Simulation of the high velocity impact of railway ballast on thermoplastic train underbody structures

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1 Abstract

Railway transportation represents an environmentally friendly alternative to automotive transportation for long distance travel. In the project Next Generation Train of the DLR, new railway solutions are developed for passenger and freight transportation for a broad range of applications (intercity, cargo, long distance). Specifically, the high-speed train NGT HST aims at reducing travel times and specific energy consumption with new technologies. At the maximal operating speed of 400 km/h, the coupling of mechanical and aerodynamical forces leads to increasing risks of ballast stone impact on the train structures (in particular underbody structures), thus threatening primary components underneath [1]. Through the repetition of stone impacts during the entire lifetime of a structure, critical damage can occur and reparation or replacement concepts are required. The present work aims at investigating an impact-resistant underbody structure made out thermoplastic composite materials for the HST train on numerical and experimental basis. By considering multiple impact scenario in the structure sizing process, the project intends to reduce the interval at which the structure has to be replaced.
Starting with two combinations of thermoplastics and preforms, an experimental test campaign is performed on specimen scale to investigate their impact resistance at low velocities. The most promising material is then tested on component level under high-velocity impact at the gas gun DLR facility. Tests on single ballast stones are performed as well for validation of the numerical methodology.
As support to time and material expensive test methods, a numerical framework is developed within LS-DYNA at all levels from low to high impact velocities. The composite parts are automatically modelled with stacked TSHELL and cohesive-element interfaces via **`*PART_STACKED_ELEMENTS`**. Composite materials and interface use the state-of-the-art material models **`*MAT_262`** and **`*MAT_240`** respectively. Random ballast stones geometries are automatically generated with the Voronoi tessellation and simulated with DEM particles.
The present paper illustrates key aspect of the modelling techniques and their influence on the numerical impact behaviour. Furthermore, achieved results along the test pyramid are presented.

2 Introduction

The project Next Generation Train (NGT) aims at developing new multi-purpose railway structures for different applications from passenger to freight transportation such as the NGT HST and NGT CARGO respectively. In the current project phase, a double end carriage is developed commonly for the two train configurations and sized for a maximal speed of 400 km/h. The definition of the installation space and of the carriage's architecture is carried out at the Institute for vehicle design DLR-FK [2] (Figure 1 left) and the design concept deals as input for the sizing of an underbody shielding at the Institute for Structures and Design DLR-BT in Stuttgart (in red in Figure 1 right). The shielding consists in a flat panel of 1200 mm x 1400 mm reinforced with omega-shaped profiles. Through the use of thermoplastic materials, a direct bonding between these two parts results from the manufacturing process.

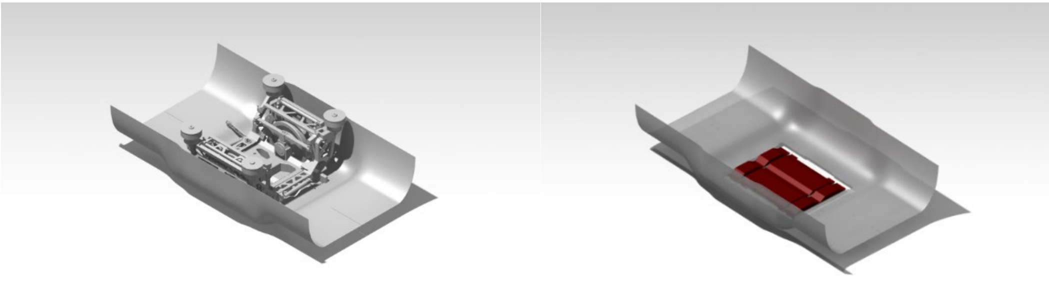

Fig.1: Train undercarriage (left) and investigated underbody structure (in red, right)

At high train speed, ballast stones are set in movement through the effect of aerodynamic forces and represent a risk of impact with the underbody structures and equipment [1]. In winter, the detachment of accumulated ice from the underbody structure can create a secondary impact scenario in which ballast stone are projected with high velocities up to 60 m/s on the train structures (Figure 2) [3]. [4] and [5] shown that the risk and the probability of ballast impact are highly increasing with increasing train speed.

