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Analysis of the Impact Resistance Capacity of 3D Spacer Fabrics Based on Impact Tests

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Abstract
The article presents the structure influence of distance spacer fabric on the ability to protect against impact based on impact test results of selected packages made of spacer fabrics. The aim of testing these materials was to check their ability to suppress the impact force and absorb the energy in anti-impact vests. The purpose of using these textile materials in protective clothing would be to reduce the weight of the final product, and thus also to reduce heat stress during use. The article contains test results of the force received under an anvil and of the energy absorbed for each of the packages tested. The textile package developed, consisting of three layers, was classified as a protective material because it meets the requirements of EN 13158:2018 Protective clothing – Protective jackets, body and shoulder protectors for equestrian activities. The package provides protection at Level 1, the force received under an anvil during tests was 1.55 kN, and the package absorbed 24.96% of all impact energy. Additionally, the selected package was tested for air permeability.

Key words: *3D spacer fabric, ability to protect against impact, energy absorbed, anti-impact vest.*

Introduction

Warp-knitted spacer fabrics have a three-layered structure in which the two outer layers are joined using monofilament yarn, thus creating a characteristic distance. The variety of structure modifications makes it possible to use the material in many technical products, among others, in mattresses, medical orthoses, pillows, seat and pouf fillings, clothing, footwear and shock-absorbing inserts. A spacer fabric is characterised by low mass, high compression strength, a wide range of stiffness and elasticity. They are antiallergic, breathable, easy to clean and do not absorb water. Parameters of individual structure features have a significant impact on the properties of the fabric. A spacer fabric has the ability to deform, which is closely related to the deformation of the spacer yarn used in the fabric. The impact strength of spacer fabrics increase when more spacer yarn thread is in the structure. The spacer yarn connectors are thick and long, respectively, and the outer layer structure is entire. All these features favour the use of spacer fabrics as a protective material in impact-resistant vests [1-4].

Nowadays, protective vests are widely used, especially by people who could be exposed to injury or even death. The key task of protective clothing is to give a sense of security, so that the user could carry out thir duties or use it in everyday life without fear. Uniformed services such as the army and police, as well as motorcyclists, jockeys and extreme sports enthusiasts are among the users of protective clothing. Commercially available vests differ one to another in terms of style, purpose, level of protection and materials used. Despite the wide range of protective clothing which fullfill the requirements, many of them are too uncomfortable due to their weight. Riot police are especially exposed to this problem. Their vests are supposed to protect them from stones, bottles and other dangerous, heavy or sharp objects during interventions or riots. They are rarely exposed to shootouts, hence their basic protective package does not contain a bulletproof vest, but an anti-impact one. Vests used by the police are made out of extremely heavy composite materials. Moreover, the PVC panels used in these vests cause poor air circulation, which results in fast perspiration and overheating of the user's body. The total mass of the vest exceeds 3.5 kg. Textile materials used as protective packages can reduce thermal stress occurring during long periods of use, and due to their very good strength parameters they can provide protection against impacts [5-7].

In accordance with the requirements of Standard EN 13185:2018, material that provides protection at least at Level 1 can be classified as a protective material. Level 1 is the lowest level among the protection levels set by the standard. Therefore, for a material to meet the requirements, during the impact test, the average force received under the anvil cannot exceed 4 kN, and none of the measurements should be greater than 6 kN. In addition, the material tested should absorb as much impact energy as possible. A low level of energy absorption may cause the transfer of energy from the package to the user's body, which may cause discomfort and even personal injury [8, 9].

The aim of the tests conducted was to develop a textile package made of spacer fabrics which would protect against impact at Level 1 and reduce the weight of the protective vest in which the package could be used.

