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NUMERICAL MODELING OF BALLISTIC RESISTANCE OF THERMOPLASTIC LAMINATE UNDER 9×19 MM PARABELLUM AMMUNITION

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Abstract: *This paper presents the examination of laminates on a thermoplastic polypropylene (PP) matrix. A preliminary homogenization of the system was performed using a scanning electron microscope (SEM). Numerical simulations were carried out and the energy dissipation of 9x19 mm Parabellum with a velocity of 360 m/s ± 10 m/s was analyzed. The results of the simulation were compared to real samples after their overshot in the ballistic test. The aim of the study was to determine the ballistic limit of material systems intended for ballistic protection against pistol and revolver bullets. The optimization of laminates for personal protection was aimed at reducing Back Face Deformation (BFD), which is the replacement measure for blunt force trauma.*

Keywords: Numerical modelling, Ballistics impact, Polymer composites, Homogenization, Thermoplastic laminates

1. Introduction

Numerical modelling of the arrangement of fabrics in the form of laminates is a challenge that needs to be precisely defined in order to obtain the correct results assumed in the numerical model. The fabric consists of fibers that can be oriented in one direction or two ones perpendicular to each other and interweaved properly. The behavior of fabric is influenced by many factors (Bohannan et al., 2008, Mazurkiewicz, et al., 2013 and Peng et al., 2005), namely the folding of the yarn (crimp interchange), relative rotation of the yarn (trellising), blocking of the yarn (shear locking or cross locking, and slip (pullout). It should be emphasized that a ballistic fabric must be resistant to impact loading (Martínez-Hergueta et al., 2018 and Park et al., 2013), i.e. it must have appropriate fiber properties as well as fabric properties such as weave, number of layers, etc. The search for optimal models of behavior of fabrics and ballistic laminates can be successfully carried out through computer simulation programs. Methods based on micromechanical modelling using a representative volume element (RVE) are quite commonly used for fabric/laminate modelling. (Bansal et al., 2009 and Pach et al., 2017). Another method of examining a fabric refers to a grid (system) of mass points connected by flexible members (Tan et al., 2006). Another one is a description based on the finite element method, where a fabric is represented by solid or coating elements. It is a direct method (discrete, three-dimensional approaches), where the shape and dimensions of yarns (weft and warp) and their mutual position (interweaving) are taken into account in the mesostructure. The last group are mixed methods modelling yarns in direct contact with a penetrator (principal yarns) considering the shape and dimensions of yarns and details of interweaving, while the others - as a homogenized continuous medium (Minh et al., 2014 and Nilakantan et al., 2010).

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The authors focused their attention on micromechanical modelling using a representative volume cell (RVC) with the ABAQUS software. In earlier studies (Kurzawa et al., 2017 and Mayer et al., 2017) they presented an approach to homogenization of the composite. This work refers to the appropriate modelling of a ballistic laminate on a polypropylene (PP) matrix.

2. Methods

To prepare a polypropylene matrix laminate sample, Twaron® aramid fabric of 173 g/m^2 basic weight and plain weave structure was used as reinforcement. For laminate production 10 layers of fabric were used, where the sample had a thickness of 6.6 mm and a weight of 67 g. The polypropylene laminates were formed in two steps. The first stage was the formation of the polypropylene film from granulate which initially was plasticized under a press at the temperature of 200°C for 2 min without load, and then for 2 min under the pressure of 2 MPa. In the result of pressing, polymer films were obtained. The laminates were produced by the alternate pressing of 11 layers of polypropylene film and 10 layers of aramid fabric arranged in the 100×100 mm metal mold. They were pressed under the pressure of 5.5 MPa. The laminates were subjected to ballistic testing. A 9×19 mm Parabellum full metal jacket (FMJ) projectile with an initial velocity of 360 m/s was used as a penetrator. The macroscopic results of the impact are presented in the Figure 1.

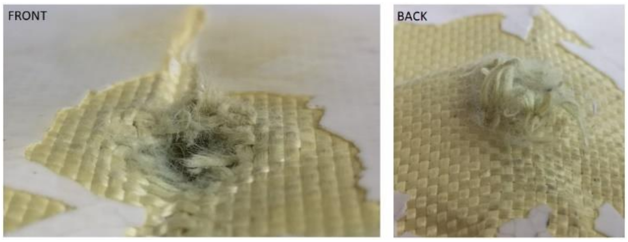

Fig. 1: Sample after shooting.