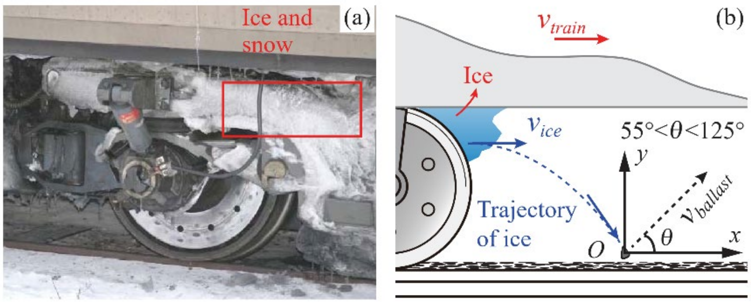

Fig.2: a) accumulation of ice on the underbody structure and b) detachment mechanism leading to ballast impact [3]

The present work investigates the potential of fibre-reinforced thermoplastic materials for the underbody shielding under impact loading. While norms exist for impact scenarios on windshield under perpendicular impact, no valuable norm could be found for impact on underbody structures. As a consequence, a generic sizing condition is defined for the sizing process in this work. The shielding shall completely absorb the impact without complete fibre failure through the thickness of the structure. Moreover, and given a repair frequency, the structure shall sustain a certain number of high-velocity impact events without catastrophic failure. As an example, five consecutive impact events will be considered.

In a first step, a modelling tool is proposed to generate and mesh random stone geometry with the Discrete Element Method (DEM). The quasistatic and dynamic behaviour of ballast stone is simulated and validated with an experimental test campaign. Then, a fibre-reinforced thermoplastic material is investigated in simulation and experiment. The results are then coupled in high-speed multi-impact simulations on composite structures.

3 Experimental work

3.1 Characterization of ballast stone

To guarantee a good cohesion of the ballast bed, ballast stones possess a specific geometry, size and weight, which have been intensively investigated in literature [6]. While their size can vary between 10 mm and 60 mm and their weight between 2.5 g and 200 g, their shape or length-to-width ratio remains almost constant as shown in Figure 3. In literature, the compression behaviour of ballast bed has been widely experimentally characterised. However, few studied the mechanical properties and failure modes of single ballast stones. In this work, single stones are compressed between two steel plates up to failure and under quasistatic loading (Figure 4). Depending on the stone geometry and on the sharpness of their surface, different compressive responses can be observed, from brittle failure modes at medium force levels to more crushing-like failure modes leading to high reaction forces. The observed behaviours deal as validation for the numerical approach.

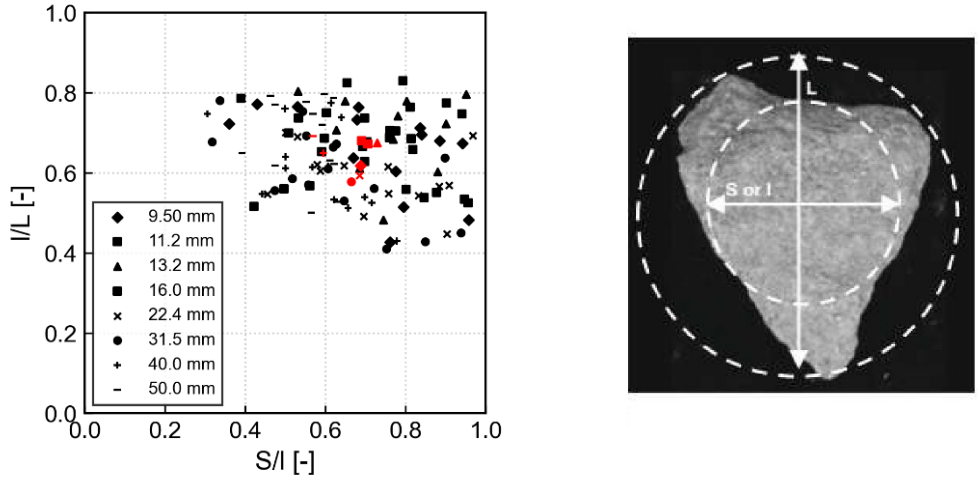

Fig.3: Length to width ratio of ballast stones depending on their average size [6]