Materials and methods

The materials used in tests were examined for impact resistance. In this groupthere are two types of 3D warp-knitted fabrics (B and C), various combinations of which were created to find a package which had the best impact resistance. Each package consisted of 1, 2 or 3 layers of 3D spacer fabrics. Characteristics of these materials are shown in ***Table 1*** [10]. The materials used in the tests were supplied by the Baltex Gedeon company. In all, eight different packages were tested. There was one package consisting of one layer (B), four packages of two layers (2B, 2C, BC, CB), and three packages of three layers (3B, 2BC, C2B). The package variants were created in a few steps based on test results. Package names were created based on the layer

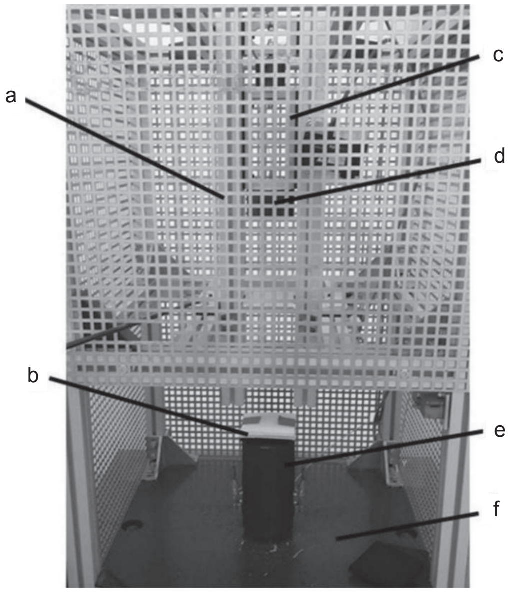
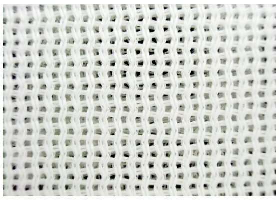
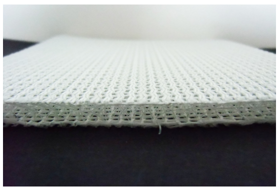
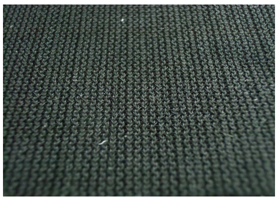
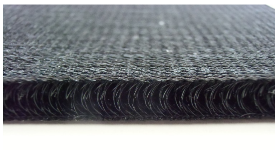


***Figure 1.** 'Drop Tower' measurement stand: a – rails, b – sample, c – magnetic grab, d – ram, e – anvil, f – foundation.*

***Table 1.** Basic parameters of 3D warp-knitted fabrics.*

Fabric	B	C
	 	 
Structure	Chain plus inlay	Locknit structure
Diameter of spacer yarn, mm	0.15	0.10
Wales per inch	11	17
Fabric thickness, mm	5.5	7.0
Surface mass, g/m^2	889	895
Composition	100% PES	100% PES

order in which spacer fabrics B and C were put. Each measurement was made three times and then average values and standard deviations calculated for them.

Impact tests

The materials described in ***Table 1*** were tested on a 'Drop Tower'. The possibility to do an impact analysis as defined by Standard EN 13158:2018, Protective clothing – Protective jackets, body and shoulder protectors for equestrian use, for horse riders and those working with horses, and for horse drivers – Requirements and test, was given by this device. The measuring instrument consists of a few basic elements, for example an anvil, which weights 10 kilograms, situated on a concrete foundation. This anvil has a semicircular upper surface which imitates the round shape of the human body. A flat, round ram was used for the tests, which weighs 2.5 kilograms and is 80 ± 2 mm in diameter and 10 mm wide. A 200 kN force transducer – a key measurement element, was assembled between the base and the anvil. Measurement was carried out with two sensors located under the anvil and on the ram. Additional elements of the instrument are: a magnetic grab, which is used to drop and pick up the ram. The measuring station with its basic elements is presented in ***Figure 1***. After the ram drops, the computer program showed the results in a Table and on a graph.

Parameters chosen for the analysis were the force received under the anvil (calculated from the acceleration sensor), the energy of the falling ram, and the energy absorbed by the sample. Appropriate parameters were set to test the samples for impact resistance at Level 1, being the lowest of the protection levels, after which the materials tested can be classified as protective. According to the standard, the height from which the ram was dropped on the sample surface equalled 1000 mm, thus the velocity of the falling ram resulted in obtaining potential energy with a value of 25 J, as determined by ***Equation (1)***, created based on the potential energy equation. The velocity of the falling ram was constant for each measurement, which was about 4.47 m/s^2. The free drop of the ram caused no rail resistance. Therefore, it was assumed that the entire value of potential energy was converted into kinetic energy.

$$E_p = m \cdot g \cdot h \qquad h = \frac{E_p}{m \cdot g} \tag{1}$$

E_p – potential energy, 25 J,
m – weight of the ram, 2.5 kg,
g – gravitational acceleration, 9.81 m/s^2.

