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EXPERIMENTAL RESEARCH AND NUMERICAL ANALYSIS OF 9 MM PARABELLUM PROJECTILE PENETRATION OF ULTRA-HIGH MOLECULAR WEIGHT POLYETHYLENE LAYERS

Abstract: The paper presents results of experimental research and numerical analysis of the 9 mm Parabellum projectile (brass jacket, lead core) impact (impact velocity V_i = 365 m/s) into layers of the nonwoven polyethylene Dyneema®SB71 (100x100 mm) placed on the backing material. 3D numerical simulations with the use of the Ansys Autodyn v14 program were made. On the basis of the literature and own results of the weight drop test into ballistic plasticine (backface signature *BFS* = 18÷24 mm) conforming to experimental tests numerical model of backing material was made. As a boundary condition in the numerical simulations of projectile impact into Dyneema®SB71 layers it was assumed loading of the tightening belt with 25 N force. In difference to experimental results in numerical simulations the front part of the jacket torn off and the core material flow outside the jacket and there were no perforated layers.

Keywords: UHMWPE, numerical simulation, Autodyn

BADANIA EKSPERYMENTALNE I ANALIZA NUMERYCZNA PENETRACJI 9 MM POCISKIEM PARABELLUM WARSTW POLIETYLENOWYCH O ULTRA-WYSOKIEJ MASIE CZĄSTECZKOWEJ

Streszczenie: W artykule przedstawiono wyniki badań ostrzałem oraz analiz numerycznych uderzenia pocisku 9 mm Parabellum (płaszcz mosiężny, rdzeń ołowiany, prędkość uderzenia V_i = 365 m/s) w warstwy nietkanego wyrobu polietylenowego Dyneema®SB71 (100x100 mm) umieszczonego na podłożu balistycznym. Symulacje numeryczne 3D zrealizowano w programie do analiz dynamicznych Ansys Autodyn v14. W oparciu o dane literaturowe oraz własne wyniki zrzutu swobodnego ciężarka na plastelinę balistyczną (głębokość deformacji podłoża *BFS* = 18÷24 mm) opracowano zgodny z wynikami badań eksperymentalnych model numeryczny podłoża balistycznego. Jako warunek brzegowy w symulacji uderzenia pocisku w warstwy Dyneema'y®SB71 przyjęto obciążenie paska dociskającego siłą 25 N. W odróżnieniu od badań ostrzałem w symulacji numerycznej oderwała się przednia część płaszcza pocisku oraz nie nastąpiło przebicie żadnej z warstw wyrobu polietylenowego Dyneema®SB71.

Słowa kluczowe: UHMWPE, symulacja numeryczna, Autodyn

1. Introduction

Novel polymer fibers in the form of fabrics, unidirectional nonwoven materials or reinforcement of composites, thanks to high tensile strength, high elastic modulus (Young's modulus) and low density find the more and more wider use as: elements of personal protection; land, water, aerial vehicle armours and stationary object armours.

Nowadays there are used following high-strength fibers: glass fibers, carbon fibers, ballistic nylon, aramid fibers (PPTA), poly(p-phenylene benzobisoxazole) fibers (PBO), polypropylene fibers, fibers from ultra-high molecular weight polyethylene (UHMWPE), poly{diimidazo pyridinylene (dihydroxy) phenylene} fibers (PIPD - produced, but there were not found any information about implementation in armours). High-strength fibers properties are given in the Table 1.

