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PROJECTILE IMPACT MODELS OF COMPOSITE PLATES FOR NUMERICAL SIMULATIONS

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Summary: *The paper deals with numerical modeling approaches of a steel projectile impact on composite plates. Currently, vehicle ballistic protection is achieved predominantly using metal-based armor which is heavy and thus negatively affects other vehicle parameters, such as maneuverability. Another option is to use a composite or hybrid sandwiches. To speed up the design of such elements for ballistic protection, it is appropriate to use numerical simulations which allow for a reduction of the number of experiments required to select appropriate alternatives for the construction features of ballistic protection. For this reason, different numerical models describing the penetration of a composite plate by a steel projectile have been developed. These models are based on different damage criteria. Since there is no universal damage criterion, it is necessary to find suitable options as well as methods to identify parameters for different types of materials. Therefore, different possibilities to adjust these models to experimental data were investigated. The proposed models will be used in the development of high-quality composite sandwiches for ballistic protection.*

1. Introduction

Experimental methods play an essential role in developing new designs or materials, but their applications are demanding in terms of time, cost and realization. Due to the development of knowledge in the field of phenomenological material models and methods themselves, especially numerical analysis methods of mechanical systems, the design process and structure analysis is commonly supported by their usage. As far as conventional construction is concerned, numerical analysis is used routinely in cases when it is necessary to assess the stiffness, durability, frequency characteristics, etc. But also for example in the analysis of breakdown situations or structures that perform their functions through a partial or total destruction, as in our case, the development of ballistic shields protection, it is desirable to carry out experiments and numerical simulations together. We expect a

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deepening understanding of experiments due to numerical simulations and also a continuous consequent promotion of rationally designed experiments, thus reducing their number.

One of the fundamental determining factors for the finite element model design is the determination of the expected material response and an appropriate phenomenological material model. Our case is a ballistic impact loading which is characterized by a very short period of its existence, a significant role of stress waves and a high-speed deformation.

Currently there is no unified theory that would cover the response of materials under impact loading for a wide range of impact velocity and different projectile mass and geometry. Our focus will be primarily on the damage of composite materials which are often used as elements of ballistic protection. If we look at the process of penetration and perforation of the laminate material in depth, which is reinforced with fibers, we can say that the deformation takes place in two phases Buchar (2003):

1. First, there is compression, shear of the material and creation of fragments.
2. In the second phase a delamination cone is formed which leads to a fracture of fibers and then the rear of the target is reached by the projectile.

For laminate materials the theory of penetration has been designed based on a large number of experimental tests. Different impact velocity intervals and different geometry of the interacting bodies produce a number of empirical relationships to determine the ballistic limit Buchar (2003).

The finite element method, as well as analytical models contain many assumptions and simplifications, and are very dependent on the choice of a computational and material model especially the damage criterion. This plays an essential role in composite simulations. Among the most common damage criteria of composite materials are Yamada-Sun criterion, Hart-Smith, Hashin, Puck, Chang, etc. These models are the building blocks or basic ideas of complex criteria. The selection of a suitable criterion depends mainly on the geometry of the interacting objects, impact velocity, the type of composite material, but also on the boundary conditions of the target etc. Therefore, the execution of the experiment with a simple geometry is crucial for its subsequent numerical simulation during which the comparison of deformation modes and the overall process of experiment with simulations lead to selection of appropriate damage criteria and adjusting their parameters. Hence ballistic experiments with armor plates and combination of armor and composite plates have been carried out. Four different woven composites after the armor strikes face layer were used. Now the critical evaluation of ballistic experiments is in progress which will lead to trying out of other new samples or to the choosing of the ultimate material. Detailed material data of such composite will then be measured to finalize the defining of the numerical model.

