Streszczenie pracy doktorskiej:

Numerical and experimental approach to the problem of textile ballistic shield construction with embroidered structure

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Textile ballistic shields, which include bulletproof vests, are commonly used by soldiers, police and civilians in high-risk jobs such as security or politicians. The protective effectiveness of soft bulletproof vests depends not only on the material used, but also on various structural parameters of the ballistic packages, such as: type of construction of the textile layer (biaxial and triaxial fabric, non-woven fabric, 2D/3D knitted fabric), thread counts and linear mass, surface mass of the layers , the number of layers in the ballistic package, hybrid orientation of the layers in the ballistic package, surfacing of layers with substances with micro- and nanoparticles, which, when used in various combinations, lead to a structural response conducive to increased ballistic effectiveness of bulletproof vests.

The aim of the research within the framework of the doctoral thesis was to produce structures embroidered with para-aramid yarn and to assess the ballistic efficiency of multi-layer textile packages with these structures after firing with a Parabellum 9x19 FMJ bullet. A research hypothesis was assumed to prove that it is possible to increase the ballistic efficiency of multi-layer textile ballistic packages by using embroidered structures in these packages. The scope of the research included the production of embroidered structures with the use of para-aramid threads, numerical and experimental tests of firing ballistic packets with different arrangements of woven and embroidered layers, numerical and experimental optimization tests in order to find the most effective structure of the ballistic packet with the use of fabrics and embroidered structures.

As part of the research, 20 cm x 20 cm embroidered structures were produced using the TFP (Tailored Fiber Placement) embroidery technique by attaching to a polypropylene non-woven fabric two systems of threads rotated by 90°, each of which consisted of parallel and straightened yarns para-aramid Twaron Microfilament 930 tex f1000. The para-aramid yarns were attached with low density embroidery threads. The developed embroidered structures and para-aramid fabrics Twaron CT709 were assembled into ballistic packages in five variants. Variant I was composed of 26 layers made of embroidered structures, Variant II - with alternating 13 layers of fabrics and 13 layers of embroidered structures, Variant III - with 13 layers of structures embroidered on the front from the side of the projectile impact and 13 layers of fabric on the back, Variant IV - with 13 layers of fabric on the front from the bullet impact side and 13 layers of embroidered structures on the back and Variant V - made of 26 layers of fabric. The assumption of making ballistic packages in Variants I and V resulted from the need to directly compare the ballistic efficiency of packages composed entirely of embroidered structures and fabrics. On the other hand, the assumption of making packages in Variants III and IV, consisting of 13 layers of embroidered structures and 13 layers of fabrics, resulted from the need to examine whether the order of placing these layers relative to the point of impact of the bullet affects the ballistic efficiency of the packages. In the case of the package made in Variant II, in which the layers of fabrics and embroidered structures were arranged alternately, it was assumed that if favorable ballistic properties were obtained, it was possible to consider eliminating the non-woven fabric as the basis for the embroidered structure and its implementation directly on the para-aramid fabric, which would allow to reduce surface weight of the ballistic package.

In the next stage of the research, numerical models of all variants of the ballistic packages and the Parabellum 9x19 mm FMJ bullet were developed, and further, using the LS-Dyna software, simulation tests of the impact of the Parabellum 9x19 mm FMJ bullet on the developed variants of the packages under the conditions of their permanent attachment on the edges and laying on standardized

