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NUMERICAL STUDY OF THE BALLISTIC RESISTANCE OF THE ARAMID FABRIC LAYERS

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ABSTRACT

The paper presents the results of the numerical investigation of the perforation problem. The ballistic resistance of the package of the aramid based fabric against 9 mm Parabellum projectile was studied. The fabric was assumed to be Twaron T750. Numerical analysis were carried out with the use of the LS-DYNA system including advanced material model for the fabric meeting the simplified mechanics of yarns and homogenization technique. Obtained results were compared with available experimental tests. The final conclusions deliver acceptable level of credibility of the developed numerical model.

Keywords: computational mechanics, ballistic resistance, body armor, fabric.

INTRODUCTION

Modern body armor is constructed of advanced materials with a very high strength and flexibility. Among this group of materials are also formed on the basis of aramid (Kevlar, Twaron, Technora) and polyethylene (Spectra, Dyneema) fibers. Proper selection of the appropriate number of layers and the material is not a trivial task. With the help come here modeling and computer simulations.

Modeling of the flexible fabric behavior is a challenging task, which is the subject of numerous studies. Shim (Shim, 1995) modeled the fabric material as a network of pin-joined flexible truss elements. Whereas Ting (Ting, 1998) used piecewise straight rigid rods joined by torsional springs and connected to overlapping rods by linear springs. Gu (Gu, 2004) explicitly modeled the fabric at the yarn level resolution what allowed for incorporation physical phenomena such as yarn-yarn interaction and yarn crimp. Rao (Rao, 2009) developed a local/global modeling approach. The local region was modeled in detail and the remaining area was treated as homogeneous continuum in which was no discrete modeling of individual yarns. Tabiei (Tabiei, 2002) developed micromechanical model based on Representative Volume Cell (RVC), which is a rectangular repeating unit in the plane of the fabric with diagonals in the fiber directions. Presented approach allows to account for reorientation of yarns and weave geometry without fabric modeling in detail.

The presented paper shows results of application micromechanics dry fabric material model, originally proposed by Tabiei (Tabiei, 2002), to predict the response of multilayer fabric package impacted by 9mm Parabellum bullet.

PROBLEM DESCRIPTION

The present study concerned the numerical analysis of the ballistic resistance of a fabric multilayer package. Examined system consisted of 22 layers of aramid, plain weaved fabric Twaron T750. Protective ability was tested against normal impact of 9 mm Parabellum bullet. As a measure of the ballistic effectiveness assumed maximum depression in the background material, which was a ballistic plasticine. Fig.1. shows ¼ of model geometry.

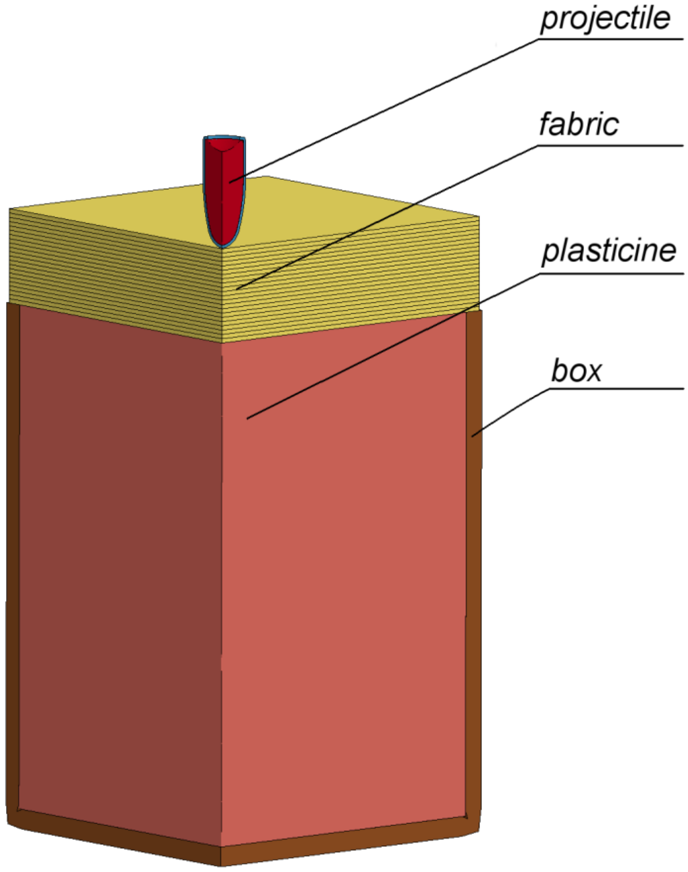

Fig.1 The ¼ of model geometry

NUMERICAL MODEL DESCRIPTION

Numerical calculations were performed with the non-linear finite element code LS-DYNA, which is commonly used tool in solving problems associated with shock wave propagation, blasts and impacts. Explicit integration scheme was used to solve the equation of motion. The numerical analysis used the symmetry of the problem, so that the spatial discretization was only quarter of the geometric model with the appropriate boundary conditions on the symmetry planes.

