



Validation of Numerical Model of the Twaron® CT709 Ballistic Fabric

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Abstract. This paper presents implementation and validation of a numerical model of the Twaron® CT709 fabric under impact of the 9 mm FMJ Parabellum projectile (with a soft lead core and a hard brass jacket with a velocity of 365 m/s). The fabric model was made with the use of Autodesk Inventor Professional 2012 program, and computer analysis was conducted with using the ANSYS-Autodyn v12.1.0 program. Geometrical model and strength parameters of the fabric were chosen from literature data. For the numerical analysis of soft body armour three variants of boundary conditions for the fabric were adopted. A sample with the dimensions of 50 × 50 mm made of 16 layers of the Twaron® CT709 fabric was used. The simulations for a quarter of the model with two planes of symmetry were performed. The physically correct behaviour of the fabric under the influence of penetration by a projectile was obtained in the numerical simulations and is demonstrated in this paper.

Keywords: mechanics, computer simulation, fabric, Twaron®, 9 mm Parabellum

1. INTRODUCTION

Computer simulations of dynamically changing (high-frequency) phenomena, such as non-linear deformation of projectiles and armour penetration, require a large number of materials, data and the use of equations of state differentiation from static mechanical equations. The simulations of impact into ballistic aramid fabrics of Kevlar[®] or Twaron[®] armour are more difficult, due to their orthotropy. Additional modelling problems are due to the complicated structure of fabrics, most importantly focused on the weave and density of the fibre.

Designing ballistic soft body armour based only on physical models requires a large amount of experimental data, which is both time consuming and expensive. Computer simulations have helped make progress in the understanding of ballistic fabric failure mechanisms, which allows us to avoid many experimental studies [1]. The use of the finite element method FEM (discretization), allows us to observe phenomena otherwise impossible to see in experimental research. However, in order to carry out computer simulations and to understand the real phenomenon, it is necessary to define various parameters of the yarn strength, dimensions of the fabric, etc. [2].

Materials made of ballistic fibres are characterized by low density, high elasticity and strength, what gives a big advantage for their use as inserts in body armour vests [3, 4].

The resistance of the Kevlar soft armour depends on its capability to absorb and dissipate energy in the impact zone, and the speed of dissipation. The main factors influencing this relation include the fibres density, their elastic modulus, tensile strength, the type of fabric weave, areal density, the number of fabric layers, as well as the shape, impact velocity and mass of the projectile [3].

2. NUMERICAL MODEL OF THE FABRIC

One of the most popular fabrics is Twaron[®] CT (High Tenacity) made from high-strength fibres, used among other things as lightweight, flexible bullet-proof vests. Twaron[®] CT709 guarantees maximum protection against soft core projectiles.

The essential problem in the numerical modelling of the fabric is to present the behaviour of the yarn, as the main load transfer component. This comes from the construction of the material, because the fabric is made from yarns of a particular density woven together each of them consisting of tiny fibres which number can range from several hundred to several thousand. The numerical model of the fabric of individual fibres is rather unrealistic because of the limited computing capabilities. Therefore, the authors have focused on a model of the fabric in which the yarn is the smallest component.

However the projectile only interacts with the fabric area of a diameter of only about 20÷30 mm, in order to model correctly the dynamic process of penetration into the armour consisting of fabric layers, the use of a larger model of the fabric is necessary.

Due to the small wave length of the interleave (about 1 mm), as well as the size of the yarn cross-section, full fabric models are problematic [5]. According to literature, to obtain smaller fabric models, the area outside the contact zone of the projectile is modelled with the use of a so-called orthotropic shell (membrane), which replaces the mapping of solid yarn, at the expense of accuracy.

In this paper a model of fabric of 50 × 50 mm dimensions was used, where a fully solid model of the yarn was applied and the symmetry conditions on two perpendicular planes were adopted, modelling in this way only a quarter of the system (25 × 25 mm). The shape of the yarn cross-section results from its density, type and the technical parameters of its weaving.

