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Effect of Velocity of the Structure-Dependent Tension Wave Propagation on Ballistic Performance of Aramid Woven Fabrics

Abstract
One of the elements defining the effectiveness of soft ballistic protection is the geometric structure of the fabric. In previous research works it was proven that the geometric structure influences the propagation velocity of the tension wave. Thus, fabrics of a geometric structure ensuring a maximum propagation velocity of the tension wave should be selected for the ballistic packets of bullet-proof vests. In such a case, the area of deformation will be larger, which will diminish the probability of local destruction and the acuteness of the ballistic stroke on the user's body. The aim of the research was to receive a ballistic packet containing layers of fabric ensuring a maximum propagating velocity of the tension wave and verification of its ballistic performance in terms of shooting through, maximum deformation and the ballistic stroke.

Key words: *bulletproof vest, woven fabric structure, tension wave propagation, ballistic performance.*

Introduction

Textile ballistic protection in the form of bulletproof vests may, in many cases, decide about the life or death of people who take part in law enforcement, participate in military operations, work in security forces or are in danger just because of being a celebrity. All of them require protection in the form of bulletproof vests, which at the same time should guarantee maximum comfort for the user.

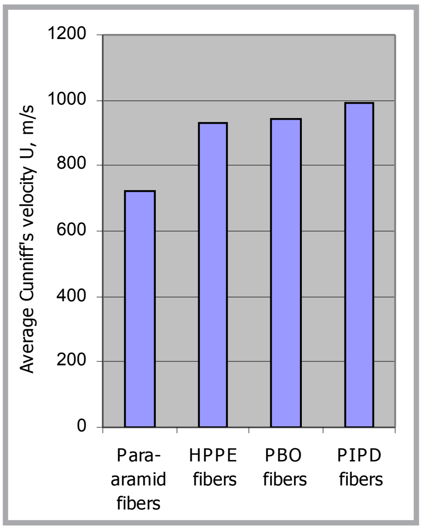

Figure. 1. Average Cunniff's velocities for different fibers used in soft ballistic protection.

Thus, it is a natural research tendency to try to improve the construction of bulletproof vests so as to ensure maximum comfort, while the two basic security criteria, that is, non-shooting through and a minimum ballistic stroke, affecting the user's body are also fulfilled. In consequence, the vests should be characterised by a smaller mass, smaller thickness and larger elasticity. In terms of constructing lighter and thinner vests, the most important seems to be the development of highly-resistant fibers that should be characterised by the largest possible resistance parameters and the greatest propagation velocity of the tension wave, defining the thread length, which undergoes deformation during a bullet impact. The ballistic effectiveness of threads was analysed in terms of the parameter formulated by Cunniff and expressed by dependence [1]:

$$U^* = \frac{\sigma\varepsilon}{2\rho}\sqrt{\frac{E}{\rho}} \qquad (1)$$

where:
ρ – thread density,
E – Young's modulus,
σ – stress,
ε – deformation.

According to this dependence, the ballistic effectiveness of threads is greater if the value of parameter U^* is larger. In literature this parameter is often described in the form of the following dependence:

$$U = \left(U^*\right)^{\frac{1}{3}} = \left(\frac{\sigma\varepsilon}{2\rho}\sqrt{\frac{E}{\rho}}\right)^{\frac{1}{3}} \qquad (2)$$

The unit of this parameter is m/s, and it is possible to compare it with the propagation velocity of the tension wave. ***Figure 1*** presents average Cunniff's velocities for aramid fibers, HPPE (High-performance polyethylene), PBO (Poly-p-phenylenebenzobisoxazole) and PIPD (Poly(diimidazo pyridinylene (dihydroxy) phenylene)), which are the most often used for soft ballistic protection.

The increasing values define successive generations of ballistic fibers. Each new generation of fibers was accompanied by a huge increase in the ballistic effectiveness of the soft packets used in bulletproof vests.

As has been observed in practice, both the raw material and geometric structure of the layers have a great influence on the final deformation, as well as on whether the vest perforates or not. The influence of the weaves of the fabric on its ballistic effectiveness was described by Cheng-Kun at al. [2]. For the same raw material, greater ballistic effectiveness was observed in the case of fabrics of plain and hopsack 2/2 weave than in that of fabrics of atlas and twill weave. Most important in terms of the effectiveness of ballistic protection may be the smaller propagation velocity of the tension wave in flat textile structures, comparing to the propagation velocity of the wave in the thread used for the construction of the fabric. Thus, assuming the raw material of the thread remains the same, it is possible to construct ballistic packets of comparable areal mass but of different performance in ballistic tests in terms of the influence on the user. The packets will differ in terms of the following:

- the amount of kinetic energy of the missile absorbed,

- the height of the defermation cone,
- the shape of the defermation cone.