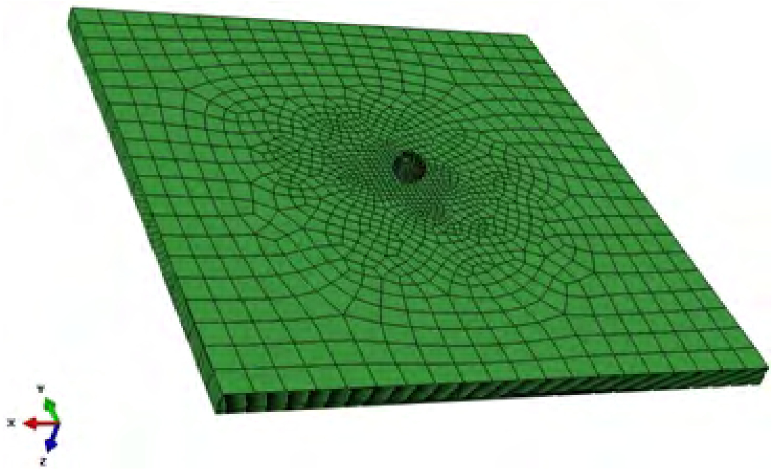

Figure 1: A model used for the simulation of a steel bullet penetrating a composite plate.

2. Numerical simulations

For the initial calculations, a geometrically simple case was chosen: a projectile impact on a composite plate see Figure 1. This case is described in DASSAULT SYSTEMES (2007) in which all necessary material data are also provided, along with the results of experiments. The projectile is a steel ball with a diameter d = 5 mm. The composite plate has a total thickness t_c = 3.6 mm. It is a square with a side length w = 90 mm and is composed of eighteen layers (thickness of one layer is t_l = 0.2 mm) of laminate with carbon fibers. The projectile impacts the plate perpendicularly, right in the center of the plate with a defined initial speed v_i = 150, 180 and 250 m/s.

The projectile is made of steel with an elasto-plastic behavior. Isotropic hardening is taken into account during the plastic deformation and it is dependent on the deformation rate. Material properties of the projectile are considered as follows: density ρ = 7800 kg/m^3, Young's modulus E = 210 GPa, Poisson's ratio ν = 0.3.

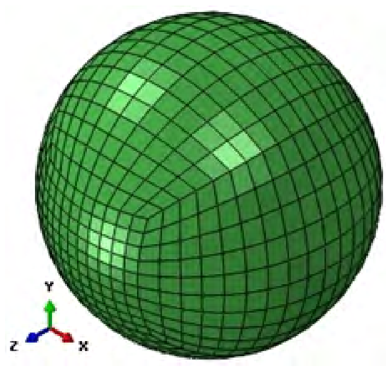

Figure 2: A detail of the projectile finite-element mesh.

Material parameters of the laminated plate including its strength are listed in Tab. 1, density is ρ_p = 1570 kg/m^3 and the lay-up is $[0/90/0]_{3S}$.

Table 1. Overview of material parameters of the composite plate.

Young's modulus E_{11}	235 GPa
Young's modulus E_{22}	17 GPa
Young's modulus E_{33}	17 GPa
Poisson's ratio ν_{12}	0.32
Poisson's ratio ν_{13}	0.32
Poisson's ratio ν_{23}	0.45
Shear modulus G_{12}	4.5 GPa
Shear modulus G_{13}	4.5 GPa
Shear modulus G_{23}	2.5 GPa
Tension strength X_{1t} / compression X_{1c}	3900 / 2400 MPa
Tension strength X_{2t} / compression X_{2c}	111 / 290 MPa
Tension strength X_{3t} / compression X_{3c}	50 /290 MPa
Shear strength S_{12}	120 MPa
Shear strength S_{13}	137 MPa
Shear strength S_{23}	90 MPa

The projectile was modeled using 4 080 linear brick elements with a reduced integration (C3D8R). A detail of the projectile mesh is shown in Fig. 2. The projectile was given an initial velocity against the composite plate (in the positive direction of the coordinate axes z). In the initial position the projectile is in contact with the plate through one node.

