre-test prediction: all three fragment clouds loaded the composite plates slightly above the ballistic limit in the very centre of the impact cloud. The impacted faces of the plates are shown in Fig. 6. Fig. 2 gives additional views of plate 4355.

In experiments 4354 and 4356 with 7 mm spheres no clear hole was noticed but scratches on witness plates behind the composite indicated composite fibres ejected from the rear surface. Loading with an 8.2 mm sphere produced a small but clear hole in the composite. In all cases, damage can be categorised into two zones:

- **Primary damage** in the central area with high hit densities and clearly visible surface delaminations on the front face.
- The adjacent area of **secondary damage** shows isolated, local impacts without obvious coalescence of damage or delamination on the surface. The observed damage patterns are summarised in Table 3.

2.3. Non-destructive damage characterisation

Through thickness failure was analysed by ultrasonic measurements before sectioning of the target for further evaluations described below. The composite panels and the ultrasonic detector were placed in water for

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**Table 2**

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>4354</th>
<th>4355</th>
<th>4356</th>
</tr>
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<tbody>
<tr>
<td>Projectile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material</td>
<td>Al 99.98%</td>
<td>AlMg3 (Al5754 H34/1/2 hard)</td>
<td>AlMg3 (Al5754 H34/1/2 hard)</td>
</tr>
<tr>
<td>Density (g/cm³)</td>
<td>2.70</td>
<td>2.70</td>
<td>2.70</td>
</tr>
<tr>
<td>Diameter (mm)</td>
<td>7.00</td>
<td>8.20</td>
<td>7.00</td>
</tr>
<tr>
<td>Mass (weighed in mg)</td>
<td>474.44</td>
<td>770.88</td>
<td>474.86</td>
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<tr>
<td>Impact velocity (km/s)</td>
<td>4.75</td>
<td>4.68</td>
<td>4.81</td>
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<tr>
<td>Impact angle</td>
<td>0°</td>
<td>0°</td>
<td>0°</td>
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</tbody>
</table>

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**Fig. 2.** Visible damage on impact and rear face. Definition of damage measures.
transmission of longitudinal waves from the source into the test object and back. The pulse travels through the water and is partially reflected at every impedance boundary such as the front side, discontinuities in the material or the rear surface of the sample.

The scanning area captured 320 × 320 mm with a scanning step of 0.2 mm. An analysis gate defined the range d1–d2 through thickness between the front side and back wall echoes to avoid misinterpretation of the plate free surfaces. The values refer to the front side, the position of which is following the curvature of the composite panels. The location of the intermediate echo, caused by delamination, correlates with the depth of the defect. A lower sensitivity threshold value d3 of 16–19% intensity was used to suppress background noise (see Fig. 3).

Fig. 6 shows scan results of the three panels from the impact side. Fig. 3 gives additionally the rear view, as only the depth of the first delamination detected in the analysis gate can be displayed in any scan. The grey scaling of the plate refers to the delamination depth measured between the specified limits d1 and d2. The following observations could be stated:

- Large areas of delamination are shown also in the outer zones where only isolated impacts occurred. The delaminated areas clearly exceed the visible ranges of heavy damage d1,f.
- Beginning from a central region of delamination through the complete thickness, the damage in the secondary region is cone shaped towards the rear surface.
- The damage patterns are mostly circular, slightly flattened normal to the laminate axis.

### Table 3
Visible composite damage after debris cloud impact; damage measure defined in Fig. 2 (right)

<table>
<thead>
<tr>
<th>Number</th>
<th>Front</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Primary damage</td>
<td>Secondary damage</td>
</tr>
<tr>
<td></td>
<td>d1,f (mm)</td>
<td>d2,f (mm)</td>
</tr>
<tr>
<td>4354</td>
<td>110</td>
<td>110</td>
</tr>
<tr>
<td>4355</td>
<td>110</td>
<td>135</td>
</tr>
<tr>
<td>4356</td>
<td>110</td>
<td>105</td>
</tr>
</tbody>
</table>

Perforation in composite/effect on witness plate

4354  Some composite layers completely destroyed, no clear hole/few scratches on witness panel
4355  Clear perforation hole visible/two bulges; distance from centre and several small bulges in the middle cratered area about 100 × 90 mm
4356  Some composite layers completely destroyed, no clear hole/few scratches on witness panel

Notation: d1,PS, diameter of damaged composite layers. Index: f, front; r, rear; 1, vertical; 2, horizontal.