It means one should look for solutions ensuring a maximum propagation velocity of the wave in the fabrics used for the layers of ballistic packets. Then the kinetic energy of the missile will be absorbed by the larger areal mass of the fabric, which will diminish the danger of local destruction and the acutteness of the ballistic stroke.

Evaluation of the effectiveness of ballistic packets consisting of a layer with a maximum propagation velocity of the tension wave requires verification at the Laboratory of Ballistic Research. The standard procedures of ballistic tests that have been used up till now are based on checking whether the package has not been shot through and whether the final deformation has not exceeded the maximum acceptable value, which is 44 mm. This value was defined on the basis of statistical analysis of former cases where a human body was struck by a missile and injuries occurred.

Real military experience and recently published scientific research concerning the effects of a ballistic stroke during a non-penetrating missile impact prove that such procedures seem to be insufficient in many cases [3, 4]. Drobin and Gryth carried out some research on animals (pigs) whose organisms are in functional terms similar to those of human beings. The aim of their research was to assess the effects and pathophysiological mechanisms occurring during a non-penetrating blow of a missile of the type NATO 7.62×51 mm flying at a speed of 800 m/s and hitting a human body wearing a bulletproof vest. The results of the research completely undermined the criteria commonly used while testing ballistic protection. It was observed that as a result of the stroke, some of the animals suffered from serious health problems, with some even dying when their only protection were vests characterised by maximum deformation not exceeding 40 mm, during tests on plastiline foundation.

Thus it seems to be fully justified to choose a geometric structure of the fabric ensuring a maximum propagation velocity of the tension wave for the construction of ballistic packets of bulletproof vests. In such a case the area affected by deformation will be larger, which will diminish the possibility of local destruction and size of ballistic stroke on the user's body. The aim of the research was to obtain a ballistic package containing layers of fabric characterised by a maximum propagation velocity of the tension wave, as well as its ballistic verification in terms of the maximum deformation, size of ballistic stroke and the probability of being shot through.

Tension wave propagation velocity in woven fabrics

When a missile strikes a fabric, its kinetic energy is absorbed mainly through the deformation of threads, thread movement towards the trajectory of the missile's formation of the so-called defermation cone, and through the friction phenomenon between warp and weft threads. Due to the huge speed of a missile which is shot from fire-arms, in the place of impact a fast changing local displacement of threads towards the missile trajectory can be observed, which initiates a tension wave propagating along warp and weft threads, symmetrically in all four directions. Numerous researches have proved that the tensions created are transferred mainly by the warp and weft threads, coming into contact with the front of the missile. The threads that come into contact with the front of the missile are called the main warp and weft threads. The effect of transferring tensions by the main warp and weft threads can be observed after the fabric is shot through, because permanent destruction and structure degradation occurs only in the area of main threads.

The propagation of the tension wave from the point where the missile strikes is accompanied by local thread deformations, and at the same time the kinetic energy of the missile is absorbed. At the moment when maximum deformation is exceeded, the threads start cracking. The increase the deformed fabric area depends on the propagation velocity of the tension wave along warp and weft threads. For a given type of raw material and geometric structure of the fabric, the propagation velocity is constant and does not depend on the missile speed. From the point of view of ballistic effectiveness, the propagation velocity of the tension wave should be as large as possible so that the tensions are distributed over the largest possible area.

In the testing phenomena of woven fabrics occurring during a missile impact, it is either accepted that the propagation velocity of the tension wave along warp and weft threads is the same as in the thread the fabric is made of, or it is determined from the Roylance dependence. In the first case the propagation velocity of the wave in the fabric along warp and weft threads is determined from the following formula:

$$c_f = c = \sqrt{\frac{E}{\rho}} \qquad (3)$$

where:

c – propagation velocity of tensions in a single thread,

E – elasticity modulus,

ρ – thread density.

On the basis of research carried out for many years concerning the impact of a missile on a fabric, Roylance at al. suggested that the reasoning should be corrected, and that the propagation velocity of the tension wave in the fabric should be treated as a fraction of the propagation velocity of the wave in the thread the fabric is made of [5, 6]. Parameter $\alpha > 1$ and the dependence between these velocities were introduced in the following form:

$$c_f = \frac{c}{\alpha} \qquad (4)$$

While analysing the cross section of the fabric along warp or weft threads, it was suggested that the mass density of the propagation medium doubles. Along a selected thread of one of the weaving systems, as a result of interlacing, the mass density of the medium is twice bigger. Hence, assuming that the elasticity modulus of the thread is identical to that of the fabric, we obtain:

$$c_f = \sqrt{\frac{E}{2\rho}} = \frac{1}{\sqrt{2}}\sqrt{\frac{E}{\rho}} = \frac{c}{\sqrt{2}} \qquad (5)$$

