Comparative Evaluation of Ballistic Resistance of Textile Armor Packages Against Steel and Lead Bullets

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Textile armor materials are widely used for protection against pistol and revolver bullets. In Russian practice the optimal number of layers and the type of ballistic fabric are usually selected empirically. However, the use of even simplest engineering models could reduce the number of required experiments and expenses for such experiments.

Russian pistol bullets feature a steel core whereas foreign short-barrel bullets use mainly lead cores. Therefore, for comparative evaluation of ballistic performance of textile packages against steel and lead-core bullets it is important to have techniques for evaluation of textile armor resistance to non-deformable and deformable impactors and to understand specifics of their interaction with textile armor.

Non-deformable impactors

Paper [1] presents an engineering model of interaction of a non-deformable penetrator with a textile armor package; the model is based on energy approach. The kinetic energy of the penetrator equates with the elastic deformation energy of the armor package yarns. It means that only the first interaction stage is considered. The second stage (i.e. dissipation of the potential deformation energy due to friction at stretching and separation of the yarns) is not considered.

From the pulse and energy conservation laws at inelastic collision it follows that after the initial (wave) interaction stage the velocity of the penetrator and the adjoint mass of the textile armor package v_1 and the kinetic energy of the penetrator and the adjoint mass W_1 will be:

$$v_1 = \frac{mv_0}{m + M_{TP}}$$

$$W_1 = \frac{(m + M_{TP})v_1^2}{2}$$

where v_0 is the initial velocity of the penetrator, m is the penetrator mass, M_{TP} is the adjoint mass of the textile package.

Energy conservation law for the penetrator and armor package after the impact-wave stage is written as follows:

$$W_1 = W_{el} + A_{fr} + A_b$$

where W_{el} is the elastic energy of yarn stretching; A_{fr} is the work of friction at yarn stretching and separating; A_b is the work of bullet deformation.

If we consider only the stage of yarn elastic stretching and take into account the fact that the penetrators are non-deformable, the energy balance is reduced to the following form:

$$W_1 = W_{el}$$

or

$$\frac{(m + M_{TP})v_1^2}{2} = \frac{E\varepsilon_p^2}{2}\frac{M}{\rho} \tag{1}$$

where E is the yarn elasticity module, ε_p is the ultimate elongation of the yarns, M is the mass of the textile deforming volume, ρ is the yarn material density.

The mass of the textile deforming volume (Fig. 1) is found from the model of equivalent yarns [1]

$$M = 4\beta d c_T t_T m_{TP}$$

where $\beta = 1\ldots2$ is an enlargement coefficient of the package area involved into movement as compared to the bullet cross-section area; d is the penetrator caliber; $c_T = \alpha c$ is the longitudinal wave velocity in equivalent yarns, c is the sound velocity in the yarns; $\alpha = 0.75\ldots1$ is the coefficient of sound velocity reduction due to yarn winding; t_T is a typical time of the penetrator braking; m_{TP} is the areal density of the textile armor package.

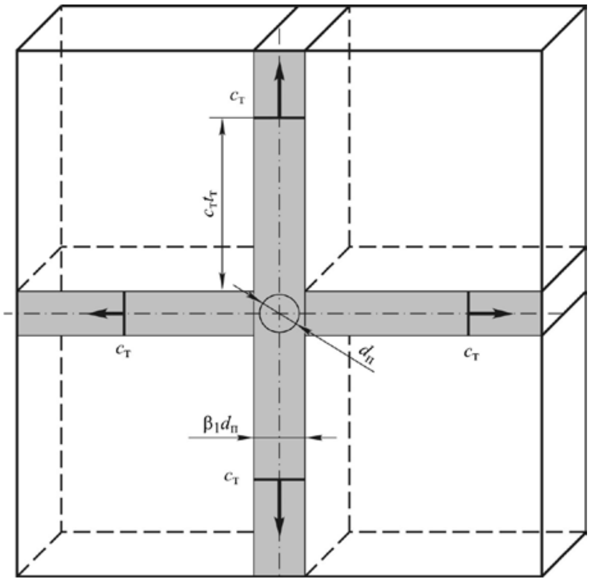

Fig.1: Diagram of deformed textile package covmputation at $t = t_T$

$$t_T = \frac{w_{max}}{v_0}$$

where w_{max} is the maximum achievable deflection at the package perforation threshold at the stage of transformation of the penetrator kinetic energy to elastic energy of yarn stretching. Such deflection is by an order less than that which is formed after termination of the process of textile package yarn stretching and which can be measured, for example, on a plasticine block. We assume that the maximum achievable deflection is proportional to the yarn ultimate strain: $w_{max} = \gamma \varepsilon_p d$, where γ is the coefficient of proportionality which depends on the textile properties.