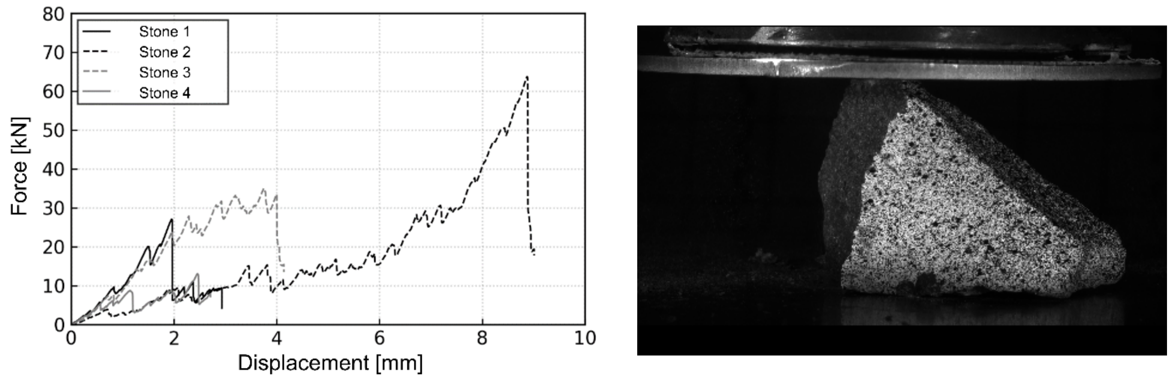

Fig.4: Force-displacement response of single ballast stones under quasistatic compression loading

3.2 Investigation of the impact behaviour of thermoplastic materials

Fibre-reinforced thermoplastics possess a higher energy absorption potential than fibre-reinforced thermosets, due to the high failure strains of the resin system and of their thermal properties [7]. In this work, one industrial glass-fibre reinforced thermoplastic from Toray Industries is investigated, namely the woven TC1100 with polyphenylene sulphide matrix. To reduce the experimental effort, no test will be performed on the specimen scale and the test campaign will focus on the impact behaviour of the materials. The quasi-static mechanical properties of the material are taken from the manufacturer's datasheets and the strain-rate dependent behaviour of the composite material is estimated based on literature values for similar materials. For the investigations, 3 mm-thick plates with 14 woven layers have been manufactured at Toray.

The impact behaviour is investigated on a fall tower with a 16 mm impactor head and a weight of about 6 kg. 150 mm x 100 mm composite plates are impacted at different speed for an impact energy of 10 J, 25 J and 40 J. Force and displacement measurement (Figure 5) are performed with the Digital Image Correlation measurement system from LIMESS [8]. Up to 40 J, the impact energy is absorbed through the failure of the composite yarns in tension and compression as well as through crack initiation and propagation. At 40 J, total fibre failure is observed through the thickness, leading to a plateau in the force-displacement curve. At this point, energy is mainly absorbed through further propagation of cracks and delaminations or via friction mechanisms in the failed woven material. The results are the basis for the validation of the finite-element model.

