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APPLICATION AND DEVELOPMENT OF NUMERICAL MODELS IN BALLISTICS

V. Sháněl[*], M. Španiel[**], K. Doubrava[***]

Abstract: *This paper presents a case of shooting into a composite target using a rifle in terms of numerical modeling with a focus on the target and the gun barrel. The composite target is composed of several layers. In this case, it is steel armor or ceramics as the first layer and the second layer is made of aramid. These three materials are so different that for their modeling very different techniques are used. It is a Finite element method (FEM), Smoothed particle hydrodynamics (SPH), Discrete element method (DEM) and their combinations. All presented models are compared with experimental data of a real shooting or with data from a drop tester. During the firing of the projectile from the rifle there is a significant loading of the rifle barrel, which leads to vibrations of the barrel. This phenomenon is treated using numerical simulations as well as experimentally.*

Keywords: Impact, Ballistics, DEM, SPH, FEM

1. Introduction

Experimental methods play an essential role in developing new designs, but their applications are demanding in terms of time, cost and feasibility. 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 constructions are concerned, numerical analysis is used routinely in cases when it is necessary to assess the stiffness, durability, frequency characteristics, etc. It is desirable to carry out experiments and numerical simulations together to validate them and determine material parameters. We expect a deepening understanding of experiments due to numerical simulations and also a continuous consequent promotion of rationally designed experiments, thus reducing their number.

Fig. 1: Shooting a rifle into a composite target – scheme.

Currently there is no unified theory that would cover the response of materials under impact loading for a wide range of impact velocity, projectile mass and geometry (Rosenberg & Dekel, 2012). Our focus will be on the damage of steel armor and ceramics which are used as one of the elements of sandwich armor called strike face – see Fig. 1. The main function of this layer is to absorb a part of the kinetic energy of a bullet, its destabilization and deformation. The second layer is called a back face and its function is to absorb the remaining kinetic energy of the projectile and catch fragments of the projectile. Hence, this layer must be resilient, yet strong enough to prevent the penetration by the projectile.

[*] Ing. Vít Sháněl: Faculty of Mechanical Engineering, CTU in Prague, Department of Mechanics, Biomechanics and Mechatronics, Technicka 4, 166 07 Prague 6; CZ, vit.shanel@fs.cvut.cz

[**] Doc. Ing. Miroslav Španiel, CSc.: Faculty of Mechanical Engineering, CTU in Prague, Department of Mechanics, Biomechanics and Mechatronics, Technicka 4, 166 07 Prague 6; CZ, miroslav.spaniel@fs.cvut.cz

[***] Ing. Karel Doubrava, Ph.D.: Faculty of Mechanical Engineering, CTU in Prague, Department of Mechanics, Biomechanics and Mechatronics, Technicka 4, 166 07 Prague 6; CZ, karel.doubrava@fs.cvut.cz

In ballistic impact numerical simulations structural models need significant simplifications and their correctness is strongly dependent on modeling approach. The proper choice of a modeling method, approach, material model and damage criteria is crucial. That is why ballistic experiments using armor plates with different impact velocities, ballistic test of ceramics and their combination have been carried out. The dynamic test of aramid back face has been done on a drop tester.

The simulation of a sandwich composite penetration is a complex task involving an interaction of three main objects with each other: the bullet, the strike face, and the back face. For this reason, the numerical simulations of the bullet impact performance on a composite sandwich were divided into three steps. The real bullet impact into the steel, ceramics strike face and aramid back face penetration on a drop tester using different numerical methods.

2. Discrete element method

Steel armor targets can be described as a continuum and it is suitable to use FEM for their modeling, employing classical elements. These elements are able to describe material damage – material degrades its properties while the damage increases. If the element is damaged and its deformation begins to grow rapidly, it must be removed from the simulation to avoid premature termination. This causes a loss of the mass and the volume of the target. The loss is not fatal for steel armor, but it is unacceptable for ceramic targets because of the high number of damaged elements and the principle of the function related to the ceramic ballistic protection.

Ceramic targets work based on the following principle (Buchar & Voldřich, 2003): ceramics fragmentation occurs when a projectile impacts the ceramic target. The fragments go against the projectile, ridding it of its kinetic energy, and deforming and destabilizing the projectile. If all the damaged FEM elements were removed from the simulation, the ceramic target would be no obstacle for the projectile. The fragmentation of ceramics occurs immediately after the first contact with the projectile without the dissipation of a large amount of energy.