The term

$$X = \frac{\pi d^2}{4} \frac{m_{TP}}{m}$$

is introduced which is the ratio of the mass of the textile package area directly under the penetrator to the penetrator mass.

Now, substituting all the above expressions into (1), we can obtain the expression for the textile package perforation threshold velocity v_{th}:

$$v_{th} = c\varepsilon_p \sqrt[3]{4\alpha\beta\gamma(1+\beta X)\frac{d^2 m_{TP}}{m}} \qquad (2)$$

If we denote $K = \sqrt[3]{4\alpha\beta\gamma}$ and take into account that $\sqrt[3]{1+\beta X} \approx 1$, we can obtain:

$$v_{th} = Kc\varepsilon_p \sqrt[3]{\frac{d^2 m_{TP}}{m}}$$

Coefficient *K* is determined by the textile properties, backup structure, method of textile armor package fixation. It follows from the fact that the threshold velocity of penetration can be measured only in the experiment as a whole, but not separately at the first stage of penetrator/armor package interaction. That's why the backup structure which determines the interaction conditions at the second stage – stage of yarn stretching and separation – will have a great effect on v_{th} and *K*.

Table 1 contains values of coefficients *K* for some Russian ballistic fabrics, calculated with the help of expression (2) from experimental data. In these calculations it was assumed that the sound velocity *c* and ultimate elongation $_p$ in para-aramid fabrics were c=9600m/s, ε=0.04; coefficient β=1.5.

Analysis of the obtained results leads to the following conclusions:

1. Coefficient *K* (if we take into account a large spread of fabric properties) does not depend on the type of the weapon, at least the types against which textile armor is typically used.
2. However, this coefficient significantly depends on the back-up material or the supporting structure: $K_{pasticine} \sim 0.95K_{felt}$; $K_{frame} \sim 1.1K_{felt}$. Frame fixation results in increase of coefficient *K*, and the plasticine back-up – in its reduction, as it reduces the height of deformation cupola and impedes formation of elastic strain (energy absorption at the elastic stage).

Deformable penetrators

Lead bullets deform heavily in the process of interaction with textile armor (Fig.1). The deformation extent depends on the bullet structure. From experimental data we can state that lead bullets take the form close to a spherical segment with the basis diameter equaling to 1.6 to 2 of the bullet caliber. The lesser number corresponds to FMJ bullets, the larger – to SWC.

Two significant amendments shall be introduced into the above model: taking into account energy consumption for bullet deformation, and increase of the bullet diameter in the process of interaction with the textile armor package.

Thus, the energy balance for deformable bullets will look as follows:

$$W_1 = W_{el} + A_b$$

Table 1.

Designations: PM– PM pistol bullet, SB – steel ball, fragment simulator
Note: Table 1 contains the average values of areal densities and threshold velocities of textile armor package perforation from many tests.
** – data from one test.*

Fabric Article/ Number of layers	Areal density, kg/m²	Backup material or supporting structure	Threat			V_{th}, m/s	K
			Type	Mass, g	Caliber, mm		
56319A 18	2.3	Plasticine	PM	5.9	9	340	**2.78**
56319A 18	2.3	Plasticine	SB	1.05	6.35	492*	**2.86**
56319A 18	2.3	Felt	SB	1.05	6.35	521	**3.03**
56319A 30	3.84	Felt	SB	1.05	6.35	632	**3.1**
56319A 30	3.92	Fixed in the frame by clamp straps	SB	1.05	6.35	680*	**3.31**
86-204-07BO 16	3.66	Plasticine	PM	5.9	9	340	**2.38**
86-204-07BO 25	5.24	Felt	SB	1.05	6.35	562	**2.48**
86-204-07BO 18	3.77	Felt	SB	1.05	6.35	510*	**2.51**
86-294-05 20	3.24	Felt	SB	1.05	6.35	565	**2.93**
84127 20	2.97	Felt	SB	1.05	6.35	578	**3.09**
84127 20	2.97	Fixed in the frame by clamp straps	SB	1.05	6.35	620*	**3.31**

To estimate the energy consumed for bullet deformation, let's approximately define the bullet deformation as uniaxial compression deformation (Fig.3)

$$\varepsilon_b = \frac{l_b - h}{l_b}$$

For lead bullets $\varepsilon_b = 0.6 \div 0.7$

The work of upsetting of the cylindrical blank will be as follows:

$$A_b = \iint_{V\ \varepsilon} \sigma_i d\varepsilon_i \approx \sigma_{fr} \varepsilon_b V_b = \sigma_{fr} \varepsilon_b \frac{m}{\rho_b}$$

where σ_T is the yield strength of the bullet material.