The fabric was described by constitutive model available in LS-DYNA material database. The micromechanics dry fabric material model (Tabiei, 2002) studied in this paper utilizes the micro-mechanical approach and the homogenization technique usually used in composite material models. The model accounts for reorientation of the yarns and the fabric architecture. The flexible behavior of fabric is obtained by discounting the shear modulus of the material in free state, which allows the simulation of the trellis mechanism before packing the yarns. The material data for the Twaron T750 are listed in Table 1.

Table 1 The material data for Twaron T750

Parameter	Symbol	Unit	Value	Source
Mass density	RO	g/cm^3	0.707	
Young's modulus of yarn	E1	GPa	67.0	
	E2	GPa	7.5	(Tabiei, 2002)
Shear modulus of yarn	G12	GPa	2.5	(Tabiei, 2002)
	G23	GPa	5.0	(Tabiei, 2002)
Poisson's ratio	V12	-	0.2	(Tabiei, 2002)
	V23	-	0.2	(Tabiei, 2002)
Stress to failure	XT	GPa	1.5	
Initial braid angle	THI	°	45.0	
Yarn locking angle	THL	°	1.0	
Angle tolerance for locking	ATLR	°	0.2	
Initial undulation angle in fill direction	BFI	°	12.3	
Initial undulation angle in warp direction	BWI	°	12.3	
Discount factor	DSCF	-	0,9	
Reorientation damping constant	CNST	-	0.1	
Transverse shear modulus of fabric layer	TRS	GPa	10.0	

Behavior of jacket material (brass) and core projectile (lead) was described by modified Johnson-Cook model. This model is typically applied in the study of explosive metal forming, armor perforation and impacts, so the situations that are accompanied by high strain rate deformations. The material data for the MJC model are given in Table 2.

Table 2 The MJC model parameters for jacket and core material.

Parameter	Symbol	Unit	Jacket	Core
Density	RO	g/cm³	8.52 (Borvik, 2009)	10,1
Young's modulus	E	GPa	115 (Borvik, 2009)	18,4
Poisson's ratio	PR	-	0.31 (Borvik, 2009)	0.42 (Borvik, 2009)
Specific heat	CP	J/kg K	375 (Borvik, 2009)	124 (Borvik, 2009)
Thermal expansion coefficient	ALPHA	µm/m K	19.0 (Borvik, 2009)	29.0 (Borvik, 2009)
Quasi-static threshold strain rate	EPSO	1/s	5E-4 (Borvik, 2009)	5E-4 (Borvik, 2009)
Room temperature	Tr	K	293 (Borvik, 2009)	293 (Borvik, 2009)
Melt temperature	Tm	K	1189 (Borvik, 2009)	760 (Borvik, 2009)
Initial temperature	T0	K	293	293
MJC:				
	A	MPa	206 (Borvik, 2009)	24 (Borvik, 2009)
	B	MPa	505 (Borvik, 2009)	40
	N	-	0.42 (Borvik, 2009)	1 (Borvik, 2009)
	C	-	0.01 (Borvik, 2009)	0,01
	M	-	1.68 (Borvik, 2009)	1 (Borvik, 2009)
CLF:				
Critical damage parameter	DC	-	1	
Critical Cockcroft-Latham parameter	WC	mJ/mm^3	914 (Borvik, 2009)	

In order to describe the response of ballistic plasticine, the power law plasticity model was employed, which is a combination of linearly elastic loading equation (1) with strain hardening equation (2):

$$\sigma = E\varepsilon \tag{1}$$

$$\sigma = k\varepsilon^{n} \tag{2}$$

The material data for the PLP model applied in this work are listed in Table 3.

Table 3 The PLP model parameters for ballistic plasticine.

Parameter	Symbol	Unit	Value	Source
Density	RO	kg/m^3	1750	
Young's modulus	E	MPa	2.866	(Sofuoglu, 2009)
Poisson's ratio	PR	-	0.4	(Ji, 2009)
Strength coefficient	K	MPa	0.3	
Hardening exponent	N	-	0.2	

The failure of core and background material was blocked in order to simulate real phenomenon as closely as possible. Their elements underwent extremely large deformations and became distorted. To prevent the negative volume of elements and premature termination remeshing was used.