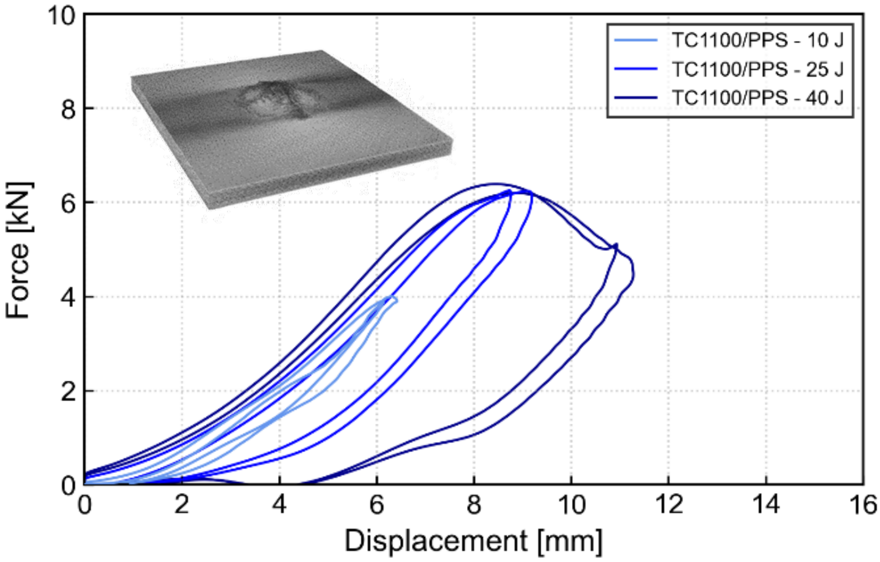

Fig.5: Force-displacement responses of TC1100 plates under low-velocity impacts and reconstruction with Computer-Tomography of the impacted region

4 Simulation work

The simulation work aims at developing and validating simulation methods for the modelling and simulation of ballast stones and of thermoplastic materials. All simulations are performed on the DLR cluster in MPP double precision with the solver version 10.2.0 on 16 CPUs. In the following, the modelling techniques are documented and the main findings are presented.

4.1 Modelling approaches

Several material models exist in LS-DYNA to simulate the behaviour of concrete-like, brittle materials (**`*MAT_072`**, **`*MAT_096`**, **`*MAT_159`**) but they generally require intensive characterization efforts. On the contrary, the DE method offers a straight-forward modelling with few parameters to describe the failure of the bond between two neighbour particles in **`*DEFINE_DE_BOND`**. The stone geometry is randomly generated with the Voronoi Tessellation technique by dividing a cube with a user-defined size into subdomains of similar volumes. The geometry and sharpness of the domains is controlled with a user-defined parameter as well, resulting in different stone characteristics. The generated domains are finally meshed with solid elements and DE particles are generated based on the solid mesh using an internally developed python script (Figure 6). The statistical repartition of the stone characteristic is in good correlation with investigations from literature [6], as shown in Figure 7.

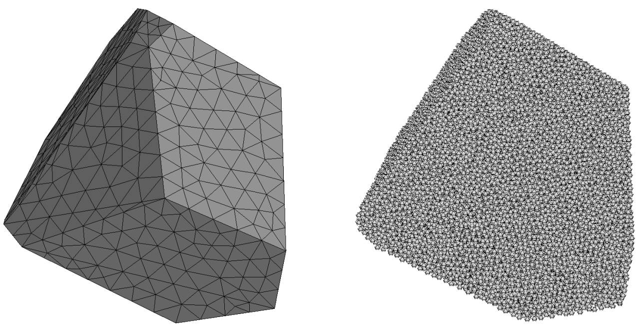

Fig.6: Generated solid mesh for a ballast stone and resulting DE particles

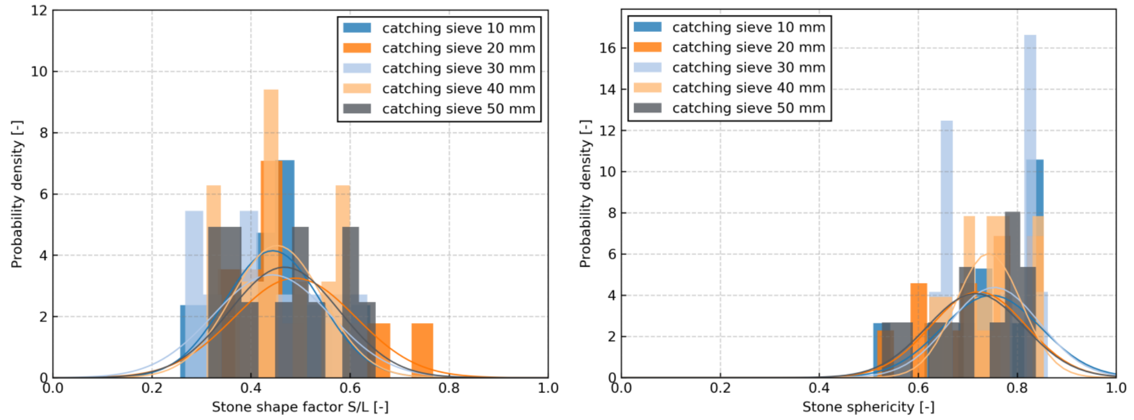

Fig.7: Statistical distribution of the shape factor and sphericity of the generated stones

The material parameters for the failure are adjusted to recreate the compression tests from paragraph 3. The simulation result is inherently dependent on the size of the discrete particles and a sensitivity study is performed to define the optimal particle size in regards to the computation time (Figure 8). The numerical results successfully depicted the brittle failure of ballast stones and a particle size of 1 mm was necessary to reach a satisfying convergence. An adjustment of the parameter **MAXGAP** guaranteed a correct bond between particles. The defined parameters in Table 1 remained unchanged at all further simulation scales.