Thus, the authors suggested that the propagation velocity of the tension wave in the fabric is $\sqrt{2}$ times smaller than that of the wave in the thread. The reasoning presented by Roylance significantly simplifies the assessment of the propagation velocity of the tension wave in fabrics. Special attention should be paid to the following facts:

- the interlacing threads form a non-continuous medium in relation to the thread along which the tension wave propagates,
- the geometric arrangement of the medium of the tension wave propagation depends on the geometric structure of the fabric (type of weave, number of warps and wefts, phases of the fabric),
- the elasticity modulus of the fabric during stretching along one of the

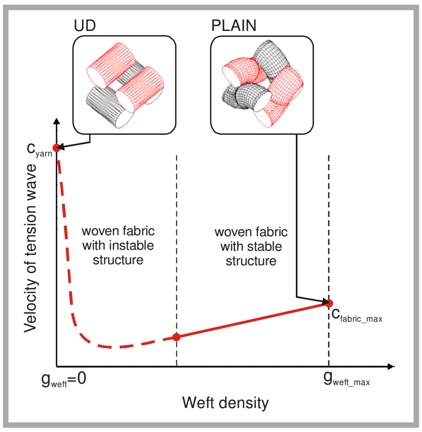

***Figure 2.** Tension wave propagation velocity in dependence on weft density and structure stability.*

systems is different to that for a single thread, and it strongly depends on the geometric structure of the fabric (type of weave, number of warps and wefts, phases of the fabric).

Taking into consideration these limitations and the thesis concerning the influence of the propagation velocity of the tension wave on the ballistic effectiveness of anti-stroke packets, research was carried out on the propagation velocity of the tension wave in fabrics for structures characterised by different weaves and weft densities. Details concerning measuring methods and research results were presented in publication [7].

This research has proven that the propagation velocity of the tension wave depends on the type of weave and number of warps and wefts. Additionally, it has proven that there are two optimum fabric structures for which the propagation velocity is the largest (***Figure 2***).

In the case of a fabric of unstable structure, with the weft density equal to zero, the tension wave will propagate in only one system, parallel to the threads. In such a case an interlacing effect is not observed, and it may be assumed that the propagation velocity of the tension wave will be the same as for an individual thread ($c_f = c$). Thus, an optimum structure will take the form of a system of two non-interlacing skeins of threads situated at an angle of 90° to each other, where the stability of the structure is achieved by means of gluing matrices. In ***Figure 2*** this structure is indicated as UD. In the case of a fabric of stable structure, the propagation velocity of the tension wave increases together with the concentration of threads, resulting from the diminishing displacements of warp and weft threads in relation to each other and increased thread concentration. The largest propagation velocity of a tension wave can be observed in a fabric of plain weave and maximum number of warp and weft threads. Taking into consideration the hypothesis that the propagation velocity of the tension wave should be as large as possible, these two structures were chosen for the construction of ballistic packets. In ***Figure 2*** this structure is indicated as PLAIN.

Forming non-interlaced unidirectional structures

On the basis of research concerning the propagation velocity of the tension wave in woven fabrics, a non-interlaced structure is accepted as optimum for application in ballistic barriers. However, forming such a structure requires using additional layers that stabilise the structure, which is in contrast to traditional fabrics, where this stability is achieved thanks to the interlacing of warp and weft threads. ***Figure 3*** presents the idea of forming non-interlaced structures, according to which a research stand was built [8].