Segment-Based contact was defined between composite panel and projectile. The Segment-Based contact algorithm detects penetration of one segment into another segment and then applies penalty forces to the segment nodes. The intensity of this force is proportional to the penetration depth.

DISCUSION OF RESULTS

Fig. 2 shows the numerical results of the simulation of the 9 mm Parabellum normal impact into 22-layer package of Twaron T750 fabric. The cross-section view presented in Fig. 2a depicts the projectile's deformation and response of the individual fabric layers. It is visible that some of them were perforated and others are not. Furthermore the depression in plasticine background is also presented in side view - Fig. 3a and front view - Fig. 3c. The front view of the deformed fabric layers were included in Fig. 2b. The obtained numerical results substantially coincide with the experimental observations, and the quantitative summary is included in Table 4. The depression in ballistic plasticine and number of perforated layers were compared here. The both experiment and the simulation proved that the bullet is stopped. And the other criteria indicate the acceptable level of divergency.

Table 4 Comparison of the numerical and experimental results

	Parameter	Experiment	Simulation
Background	Depression DP [mm]	28	32
Fabric	Number of perforated/damaged layers	7/11	7/7
Result	P/S (P – Perforated, S – Stopped)	S	S

Micromechanics dry fabric model proved that it can be used to simulate ballistic resistance of plain weaved fabric. However, assumed value of discount factor during calibration of model and observation of history variables (braid and undulation angles) indicate limited influence of fabric architecture on final solution. For used parameters material model worked more like standard orthotropic material model.

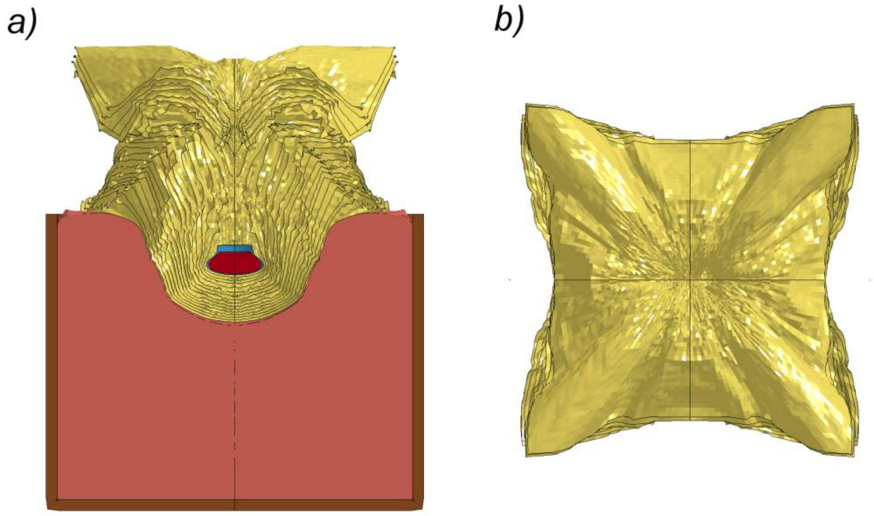

Fig. 2 Simulation of the 9 mm Parabellum normal impact into 22-layer package of Twaron T750 fabric at t = 0.8ms: (a) crossed side view, (b) fabric layers front view

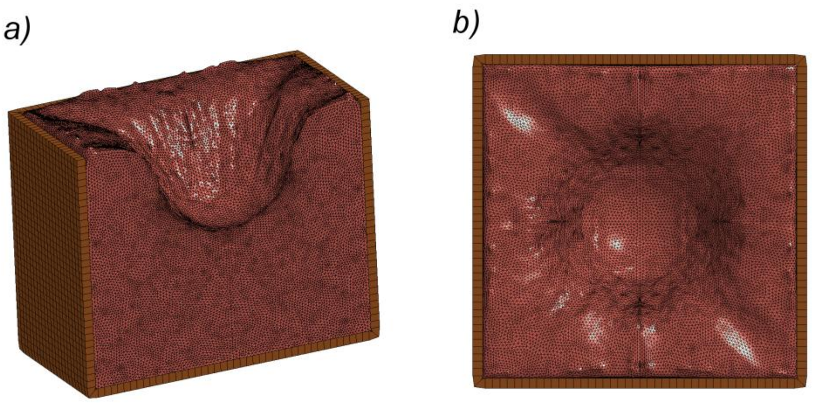

Fig. 3 Simulation of the 9 mm Parabellum normal impact into 22-layer package of Twaron T750 fabric at t = 0.8ms: (a) background crossed side view, (b) background front view

CONCLUSIONS

The problem of fabric perforation was numerically investigated. Obtained results were compared with available experimental tests and good agreement between them was achieved. The final conclusions deliver acceptable level of credibility of the developed numerical model.

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