Table 1: Material parameters for the stone with the DE method

RHO	PBN	PBS	PBN_S	PBS_S	SFA	ALPHA	MAXGAP
5,0e-6 kg/mm³	50 GPa	0.2 GPa	0.030 GPa	0.030 GPa	1.2	-	1.5

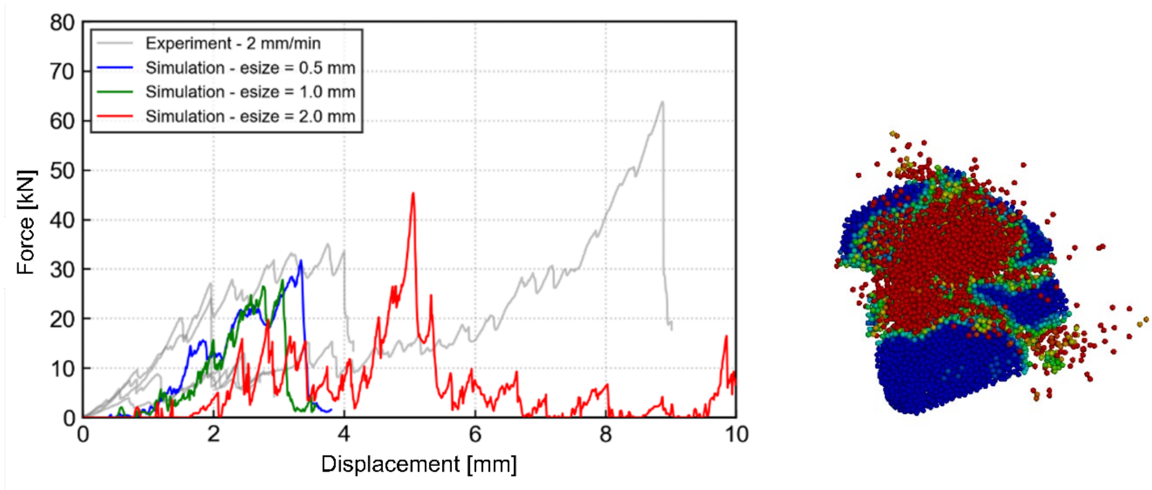

Fig.8: Sensitivity of the compression response to the particle size (left) and brittle failure pattern (right)

Composite materials under impact loading are particularly sensitive to delaminations. In order to simulate precisely their failure mechanisms, the stacked element approach has been chosen for the thermoplastic material, in which each fabric layer is modelled with a single ply of thick shell elements. To avoid tedious meshing steps, the thick-shell meshes including cohesive interfaces are automatically generated using ***PART_STACKED_ELEMENTS** starting with a shell mesh representing the lower surface of the composite and given a user-defined number of layers to generate. The composite plies are modelled with the 3D thick shell elements with **ELFORM 5** and the cohesive layer with solid elements with **ELFORM 19**. Based on literature data and manufacturer's datasheets, a material card ***MAT_262_LAMINATED_FRACTURE_DAIMLER_CAMANHO** is generated for the composite material which considers strain-rate dependency of the strengths and of the energy release rates. The cohesive zone is modelled with ***MAT_240_COHESIVE_MIXED_MODE_ELASTOPLASTIC_RATE**, which trilinear traction-separation law is adjusted to fit previously performed short beam shear (SBS) tests. In particular, the plateau in the cohesive zone model, described with the parameter **FG1** and **FG2**, has a strong influence on the delamination behaviour. As for the stone model, no change of the material parameters will be undertaken through all simulation scales.