plasticine substrate. Before starting the calculations, material models were defined and appropriate parameters of these models were adopted. The impact velocity of the bullet was 380 m/s. The results of the numerical tests were verified by means of experimental tests at the Ballistic Research Laboratory at the Lodz University of Technology. The ballistic test stand consisted of a UPB1 ballistic cannon (Fabryka Broni Łucznik Radom, Poland) for firing Parabellum 9x19 rounds, a system of gates for measuring the bullet impact velocity and a Cordin 550 camera (Cordin, USA) for imaging the back side of the ballistic package. Before firing, the tested ballistic package was placed between two steel frames with internal dimensions of 20x20 cm, which were then pressed together using eight clamps placed two on each side of the frames. During the firing, a sequence of sixteen images of the rear part of the ballistic package was recorded using the Cordin 550 camera with a recording speed of 12,800 images/s. The second experimental test to which the variants of the ballistic packages were subjected was the test of ballistic efficiency on a standardized plasticine substrate and subjected to firing with a Parabellum 9x19 FMJ bullet. A plasticine substrate was prepared for the tests in accordance with the recommendations of the American NIJ Standard. In order to measure the deformation of the plasticine substrate after firing, it was scanned on a station equipped with a laser distance sensor. Ballistic packets after firing were also analyzed in terms of the number of layers shot through. On this basis, the perforation coefficient of the ballistic package was calculated. The expansion of the bullet was also calculated.

The conducted firing tests of packets fixed in steel frames showed that in the conditions of experimental tests there is an effect of partial slipping of the packet layers from the steel frames, which does not occur in the conditions of numerical tests due to trapped nodes, and which significantly affects the ballistic response of the packet. This effect is known and described in the literature, and despite the best efforts in research methodology, it was not possible to completely eliminate it. The sliding of the layers significantly increases the maximum transverse deformation of the ballistic package, causes the projectile to stop for a longer time and the formation of a deformation cone on a larger area at a given time than it results from simulation tests. For this reason, the results of simulation and experimental tests during the testing of packages fixed in steel frames were compared in terms of ballistic efficiency of individual variants of ballistic packages. The maximum lateral deformation of the package, the bullet stopping time, equivalent to achieving zero kinetic energy of the bullet, the perforation coefficient and the expansion of the bullet were taken into account as efficiency indicators. Taking into account these indicators, it should be stated that there was full agreement between the simulation and experimental tests. In both of these tests, the highest ballistic efficiency was achieved by the package made in Variant IV, consisting of a hybrid combination of 13 layers woven on the front and 13 layers of structures embroidered on the back. On the other hand, the lowest ballistic efficiency was shown by the package made in Variant III with the reverse connection of layers in relation to Variant IV. Ballistic impact response embroidered structures have been found to have two advantages and one disadvantage. The advantages are straightened threads and lack of interlacing, which favors high propagation speed, which has a positive effect on lower transverse deformation of the bundle. The disadvantage of these structures is the spreading of the threads in contact with the bullet face, which adversely affects the number of pierced layers in the ballistic package. It should be noted that the intensity of thread separation depends on the angle of the conical surface pressing on the embroidered structure. In the case of a multi-layer ballistic package, the separation of the threads in subsequent layers will be smaller, and in the final layers it may not occur at all. Woven structures, in turn, have advantages and disadvantages in terms of ballistic impact response, which are the opposite of the advantages and disadvantages of embroidered structures. The advantage here is the structure jammed by the interlacing of the weft and warp threads, which prevents the threads from moving apart in contact with the head of the bullet. In turn, the disadvantages of this structure are the weft and warp threads and the lower propagation speed of the stress wave due to the interlaced structure, which promotes increased transverse deformation. The tests carried out showed that in order to take advantage of the advantages of both structures and at the same time limit their disadvantages, it is necessary to assemble a multi-layer hybrid package that contains woven structures on the front and embroidered structures on the back. Taking this into account, in the last stage of the research, the most effective package made in Variant IV was optimized in order to find the optimal border between the woven and embroidered phases. In the package made according to Variant IV, the boundary of these phases was in the middle between the 13th and 14th layers. Tests on a calibrated plasticine substrate showed that the highest efficiency was achieved by a package containing 9 woven layers and 17 embroidered layers. This was confirmed by both simulation and experimental tests in the conditions of mounting the package in steel frames and experimental tests in the conditions of laying the package on a calibrated plasticine substrate.

Numerical and experimental studies of the ballistic efficiency of ballistic packages with the use of embroidered structures allowed to prove the thesis that it is possible to increase the ballistic efficiency of multi-layer textile ballistic packages by using embroidered structures in these packages.