Fig. 3. Left pair: Depth of delamination measured from impact and rear side: cone-shaped delamination shape. Right pair: Intensity of reflection from impact and rear side.
– The large sphere (8.2 mm, no. 4355) creates a bigger central damage zone especially on the rear surface compared to the smaller projectile of equal strength (7.0 mm, no. 4354). But the total area around the outer zones of damage is of the same size.
– Comparing effects created by the small spheres (no. 4354 and 4356), the harder alloy (no. 4356) provides a smaller extent of damage with a sharper transition zone. The delamination cone is steeper through thickness.

2.4. Destructive testing: visible inspections and residual strength

Sectioning in strips of 20 mm width, visual inspection and residual strength testing provided deepened insight to the amount of damage. Hydrocutting was used to minimise additional damage. Visual inspection of all sections, as exemplarily demonstrated in Fig. 4, showed very fine delaminations in the zone of secondary damage, proving high sensitivity of ultrasonic scanning.

Advanced damage measures in constitutive models not only describe the areal extension but also the quantitative effects in terms of strength or stiffness loss. To establish the link between observed damage and its strength effects, local shearing was applied to every section as shown in Fig. 5. Testing every 30 mm (see scale

Fig. 4. Visual inspection of in-depth damage after sectioning: example central section 4355_8 (out of 16). Positions of transverse shear testing 0, 3, 6, ..., 30 of each section.

Fig. 5. Left: shear test curves of section 4355_8. Right: Damage distribution (shear strength ratio) in plate 4355.
above Fig. 4) provided a strength analysis grid with 20 × 30 mm resolution in the central area of 300 × 300 mm of each composite panel. A surface plot of damage in terms of shear strength degradation is shown in Fig. 5, right.

Fig. 6 correlates visual surface damage, depth of delaminations and strength reduction for all three plates. Quantitative comparison of all three techniques provides:

– Secondary damage by isolated cloud fragments causes substantial delamination around the primary damage zone.
– Although hardly visible in sections, delamination in the secondary damage zone reduces the shear strength by 10–30%.
– Ultrasonic scanning can detect secondary damage with high resolution.
– Primary damage results in strength and stiffness losses from 60% to 100%.

2.5. Simulation of HVI damage experiments

The axisymmetric simulation model of test 4355 was established using smooth particle hydrodynamics discretisation (AUTODYN [4], Fig. 7). A smoothing length of 0.2 mm throughout allowed one to resolve the composite panel with 29 particles through thickness. The Al2017A bumper shield of thickness 2.0 mm was modelled to a radial extent of 75 mm (3750 particles), and the nominally 5.7 mm thick Kevlar-epoxy target to 200 mm (29,725 particles).
More realistic simulations of the outer area with loading by isolated fragment impacts were achieved by additional three-dimensional models. However, meshing with 0.6 mm diameters or only three particles through composite thickness already resulted in a total of 590,000 particles. Details on composite material model and data for both approaches are given in Ref. [1]. Analysis of the simulation allows the following conclusions:

- The central perforation hole is very accurately predicted by the modelling approach. Earlier model approaches [5] with shock and orthotropic strength descriptions but simpler failure models provided too large perforation holes (Fig. 1, left).
- Extents of surface damage on front and rear faces are well captured.
- In-depth delamination is correctly modelled in the primary damage zone. Coalescence in the secondary zone is partly replicated as damage and plastic strain in the fine axisymmetric model with tendency to underpredict the extent.
- The implementation of the model in three-dimensional SPH discretisation provides in the coarse model qualitatively good results. Higher mesh refinement with the associated computational effort would be required to validate in detail the extent of delamination (Fig. 8).
3. Plate impact damage

Locally varying loading conditions are an inconvenience of the above-described debris cloud damage experiments. Statistics become more important for the smaller damage amounts in the secondary zone, making validation of limited degradation more difficult.