Let's find the fraction of the work of bullet deformation from its initial kinetic energy:

$$\frac{A_b}{W_0} = \frac{\sigma_{fr} \varepsilon_b \dfrac{m}{\rho_b}}{m \dfrac{v_0^2}{2}} = \frac{2\sigma_T \varepsilon_b}{\rho_b v_0^2} \qquad (3)$$

After substituting the values of actual bullet characteristics into expression (3) we can see that the deformation work constitutes a very small portion as compared to the initial kinetic energy of the bullet. For example, for JHP bullets of 0.44 Magnum revolver the bullet deformation work is about 1.5% of the initial kinetic energy (lead density ρ_b=11300 kg/m³, ε_p=0.6, σ_T=50 MPa, v_0=436 m/s). Therefore, it can be ignored.

When lead bullets interact with textile armor, an important factor is an increase of the penetrator diameter in the process of its deformation. That's why it would be expedient to multiply parameter *d* in the model for a non-deformable bullet by coefficient *f* which takes into account the penetrator diameter increase.

a

b

Fig.2: Lead bullets after interaction with textile armor
a) [top] FMJ 9mm Parabellum
b) [bottom] JHP 0.44 Magnum

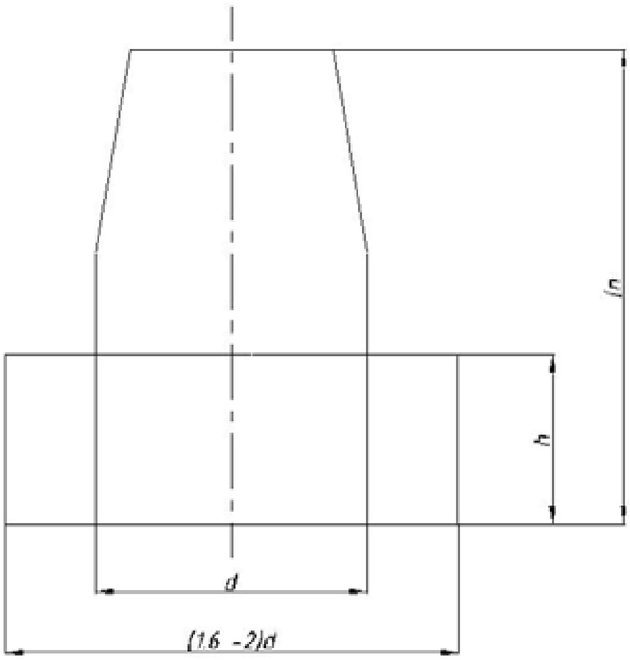

Fig.3: Diagram of bullet deformation estimation

Table 2.
** NP – non-perforation; P – perforation.*
*** re-calculated coefficient:* $K_{plasticine} \sim 0.95K_{felt}$

Fabric Article / Number of layers	Areal density, kg/m²	Threat	Velocity, m/s	Result	Assumed coef. K	Rated V_{th}, m/s
56319A 36	4.6	0.44 Magnum m=15.6g, d=11mm	432 449 442	NP NP NP	2.82	**512**
56319A 24	3.1	0.44Magnum m=15.6g, d=11mm	448 443 442	NP NP NP	2.82	**444**
56319A 30	3.8	Parabellum m=8г d=9мм	461 467 475	NP NP NP	2.82	**514**
86-204-07BO 18	3.7	0.44 Magnum m=15,6г, d=11мм	447	P	2.38	**400**
86-204-07BO 22	4.52	0.44 Magnum m=15,6г, d=11мм	425 442 430	NP NP NP	2.38	**431**
86-294-05 20	3.24	0.44 Magnum m=15,6г, d=11мм	422 442 442	NP P P	2.78**	**440**
86-294-05 25	4.1	0.44 Magnum m=15,6г, d=11мм	438 438 435	NP NP P	2.78**	**480**

As we emphasized above, from our experimental data it follows that coefficient $f = 1.6\ldots2$. Assuming such approximation, from (2) we'll obtain the following equation:

$$v_{th} = Kc\varepsilon_p \sqrt[3]{\frac{(fd)^2 m_{TP}}{m}} \quad (4)$$

Table 2 contains test data for textile armor packages with plasticine back-up and values of vth calculated on the described model with the use of coefficients *K* from Table 1. The sound velocity in para-aramid yarns, the ultimate elongation and coefficient β we assumed to be the same as above. Coefficient *f*=1.8.

