Ballistic Resistance Modeling of Aramid Fabric with Surface Treatment

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Abstract. The minimization of mass and reducing the value of deflection of the back surface of an armored panel, which will lower the level of trauma to the human body, are crucial tasks in the current development of body armors. A significant part of the bullet energy is dissipated due to the friction of pulling-out yarns from ballistic fabrics in the body armor. We present a method for controlling the process of dry friction between yarns – surface treatment with various compositions (PVA suspension, rosin). This procedure causes only a slight increase weighting of the fabric. We investigated an impact loading of aramid fabrics of plain weave P110 with different types of surface treatment and without it (the samples were located on the backing material – technical plasticine). The indenter speed was in the range of 100 – 130 m/s. We also developed a model of an impact loading of considered samples in explicit FE code LS-DYNA. The surface treatment of the fabric in the model was taken into account by only one parameter – the coefficient of dry friction. We considered several methods of the task parallelizing. Numerical experiments were conducted to study the problem scalability. We found that the surface treatment reduces deflection of fabric up to 37% with an increase in weight up to 5.1%. The numerical values of the depths of the dents in the technical plasticine are in good agreement with the experimental data.

Keywords: Supercomputer modelling, FEA model, Aramid fabric, Impact, Surface treatment, Frictional coefficient, Technical plasticine, LS-DYNA.

1 Introduction

Minimization of armored panels mass while maintaining a given level of protection is the main task in their designing. In outer layers of armored panels, which contact with the high-speed bullet, the dynamic phase predominates, and in back layers – the friction-based and low speed phase. In a fabric armored panel the most part of the kinetic energy of a bullet is dissipated due to the yarns pull-out from the fabric, frictional interaction, and the rest of the impact energy is spent on straining and failure the yarns [1-3]. Thus, to reduce the energy transferred to the protected object, i.e. to reduce the deflection of the rear side of the armored panel, the armored panel should dissipate the possible maximum of the bullet kinetic energy. The deflection of the rear side of armored panels resulting from local impacts can be lowered by the modernization of fabric panels: the combination of fabrics with different types of weave (fabric with minimal curvature of yarns in outer layers, and with maximum curvature – in rear layers) [4]; the use of fabric layers made of polyamide fibers, which reduce the speed of sound and extend the work dynamic phase of the back layers of panel, between the fabrics of aramid fiber [4]; through-the-thickness stitching of package [5-9]; polymer layer covering [10, 11]; the use of non-Newtonian fluids [8, 9, 11, 12-15]; abrasive particles insertion [10, 16]. However, these methods have drawbacks: the fabrics combination complicates logistics and increases the product cost; the stitching reduces the flexibility and comfort of wearing; abnormally viscous liquids increase the fabrics surface density by many times; polymer covering significantly increases the fabric mass and prevent the yarns pulling out (local impact results in yarns failure); abrasive particles work only for the case of a puncture. At the same time, fabric surface treatment allows us to increase the frictional interaction of yarns and to reduce the deflection of fabric after a local impact with the minimal increase of weight. To investigate the mechanism of deformation and failure of fabrics under local impact, both numerical approach and experimental study were used [1, 11, 17]. Unfortunately, experiments cannot reveal the influence of individual factors on the impact interaction of the bullet with the armored panel. By means of the finite element method fabrics were modeled by a continuous medium [18], individual yarns modeled by beams [3, 19], shells [14, 20] and solids [1, 21] finite elements. Models of a continuous medium do not allow us to investigate the yarn pull-out from a fabric. In models with beam finite elements, it is impossible to take into account the contact interaction between the yarns. Fabric models with solid anisotropic finite element yarns require large computational resources. In our opinion, models with shell finite elements [22, 23] have great prospects. This approach allow us to take into account multiple contact interactions, the anisotropy of yarns and require an order of magnitude less computational resources in comparison with models with solid anisotropic finite elements.

The work is structured as follows. The problem is formulated in section 2. Section 3 describes the ballistic tests. Section 4 contains ballistic impact simulations. In section 5 the key results are provided.