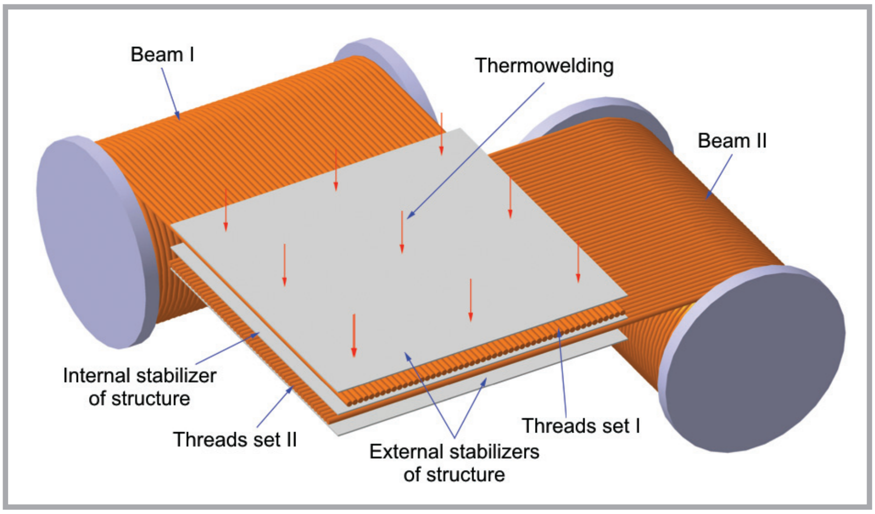

***Figure 3.** Forming of UD structures.*

The two systems of threads I and II, crossing at an angle of 90º, are unwound from beams I and II. A stable structure is achieved thanks to using an internal stabiliser characterised by two-sided thermo-welding, situated between thread systems I & II, and external stabilisers characterised by one-sided thermo-welding from the side of the thread systems. The structure obtained is finally welded by means of a heat stream with an adequate pressure force of the press.

The structure obtained in this way is a rectangle sheet, the dimensions of which correspond to the width of thread systems I and II. While carrying out research on establishing textile structures of a maximum propagation velocity of the tension wave, a prototype for producing non-interlacing structures was designed and constructed. In the design phase the following assumptions were made:

- the thread will be made of aramid fibers of third generation Twaron CT Microfilament 930 dtex/f1000,
- the width of thread systems I and II will be 30 cm so that the dimensions of the sheet obtained are comparable to those of the human body,
- in order to compare the ballistic properties of the non-interlacing structures and fabrics of plain weave obtained, made of the same threads and available on the market, an identical number of warps was introduced in the non-interlacing structure as in the fabric.

For the geometric and raw material parameters of the sheet assumed, the areal mass equaled about 204.6 g/m^2. In counting the areal mass of a single sheet, one did not take into consideration the areal mass of thermo non-wovens, which equals about 24 g/m^2.

It was not taken into account for two reasons: firstly, the optimisation of the process of forming a non-interlacing structure was not the subject of the research. In practice, polyethylene matrices together with proper welding technology can be used for stabilising the threads in the structure. The areal mass of a polyethylene matrix is negligible in relation to that of the thread system, and it does not actually increase the areal mass of the whole sheet.

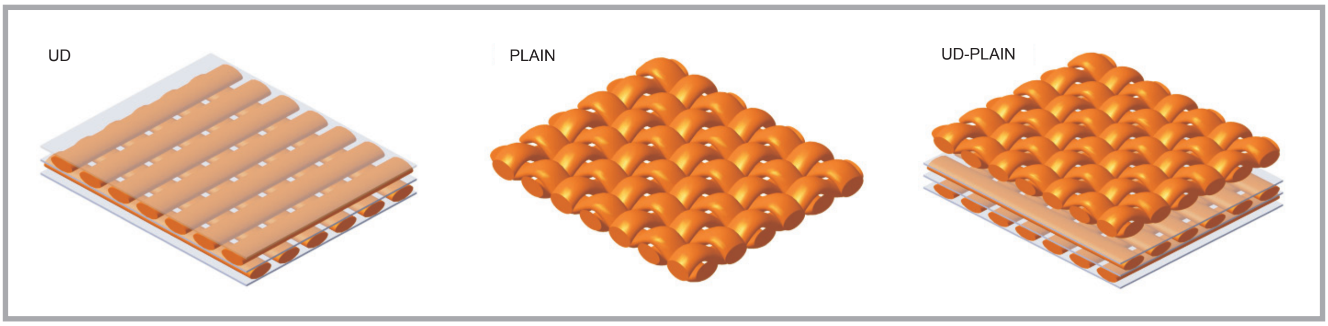

***Figure 4.** Structures of ballistic packets tested.*

Secondly thermo non-wovens are not important from the point of view of mechanical properties, and they could cause unnecessary disturbance in the assessment of the influence of the areal mass of the ballistic barrier on the amount of kinetic energy of the missile absorbed, which was one of the aims of the research. ***Table 1*** presents some basic parameters of a sheet of non-interlacing structure made on a stand constructed specially for the research.

***Table 1.** Basic parameters of a sheet of non-interlacing structure.*

Parameter	Value
Dimension, cm×cm	30×30
Areal density, g/m²	204,6
Thickness, mm	0,8
Number of threads per dm: I set II set	 110 110

The thickness of the sheet was measured by means of a Tilmet 59 thickness gauge of a total uncertainty of 0.1 mm. The thickness value in the table is an average from the measurements of 10 sheets. It should be noted that this parameter was not optimised during the tests. The factors that influence the thickness of the sheet are the parameters of the thread, the thickness of the thermo non-wovens and the pressure force during the thermo-welding process.