Fibres exert some pressure on each other, forming the so-called „tear” cross-section (Fig. 1), which can be parameterized by its height (h) and length (b), making it possible to create a simple computer model.

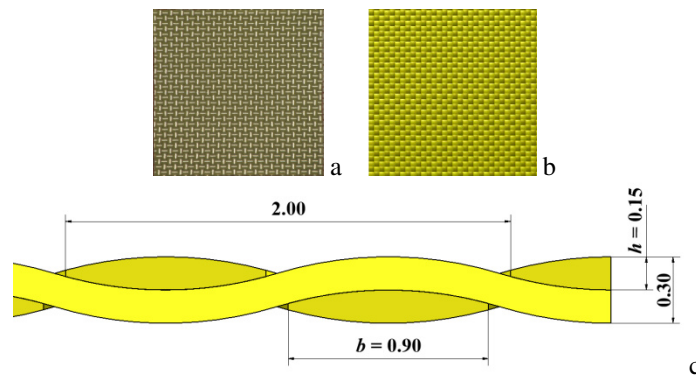


Fig. 1. Twaron[®] CT709 fabric: a – image of the fabric (30 × 30 mm), b – fabric layer numerical model (30 × 30 mm), c – dimensions for the computer model of the fabric

The computer model of the Twaron[®] CT709 fabric (Fig. 1) was constructed with the use of the Autodesk Inventor Professional 2012 (CAD software). The dimensions of the components, i.e. the fabrics thickness, width and the height of the yarn cross-section and yarn spun, were adopted from the data [6]. A high resolution image of one of the fabric layers (Fig. 1a) of known dimensions was taken, and the number of wefts and warps per unit was calculated.

With regard to the necessary simplification of the model the width of tear being $b = 0.9$ mm (Fig. 1c) and the height $h = 0.15$ was taken from the literature. The fabric with the plain type of the weave is shown in Figure 1b. This weave provides good stability of the fabric, but causes it to be more rigid.

3. DISCRETIZATION OF THE FABRIC MODEL AND BOUNDARY CONDITIONS

A completed fabric model was imported into Ansys-Workbench program to carry out the discretization and selection of materials and strength parameters. The splitting of the yarn into finite elements (Fig. 2) in the ANSYS-Mechanical program was performed. Initial and boundary conditions as well as the relations between each elements of the model were defined here. The statistical number of elements for a single layer of fabric amounted to 11858.

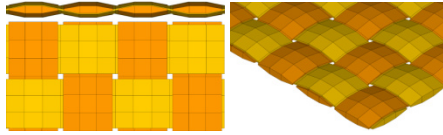


Fig. 2. The yarn divided into finite elements

The boundary conditions for the fabric model were adopted for the fabric outermost edges and corners, fixed in all directions for the following cases:

- all the edges fixed (variant 1),
- two edges fixed (variant 2),
- four corners of the fabric fixed (variant 3).

The axial response of the yarn can easily be described by the Young's modulus and strain at the destruction point.

The aramid yarns present a linear elastic behaviour until rupture. Crimped yarns do not transfer stress until they are completely straight (Fig. 3).

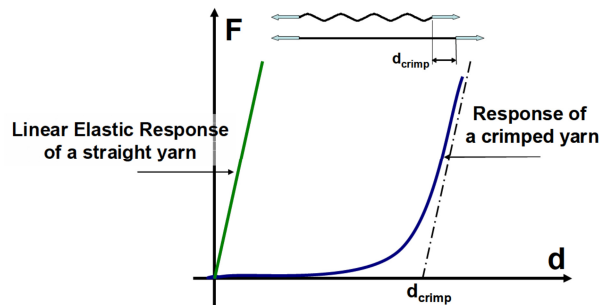


Fig. 3. Linear dependence of elastic stretch yarns in comparison to crimped yarns [7]

During axial compression the individual fibres bend easily, decreasing the yarns capability to carry loads. The yarn shear modulus compared to the Young's modulus is much lower because of the nonbonding between the fibres [7].