2 Problem Statement

We considered aramid fabrics of plain weave P110 with a surface density of 110 g/m^2. Methods of fabric surface treatment were chosen based on the following conditions: the processing should allow us to control the frictional interaction between the yarns – increase or decrease of the coefficient of friction; the weighting of the fabric should be negligible; the connections between the yarns should be not too strong to exclude yarn failure in the process of pulling out.

We considered the following surface treatments:

1. Fabric with no treatment.
2. Water emulsion PVA, solid content 38%, fabric weighting increase on 5.1%.

3. PVA-T – water emulsion PVA, solid content 38%, fabric weighting increase on 5.1%. Further temperature treatment of the fabric at +98°C.
4. Pine rosin B10, fabric weighting increase on 3.1%.

We performed experiments and supercomputer modeling to determine the deflection of the back side of two layers of ballistic fabric with and without surface treatment after local impact. Samples were located on the backing material. The edges of the fabrics were not fixed (Fig. 1). We chose two layers of fabric to ensure that the depth of a dent on the technical plasticine surface could be measured clearly. In calculations and experiments, the fabric size constituted 100×100 mm, the size of backing material equaled to 100×100×30 mm, the indenter was a ball with the diameter of 4.5 mm, the mass of 0.5 g, and the velocity of 100 – 130 m/s. Several ways of problem parallelizing were considered, and we obtained speedup graphs.

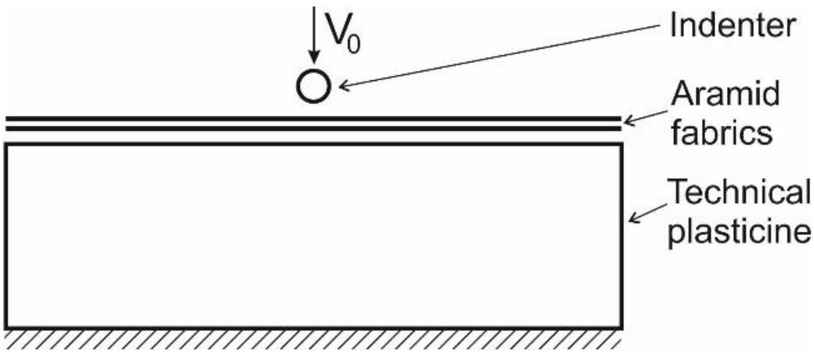

Fig. 1. Schematic representation of the problem

3 Ballistic Tests

Two layers of the fabric were placed on the surface of the backing material without fixing. Shots were produced by steel balls at right angle using pneumatic pistol IZH53M. The speed of the ball was fixed with the S04 chronograph with an accuracy of 1 m/s. We measured the depth of the dent in the technical plasticine, which was left by the fabrics after impact. The impact velocities were not sufficient to failure yarns in the fabric, so the ball kinetic energy was dissipated by yarn pull-out and the plasticine deformation.

The treatment allowed us to reduce the deflection of the ballistic fabric back surface: treatment with rosin (with addition of 3.1% of weight) reduced the deflection by up to 32%, water suspension PVA-T and PVA (with addition of 5.1% weight) – by 35% and 37.4%, respectively. The fabric and plasticine deformations under local impact are shown in Fig. 2. The features of the fabric after different types of surface treatment are presented in Table 1.

Fig. 2. Deformation of two layers of the fabric of plain weave P110 with PVA treatment and technical plasticine after the local impact

Table 1. The features of the fabric of plain weave P110 with different types of surface treatment after a local impact

Treatment	Surface density ρ, kg/m^2	Increase in fabric weight, %	Bullet velocity, m/s	Dent depth w, mm
No treatment	110	–	123	6.5
			124	6.6
			125	6.8
PVA	115.8	5.3	108	3.5
			113	3.8
			122	3.9
PVA-T	115.2	4.7	120	3.8
			122	4.1
			128	4.8
Pine rosin B10	114.1	3.7	110	3.7
			111	3.8
			114	4.5

4 Ballistic Impact Simulations

4.1 Model Description

We developed a model of deformation and failure of ballistic fabrics, which consist of individual yarns with and without surface treatment, using the LS-DYNA software package. The geometry of the yarn was simplified and was represented by a piecewise linear set of shell elements with a constant width and thickness (Fig. 3). This representation provides us with the minimum of geometric parameters and numerical efficiency – minimal time for computer calculations. In the model the yarns have relative freedom of movement with the possibility of pulling-out with dry friction. The thickness of the yarns (shells) is 50 μm, width – 410 μm.