Table 1. High-strength fibers physicomechanical properties

Fiber name	Density, ρ, g/cm^3	Young modulus, E, GPa	Strength, σ_c, GPa	Failure strain, ε_c, %	Cunnif Coefficient $(U^*)^{\frac{1}{3}}$, m/s	Reference
E-Glass	2.46	74.00	3.50	4.70	559	[1] [2]
S-Glass	2.48	90.00	4.40	5.70	-	[3]
Carbon fiber	1.76	231.00	3.80	1.80	-	[3]
nylon	1.14	9.57	0.91	-	482	[1]
850 den. Kevlar® KM2	1.44	73.70	3.34	3.80	681	[1]
600 den. Kevlar® KM2	1.44	82.60	3.40	3.55	682	[1]
Zylon® AS	1.54	180.00	5.80	3.50	-	[3]
Zylon® HM	1.56	270.00	5.80	2.50	-	[3]
Dyneema® SK66	0.97	99.00	3.20	3.70	-	[3]
Dyneema® SK76	0.97	116.40	3.60	3.80	-	[4]
Spectra® 1000	0.97	120.00	2.57	3.50	801	[1]
M5® (2001 Sample)	1.70	271.00	3.96	1.40	583	[1]
M5® Goal	1.70	450.00	9.50	2.50	1043	[1]

UHMWPE fibers are produced by: DSM (Dyneema®), Honeywell (Spectra®), Quadrant EPP (TIVAR®), Röchling Engineering Plastics (Polystone® M), Integrated Textile Systems (Tensylon®), Garland Manufacturing (GARDUR®), Ticona (GAR-DUR®) and Braskem (UTEC®).

Experimental tests and numerical simulations described in the article were performed for nonwoven polyethylene Dyneema®SB71 (Table 2). The aim of the works was development of the numerical model of the projectile impact into UHMWPE. Future complementing of this numerical model with e.g. elements which decrease behind armour blunt trauma (BABT) will aid designing of bullet-proof vests.

Table 2. Physicomechanical properties of ballistic nonwoven polyethylene Dyneema®SB 71

Parameters	Value	Test method	Reference
Density, ρ, g/cm^3	0.95÷0.98	-	[5]
Areal density, m_p, g/m^2	191 ± 2	PN-EN ISO 2286-2:1999	[6]
Thickness, t, mm	0.21 ± 0.02	PN-EN ISO 2286-3:2000	[6]
Maksimum tensile force, F_{max}, N: - lengthwise - widthwise	 5264 ± 400 6990 ± 450	PN-EN ISO 1421:2001 Metoda 1	[6]
Elongation at break, ε, %: - lengthwise - widthwise	 3.6 4.0	PN-EN ISO 1421:2001 Metoda 1	[6]
Specific energy absorption (against 9 mm Parabellum Full Metal Steel Jacket), E_{abs}, J/(kg/m^2)	300	DSM Dyneema Energy Absorption Test Method, LP16	[5]
Melting point, T_{melt}, °C	150÷200	-	[5]

2. Experimental tests

In the Military Institute of Armament Technology (Wojskowy Instytut Techniczny Uzbrojenia) the experimental test (depth of penetration test - DOP) of the nonwoven polyethylene Dyneema®SB71 soft ballistic layers (dimensions: 100x100 mm) resistance against 9 mm Parabellum FMJ (full metal jacket) projectile penetration (impact velocity: V_i = 365 m/s) were carried out. 9 mm Parabellum FMJ projectile consists of a brass jacket and a lead core.

Dyneema®SB71 layers were placed in the polyester cover and then fixed by two belts (loaded with 5 kg weight) to box with armour backing material (Balistic Plasticine item No. 071756; Carl Weible KG). The test stand, the layers gripping, cartridge and the projectile are shown in Figure 1.