As yarn testing is impossible, the mechanical properties, strength model, failure model, and the equation of state were adopted from the literature [5].

The numerical simulation based on these parameters was compared to tests carried out in the Military Institute of Armament Technology (MIAT), Zielonka, Poland.

Following adoption of the orthotropic linear-elastic equation of state for textiles, three main directions consistent with the principal axes of the coordinate system Ox, Oy and Oz were adopted. The value of the longitudinal Young's modulus of yarn elasticity (E_{11}) amounted to 120 GPa, while the value of transverse moduli (E_{22} , E_{33}) reduced by one order of magnitude amounting to 12 GPa. Shear modulus (G) for all directions (G_{12} , G_{13} , G_{23}) amounted to 3.6 GPa, with an adopted elongation at break of 4.6% stress at break of 5.52 GPa and a material density of 1.44 g/cm³.

Friction between the contacting surfaces was determined using the following formula:

$$\mu = \mu_k + (\mu_s - \mu_k) \cdot e^{-\alpha|v_{rel}|} \quad (1)$$

where: μ_s – is the static coefficient of friction, μ_k – the dynamic coefficient of friction, and v_{rel} – the relative velocity between two surfaces in contact, α – exponential conversion factor determining the transition from static to kinematic friction.

The following parameter values of friction were adopted:

- for the yarn-yarn contact: $\mu_k = 0.19$; $\mu_s = 0.23$, $\alpha = 108$,
- for the projectile-fabric contact: $\mu_k = \mu_s = 0.18$.

4. THE NUMERICAL MODEL OF THE 9 MM PARABELLUM PROJECTILE

Projectiles can be divided into two main groups: for vis viva injuring and for armour piercing. The projectiles for vis viva injuring cause extensive wounds through crushing, cutting and the relocation of soft tissues. The penetrating projectile creates a so-called temporary cavity around itself because of the rapid acceleration and stretching of soft body tissues. Consequently, the wound is contaminated, among others things, with parts of fabric and dirt [8], while the occurring shock wave destroys internal organs.

After World War II the most popular projectile in the world was the 9 mm calibre cartridge with a 19 mm case length. This cartridge is commonly used in Europe, in Belgium, Bulgaria, Czech Republic, Slovakia, Poland, Sweden and Switzerland. The 9 mm Parabellum cartridges with the FMJ (Full Metal Jacket) bullet are produced in at least 70 countries around the world. They have become standard for NATO forces [9] and are used in small arms and machine guns.

In the research, a 9 mm FMJ projectile (Fig. 4) was used for the computer simulations for the validation of the fabric model. The projectile parameters were as follows: weight – 8.0 g, muzzle velocity – 365 m/s, initial energy – 530 J.

The resistance of the bullet-proof vests, and other body armours against the 9 mm Parabellum projectile is described in the NIJ Standard-0101.04, „Ballistic Resistance of Personal Body Armour”.

According to the standard, the bullet-proof vests protection capability against this kind of projectile given an initial velocity that is of the 2nd level of protection.

The results of the research [10] performed in the MIAT were used to create a model of the projectile. The 9 mm Parabellum FMJ projectile consists of a lead core and a brass jacket (Fig. 4).