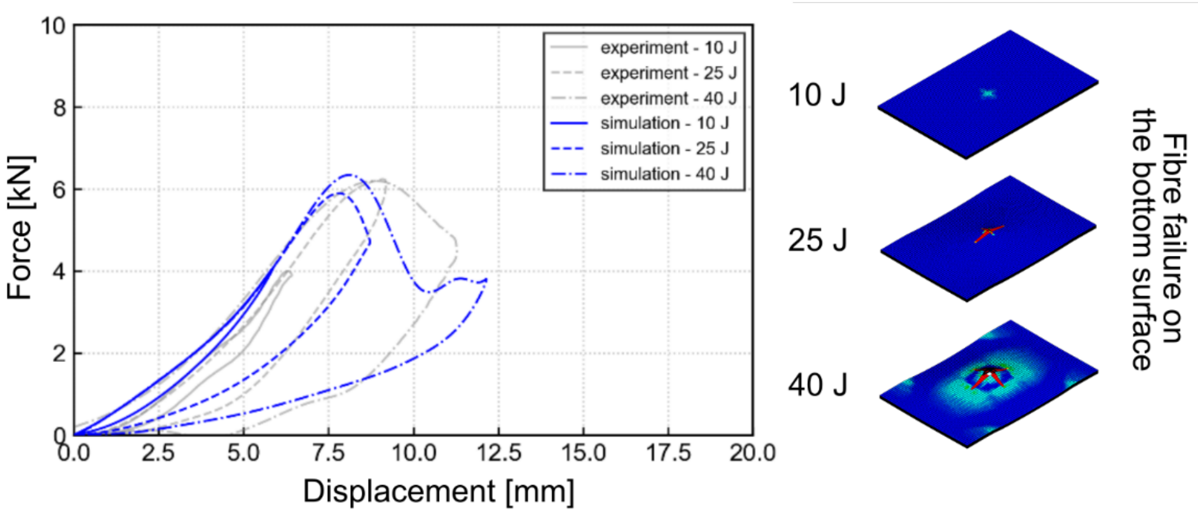

Fig.9: Simulation of the low-velocity impact tests for three impact energies

To validate the numerical approach, the low-velocity impact tests described in paragraph 3 are reproduced in simulation using the same boundary conditions. The simulation results are in very good agreement with the experimental curves as shown in Figure 7. The maximal force is well reproduced in simulation for every impact energy. The simulation predicts the drop in the reaction force at 40 J due to the complete failure of the laminate in the impact zone as well (Figure 9). However, the drop observed in the simulation is stronger than in experiment because of the element erosion occurring at large local strains (Figure 10). An increase of the energy release rate in the fibre failure modes could change slightly the post-failure behaviour of the plate.

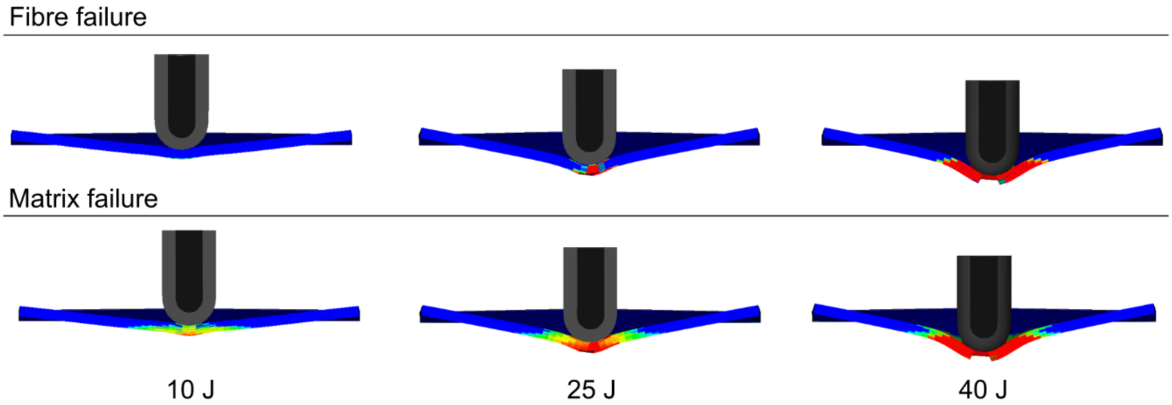

Fig.10: Failure modes in the TC1100 plate under an impact with 10 J, 25 J and 40 J