The measuring device registered the energy transferred to the anvil using a sensor placed under the anvil. The difference between the potential energy and the energy received by this sensor showed how much energy was absorbed by the package tested, as shown in ***Equation (2)***. The value of energy absorbed should be as high as possible.

$$\Delta E = E_p - E_1, \text{ J} \tag{2}$$

E_p – potential energy, 25 J,
E_1 – energy received by the sensor, J,
ΔE – energy absorbed by the package, J.

Standard requirements determine the value of the force measured under the anvil, which should be less than 4 kN, and none of the other values should exceed 6 kN [10-12]. These force values refer to all protection levels. The contact force with which the ram hits the sample is calculated from ***Equation (3)***. The force received by the anvil depends on the course of the force value over time determined by the device [11-13].

$$F = m \cdot a, \text{N} \quad (3)$$

F – contact force of the sample, N,
a – acceleration.

Air permeability

Air permeability tests were performed for the selected package to check whether it shows an ability to provide thermal comfort. The measurement method consists in analysing the height of the liquid column on the manometer, where the pressure difference is read. According to PN-EN ISO 9237 Textiles. Determination of air permeability of textiles [15], a pressure drop value of 200 Pa was determined, which is the pressure difference before and after the measuring venturi of 20 mm H_2O. To obtain the pressure Δp_{zw}, the difference in height between two columns with liquid (Δh_{zw}) needed to be read and converted according to the standard. Then the average air flow intensity after the venturi q_V should be determined. Finally, the air permeability was determined based on ***Equation (4)***, contained in the standard [14]**.**

$$R = \frac{q_v}{A} \cdot 167, \text{mm/s} \quad (4)$$

A – sample surface area, 19.63 cm,
q_V – average air flow intensity.