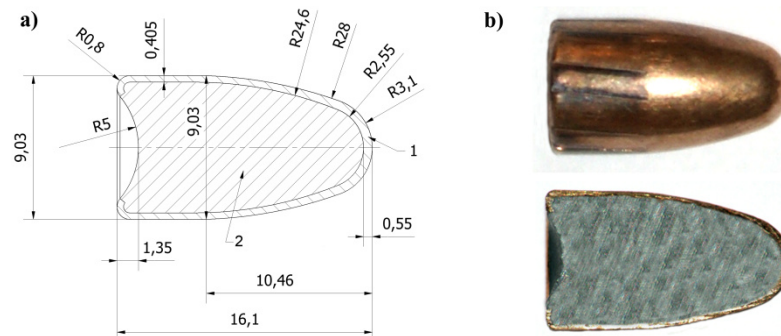


Fig. 4. The 9 mm Parabellum FMJ projectile:
a – dimensions of the projectile, b – projectile and its cross-section,
1 – brass jacket, 2 – lead core

For impact simulations the lead core was adopted according to the Stainberg–Guinane strength model, available in the Ansys Autodyn library and in article [11]. The equation of state, Johnson–Cook (J–C) strength model (Table 1) and the failure model data of the brass jacket was adopted on the basis of the article review [12, 13] and studies [10].

In order to reduce the time needed to complete a simulation of the projectile-armour system it was presented in plane symmetry, adopting only a quarter of the tested model (Fig. 5).

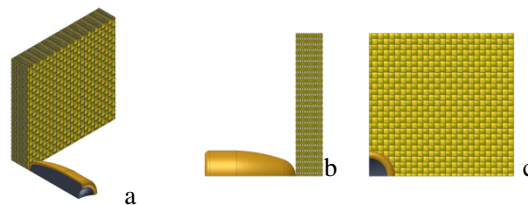


Fig. 5. A quarter of the CAD model projectile-armour system:
a – isometric view, b – side view, c – top view

The core and the jacket of the projectile were modelled and divided into finite elements with the use of the Lagrange method (Fig. 6). The statistical number of elements for the jacket and the core was 6372 and 10852 respectively. For the initial conditions of simulation, the adopted velocity of the projectile was of 365 m/s at the point of contact with the fabric. The angular velocity of the projectile was omitted following the use of only a quarter of its symmetry. Contacts between the jacket and the core were adopted according to the simulations described in the article [10].

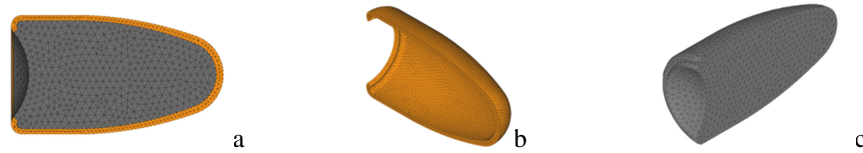


Fig. 6. Numerical model of the projectile coated with FEM mesh for the Lagrange method: a – cross section of the projectile, b – the projectile jacket, c – the projectile core

Table 1. Material constants for the J–C strength model for brass

Parameter	A , MPa	B , MPa	n	C	m	T_m , K
Value of the parameter	206	505	0.42	0.01	1.68	1189

5. NUMERICAL ANALYSIS OF THE 9 MM PARABELLUM PROJECTILE PENETRATION INTO THE ARMOUR

The numerical model of the fabric behaved correctly until the brake. In Figure 7 it is shown, that the numerical model of the fabric, penetrated with the 9 mm Parabellum projectile demonstrated a normal distribution of reduced stress (Von Misses Stress).

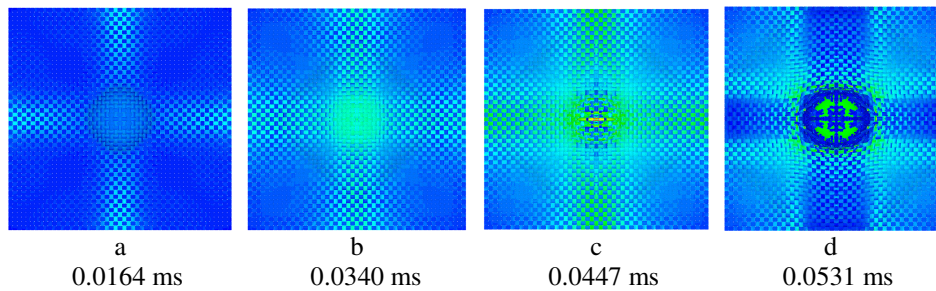


Fig. 7. Von Misses stress for the last fabric layer of the 16-layer package of the Twaron® CT709 numerical model

The break of the yarn (Fig. 7c) occurred after reaching a maximum stress of 5.52 GPa, adopted in the failure model. After the yarn broke transferring the main load, the stress reached a value of zero (Fig. 7d).