The main difficulties during the simulated shooting into ceramics are high strain rate, significant deformations, fragility and hardness of the targets. Not even the latest versions of commercial software products provide a tool to simulate this kind of situation. For this reason, a new modeling approach was developed. This method of modeling is suitable for the interaction of the projectile with the ceramic target simulation which removes all major issues with the classical approaches, such as deleting of damaged elements and the related loss of mass and volume. This new approach is based on DEM.

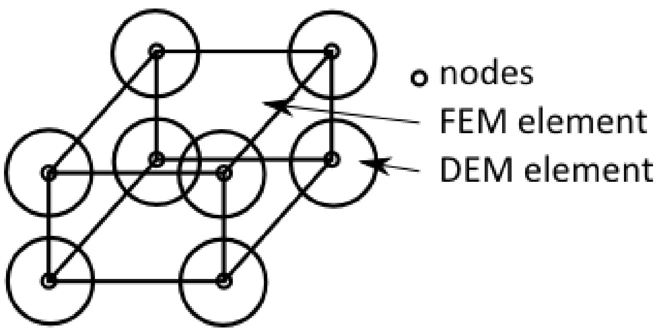

Fig. 2: The classic FEM element with the DEM elements with the common corner nodes.

DEM is a versatile tool for modeling the behavior of a particle material. ABAQUS software manual says that using DEM is appropriate for such modeling situations in which a large number of discrete particles come into contact, but this method is not suitable for describing continuum deformations (DASSAULT SYSTEMES, 2014). DEM does not require removal of elements during the simulation due to large distortions, thus maintaining the target mass and volume during the simulation. However, a disadvantage is that targets are not described as a continuum – consistency of the material is not captured and therefore no description of the damage is included either. Nevertheless, DEM can be used in combination with conventional finite elements to describe target deformations and damage. The ceramic target described using such a combination of FEM and DEM (Fig. 2) would maintain its mass, volume and capture the material damage. The respective qualitative behavior during the impact corresponds well with experiments.

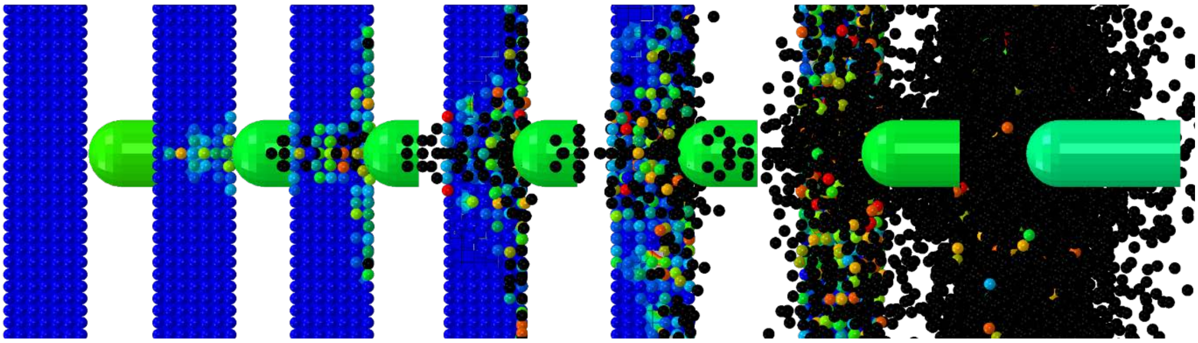

Fig. 3: Demonstration of projectile penetration into the ceramic target during the simulation.

A series of penetration simulation pictures is shown in Fig. 3. The view is perpendicular to the flying projectile, and ceramics can be seen in the cross section to show the spreading of the shock which is mainly propagated in the direction of the bullet flight as well as in directions perpendicular to each other and to the flight of the projectile.

3. Smoothed particle hydrodynamics

SPH is another method used in projectile penetration simulations. This was used to describe the lead core projectile during the penetration of the target armor and also proved to be suitable for modeling the aramid back face.

Due to the nature of the aramid material and the conditions prevailing during the clean shot of the back face with a real bullet – at a high speed and with the geometry of a real bullet – it is not possible to perform experiments using aramid panels with a bullet directly. A parting of the fabric and the simple passage of the bullet would occur; for that reason, the armor is always used on the strike face side which distorts and destabilizes the projectile. Moreover, many items of the available measuring equipment cannot be used during the experiments in combination with a real weapon so as not to risk their destruction. We therefore proceeded to perform experiments on the drop tester which allows considerably greater possibility of recording the entire experiment. For our testing purposes, we created a drop tester impactor of a real bullet.

