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Experimental Tests of a Property of Composite Material Assigned for Ballistic Products

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Abstract
An empirical investigation of a selected static property of a composite is presented in this paper. For the purpose of studying the quality and property of multilayer composite material assigned for manufacturing some ballistic products, the following were conducted: tensile test, hardness test, bending test and delamination test. Before the tests were carried out, procedures were created for each of them. Selected results of the tests performed are shown and discussed.

Key words: *composite material, experimental study, tensile test, delamination test.*

Introduction

Empirical tests and investigation of the property of major composites can cause difficulties in its determination, mainly resulting in an inhomogeneous material which has a directional property (orthotropic or anisotropic material). Additionally, a great part of composites consists of many layers of different properties connected to each other which significantly makes the investigations more complicated . As many composites can be differently defined considering their structure, for a given type of composite material, special procedures have to be developed separately.

In literature there are many works devoted to experimental tests of different composite materials, only a small portion of which have been specified here. The authors of paper [1] investigated phenomenological plane-stress damage-mechanics based on a model for textile-reinforced composites and determined the predictive capability by carrying out a series of experimental tests. They performed directional and bidirectional tests in order to determine the specific properties of the material. Barchan and Chatys [2] conducted tests on tension and compression unidirectional composites to obtain some constants, and next they made a comparison of experimental and analytical results. Tarnopolskii, Arnautov and Kulakov [3] determined experimentally the shear properties of four types of composites fabricated by different processing methods. In their work [4] results of a tensile test and the phenomenon of the fracture mechanisms of composites are presented. Kucher, Zemtsov and Zarazovskii [5] analysed the behaviour of the elastic deformation of laminated epoxy composites reinforced with unidirectional carbon fibres and satin-woven glass fabric. Kattell and Kibble [6] carried out three common tests: tensile, three-point flexure and four-point flexure for a glass fibre epoxy composite. Wang, Li and Zhao [7] performed an experimental study on a woven fabric epoxy composite and found the property of this composite by conducting uniaxial tension, three point flexure, compression, short beam shear and interlaminar fracture. They studied a composite with fibre glass and Kevlar woven fabric.

There are many European Standards for the investigation of composite material for different properties, but in the case of material which is used for special products (impact-resistant suits, helmets or protective shields), proper procedures had to be developed (modified accessible standards concerning composite materials). The standards mentioned above are rather suitable for multilayer laminates – a composite characterised by a brittle fracture form. The tests performed relied upon the study of many multilayer composites manufactured in different conditions (different pressing pressure for some parts of the layers or the application of two other materials glued to each other), which caused difficulties in the assumption of material type defined by present standards. It should be mentioned that the properties of many of the materials investigated gradually changed inside (with regard to the thickness of the specimen) This forced us, among others, to design special holders for the tensile tests carried out.

The main purpose of the investigation performed was the evaluation of the quality of materials manufactured in this testing as well as finished products using static testing methods The connection of layers and the repeability of the material properties obtained were evaluated, among others. Moreover taking into consideration the static methods, the exact values of some mechanical magnitudes can be determined, allowing for a selection of composite materials which satisfy the intention of the producer (many materials for comparison were manufactured in different physical and chemical conditions). Additional evaluation of the utility of the results of static testing in comparison to ballistic investigation can be left to the manufacturer, but in literature [8] information describing the relations between static and ballistic material property methods can be found (for example penetration of projectile upon material hardness).

Description of materials and tests applied

In this chapter, tests are described which were adopted to determine the material property, in which the following tests were performed: the tensile test, the hardness test, the three-point bending test and the delamination test. For each test mentioned, a procedurewas created based on European standards, among others.

For the manufacture of a lightweight composite, the following raw materials were used:

- Dyneema® HB 50 - made of ultra-high-molecular-weight polyethylene fibres (UHMWPE) oriented in the polymer matrix in the form of flat sheets;
- Dyneema® HB 80 - made of ultra-high-molecular-weight polyethylene fibres (UHMWPE) oriented in the polymer matrix in the form of flat sheets;
- pre-impregnate based on a fabric of para-aramide fibres - Twaron CT 736 coated with phenolic resin modified with PVB.