Three boundary conditions for the fabric, were adopted in the simulations (fabric fixed on the 4 and 2 edges and four corners of the model), and showed the behaviour of the fabric similar to the results obtained in research [2, 3, 5, 14, 15].

The results of the first variant of the boundary conditions showed the smallest decrease in the projectiles velocity, from 365 m/s to 292 m/s. However, this type of fabric (Twaron® CT709, with a sample of 16 layers, tested on ballistic ground) stopped the 9 mm Parabellum projectile, as a result of research conducted in the Institute Security of Technology MORATEX (Poland) and in the MIAT. Several phenomena influenced simulation results:

1. the deformation of elementary cells connected with erosion of the yarn, observed during the simulation,
2. a small number of the finite elements in the yarn cross-section,
3. not all the data was available for the numerical models,
4. much smaller model of the fabric (50 × 50 mm).

During the penetration of the fabric the characteristically tension of the yarn was observed. After the yarn was fully the fabric began to carry loads.

In the second and third variants the fibres movement in the plane was shown which was the most important thing for the absorption of the projectiles energy.

Simulations for all the three boundary conditions showed the characteristic bending of the fabric, which occurs in this type of phenomena.

In the first variant (four fixed edges), the fabric is locally bent forming the so-called transverse wave on the rear surface of the sample (Fig. 8), which was a result of the stress gradient in the fabric.

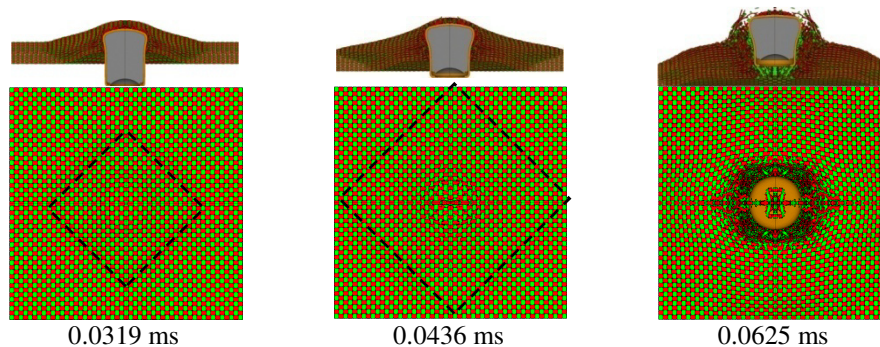


Fig. 8. Half and all geometry of the fabric and projectile model during penetration process for the first variant of the boundary conditions (four fixed edges)

The deformation of the projectile for all variants was obtained after 0.0082 ms from the moment of contact with the fabric. The piercing of the first four layers of the model was obtained after 0.0234 ms. Further penetration of the projectile was connected with its increasing deformation.

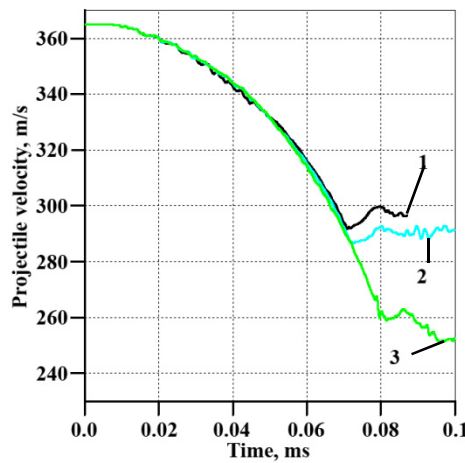


Fig. 9. Velocity of the projectile for the variants 1÷3 of the boundary conditions

The measurements of the velocity (Fig. 9) showed that the deceleration of the penetrator for the first two variants follows after about 0.07 ms, which corresponds to the moment of the yarn brake for the last layer of the model.