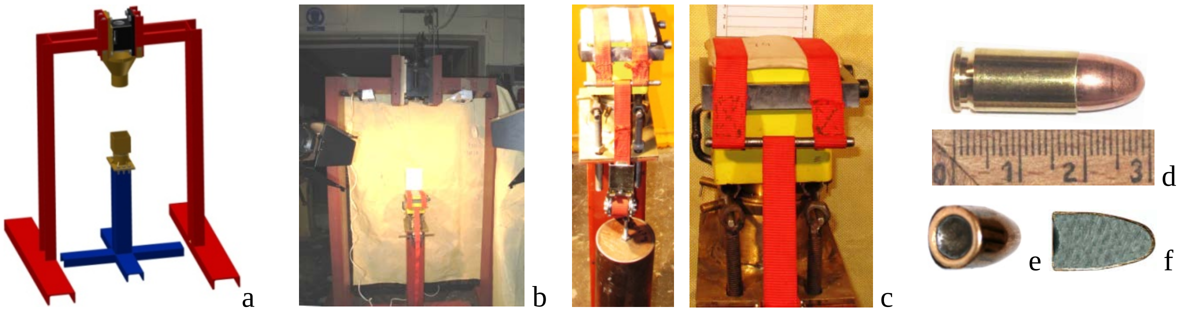


Fig. 1. Stand for DOP test: a - CAD model of stand; b - real stand; c - Dyneema®SB71 layers gripping, d - 9 mm Parabellum FMJ cartridge; e, f - 9 mm Parabellum FMJ projectile and its cross-section

When the sample was shot, the number of perforated and damaged layers of the investigated nonwoven polyethylene Dyneema®SB71 were counted and dimensions of the deformed 9 mm Parabellum projectile (minimum / maximum diameter of the mushroom, length of the projectile) were measured.

Results of the DOP test are shown in Table 3. Layers of nonwoven polyethylene Dyneema®SB71 and projectile after test are presented in figures 2 and 3.

Table 3. Results of the ballistic tests

No. of Dyneema® SB71 layers	Projectile impact velocity, V_i, m/s	Perforation: Yes / No	Backface Signature *BFS*, mm	No. of layers perforated / damaged	Dimensions of deformed projectile		
					length, *L*, mm	mushroom diameter, mm	
						D_{Min}	D_{Max}
16	365	No	37	3 / 4	6.7	15.3	15.7

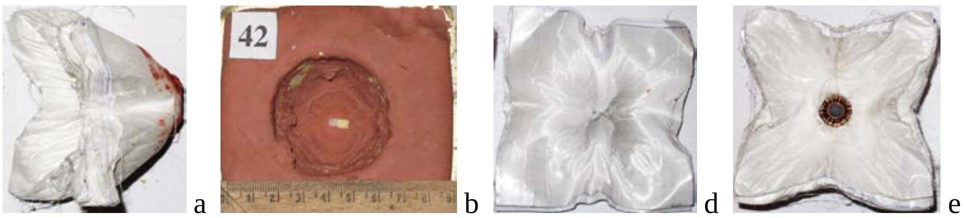


Fig. 2. Elements after DOP test: a - sample, b - armour backing material, d - perforated layers, e - not perforated layers

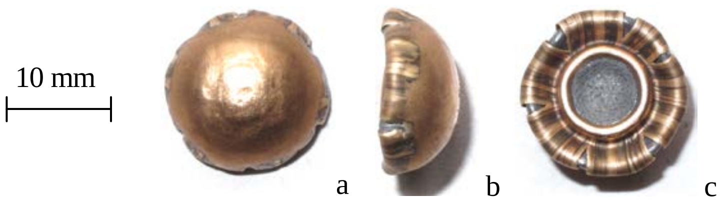


Fig. 3. Projectile after ballistic test: a - front, b - side, c - back

3. Numerical model of armour backing material

Before DOP test plasticity of the armour backing material were investigated by 3 drop tests of 1 kg steel weight (spherical ending cylinder with diameter φ = 44 mm) from 2 m altitude. According to Polish Standard PN-V-8700:2011 backface signature should be 25±3 mm.

In the performed DOP tests plasticity of the armour backing material was in the range 18÷24 mm.

On the basis of the literature data and the performed drop tests preliminary numerical model of the armour backing material was made. Selected and used in numerical simulations parameters for armour backing material are included in Table 4. Figure 9 shows armour backing material deformations at chosen points of time.