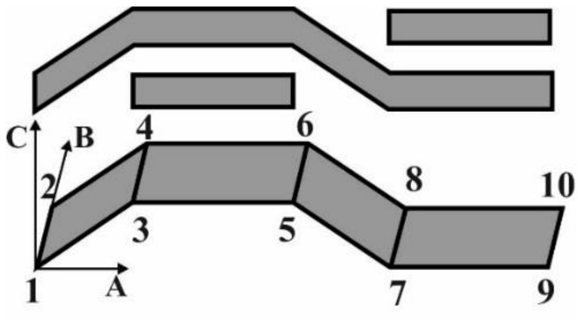

Fig. 3. The geometry of the yarn (plain weave)

The yarn material was orthotropic (*MAT_ENHANCED_ COMPOSITE_DAMAGE) [24]. The material characteristics are shown in Table 2. The modulus of elasticity along the yarn (E_A) was determined experimentally [25], the remaining modules of elasticity (E_B, E_C), two shear modules (G_{AB}, G_{BC}) and three Poisson's ratios were chosen according to the literature recommendations [14, 26-28].

Table 2. Yarns material characteristics

Parameter	Symbol	Value
Modules of elasticity, Pa	E_A	$1.4 \cdot 10^{11}$
	E_B, E_C	$1.4 \cdot 10^{10}$
Density, kg/m^3	ρ	1 440
Poisson's ratios	μ_{AB}, μ_{BC}, μ_{AC}	0.001
Shear modules, Pa	G_{AB}, G_{BC}	$1.4 \cdot 10^{10}$
	G_{CA}	$4 \cdot 10^{7}$

Aramid yarns in P110 fabric consist of many fibers with a diameter of 10 – 15 microns and a small twist and have a weak bending resistance. Therefore, to consider the bending in the model, three integration points over the thickness were used. The resistance to bending is affected by the transversal shear modulus G_{CA}. We found this parameter from preliminary calculations by comparing the calculated and experimental dependences of the load on displacement when pulling-out a yarn from a fabric without surface treatment [25].

For a fabric without treatment the static coefficient of friction was determined experimentally, its value equals to 0.174 [25]. Surface treatment of fabrics in models was incorporated by a corresponding change in the value of the static dry friction coefficient. Therefore, we made calculations for pulling-out the yarn from the fabric with different static friction coefficient so that the calculated force-displacement dependencies coincided with the experimental for all types of surface treatment. We found that for fabrics treated with PVA, PVA-T, and Rosin the coefficient of dry friction constituted 0.261 [25]. Contact type were assigned by the command *CONTACT_AUTOMATIC_SURFACE_TO_SURFACE. The weight of the surface treatment in the model was attached to the mass of the yarns.

In the model fabric armor panels, which consist of two layers of fabric, were placed without fixing on the backing material. The indenter, made of the rigid material, had a spherical shape, the diameter of 4.5 mm, and the mass of 0.5 g. The initial speed of the indenter for each type of fabric was the same as in the experiment.

The material of the backing material – technical plasticine is elastic–plastic model, in which the yield stress depends on the rate of strain. From the list of materials in the software package LS-DYNA for plasticine we chose *MAT_STRAIN_RATE_DEPENDENT_PLASTICITY, which allowed us to take into account the dependence of the yield stress on the strain rate in a tabular form [24]. The parameters for the material model were determined experimentally [29]. The elastic modulus E of plasticine is 20 MPa, the Poisson's ratio μ is 0.45, and the density ρ is 1400 kg/m^3. The mesh of the finite elements of the developed model is shown in **Fig. 4**.