For the second variant of the boundary conditions, where only two edges were fixed, the extreme fibres pulling out and the fabric moving to the centre were observed (Fig. 10).

It can be concluded, that only the yarns fixed normally to the fabric edge were the most important for the transmission of dynamic loads. These yarns absorbed energy until they were completely stretched and straightened, and broke after reaching the maximum strain. The yarns parallel to the fixed fabric edges absorbed energy due to friction between them and the fibres pulling out. Therefore, the projectile velocity obtained for this case was 287 m/s (Fig. 9) which was about 5 m/s lower in comparison to the first variant.

The biggest decrease of the projectiles velocity was obtained for the third variant (four corners of the fabric fixed – Fig. 11). The absorption of impact energy occurred as a consequence of friction among the yarns and layers of the model, because the main fibres (transferring the biggest loads) were not fixed.

All the extreme fabric fibres were pulled out and also the typical movement of the layers of fabric to the centre of the sample was observed. The obtained velocity for the third variant (252 m/s) was 13.7% smaller than velocity for the first boundary conditions.

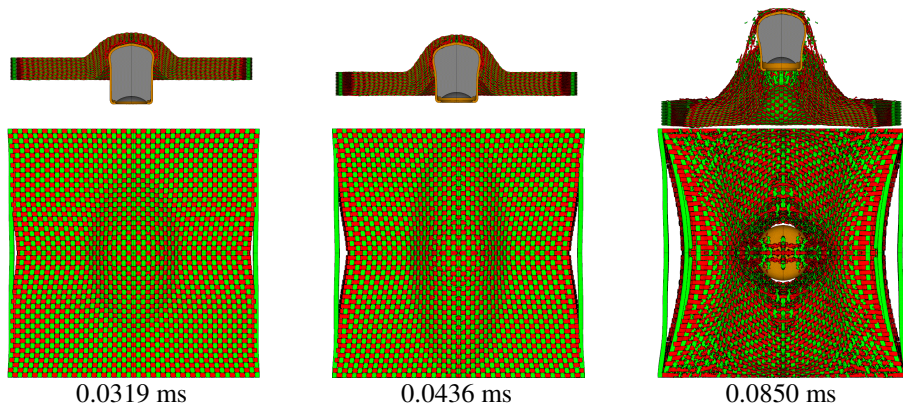


Fig. 10. Half and all geometry of the fabric and projectile model during penetration process for the second variant of the boundary conditions (two edges were fixed)

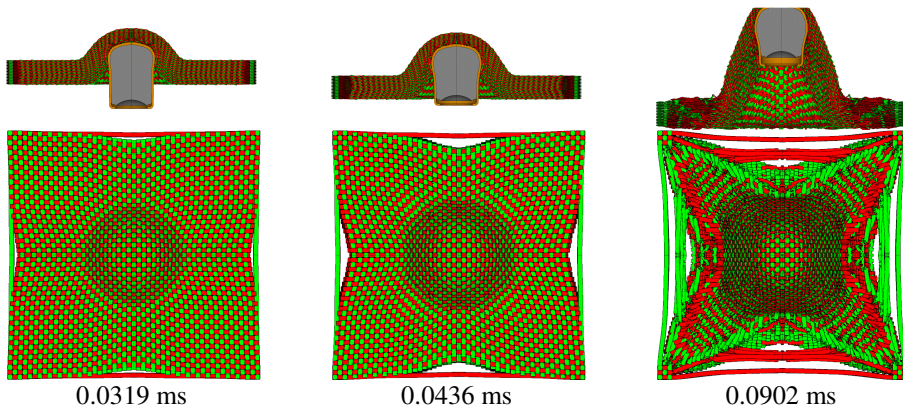


Fig. 11. Half and all geometry of the fabric and projectile model during penetration process for the third variant of the boundary conditions (four corners fixed)

Small increase of the projectile velocity after moment of the fabric penetration (Fig. 9) comes from the fact that the data was obtained from the points located in the deformable part of the projectile.