Table 4. Selected parameters of armour backing material

Material configuration name		BP5
Parameters	Density, ρ, g/cm^3	1.56
	Young's modulus, *E*, MPa	3
	Shear modulus, *G*, MPa	1.007
	Bulk modulus, *K*, MPa	50
	Yield stress, *A*, MPa	0.065
	Hardening constant, *B*, MPa	0.37
	Hardening exponent, *n*	0.6
	Thermal softening exponent, *m*	1
	Poisson ratio, ν	0.49
	Thermal conductivity, J/(m*K*s)	0.6
	Heat capacity, J/(kg*K)	1280

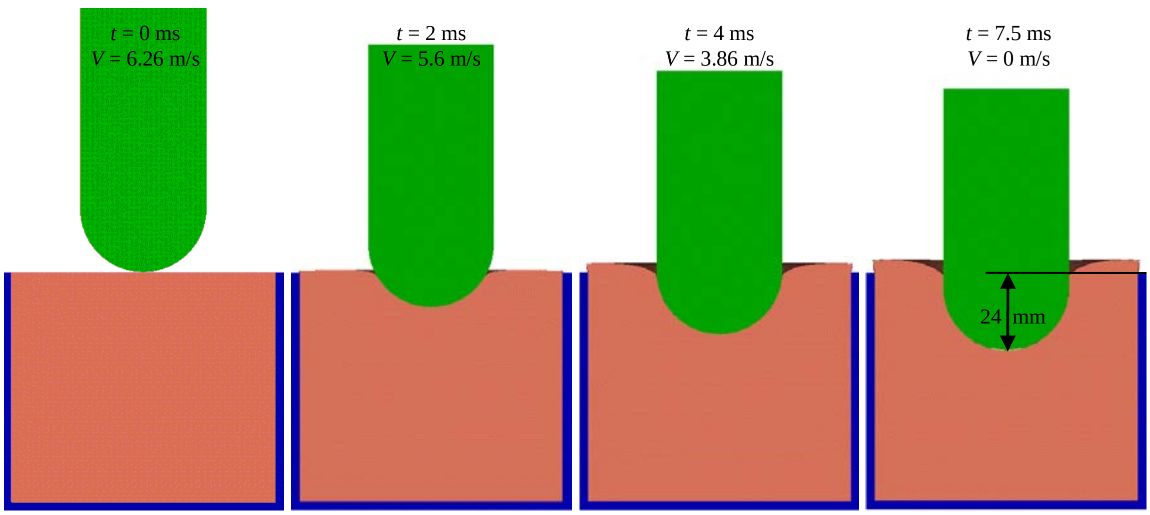


Fig. 4. Armour backing material deformations at chosen points of time

4. Numerical model of Dyneema®SB71

Nonwoven polyethylene Dyneema®SB71 consists of 6 layered in low-molecular polyethylene matrix in a criss-cross (0/90°) orientation group of aligned in the same direction filament fibers SK76 and 2 foils to protect material from abrasion and dirt.

This type of composites (laminates) in numerical simulations could be presented by: overall replacement model, layered replacement model or micro-mechanical replacement model (Fig. 5).

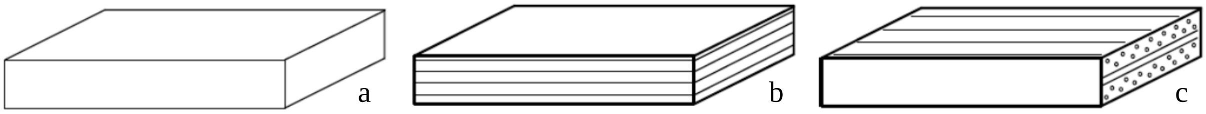


Fig. 5. Numerical models for laminates: a - overall replacement model, b - layered replacement model, micro-mechanical replacement model [7]

Layered replacement model in comparison to overall replacement model allow more detailed modelling of delamination phenomena and taking into account different orientation of laminas to each other. Micro-mechanical replacement model give possibility to model fiber sliding and fiber-matrix interactions. In a case of 9 mm Parabellum penetration into loosely arranged plies of soft ballistic type of nonwoven polyethylene Dyneema®SB71 (chapter 2) it was not observed delamination of single plies. Considering that and small size of each ply (t = 0,2 mm) in the described in the present article numerical simulations for nonwoven polyethylene Dyneema®SB71 it was used overall replacement model.