3. The SEM and tomography analyses

After shooting on a ballistic track, the microstructure of the samples on the PP matrix was subjected to the analysis. Microscopic pictures (Fig. 2) show the saturation of PP fiber matrix in aramid bands. The distribution of fibers in the band on the PP matrix is uneven, which shows the density of the bands on the piston rod side. Noticeable micro-cracks in the PP structure indicate brittle properties of the material subjected to impact loading.

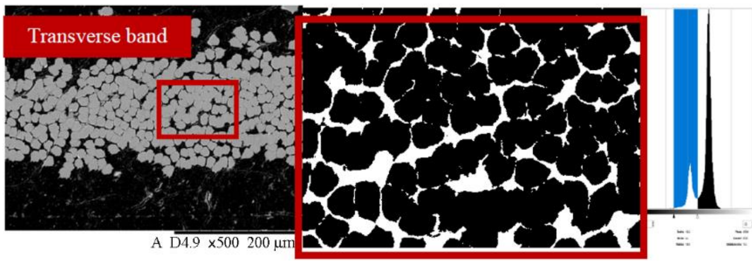

Fig. 2: Calculation of percentage of the fiber to warp ratio.

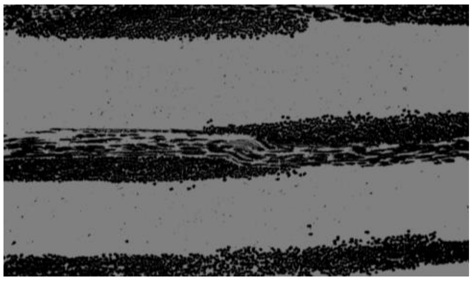

Fig. 3: The photo used to calculate the percentage.

The calculation of the percentage of fibers in the matrix was performed in the GIMP program by determining the histogram of the percentage of colors in the selected area of the photo. For this purpose, 10 areas were randomly chosen. The proportion of the fibers (black) to the warp (white) is 80.8%., The percentage share of aramid fibers (transverse and longitudinal bands) in the cross-section of the fabric was checked using the same method (Fig. 3). A fragment with 3 layers of fabric was selected and the percentage share was calculated using a histogram. The share of aramid fabric in the laminate was 29.6%. Empty places were classified as residues from aramid fibers.

4. Numerical analysis

Three methods were selected for preliminary analyses of modelling of laminates. The first method involves the process of two-stage homogenization of parameters and then the modelling of the laminate as one volumetric element. The second method assumes the share of a separately defined number of layers in the composite, which are modelled as volumetric elements and their parameters are specified based on homogenization. In the third method the reinforcement and warp are distinguished. The reinforcement is considered as a fabric with the exception that it is given parameters from the first order homogenization. Replacement parameters are determined for each strand of fabric. The warp is modelled as a volumetric material of a preset thickness, while its parameters remain the same as in the base material.

Table 1: Summary of numerical methods.

Sample no.	Method	Layer thickness [mm]	Number of layers	Name and size of finite elements
S1.	Complete homogenization	5.0	1	Hex/tetra 0.1 mm
S2.	Layered homogenization	0.5	10	Hex/tetra 0.1 mm
S3.	Fabric homogenization	0.2/0.2	20	Hex/tetra 0.1 mm

Numerical simulations were performed in the ABAQUS program using the finite element method. In the first step, the strength parameters were homogenized in two stages. In the first of them, the percentage share of aramid fibers in the studied band was examined. The Young's modulus, Poisson's coefficient and equivalent density were determined using the elasticity theory dependencies.

After having carried out the homogenization process of the fabric layer and matrix parameters, they were modelled as plates with the dimensions of 100×100 mm and the thickness of 0.5 mm. The contact between the layers was specified as "hard contact". The initial velocity of the projectile was set at 360 m/s, with the longitudinal rotation of the projectile as 1/100 of the initial velocity taken account of. The restraint of the shield was blocked as translations and rotations in the three *X*, *Y* and *Z* axes. After exceeding 2 % elongation, the shield was destroyed. The comparison of final results of simulations performed with three methods is presented in the Figure 4.