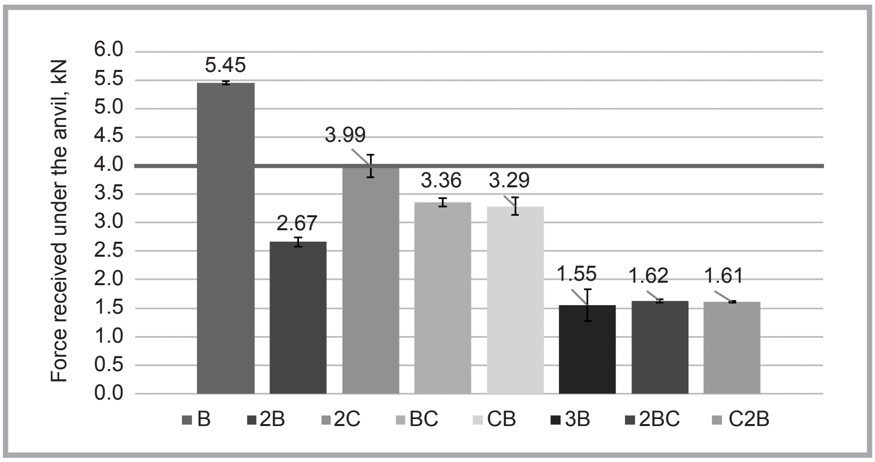


***Figure 2.** Force received under the anvil for packages tested, kN.*

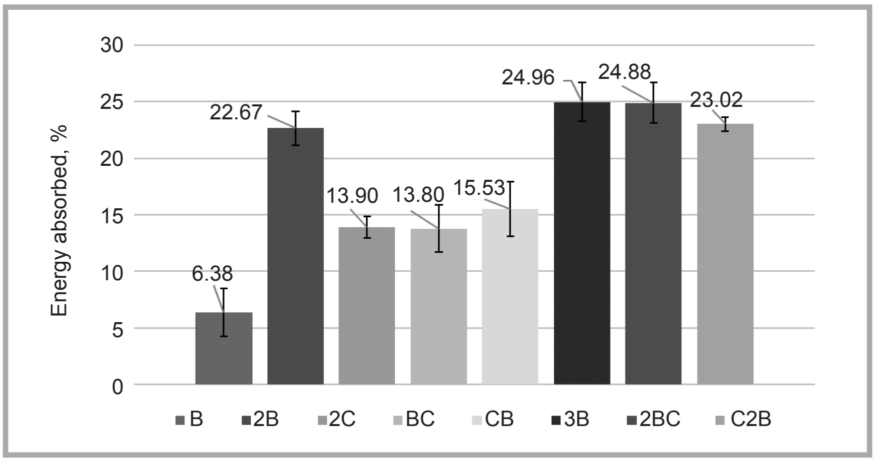


***Figure 3.** Value of energy absorbed, %.*

Results and discussion

The aim of the research was to check whether the packages prepared had impact resistance ability at the lowest protection level, i.e. Level 1, which allows to classify tested material as protective. The specific goal was to select a package that has the lowest force received by the sensor that is located under the anvil and at the same time does not exceed 4 kN. In addition, the package should have the maximal ability to absorb the energy.

Force received under the anvil

The average forces received under the anvil for all packages are shown in ***Figure 2***. The highest value of the force received under the anvil was achieved by package B, consisting only of a single layer, and reaching an average force of 5.45 kN. In accordance with the requirements of the EN 13185:2018 standard, the value was too high to use this package for impact resistance material. If the fabric is not thick enough and at the same time it is stiff, like package B, then the reaction forces between the ram and the package increase, which may cause an increase in the value of the force received under the anvil. Based on that, double layer packages were prepared and tested.

After testing of the double-layer packages, results shows that the force received under the anvil for all packages was lower than 4 kN. Looking at samples 2B and B, it was easy to see that doubling the same spacer fabric layer caused a decrease in the force received under the anvil more than twice. Therefore, it could be found that the additional layer improved the impact capacity, and these materials could be classified as protective. Packages BC and CB were made of the same spacer fabrics but in reverse order. However, this did not affect the force value because the packages has the same thickness. Although package 2C was the thickest tested in second stage, it achieved the worst result. This was caused by the fact that in its structure this package has thinner spacer yarn than, for example, package 2B, which achieved the best result. The force received under the anvil for this package equalled 2.67 kN. These results defined the next stage of tests – the examination of three-layer packages created from package 2B and an additional spacer fabric B or C. For packages 2BC and C2B the force received under the anvil was almost the same i.e. there were no statistical differences. Again, as in the previous stage, the reason was the same – thickness of the packages. The combination of package 2B and spacer fabric C resulted in the creation of the greatest thickness package (18 mm). Thanks to the use of an additional layer, the force received under the anvil was reduced, but not as much as when combined with spacer fabric B. Spacer fabric C has thinner spacer yarn of lower durability, hence it was easier to bend. The lowest value of the force and, at the same time, the best result of all packages tested in the first, second and third stages was achieved by sample 3B, reaching an average force of 1.55 kN. It should be noted that this package had the smallest thickness (16.5 mm) of the three- layer packages, and only one type of fabric was used to create the three layers. The most important element that influenced the result was the diameter of the spacer yarn and the number of points connecting the layers. Despite the many positive features, thick spacer yarn causes high stiffness of the material, thereby decreasing the comfort of use, which is important during the designing of protective clothing.

Energy absorbed

The EN 13185:2018 standard does not specify how much energy the material should absorb during impact, and therefore it could be treated as impact protection. However, low energy absorption of the protective package may cause the transmission of the impact to the human body. Based on this, sources and scientific research, it could be stated that the value of the energy absorbed should be as high as possible [1, 2].

Analysis of the energy absorbed was performed in stages, for example, the analysis of the force received under the anvil. All of the energy absorbed values are presented in ***Figure 3***. In the first stage the single layer package was tested, and it absorbed only 6.38% of the impact energy value. The source of this result was the too low thickness and too high material stiffness.