Nonwoven polyethylene Dyneema®SB71 layers were described with the use of orthotropic equation of state. Parameters determinating material stiffness (Young's moduli E_{11}, E_{22}, E_{33}, shear moduli G_{12}, G_{23}, G_{31} and Poissons ratios ν_{12}, ν_{23}, ν_{31}) were choosen on the basis of parameters of KFRP material from Ansys Autodyn v14 program library database and available in literature [4] informations about sound velocities for ultra-high molecular weight polyethylene fibers. From the range of values given in [4] there were adopted the greatest ones- respectively for sound velocity along and across fiber: 12 km/s and 2 km/s.

In the first numerical simulations because of too large deformations of Dyneema®SB71 layers the satisfying results were not achieved. It was decided to change on the basis of the experimental results described in the paper [7] the parameters of the equation of state. In this experimental research on the basis of recordings from SVR camera (Still Video Range Camera) of two kinds of penetrator (cylinder and saddle) impacts (V_i = 200÷500 m/s) into single Dyneema fiber it dynamic value of longitudinal Young's modulus of Dyeneema fiber (E_{11} = 200 GPa) was estimated (Fig. 6).

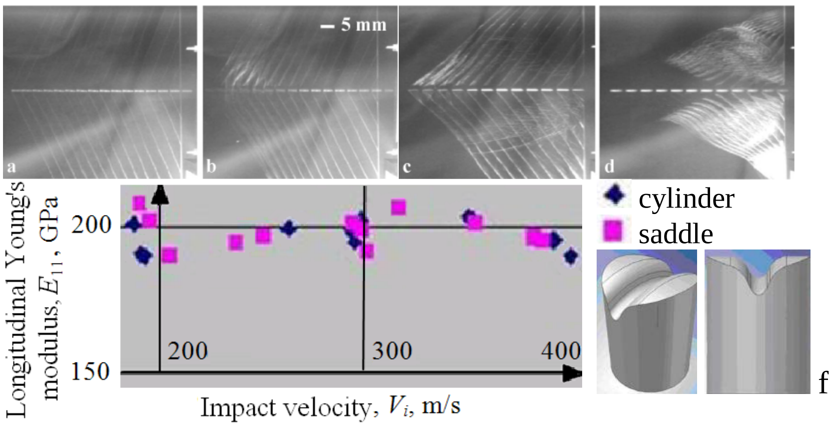


Fig. 6. Literature results of experimental tests: images from SVR camera for projectile impact velocities: a - 200 m/s, b - 300 m/s, c - 400 m/s, d - 500 m/s; e - longitudinal Young's modulus E_{11} in function of projectile impact velocity, f - saddle [7, 8]

Strength model used in numerical simulation was based on the stress-strain relation (strain rate $\dot{\varepsilon} = 10^3$) of yarn composed from 780 Dyneema®SK76 fibers [9] (Fig. 7).

In numerical simulations orthotropic failure model was used. In this model influence of damage mechanisms such as delamination, matrix cracking, fiber failure, and both through laminate thickness and shear strains are taken into consideration as a single phenomena - softening. Together with failure initiation material stresses are not instantaneously set to zero but linearly in function of so called crack strain ε^{cr} (Fig. 8).