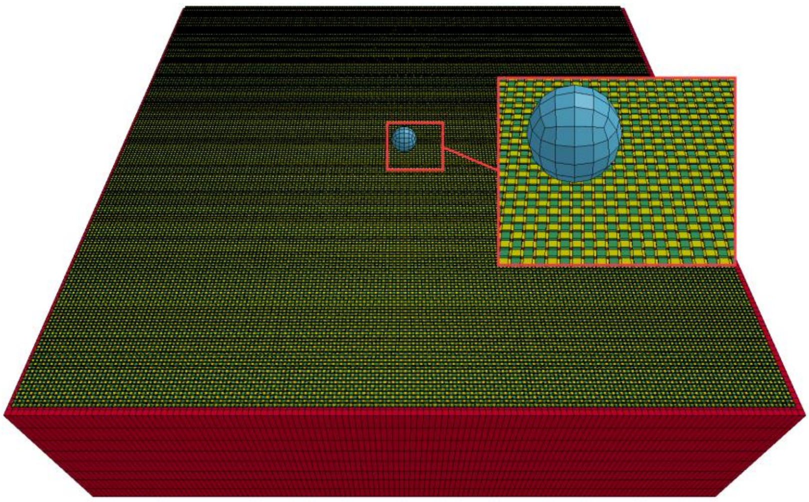

Fig. 4. Finite element mesh

4.2 Results of the Simulation

Calculations were performed on the supercomputer "Tornado SUSU" [30]. We considered three different methods of the model parallelization for fabrics without treatment. Firstly, we used the automatic parallelization of the model (**Fig. 5**a). In the second case, the model was divided into bands lying along one side of the model and passing through the entire thickness (**Fig. 5**b). Finally, we divided the model in the cylindrical coordinate system (**Fig. 5**c).

The speedup graphs are shown in **Fig. 6**. This task was calculated maximum to 48 cores. The number of cores was limited by the existing license for the software package LS-DYNA. The time for solving the problem on one core is 269,793 s. We found that, with the increase in the number of cores, the first parallelization method – automatic parallelization of the model gives a lowest speedup. In this case, fabrics and technical plasticine which contacting between themselves are distributed on different supercomputer cores. The time for calculating the task is increased by increasing the amount of data to transfer messages between these cores. The second method of parallelization gives the best speedup. Model was divided into bands lying along one side of the model and passing through the entire thickness. Contact surfaces are not distributed to different supercomputer cores. The intensity of data transfer between the cores in this case is lower than, in the first method of parallelization. The third method of parallelization gives an average speedup. In this case, we divided the model in the cylindrical coordinate system, parts of the model are divided through the entire thickness. The intensity of data transfer is higher here than in the second method of parallelization. This is due to the fact that the center of the model where there is intensive interaction between the bullet, fabrics and technical plasticine is divided into all the cores of the supercomputer.