Looking at the results of the energy absorbed by the double layer packages, it was easy to see the difference between them and a single layer package. The most energy was absorbed by packages 2B and CB,more than 15% of the whole impact energy value. Package 2B absorbed 15.27% of the energy value, times more than for package B. The best result was achieved by package CB, which absorbed 15.53% of the energy. Packages BC and CB were made of the same spacer fabrics but in reverse order. However, the packages had the same thickness, and the layer order slightly affected the energy absorbed. The difference between the results was 0.31 J, which is statistically insignificant.

The decision about variants examined in the next stage was based on the lowest value of the force received under the anvil, because it was the most important parameter analysed. Even though package CB absorbed more energy, package 2B was tested in the third stage, reinforced with an additional layer of fabric B and C. It could be noticed that the values were higher than for the basic 2B package. The best result was achieved by package 3B, which absorbed 24.96 % of the whole energy. The differences in the result of the test between values of the energy absorbed by the packages were the effect of using different spacer yarns. A monofilament of 0.15 mm thickness was used in sample B. The three layers of this sample absorbed the most energy, because thicker spacer yarn has better ability to absorb energy, which is connected with the low flexibility module and better strength properties. In addition, the layered construction of the packages caused an increase in the number of points connecting the layers, which also had a positive influence on increasing the amount of energy absorbed. The energy absorbed by the package increased from about 6% for the sinlge- layer package, to about 25% for the three- layer package. For variants 2BC and C2B, the average amount of energy absorbed was 24.88% and 23.02%. The results were worse than for package 3B, because two out the three layers consisted of thinner spacer yarn, that is 0.10 mm thick.

Results of air permeability

In addition to good impact reduction properties and energy absorption, protective material should provide air permeability to minimise heat stress. In old-fashioned police vests, the most common protective materials are PVC panels. It is known that PVC has an air permeability of 0.0-0.45 mm/s [15]. Therefore, it could be assumed that a textile package made of warp-knitted spacer fabric will be more air-permeable than those of PVC. Therefore, air permeability tests were carried out on package 3B.

Result showed that the permeability of the package tested was 19.22 mm/s. This was definitely a better result than for PVC. The air permeability of package 3B is owed to the presence of free space between eyeletes and spacer yarn.

Impact vest

Based on an interview with policemen, it was proven that protective vests for uniformed services weigh about 3.5 kg. In their opinion, this is too much to be able to perform the necessary duties while maintaining physical comfort. The choice of materials was guided by the desire to obtain an appropriate material structure that provides protection at Level 1 according to the standard and allows to classify the material as protective. In addition, the low mass of the final product is an important aspect. Due to thebest ability to reduce the force and absorb the energy, package 3B was selected. Therefore, this package could be used in the production of anti-impact vests. In addition to very good strength parameters and air permeability, the package has a relatively low surface mass (2667 g/m^2) and thickness of 16.5 mm. According to calculations, a prototype of the vest made by using the specified package will weigh about 2 kg [16].

Summary and conclusions

The main aim of the tests was to select a package which has the lowest force received under the anvil and absorbs the most energy given which would make it possible to classify this package as protective material according to the standard. In order to achieve this, many variants of packages were tested. Based on the results, package 3B was selected. Besides meeting the standard requirements, the package selected showed the lowest amount of force received under the anvil and at the same time the highest amount of energy absorbed.

Analysing the results of the tests, the following conclusions were drawn:

- Depending on the number of layers, the textile packages made of warp-kniteed spacer fabrics showed different protective properties. Taking into consideration the order of the layers in the package, the differences in the results were not statistically significant.
- The great thickness of the package increased the ability of energy absorption and gradually decreased the value of force received under the anvil.
- The thickness of spacer yarn has an influence on the ability to reduce the impact. The thicker the spacer yarn is, the greater the material ability to absorb energy and reduce the force is.
- Thick spacer yarn increased the stiffness of the material. In the case of a vest, too stiff material can transfer the impact force outside the material, to the human body. Therefore, it is important to choose a material that, on the one hand, provides protection at Level 1 and, on the other, is flexible and adapts to the shape of the body.

- By using textiles such as warp-spacer fabrics, it was possible to obtain a protective package which provides air circulation and impact protection. In addition, the product may be light enough not to cause heat stress during usage.
- The usage of textiles in a protective package can reduce the mass of the final product, which can reach about 2 kg for the variant in size L, which would be 1.5 kg less than those currently in use.

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