Ballistics tests

Testing the ballistic effectiveness of the packets was carried out in a ballistic tunnel. Three variants of packets were formed, differing in the type of structure in the successive layers. The number of layers in the packets for each variant was 6, 8, 10, 12, 16 & 24. The first variant was a packet containing non-interlacing structures UD in its layers (***Figure 4***). The second variant was a ballistic packet made of a fabric of plain weave PLAIN (***Figure 4***). For this structure the propagation velocity of the tension wave is approximately twice smaller than in the case of a non-interlacing structure. The third variant contained a packet of a two-phase module, consisting of a non-interlacing structure and fabric of plain weave UD-PLAIN (***Figure 4***). In that way the advantages of the two structures were combined, and it was possible to achieve a huge propagation velocity of the tension wave and structure stability.

In order to demonstrate the influence of the geometric structure of the packets on their ballistic properties, all the modules (***Figure 4***) were made of the same raw material – aramid yarn of 3rd generation Twaron CT Microfilament 930 dtex/f1000. At the Laboratory of Ballistic Research, the three variants of packets were shot with missiles of the type Parebellum 9x19 mm FMJ, according to the chart presented in ***Figure 5***. The tests with this type of missile, with a striking velocity of (365±10) m/s, correspond to ballistic tests in the second bulletproof class, according to the norm NIJ Standard 0101.03 [9].

Before firing, the ballistic packets were fixed in a grip 5 (***Figure 5***). Such a way of fixing imposes boundary conditions according to which transverse deformation of the packet at the points of fixing equals zero. At the same time longitudinal deformation at the fixing points should also equal zero; in practice, however, the layers tend to slightly slip from the grip.

The dimensions of the area absorbing the impact of the missile were constant and equaled 30 cm x 30 cm. This parameter was chosen intentionally so that the dimensions of the ballistic packet were comparable to those of a human body. During the tests at the Laboratory of Ballistic Research, one missile was fired at each packet at a zero angle to the centre of the sample. During the firing, the measuring system measured both the striking speed of the missile and its speed after passing the barrier – the so-called residual speed, if the sample was shot through. The series of measurments was repeated four times for each type of packet, and the speeds measured were used to count arithmetic averages. On the basis of the average impact speeds and residual speeds calculated, the input

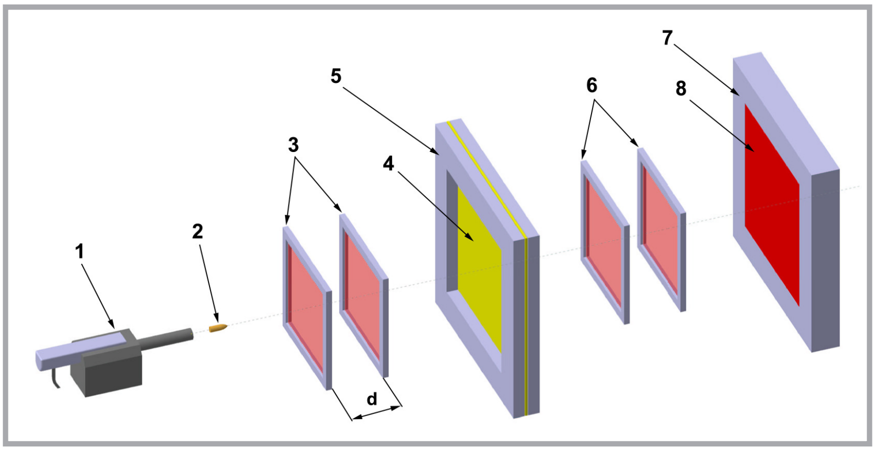

***Figure 5.** Ballistic tests – experimental set-up: 1 – gun, 2 –missile, 3 – striking velocity measuring system, 4 – ballistic packet tested, 5 – clamping system of the packet, 6 – residual velocity measuring system, 7 – bullet catcher, 8 – plastiline.*