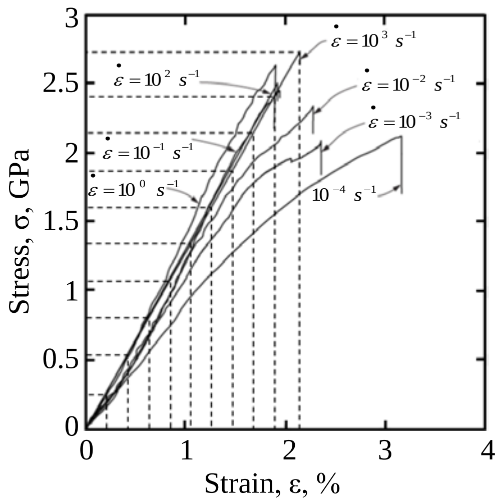
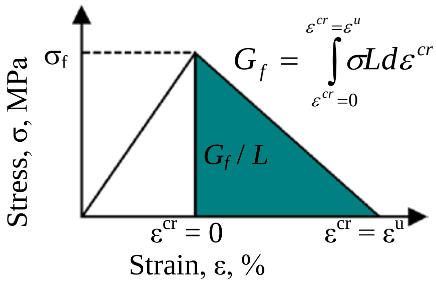


Fig. 7. Stress-strain relations of yarn composed from SK76 fibers for different strain rates



σ_f - value of stress corresponding to failure initiation
ε^{cr} - crack strain;
ε^{u} - ultimate crack strain
G_f - fracture energy
L - characteristic cell dimension in the direction of failure

Fig. 8. Schematic illustration of softening algorithm

The area under the softening part of the stress-strain curve is related to material properties called fracture energy G_f and to characteristic cell dimension in the direction of failure.

In Ansys Autodyn v14 program for described failure model it is required to define values of stresses which initiate material failure in the three axial directions F_{11}, F_{22}, F_{33} as well as in 3 shear directions F_{12}, F_{23}, F_{31} and also values of fracture energy in the respective directions G_{11}, G_{22}, G_{33}, G_{12}, G_{23}, G_{31}. These values could be determined by the following experimental tests: 0°, 45° and 90° tension tests, double cantilever beam test (DCB), end notched flexure test (ENF) and double notch shear test (DNS).

In view of no experimental data for nonwoven polyethylene Dyneema®SB71 in numerical simulations were taken appropriately increased values of parameters of failure model of similar, available in Ansys Autodyn v14 program library database KFRP material. In comparison to Dyneema®SK76 fibers KFRP fibers are about 10 times less resistant to tension. Assuming for both materials the same difference between ultimate strain and cracking strain ($\varepsilon^{u\ SB71} - \varepsilon^{cr\ SB71} = \varepsilon^{u\ KFRP} - \varepsilon^{cr\ KFRP}$) tenfold enlarged failure model parameters of KFRP were adopted.

5. Numerical simulation of 9 mm Parabellum FMJ projectile impact into nonwoven polyethylene Dyneema®SB71

After being built with the use of the Inventor Professional 2012 program, the CAD model was imported into the subprogram Workbench of Ansys v14 program. The mesh, initial and boundary conditions as well as the relations among each elements of the model were defined there. To reduce computing time symmetry conditions on two orthogonal planes were assumed, and eventually the numerical model was diminished to a quarter of the whole assumed system. Further works for the numerical model building, among others assignment of materials, were carried out in the Ansys Autodyn v14 program, which is dedicated to dynamic analyses. According to the DOP test the impact velocity (V_i = 365 m/s) and the boundary condition (loading with 25 N force belt tightening nonwoven polyethylene Dyneema®SB71 layers) were adopted. The parameters for equation of state, the strength model and the failure model for the projectile core (lead) and jacket (brass) were adopted on the basis of the earlier tests and numerical models [8].

The projectile core were discretized by means of 0.25 mm size SPH-particle while jacket by means of 0.25 mm size tetragonal solid elements (Fig. 5). For discretization of nonwoven polyethylene Dyneema®SB71 layers hexagonal solid elements with dimensions 0.4x0.4x0.2 mm were used (Fig. 9). Overall number of finite element in the numerical model (taking into account also armour backing material, box and belt) were 351 729 elements.

The results of the simulations are presented in Table 5 and in Figure 10.