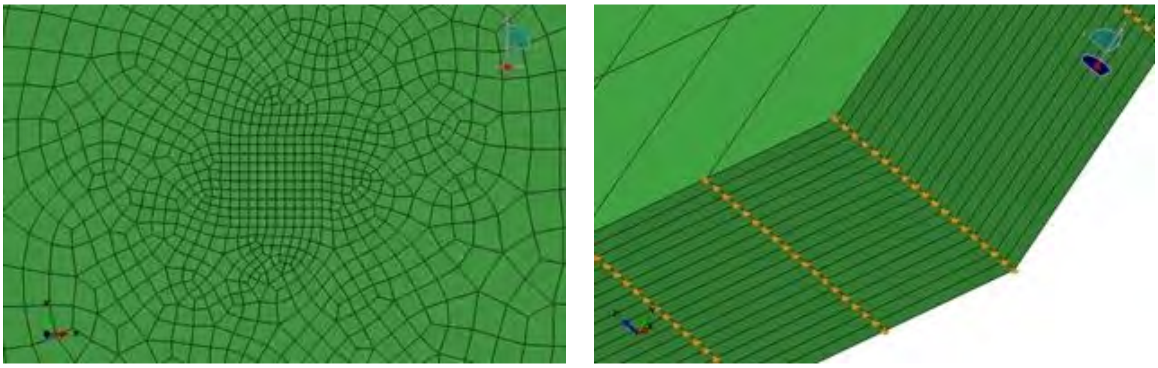

Figure 3: Detail of the plate mesh at which place the projectile impacts the plate (left), and the distribution of elements along the corner of the plate (right).

The composite plate is composed of 20 592 linear brick elements with a reduced integration (C3D8R). The maximum size of elements at the place of the projectile impacting the plate is 1 mm Fig. 3 (left). The plate is constrained at the periphery by prescribing zero displacements in x, y, and z directions. Interacting pairs of contact surfaces were set up in two ways: the surface of the projectile with the plate surface and also the surfaces of layers with each other thus ensuring interaction between delaminated layers of the plate. The coefficient of friction was set to f = 0.5.

One of the most important features of the damage modeling of the composite is the used damage criterion. In this case, damage criteria were included into the simulation using a user material subroutine VUMAT. We used a combination of two criteria. Hashin criterion describes the damage of fibers and Puck criterion is used to describe the damage of a matrix.

Software Abaqus/Explicit by Dassault Systemes was used for the calculation together with Intel Visual Fortran which compiled the material model and integrated it into a solver. The task was solved in large deformations. The simulation time was 0.00015 s for all cases.

Graph Fig. 4 shows the dependence of projectile velocity on its position in the z axis for three different initial velocities. All these data are recorded from the opposite end of the projectile (rear). The graph shows that all the projectiles penetrated the target and continued further with residual velocity.

Table 2. The influence of damage criteria parts on residual velocity at impact velocity 150 m/s.

Residual velocity [m/s]	Part of damage criteria: Fiber		Matrix	
	Tension	Compresion	Tension	Compresion
87	Yes	Yes	Yes	Yes
83	Yes	No	Yes	No
0	Yes	Yes	No	No
0	Yes	No	No	Yes
85	No	Yes	Yes	Yes
0	No	Yes	No	No
59	No	No	Yes	No
0	No	No	No	Yes

Because of the construction of the model which has implemented damage criteria in an external subroutine VUMAT, it is possible to make modifications of these criteria and thus tune the model to a particular type of samples. The described model was tuned according to the results obtained from the DASSAULT SYSTEMES (2007) experiment by selecting which part of the criteria should be taken into account for the element deletion during the simulation because of its damage. The damage model now consists of four parts: Hashin's criteria for fiber tension and compression and Puck's criterion for matrix tension and compression damage. This paper studies the influence of criterion part selection on the results of the simulation. The following table shows the comparison of the simulation results with experimental data.

Table 3. Initial and computed residual velocity of the projectile compared with experimental data.