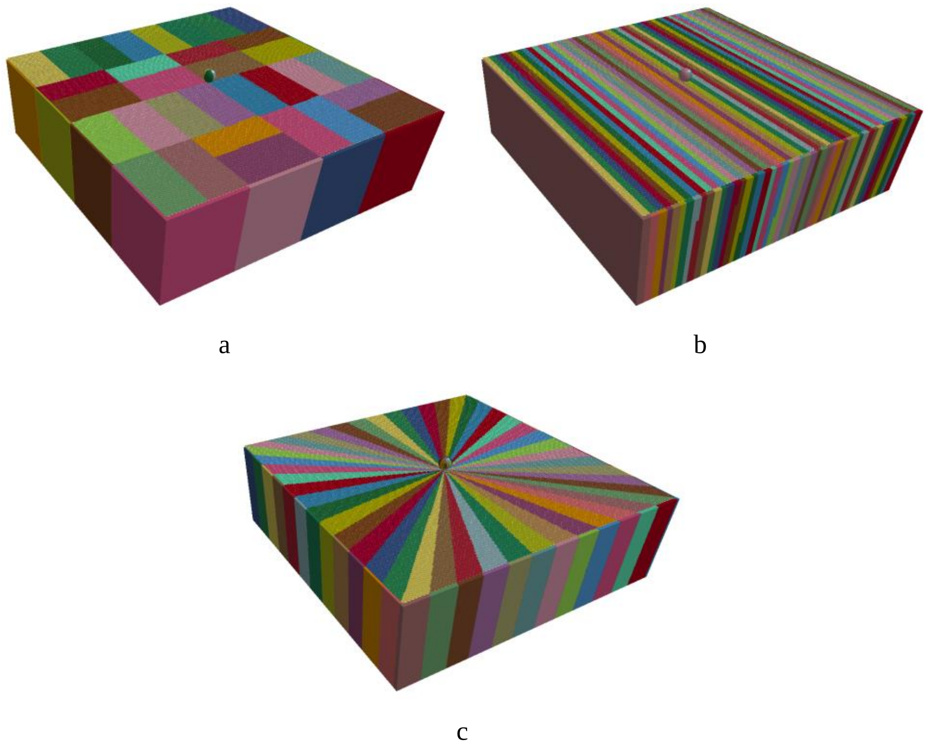

Fig. 5. Parallelization of the models on 48 cores (a – automatic, b – the bands passing through the entire thickness of the model, c – parallelization in the cylindrical coordinate system)

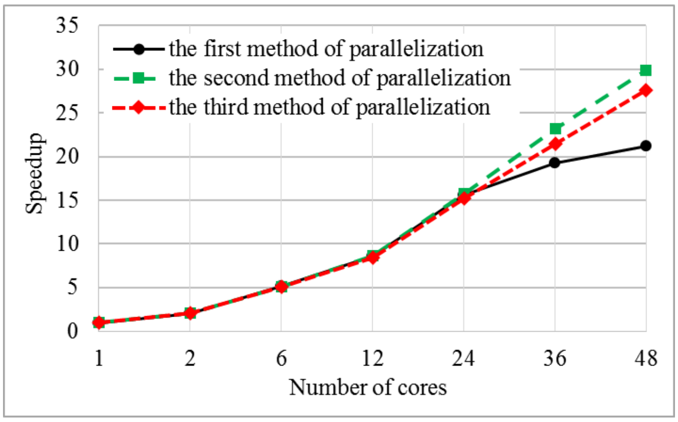

Fig. 6. Relative speedup

The nature of deformation of the fabrics with PVA surface treatment and the backing material after dynamic interaction with the indenter in the finite element model coincides with those observed in the experiment (**Fig. 7**). The calculated values of the dent depth in the technical plasticine are in good agreement with the experimental data. We have created a numerical model that adequately describes the experiments.

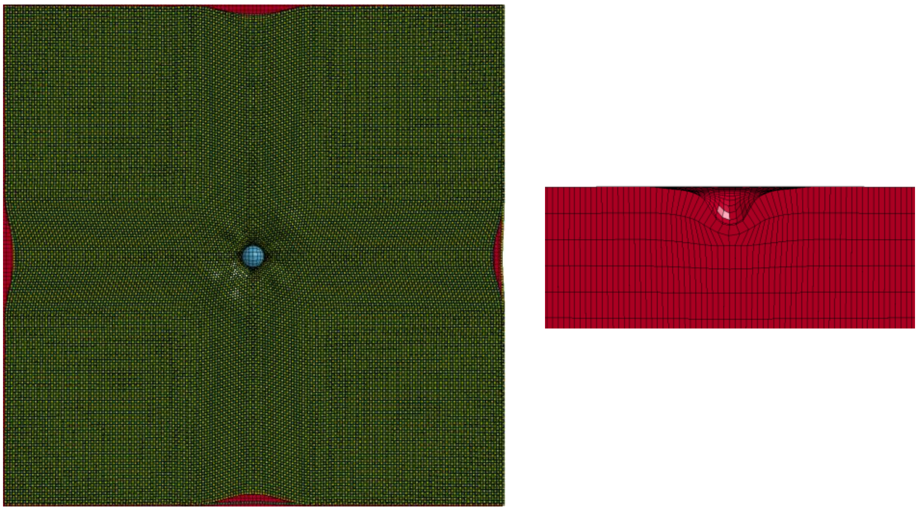

Fig. 7. The dent in the fabrics with PVA surface treatment and in the backing material after dynamic interaction with the indenter

5 Conclusion

We experimentally determined the depth of a dent in the backing material in case of a local impact on ballistic fabrics P110 with and without surface treatments. We showed that the treatment with pine rosin reduced the deflection up to 32% with the increase weighting of the fabric on 3.1%, the water suspension PVA-T and PVA – by 35% and by 37.4%, respectively, with the increase weighting on 5.1%.