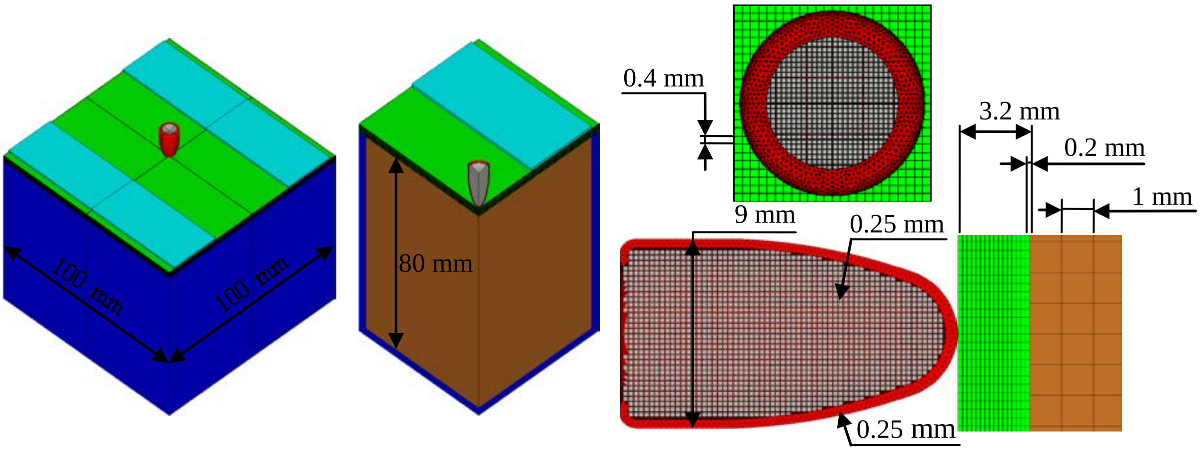


Fig. 9. Numerical model discretization

Table 5. Numerical results

	Perforation: Yes / No	Backface Signature *BFS*, mm	No. of layers perforated / damaged	Projectile deformation
Numerical results	No	12 mm	0 / 0	front part of the jacket torn off; the core material (lead) outside the jacket
Differences between results of experiment and numerical simulation	in agreement	Δ = 25 mm	Δ = 3 / 4	In the experiment 6 about 3 mm long cracking on the jacket surface; the core inside the jacket