Therefore, small amounts of damage at relevant stresses and strain rates for HVI applications have been generated in additional experiments of uniaxial strain loading. Two types of ‘plate impact damage’ experiments have been performed on the basis of established flyer plate methods. The first type of axial compression and subsequent axial tension (spallation) is described and validated in Ref. [1]. The following description will focus on the second type of multiple dynamic compression and later radial extension.

A symmetric configuration of composite and aluminium plates was used to prevent heavy delamination caused by superposition of release waves. In this way pre-damaged but solid, monolithic plates could be produced to perform residual strength tests. Properties of plates and impact velocities for all tests are summarised in Table 4.

Owing to the symmetric impact conditions, half of the projectile momentum is transferred to the target. Considering the different impedances of composite (AFRP) and aluminium (Al), the $\sigma$–up and the $X$–$t$ diagram can be derived according to Fig. 9. Pressure in the composite samples increases stepwise up to the state (3,III) before release waves (5) and (V) from the backing and target free surface arrive inside the composite plates. Subsequently the compressive stress is iteratively decreased by complex wave superposition, but no tensile loading in through thickness direction occurs during the whole process. However, tensile loading and complex stress–strain states occur when lateral release waves arrive from the circumference. At these late stages, no one-dimensional analysis of stress and strain states is possible, but the loading history can be numerically simulated in two dimensions, e.g. using axisymmetric modelling approaches.

The free surface velocity measured with the VISAR during early stages of the plate impact damage experiments is shown in Fig. 9, right. They were not used to derive directly constitutive data, but to validate simulated free surface velocities of the early arriving stress waves. For the lowest impact velocity of 124.4 m/s

<table>
<thead>
<tr>
<th>Test number</th>
<th>2606</th>
<th>2607</th>
<th>2608</th>
<th>2609</th>
<th>2610</th>
</tr>
</thead>
<tbody>
<tr>
<td>Projectile thickness (Al+comp.) (mm)</td>
<td>10.00 + 5.63</td>
<td>9.96 + 5.63</td>
<td>10.01 + 5.64</td>
<td>10.00 + 5.56</td>
<td>9.96 + 5.52</td>
</tr>
<tr>
<td>Target thickness (comp.+Al) (mm)</td>
<td>5.63 + 10.00</td>
<td>5.56 + 9.95</td>
<td>5.57 + 10.01</td>
<td>5.58 + 10.00</td>
<td>5.52 + 10.00</td>
</tr>
<tr>
<td>Impact velocity (m/s)</td>
<td>124.4</td>
<td>206.6</td>
<td>276.1</td>
<td>255.6</td>
<td>241.7</td>
</tr>
</tbody>
</table>

Fig. 9. Lagrange and $X$–$t$ diagrams of symmetric uniaxial strain damage experiment. Right: Measured and simulated free surface velocities. Similar stress wave levels occur for the baseline model ‘AMMHIS’ [3] and the new ‘ADAMMO’ approach [1].
(no. 2606), almost no damage is apparent on the recovered samples. With increasing impact velocity more stiffness loss can be assumed from visible inspection. For intermediate to fast impacts, up to 276 m/s delamination of the discs are observed.

In the same manner as the debris cloud damage panels, the preloaded plate impact samples were sectioned to 20 mm strips and shear tested. Fig. 10 shows the measured shear stiffness and strength decrease. Already 124 m/s impact loading caused strength and stiffness decreases by 25–30%. Above 220 m/s, the plates are mostly damaged with a residual strength of about 20%. Again, delaminations hardly observable in sections have major effects on the residual strength.