Impact velocity s [m/s]	Residual velocity experimetal [m/s]	Residual velocity simulation [m/s]
150	45	59
180	102	104
250	184	165

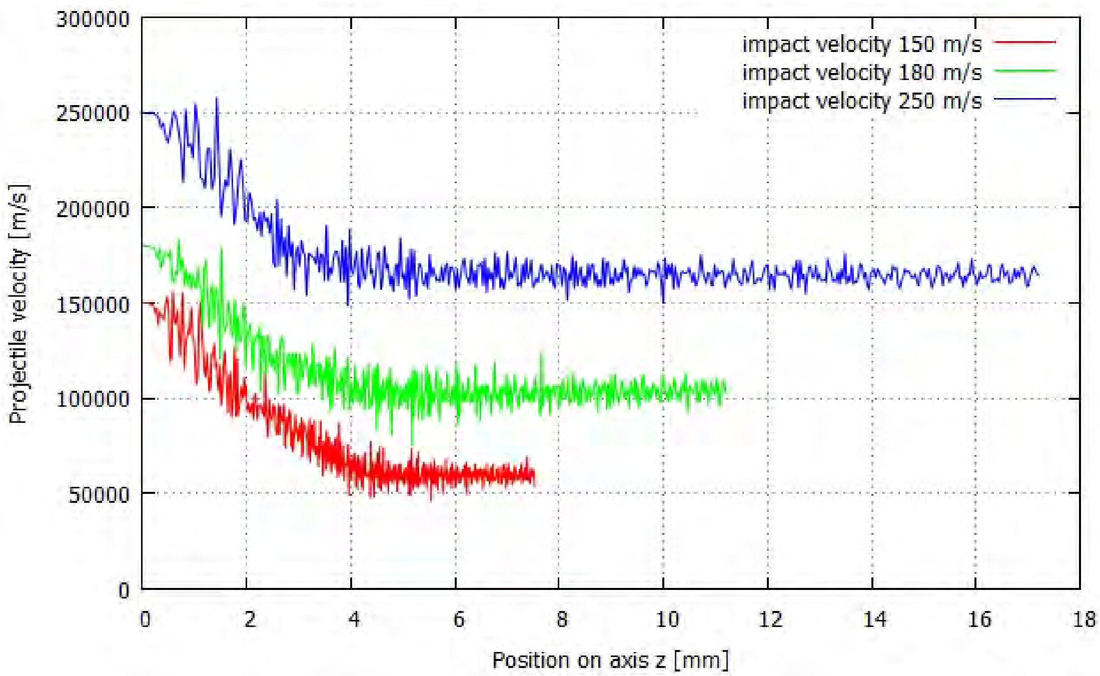

Figure 4: A velocity dependence on the projectile position during the impact for three different initial velocities.

In the presented simulations the element is deleted when it reaches the deformation limit or if the damage criterion evaluates a tensile matrix damage. This model setting has good agreement with the experimental data Tab. 3. The analysis of the numerical simulation (Fig. 5) shows that there is an element deletion at the forefront of the projectile, but also before the front of its face. Observations of experimental tests confirm that the projectile in the case of a fabric composite target tears the fabric and opens it. But in the case of armor targets a considerable amount of the target is stamped by the projectile. In order to capture and simulate this process, it is appropriate to use element conversion to particles instead of deleting the element in damage criteria, which, despite the material failure, maintain mass on the projectile forehead, allowing a description of this material drift with the projectile. It should lead to more accurate simulations.

3. Conclusions

Initially, the aim of the performed simulations had been to test the software possibilities in dealing with composite materials projectile impacts at different impact speeds. Based on the obtained experimental data, a modification of the model damage deformation was made to determine the moment of removing the element from the simulation. The results of the simulation showed a good agreement with the experimental data. This model is ready for an impact simulation of composite plates now which will be carried out after selecting the ultimate material. The model will then be adjusted to the experimental data obtained to support the development of elements for vehicle ballistic protection elements.