We developed numerically effective models, which allowed us to calculate the dent depth in considered cases. The surface treatment of the fabric in the model was taken into account by changing one parameter – the coefficient of dry friction. The calculated and experimental values of the dent depths in technical plasticine agree with each other. Three methods of parallelization of the model are considered and speedup graphs are obtained.

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References

1. Zhu, D., Soranakom, C., Mobasher, B., Rajan, S.D.: Experimental study and modeling of single yarn pull-out behavior of Kevlar® 49 fabric. Composites: Part A 42, 868–879 (2011). doi: 10.1016/j.compositesa.2011.03.017
2. Nilakantan, G., Merrill, R.L., Keefe, M., Gillespie, J.W. Jr., Wetzel, E.D.: Experimental investigation of the role of frictional yarn pull-out and windowing on the probabilistic impact response of Kevlar fabrics. Composites: Part B 68, 215–229 (2015). doi: 10.1016/j.compositesb.2014.08.033
3. Das, S., Jagan, S., Shaw, A., Pal, A.: Determination of inter-yarn friction and its effect on ballistic response of para-aramid woven fabric under low velocity impact. Composite Structures 120, 129–140 (2015). doi: 10.1016/j.compstruct.2014.09.063
4. Dolganina, N.Yu.: Deformirovanie i razrushenie sloistykh tkanevykh plastin pri lokal'nom udare. PhD thesis [Deformation and fracture layered tissue plates under local impact. PhD thesis]. Chelyabinsk (2010), 128 p.
5. Bhatnagar, A.: Lightweight ballistic composites. Woodhead publishing limited, Cambridge (2006), 429 p.
6. Ahmad, M.R., Ahmad, W.Y.W., Salleh, J., Samsuri, A.: Effect of fabric stitching on ballistic impact resistance of natural rubber coated fabric systems. Materials and Design 29, 1353–1358 (2008). doi: 10.1016/j.matdes.2007.06.007
7. Karahan, M., Kus, A., Eren, R.: An investigation into ballistic performance and energy absorption capabilities of woven aramid fabrics. International Journal of Impact Engineering 35, 499–510 (2008). doi: 10.1016/j.ijimpeng.2007.04.003
8. Kang, T.J., Lee, S.H.: Effect of stitching on the mechanical and impact properties of woven laminate composite. Journal of Composite Materials 28(16), 1574–1587 (1994). doi: 10.1177/002199839402801604
9. Park, J.L., Yoon, B. II, Paik, J.G., Kang, T.J.: Ballistic performance of p-aramid fabrics impregnated with shear thickening fluid; Part I – Effect of laminating sequence. Textile Research Journal 82(6), 527–541 (2012). doi: 10.1177/0040517511420753
10. Ahmad, M.R., Ahmad, W.Y.W., Samsuri, A., Salleh, J., Abidin, M.H.: Blunt Trauma Performance of Fabric Systems Utilizing Natural Rubber Coated High Strength Fabrics. In: Proceeding of the International Conference on Advancement of Materials and Nanotechnology (ICAMN 2007, 29 May – 1 June 2007), pp. 328–334. Langkawi 1217 (2010).