4.2 Simulating the impact behaviour of railway ballast on a composite structure

The validated stone and composite models are finally coupled in the structure simulation, which simulates consecutive impacts with random stones, random impact angles and velocities (horizontal and vertical) on a 5 mm thick shielding. Figure 11 illustrates the parametrization of the impact conditions and the positions of the simulated impacts. The boundary to the surrounding structure is modelled with solid element and an elastomer material (in green in Figure 11). Previous simulations of the impact of stones on flat panels, which won't be developed in detail in this paper, dealt with the sizing of the shielding thickness to guaranty the structural integrity after multiple impacts.

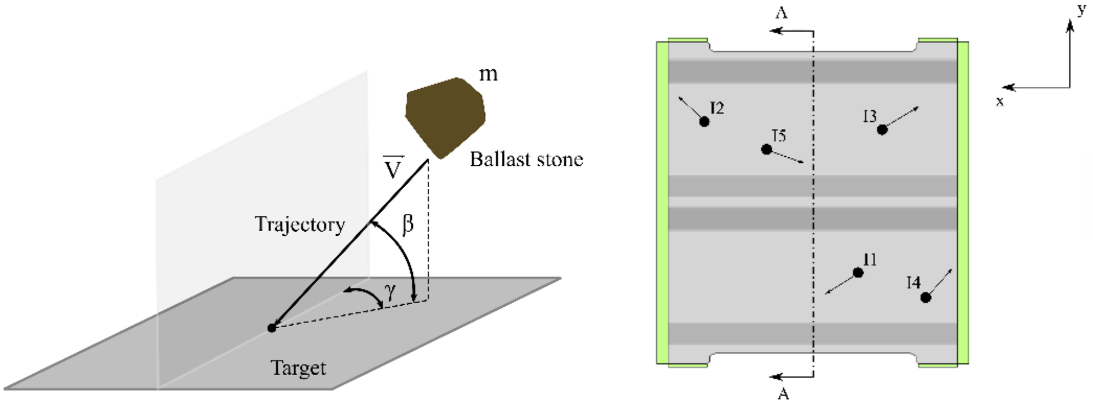

Fig.11: Parametrization of an impact scenario (left) and positions of the simulated impacts (right)

The simulated impacts have an energy between 250 J (52 g and 100 m/s) and 1100 J (185 g and 108 m/s). The first impact with the highest energy creates a large delaminated area, which however have a small influence on the later plate behaviour. The DE model depicts well the splitting of the ballast stone through shear forces under the impact loading (Figure 12). Due to the plate thickness of 5 mm, no large fibre failure is visible after the five simulated impacts (Figure 13). Most of the energy is absorbed by the principal flat panel through the damage of the composite material as shown in Figure 14. Friction between the delaminated layers and between the panel and the stone represent one fourth of the overall energy dissipation. The reinforcing secondary panel does not contribute much to the energy absorption and only stiffen the principal panel. Its further function is to offer a second protection to the primary components in case of a critical perforation of the first panel.

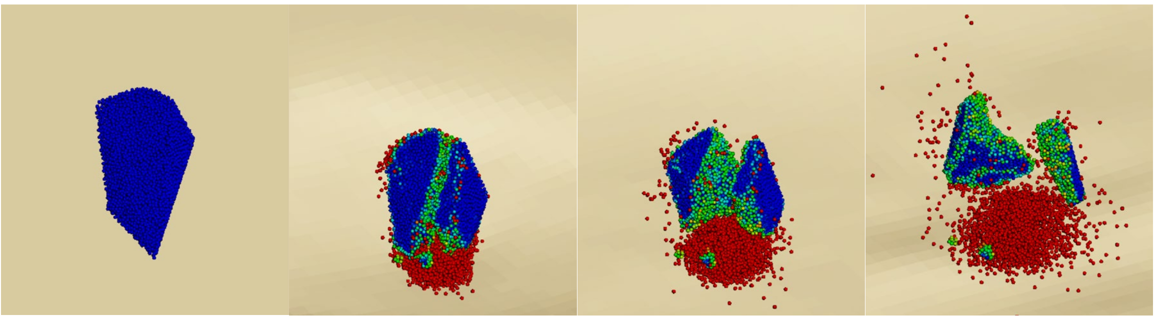

Fig.12: Failure of the ballast stone during the first impact on the composite plate