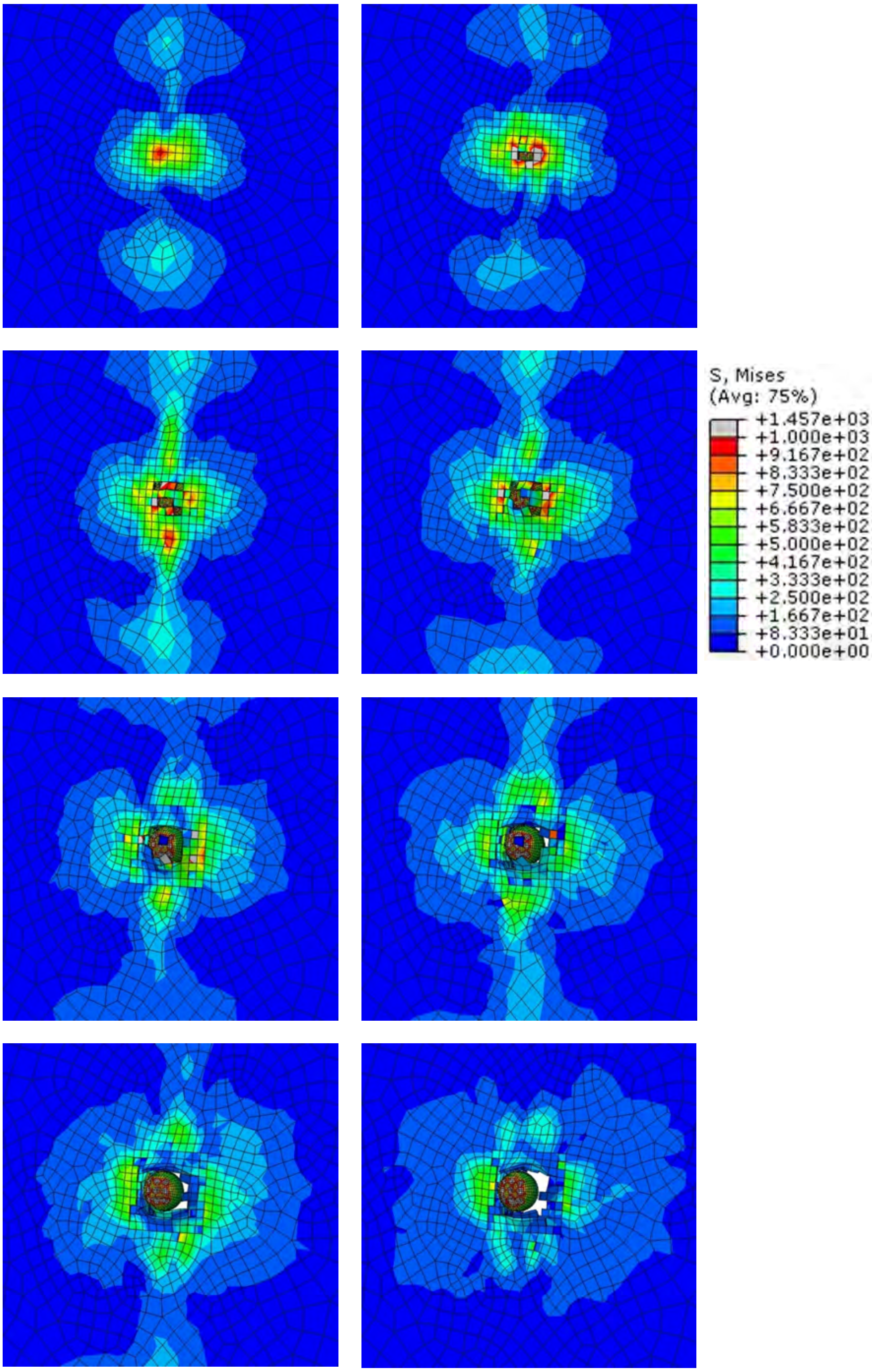

Figure 5: Sequence of images that capture the composite plate penetration with projectile initial velocity $v_i = 250$ m/s, contours show the von Mises stress.

4. Acknowledgment

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