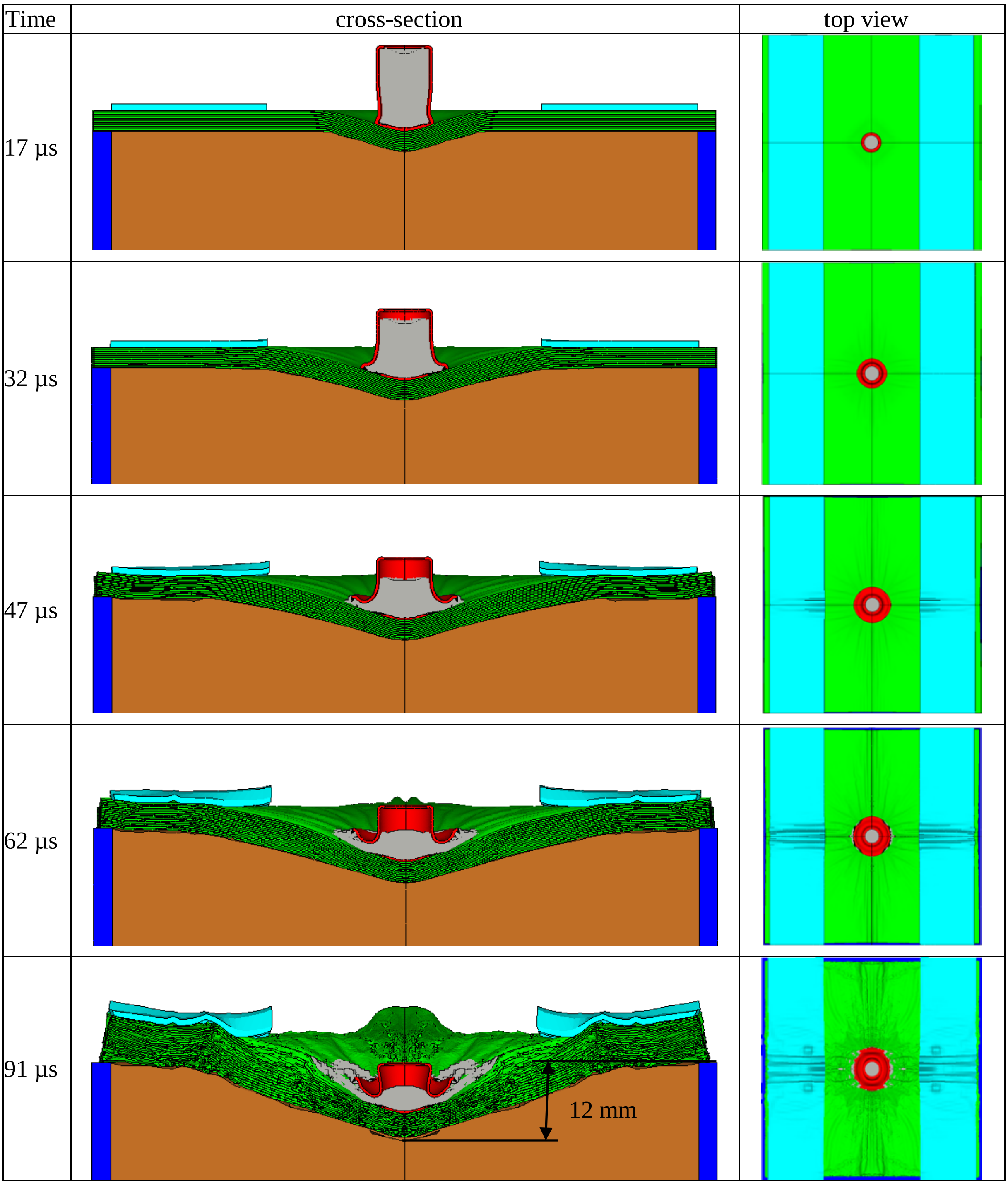


Fig. 10. Views of the 9 mm Parabellum projectile and 16 layers of the nonwoven polyethylene product Dyneema®SB71 after impact

6. Conclusions

On the basis of the tests and the numerical simulations the following conclusions can be drawn:

1. Overall replacement model, in a case of 9 mm Parabellum penetration into loosly arranged plies of soft ballistic type of nonwoven polyethylene Dyneema®SB71 is computationally efficient and sufficiently accurate. In the performed numerical simulations how-

ever the satisfying agreement with the experiment was not achieved and further works over numerical model are necessary. Material tests to verify the correctness of the values of the parameters adopted from the literature and simulations with more dense discretization of the numerical model are considered to be done.

2. The 16 layers of nonwoven polyethylene Dyneema®SB71 with dimensions 100x100 mm are able to stop 9 mm Parabellum projectile with 3 perforated layers and BFS = 37 mm (3 mm belove value allowed by PN-V-8700:2011 in correspondence to armour with bigger dimensions - shot in distance at least 76 mm to armour and background edges).
3. Armour with nonwoven polyethylene Dyneema®SB71 should contain trauma pack.
4. To evaluate if investigated nonwoven polyethylene Dyneema®SB71 layers meet requirements of Polish standard PN-V-8700:2011 it is necessary to perform DOP tests with bigger dimensions of layers.

7. Future works

Currently in the Military Institute of Armament Technology DOP tests of samples consisted of nonwoven polyethylene Dyneema®SB71 layers and different trauma packs are carried out. There are investigated commercially available trauma packs and made in the range of Smart Armour project innovative trauma packs based on magnetorheological fluids (MRF) and shear-thickening fluids (STF).

On the basis of this experimental results numerical models will be validated.

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