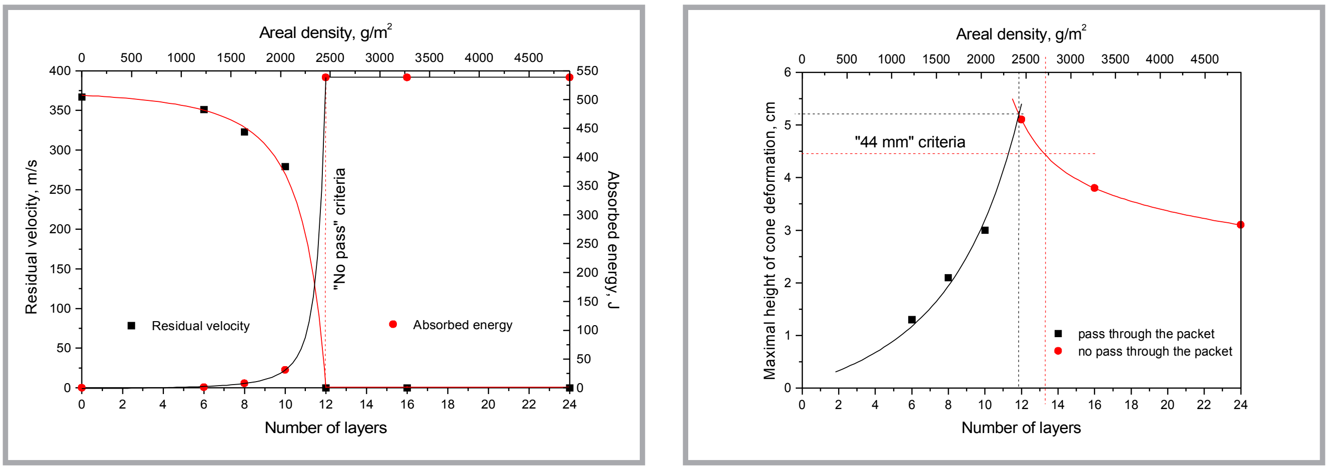

Figure 6. Ballistic test results for UD packets.

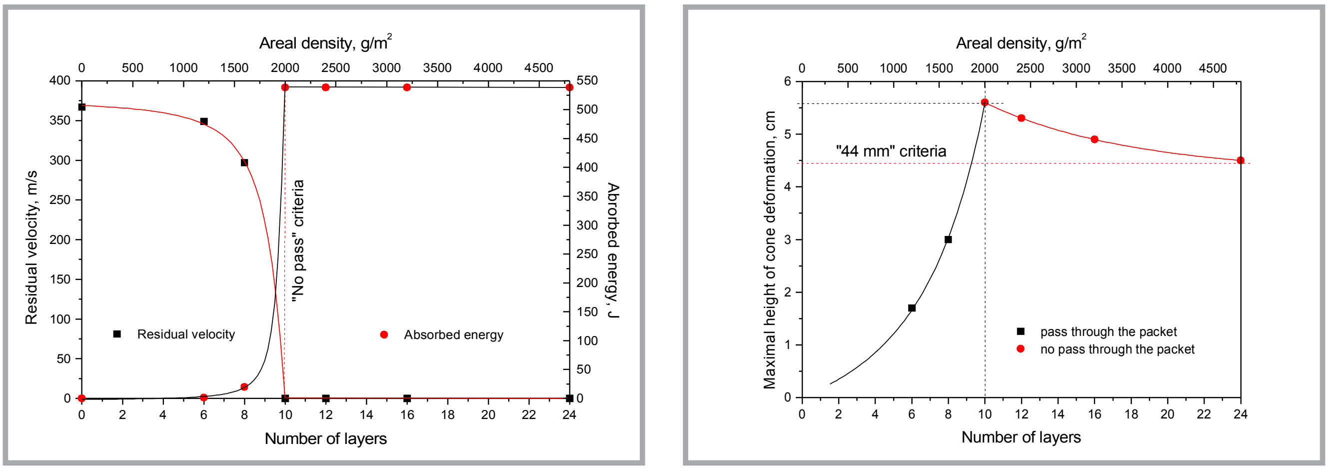

Figure 7. Ballistic test results for the PLAIN packets.