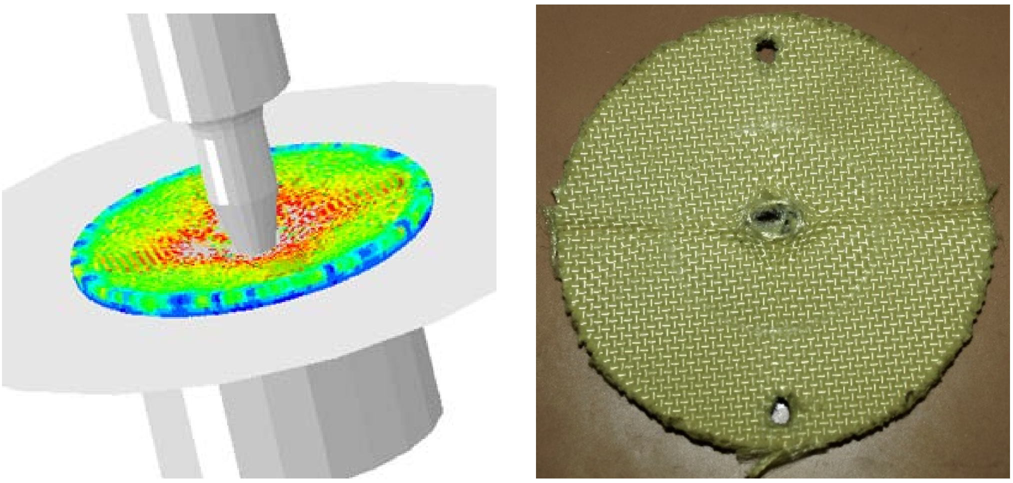

Fig. 4: Simulation of the drop test with aramid specimen using SPH formulation (left). Aramid specimen after impact on drop tester (right).

Subsequently a numerical model of the drop test experiments was created (Fig. 4) to enable identification of missing material parameters, and then allowed the usage of a model for the simulation of a complex sandwich. The impactor was modeled as a non-deformable body as well as a device for mounting the composite sample. We used a particle model based on a smoothed particle hydrodynamics method for the sample. This method is one of meshless methods which enables a simulation of problems involving a significant deformation.

The material damage was introduced into the model through SPH formulation wherein each particle has a predetermined area, interacting with other particles. If particles are moving away from each other their interaction strength decreases. Thanks to this description, a simulation of the aramid sample damage was achieved, although we did not use any standard description of the material damage. The model described above reached a good agreement during the drop test when comparing the absorbed energy during the impactor passing through the sample.

4. The barrel of the rifle

Shooting from a rifle into a composite target is interesting not only from the perspective of penetration the targets. A rifle barrel is under a heavy stress caused by the shot when the projectile is accelerated by the expanding gases that emerge as gunpowder is burned. During this process the pressure in the chamber reaches values exceeding the yield stress limit of conventional steels. The stress pulse is short but excites vibrations of the barrel. At that point, we focused on the bending vibrations which are captured by strain gauges during the shooting. We created a numerical model for the very same situation which extended the discreet results of the experiment to the entire rifle barrel.

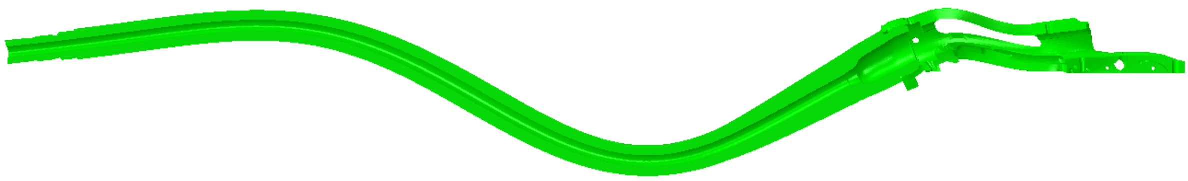

Fig. 5: Deformation of the rifle barrel during the shooting.

5. Conclusions

We focused on shooting from a rifle into a composite target from several perspectives. We paid attention especially to the perforation of a target composed of different materials as well as the barrel vibrations caused by the shot. In the course of the experiments, these processes were captured using different methods (high-speed camera, radar, optical gates, strain gauges, analysis of the deformed samples etc.). For the purpose of describing these processes, numerical models were devised. Due to high deformation rates and the impossibility to use standard approaches (deleting damaged elements), these simulations exhaust the possibilities of commercial software and even go beyond what such standard software tools can offer. We have developed special approaches (combination of DEM and FEM methods) that make it possible to numerically simulate such processes. The resultant numerical models enabled us to broaden the range of the data obtained from experiments (often at discrete points) on whole parts and thus allow for a more complex description of the monitored processes.

Acknowledgement

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