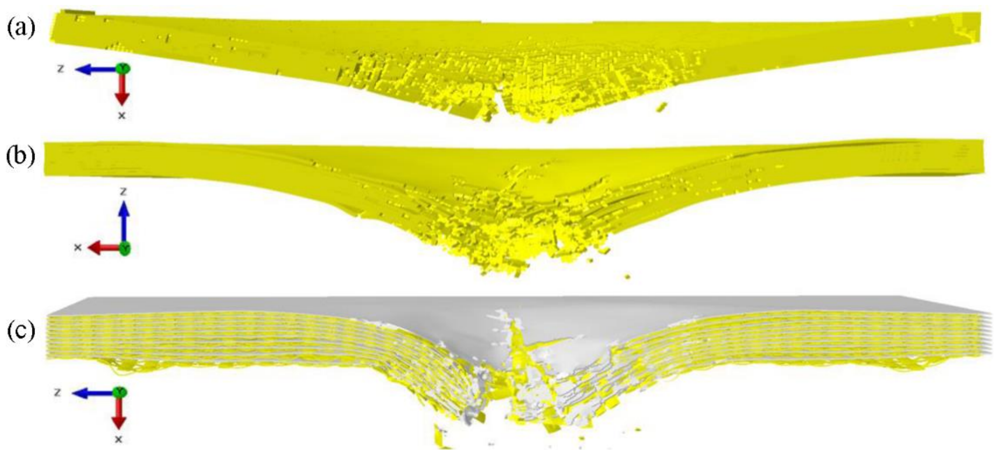

Fig. 4: Results of simulation using the following methods: a - complete homogenization, b - layered homogenization, c - fabric homogenization.

Diagrams for three simulations are shown in the figure below (Fig. 5a). As a result of simulation using the method of complete homogenization, the projectile was stopped (Fig. 4a and Fig.5a). In the Fig. 4b) and 4c) the laminates were pierced. The visual results of simulations (4b, c) are very similar to the real sample (Fig.1). The second diagram (Fig. 5b) shows the central processing unit (CPU) time. The calculation time of each simulation was almost the same. In the Fig. 6 the experimental and numerical results were compared. A comparison of sample piercing test was illustrated with the result of layered homogenization method. As it is shown in the Fig. 6, the consistency of the results is valid.

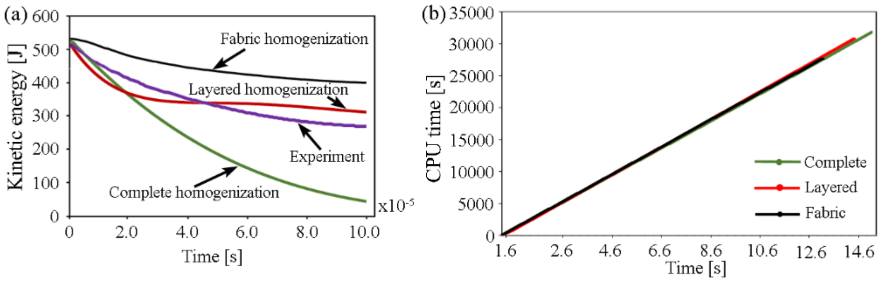

Fig. 5: Comparison of numerical computational parameters: a - dissipation energy, b - CPU time.

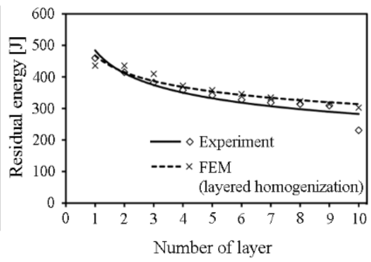

Fig. 6: Comparison of numerical and experimental test.

5. Conclusions

In the result of the work carried out, the final results of the numerical analysis were obtained. On the basis of Figure 4 it can be stated that the modeling with layered homogenization is the most reliable method. As was shown at the beginning, an important undertaking related to conducting basic experiments was to generate an appropriate band of laminate for modelling in the form of RVC. While comparing the presented methods based on absorbed impact energy (Fig. 5a) it appears obvious that the method of modelling the tested laminate has a significant impact on the results obtained. With the same material constants, the size of the element of discretization and boundary conditions, the results may differ by as much as 200%. Method 2 has demonstrated the slightest measurement error with real samples (Fig. 5a and Fig. 6).

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