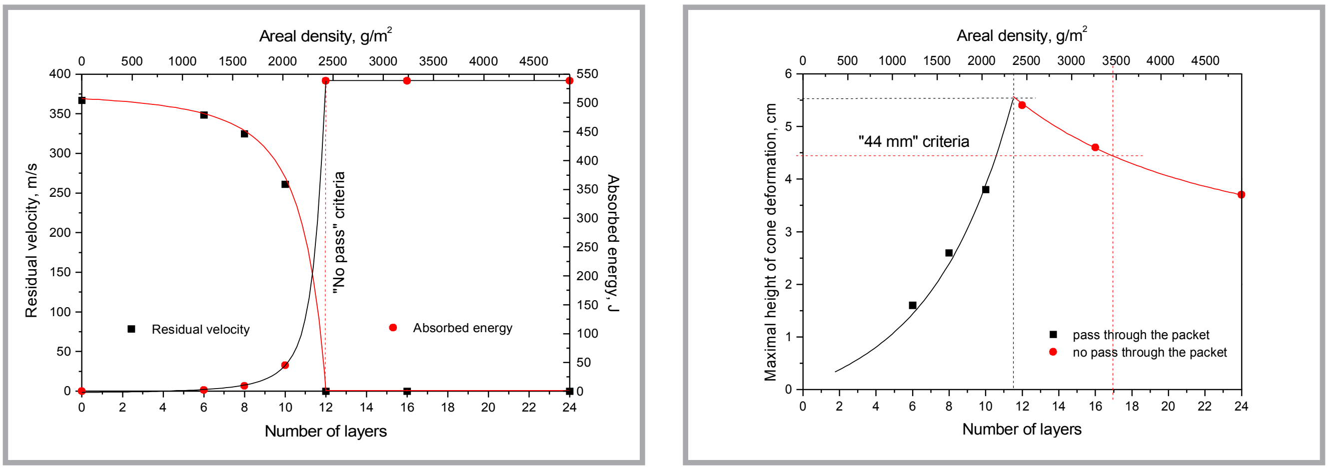

Figure 8. Ballistic test results for the UD-PLAIN packets.

and output kinetic energy of the missile was also established. The difference between the kinetic energy of the missile after it was shot and its energy after going through the ballistic barrier is the dispersed energy (energy absorbed by the ballistic packet), described by the following formula:

$$E_r = \frac{m \cdot (\Delta v)^2}{2} = \frac{m(v_u - v_r)^2}{2} \qquad (6)$$

where:
E_r – dispersed energy,
m – missile mass,
Δv – difference between the striking and residual speed,
v_u – striking speed,
v_r – residual speed.

During the firing, a visualisation of the defermation cone was also carried out in real time by means of an high-speed 3D registering system.

Figure 6 presents the results of ballistic tests carried out on ballistic packets containing non-interlacing structures UD.

The left-hand side presents the dependence of the residual speed and dispersed energy in the function of the number of layers and areal mass of the packet. The figure presents the safety border, determined by the minimum number of layers and minimum areal mass of the packet fulfilling the first security criterion, which is the non-shooting through of the packet. A ballistic packet containing layers of a non-interlacing structure fulfills the first safety criterion for 12 layers, which corresponds to a areal mass of about 2455 g/m^2.

The right side of ***Figure 6*** presents the maximum height of the defermation cone, which is always observed at the point of impact of the missile, in the function of the number of layers and areal mass of the packet. The dependence of the maximum height of the defermation cone on the number of layers and areal mass shows two tendencies.

The increased number of layers is accompanied by a progression of the defermation cone as a result of more energy dispersed by the textile structure of the ballistic packet. The progression curve stops due to the number of layers of the packet absorbing the total kinetic energy of the missile. For a ballistic packet made of non-interlacing structures, the maximum value of the cone can be observed for 12 layers, which corresponds to an areal mass of 2455 g/m^2. Further increasing the number of layers of the ballistic packet results in a decrease in the maximum height of the defermation cone, according to the degression curve.

The figure presents the border of the second security criterion, according to which the maximum height of the defermation cone should not exceed 4.4 cm. This value results from the analysis of possible injuries that a person may suffer and is described by a norm in the case of the presence of a stricken object in the form of a plastiline foundation. Thus, if the criterion is sharpened by the lack of a stricken object, then for the boundary conditions the second security criterion is fulfilled if a ballistic packet of non-interlacing structures contains 13 layers, which corresponds to an areal mass of 2660 g/m^2. As both criteria have to be fulfilled simultaneously, the minimum number of layers for this particular missileis 13, which corresponds to an areal mass of the packet of 2660 g/m^2.

The following figures present analogical results of ballistic tests for packets consisting of fabrics of plain weave PLAIN (***Figure 7***) and for packets containing alternately non-interlacing structures and fabrics of plain weave UD-PLAIN (***Figure 8***).

An analysis of the figures presented shows that the minimum number of layers fulfilling both security criteria is 24 for packets made of fabrics of plain weave, which corresponds to an areal mass of the packet of 4800 g/m^2 (***Figure 7***). In the case of packets consisting of non-interlacing structures and fabrics of plain weave, the minimum number of layers fulfilling both security criteria simultaneously is 17, which corresponds to an areal mass of the packet of 3500 g/m^2 (***Figure 8***).

From the point of view of possible injuries the user may suffer during a non-penetrating impact, the most important factors are the maximum cavity, resulting from the cone height at the point of missile stroke, the impact area of non-zero pressure on the stricken object, and the maximum deformation speed. Due to the elasticity and plasticity of the elements of the human body, the value of tension occurring inside the body as a result of a non-penetrating impact depends not only on the deformation depth but also on its speed. The area of non-zero pressure was analysed during the ballistic tests on the basis of the visualisation of the defermation cone at the moment the missile is stopped.

In such a case the ballistic packets containing non-interlacing structures show the best properties, as the are of non-zero pressure for a given number of layers is in that case the smallest of all the types of packets. ***Figure 9*** presents a visualization of a defermation cone at the moment the missile is stopped for a packet containing 24 layers in all the tested variants.