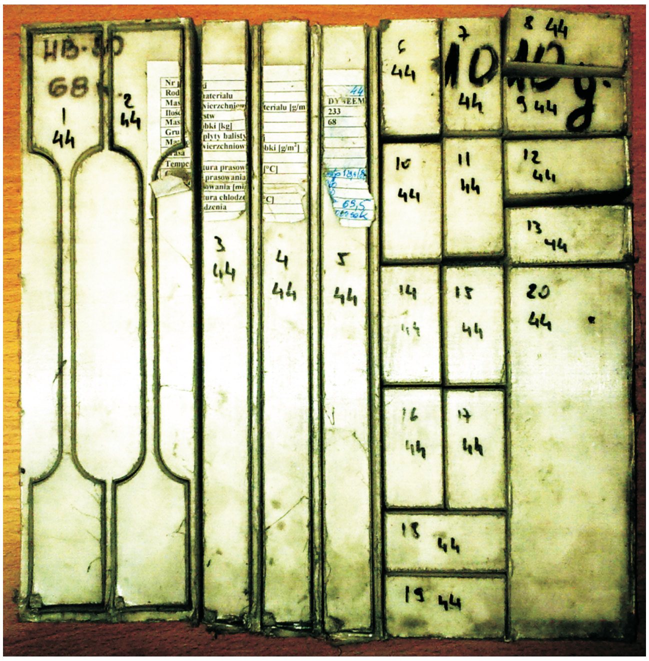

Figure 1. Specimens prepared for study taken from the composite plate.

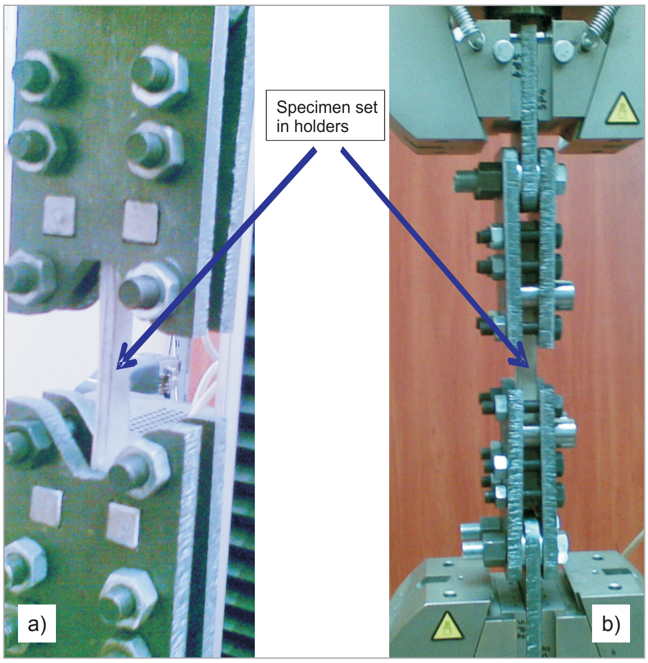

Figure 2. Particular holders used in the tensile test.

The composite materials studied were mostly *Twaron*® and *Dyneema*® (ultra-high molecular weight polythene).

The ballistic panels were designed in two combinations:

a) as a homogenous composite, as follows:
   - Dyneema® HB 50 sheets or,
   - Dyneema® HB 80 sheets or,
   - preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB,

b) as a hybrid consisting of two raw materials: Dyneema® HB 80 sheets and preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB.

The ballistic panels produced feature a coherent multi-layer structure, which allows for gaining precisely defined mechanical and ballistic properties. They differed in surface weight, thickness as well as composition. Some of them have been characterised previously [9]. The composites were made by the press-method based on the procedure elaborated at the Institute of Security Technologies “MORATEX” [8].

In order to prevent from burning edges during the cut-out, specimens of the composites were taken from the plate using the water cutting method. One of the composite plates investigated after cutting is presented in ***Figure 1***.