11. Gawandi, A., Thostenson, E.T., Gilllespie, J.W. Jr.: Tow pullout behavior of polymer-coated Kevlar fabric. Journal of Materials Science 46, 77–89 (2011). doi: 10.1007/s10853-010-4819-3
12. Majumdar, A., Butola, B.S., Srivastava, A.: Development of soft composite materials with improved impact resistance using Kevlar fabric and nano-silica based shear thickening fluid. Materials and Design 54, 295–300 (2014). doi: 10.1016/j.matdes.2013.07.086
13. Lee, B.-W., Kim, I.-J., Kim, Ch.-G.: The influence of the particle size of silica on the ballistic performance of fabrics impregnated with silica colloidal suspension. Journal of composite materials 43(23), 2679–2698 (2009). doi: 10.1177/0021998309345292
14. Lee, B.-W., Kim, C.-G.: Computational analysis of shear thickening fluid impregnated fabrics subjected to ballistic impacts. Advanced Composite Materials 21(2), 177–192 (2012). doi: 10.1080/09243046.2012.690298
15. Hassan, T.A., Rangari, V.K., Jeelani, S.: Synthesis, processing and characterization of shear thickening fluid (STF) impregnated fabric composites. Materials Science and Engineering A 527, 2892–2899 (2010). doi: 10.1016/j.msea.2010.01.018
16. Mayo, J.B. Jr., Wetzel, E.D., Hosur, M.V., Jeelani, S.: Stab and puncture characterization of thermoplastic-impregnated aramid fabrics. International Journal of Impact Engineering 36, 1095–1105 (2009). doi: 10.1016/j.ijimpeng.2009.03.006
17. Bazhenov, S.L., Goncharuk, G.P.: A Study of Yarn Friction in Aramid Fabrics. Polymer Science Ser. A 54(10), 803–808 (2012). doi: 10.1134/S0965545X12090015
18. Lim, C.T, Shim, V.P.W., Ng, Y.H.: Finite-element modeling of the ballistic impact of fabric armor. International Journal of Impact Engineering 28, 13–31 (2003). doi: 10.1016/S0734-743X(02)00031-3
19. Tan, V.B.C., Ching, T.W.: Computational simulation of fabric armor subjected to ballistic impacts. International Journal of Impact Engineering 32(11), 1737–1751 (2006). doi: 10.1016/j.ijimpeng.2005.05.006
20. Barauskasa, R., Abraitiene, A.: Computational analysis of impact of a bullet against the multilayer fabrics in LS-DYNA. International Journal of Impact Engineering 34, 1286–1305 (2007). doi: 10.1016/j.ijimpeng.2006.06.002
21. Ha-Minh, C., Imad, A., Kanit, T., Boussu, F.: Numerical analysis of a ballistic impact on textile fabric. International Journal of Mechanical Sciences 69, 32–39 (2013). doi: 10.1016/j.ijmecsci.2013.01.014
22. Sapozhnikov, S.B., Forental, M.V., Dolganina, N.Yu.: Improved methodology for ballistic limit and blunt trauma estimation for use with hybrid metal/textile body armor. In: Proceeding of conference “Finite element modelling of textiles and textile composites”. 1 CD-ROM. St-Petersburg (2007).
23. Gatouillat, S., Bareggi, A., Vidal-Sallé, E., Boisse, P.: Meso modelling for composite preform shaping – Simulation of the loss of cohesion of the woven fibre network. Composites: Part A 54, 135–144 (2013). doi: 10.1016/j.compositesa.2013.07.010
24. LS-DYNA R7.0 Keyword user's manual, http://www.lstc.com, last accessed 2018/04/11.
25. Ignatova, A.V., Dolganina, N.Yu., Sapozhnikov, S.B., Shabley, A.A.: Aramid fabric surface treatment and its impact on the mechanics of yarn’s frictional interaction. PNRPU Mechanics Bulletin 4, 121–137 (2017). doi: 10.15593/perm.mech/2017.4.09
26. Nilakantan G., Nutt S. Effects of clamping design on the ballistic impact response of soft body armor. Composite Structures 108, 137–150 (2014). doi: 10.1016/j.compstruct.2013.09.017
27. Nilakantan, G., Wetzel, E.D., Bogetti, T.A., Gillespie, J.W.: Finite element analysis of projectile size and shape effects on the probabilistic penetration response of high strength fab-

rics. Composite Structures 94(5), 1846–1854 (2012). doi: 10.1016/j.compstruct.2011.12.028

28. Nilakantan, G., Keefe, M., Wetzel, E.D., Bogetti, T.A., Gillespie, J.W.: Effect of statistical yarn tensile strength on the probabilistic impact response of woven fabrics. Composites Science and Technology 72(2), 320–329 (2012). doi: 10.1016/j.compscitech.2011.11.021
29. Sapozhnikov, S.B., Ignatova, A.V.: Mechanical properties of technical plasticine under static and dynamic loadings. PNRPU Mechanics Bulletin 2, 201–219 (2014).
30. Kostenetskiy, P.S., Safonov, A.Y.: SUSU Supercomputer Resources. In: Proceedings of the 10th Annual International Scientific Conference on Parallel Computing Technologies (PCT 2016), pp. 561–573. Arkhangelsk 1576 (2016).