An analysis of the figure proves that both the maximum height of the defermation cone and the non-zero pressure area are the smallest for packets containing non-interlacing structures.

Conclusion

Bearing in mind the propagation velocity of the tension wave, two fabric structures seems to be optimum for the layers of a textile ballistic packet- a non-interlacing structure thermally stabilised by means of a polymer matrix and a fabric of plain weave with a maximum number of warp and weft threads. The ballistic tests carried out confirmed the hypothesis concerning a connection between the propagation velocity of the tension wave and ballistic effectiveness of anti-stroke packets.

For ballistic packets made of non-interlacing structures in which the propagation velocity of the tension wave is the

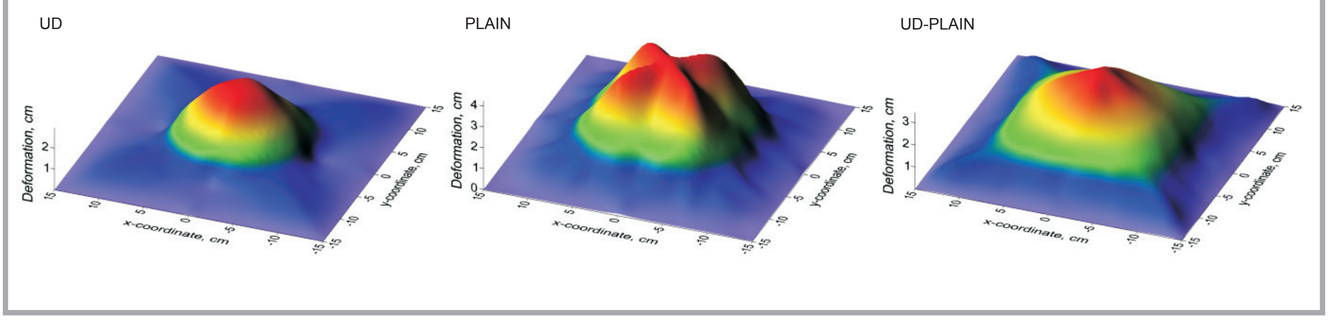

Figure 9. *Visualisation of the strain cone during stopping of a missile for packets consisting of 24 layers.*

largest and comparable to that of the tension wave in a single thread, both security criteria may be fulfilled by a significantly smaller areal mass than in the case of ballistic packets made of fabrics of plain weave or those containing both non-interlacing structures and the fabric. At the moment the missile is stopped, for a ballistic packet made of non-interlacing structures the non-zero pressure area is, for a given number of layers, the smallest of all the variants of packets tested, and at the same time the height of the defermation cone is also the smallest. ❑

References

1. *Cunniff P.M., Dimensionless Parameters for Optimization of Textile-Based Body Armor Systems, Proceeding of the 18th International Symposium on Ballistics, San Antonio, 1999.*
2. *Cheng-Kun Chu Yu-Liang Chen; Ballistic-proof Effects of Various Woven Constructions. FIBRES & TEXTILES in Eastern Europe 2010, Vol. 18, No. 6 (83) pp. 63-67.*
3. *Drobin D., Hemodynamic, Respiratory and Neurophysiological Reactions after High-Velocity Behind Armor Blunt Trauma, PhD Thesis, Karolinska Institutet, Stockholm, Sweden, 2007.*
4. *Drobin D., Gryth D., Persson J.K.E., Rocksen D., Arborelius U.P., Olsson L.G., Bursell J., Kjellstrom B.T., Electroencephalogram, Circulation, and Lung Function After High-Velocity Behind Armor Blunt Trauma, Journal of Trauma-Injury Infection & Critical Care, 63(2), 405-413, 2007.*
5. *Roylance D.K., Wang S.S., Penetration Mechanics of Textile Structures, Technical Report Contract No. Daag 17-76-C-0013, Massachusetts Institute of Technology, Cambridge, 1979.*
6. *Roylance D.K., Wang S.S., Penetration Mechanics of Textile Structures. Ballistic Materials and Penetration Mechanics, Elsevier Scientific Publishing Co., 273-292, 1980.*
7. *Stempień Z., Influence of a Woven Fabric Structure on the Propagation Velocity of a Tension Wave, FIBRES & TEXTILES in Eastern Europe, 2007, Vol. 15, No. 5-6 (64-65).*
8. *Stempień Z., Strukturalna barierowosc balistyczna tekstyliow, Zeszyty Naukowe Politechniki Lodzkiej, 2009, (in Polish).*
9. *NIJ Standard, Ballistic Resistance of Body Armor NIJ Standard-0101.06, U.S. U.S. Department of Justice, Office of Justice Programs, National Institute of Justice, 2008.*

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