The biggest deformation of the projectile (Fig. 12) was obtained from the first variant of the boundary conditions.

The projectile „mushroom” was flatter and the deformed penetrator with the 11.33 mm length was 4.77 mm shorter in comparison to the 16.1 mm length of the not deformed projectile (Fig. 4). The model for the first variant maintained a higher rigidity than the other models. The lengths of the deformed projectiles for the second and the third variant were smaller and amounted to 11.95 mm and 12.4 mm respectively (Fig. 12 b, c).

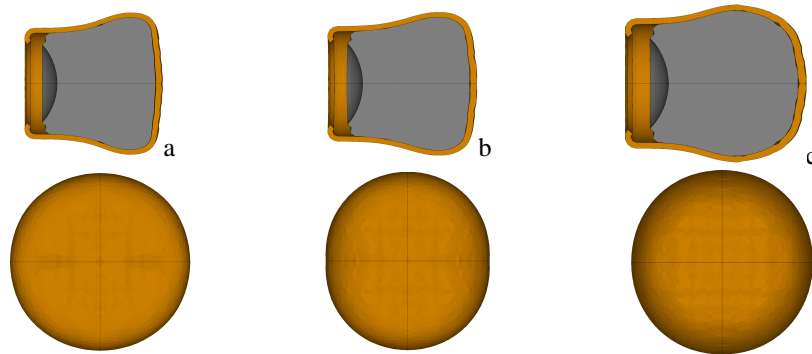


Fig. 12. Projectile shape after penetration process of the fabric model for three variants of the boundary conditions:
a – four fixed edges, b – two fixed edges, c – four fixed corners

The specific „mushroom” shaped projectile for the second variant of the boundary conditions was elliptic. It resulted from bigger stress working in the same directions which came from fixed yarns of the model.

6. CONCLUSIONS

On the basis of the performed simulations the following conclusions can be drawn:

1. The numerical model of the fabric penetration with the 9 mm Parabellum projectile showed the correct distribution of the Von Mises stress and the yarn break occurred after a maximum stress value of 5.52 GPa.
2. The smallest decrease of the projectiles velocity to 252 m/s and the biggest shortening of the projectile (4.77 mm), were obtained for the first variant (fixed four edges of the sample). In these boundary conditions the biggest strain of the projectile corresponded to a higher rigidity in the fabric. The shortening of the projectiles for the other cases is smaller and equals to 4.15 mm and to 3.7 mm.
3. With regard to the high erosion of the numerical model of the ballistic fabric, the number of elementary cells in the yarn cross-section is very important, however due to limited hardware capabilities it is impossible to achieve a denser mesh.
4. The boundary conditions selected for the fabric model have a strong influence on the projectiles deformation.
5. In the simulations, the correct response of the fabric to the penetration of a projectile was obtained. The shape of the transverse wave consistent with the literature review was shown.

6. Future work assumes the implementation of a larger fabric model (a sample of 100×100 mm dimensions) with the use of backing material and comparison of the obtained numerical results with the results of firing tests and will be carried out in the MIAT.
7. Lack of the projectile stop, which was obtained during experimental studies made in MIAT, in the numerical model is connected with the fact that there were not available all experimental tests (e.g. tests of yarns on the Split Hopkinson Pressure Bar) needed for describing dynamic material parameters, which are necessary in numerical simulations. The tested model requires further verification.

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