The experiments were simulated using the composite model approach [1]. Lagrangian cells of size 0.125 mm$^2$ were used to model the thickness of the composite plates in axial symmetry. Fig. 15 shows the comparison of simulated free surface velocities of the aluminium target plate. Differences were observed in detail of shock amplitudes and deceleration by release waves. But the overall match of acceleration during the first 20 µs proved good replication of the momentum balance between projectile and target plates. Interestingly, the earlier model approach [3] describing non-linear equation of state with linear-orthotropic strength and instantaneous failure simulates very similar free surface velocities. Obviously, the uniaxial strain compression properties are not strongly influenced by additional dissipation from non-linear inelastic deformations as modelled in the new approach.

Detailed consideration of simulated deformation and damage contours (Fig. 11) shows that the new damage model replicates the intact composite samples. Delamination damage is not directly predicted (as ORT DAM 11). But the slowest impact velocities cause plastic deformations up to 3% and up to 10% local deformations are reached in the samples impacted at 276 m/s. Compared to the previous model approach with linear-orthotropic strength up to failure, much improved prediction of material states is observed. With the earlier model, both loading types caused complete through thickness delamination, which was not observed experimentally.

4. Conclusions

Delamination damage in the aramid–weave–epoxy composite panels impacted by space debris clouds extends far beyond the area of primary damage into areas where only isolated impacts are visible on the surface. In the secondary zone of the debris cloud damage test, ultrasonic testing detected very fine areal delaminations, which were hardly visible in sections of samples.

However, subsequent destructive shear testing across the samples showed the important mechanical effects of small delaminations on shear stiffness and strength. The following damage quantities could be identified:

- The zone of primary damage with high densities of impacting debris resulting in obvious surface delamination correlated with strength and stiffness losses from 100% to 70%.
In the zone of secondary damage with low hit densities and isolated impacts, delaminations extended almost to the external limit of debris impacts. They caused strength and stiffness losses from 20% to 60%.

Loading by hypervelocity debris clouds results in strong local variations, especially in the secondary zone of the debris cloud damage experiments. These variations make validation of numerical methods in the area of limited degradation more difficult. Therefore, plate impact damage experiments were designed to create smaller damage amounts under well-defined loading conditions at relevant strain rates. A number of samples ranging from weak damage (<30%) to strong damage (80%) could be produced and recovered. Sectioning, visible inspection and shear testing again underlined the effect of hardly visible in-depth delaminations on strength degradation. Free surface velocities were recorded using VISAR techniques to validate numerical simulations.

Numerical simulations with the SPH and mesh-based hydrocode AUTODYN [4] of both debris cloud damage and plate impact damage experiments were performed with the new composite model introduced in Refs. [1] and [2]. For both loading types, improved damage and directional plasticity patterns could be described. In contrast to excessive delamination in earlier approaches [3], the new model provides contained delamination with tendency to slight underprediction in areas of weaker loading. But summing up, deformations and damage of the aramid–weave–epoxy composite plates (ISS configuration) could generally be well simulated.

The modelling approach seems generally applicable to high-strength composite structures, as they show similar deformation phenomena, but more brittleness. Predictive simulations of aluminium honeycomb structures with face sheets of carbon fibre-reinforced plastics (CFRP) gave promising deformation and

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**Fig. 11.** Simulated plate impact damage tests: negligible damage, permanent strains below 3% for 124 m/s impact; strains up to 10% for 276 m/s impact, no delaminations simulated. Overpredicted failure simulation with earlier model status [3].

- In the zone of secondary damage with low hit densities and isolated impacts, delaminations extended almost to the external limit of debris impacts. They caused strength and stiffness losses from 20% to 60%.
damage patterns (see Fig. 12 and Refs. [2,6]). These types of structures are currently applied in numerous satellites and spacecraft.

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References