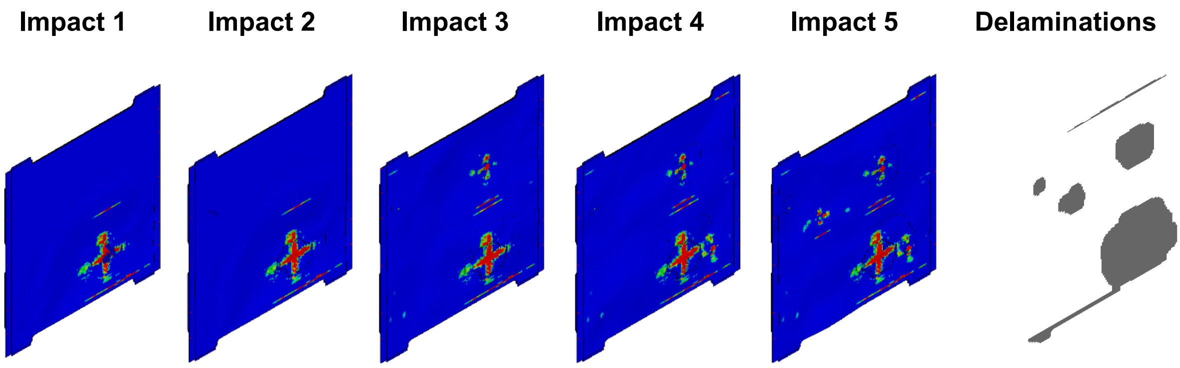

Fig.13: Development of matrix failure after each impact event and resulting delamination surface in grey

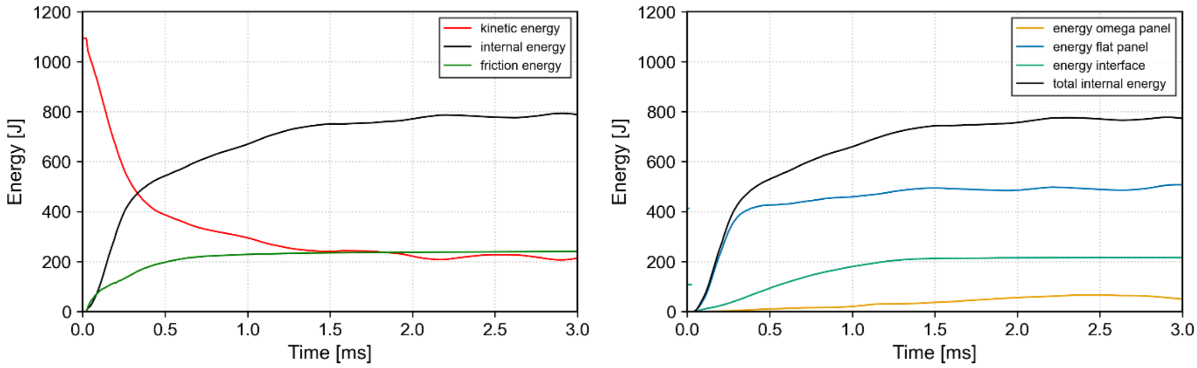

Fig.14: Global energy balance (left) and energy absorption in the single components (right) for the first impact scenario

5 Summary and outlooks

In the present study, a modelling approach has been developed to simulate the behaviour of fibre-reinforced thermoplastic structures under high-velocity impact by ballast stones. Through the use of the DE method and state-of-the-art material models **`*MAT_262`** and **`*MAT_240`**, the behaviour of the of ballast stones and composite structures were depicted with accuracy compared to experimental measurements. While the present approach has been performed with reduced experimental effort for the characterization of the materials, further improvements could be achieved by performing intensive tests on the coupon scale. A validation of the simulation approach on composite plates impacted by ballast stones under high velocities is planned.
With help of the developed methodology, a shielding structure has been sized on the example of multiple successive impacts. A more accurate sizing remains to be performed by considering more realistic boundary conditions (repair concept, lifetime of the structure etc.).

6 Literature

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