As we can see from Table 2, the calculated data correlate well with the experimental one.

Comparative evaluation of textile armor packages to steel and lead bullets

To compare the threshold penetration velocities (v_{th}) of deformable and non-deformable bullets for the same armor package we can divide (2) by (4):

$$\eta = \frac{v_{th}^{st}}{v_{th}^{lead}} = \sqrt[3]{\frac{d_{st}^2 m_{lead}}{f^2 d_{lead}^2 m_{st}}} \quad (5)$$

where subindexes *st* and *lead* refer accordingly to steel and lead penetrators.

Thus, η is the parameter for recalculation of the armor package ballistic performance against different bullets. If we assume *f=1.8* and substitute the values of masses and calibers of steel and lead bullets into (5), we can obtain, for example, the following:

$$v_{th}^{PM} = 0{,}75 v_{th}^{Parabellum}$$
$$v_{th}^{TT} = 0{,}68 v_{th}^{Parabellum}$$
$$v_{th}^{PM} = 0{,}82 v_{th}^{0.44 Magnum} \quad (6)$$

These relations shall be understood as follows: if the textile package has $v_{th} = 436$ *m/s* when impacted by 0.44 Magnum revolver bullet, then it will have $v_{th} = 0.82 \cdot 436$ *m/s* = *356 m/s* when impacted by PM pistol bullet. This value is much higher that the standard velocity of PM pistol bullet (315±10 m/s), therefore the armor package which belongs to Ballistic Level IIIA of NIJ 0101.04 (USA) will correspond to Level 1 of the Russian standard GOST 50744-95. And vice versa, if the armor package has v_{th} = *445 m/s* when impacted by TT pistol bullet, it will have v_{th} = *445 m/s ÷ 0.68 = 652 m/s* when hit by Parabellum bullet, therefore the armor package belonging to Ballistic Level IIIA of NIJ 0101.04 (USA) will not correspond to Level 2 of the Russian standard GOST 50744-95. From the above it follows that armor structures with Level 2 of the Russian standard GOST 50744-95 are superior by their ballistic performance to similar structures with Level IIIA of NIJ 0101.04.

Thus, we managed to expand the range of tasks performed with the help of computational model of penetrator/textile armor interaction. We obtained the values of coefficient K for most widely used para-aramid fabrics manufactured in Russia. We established the correlation parameter of perforation ability of steel and lead bullets against textile armor packages; the parameter can be used to compare the ballistic resistance of armor structures belonging to different classes of Russian and foreign standards.

References

1. *Materials and protective structures for local and personal armouring (text) / V.A. Grigoryan, I.F. Kobylkin, V.M. Marinin, E.N. Chistyakov. – Moscow. Radiosoft Publishing House, 2008*

Investigation of Anti-Ricochet Properties of Body Armor with Steel Armor Panels

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Exploitation of body armor with steel armor panels has shown, that fragments formed in interaction of destructive elements (bullets or high -velocity fragments) with high hardness steel surface are ricocheting and can lead to arm, face or neck injuries. In that case in front of steel armor panels anti -ricochet structure (ARS) is mounted as protective element, providing partial or full localization of secondary fragments.

The aim of the investigation, that included study of the structure of witness plates, their damage criteria, target conditions and real body armor tests, was creation of ARS evaluation procedure and working out of recommendations on ARS composition for body armor with steel armor panels.

0.5 mm-thick aluminum sheet of AMG6 alloy was selected as the witness plate. For confirmation of the right choice of the witness plate, values of V_{50}, energy intensity (ΔE), and energy density E_{den} were determined. Possible effect of test conditions, and in particular of the characteristics of test means – weight

Fig. 1

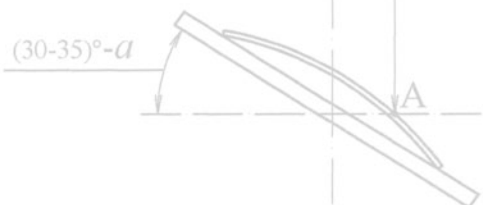

Fig. 2