Tensile test

One of the most basic and important tests allowing to determine the mechanical properties is the tensile test presenting the material tension as a function of strain. This empirical investigation allows to determine some material properties, among others: the ultimate strength, Young modulus and yield stress. Additionally, during a tensile test, a diagram presenting the stress dependent upon the strain in the whole range is obtained. This study was conducted on an Instron tensile tester, which it makes possible to stretch and compress specimens with a loading from 200 N up to 200 kN. If it was necessary to apply a minor total load (for little specimens), a force gauge of a small range could be used.

Because of the easy slipping-out of the composite material from the jaws of the machine or/and inner layer of composite from the specimen, apart from proper preparation of specimens with reference to their shapes, special holders had been designed and applied for the tensile test (***Figures 2.a*** and ***2.b***). Specimens used for tension had dimensions and shape as displayed in ***Figure 3***. The length as well as the width of the specimen (at the point of contact with the holder) were changed (on the basis of the standard used, this assumption is admissible).

The suitable performing of tensile tests, especially for Dyneema®, was made possible by the specially designed handles. To our knowledge, even the producer of Dyneema® plates does not perform tensile tests, precisely because of the phenomenon of a specimen slipping out of the jaws and inner layers of the entire specimen. This second type of slipping-out occurs due to the ease of delamination in the material, and after a crack or hold, the outer layers in the jaws of the

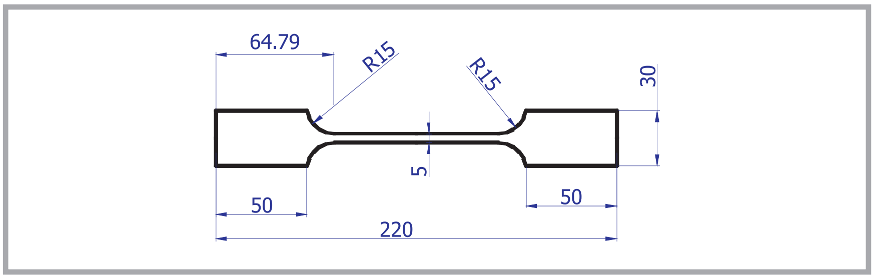

Figure 3. Dimensions and shape specimen applied for the tensile test.

inner layers slip out, making it impossible to carry out tests in the traditional way (without special holders).

Three-bending test

The specimens were bent in a three-point bending test to compare it to four-point bending, allowing to obtain the full breaking of specimens at the place of force action (in this way it can achieve greater bending angles). The distance between two supports amounted to 150 mm. The length and width of the specimens subjected to the bending test amounted to 220 mm an d 20 mm, respectively. The thickness of each specimens equalled that of the plate (usually the dimension of the plate amounted to 250 × 250 mm) produced for the study.

Delamination test

This test allows to evaluate the state of layers connected to each other. Generally it relies upon the pushing of the intender of some shape transversally in the material investigated (shown in ***Figure 4***). The length and width of specimens subjected to the delemination test amounted to 50 mm and 25 mm, respectively.

Hardness test

A hardness test was carried out by applying the Brinell machine. As an intender, a ball of 5 mm diameter was pushed at a force of 613 N. The hardness of the material was measured at six points on each side of the plate.

Results of experimental studies

In this paper, the presentation concerns composite material made of *Dyneema® HB80* (multilayers of polythene fibre sheet of ultra-high molecular weight), *Dyneema® HB50* (multilayers of polythene fibre sheet of ultra-high molecular weight), preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB (called *Twaron® CT735 prepreg)* (multilayer para-aramide woven impregnates) and a combination of these materials glued to each other. Specimens were taken parallel (x-direction) or perpendicular (y-direction) to the edges of a plate of 250 × 250 mm or 300 × 200 mm dimensions. On the diagrams in the description for each material investigated, only the surface weight of the plates was determined (the number of layers used is known to the manufacturer).

Tensile test

Stress-strain curves of the tension for specimens taken from the plate the in x-direction are displayed in ***Figures 5 ÷ 8***. Composites made of *Dyneema® HB80* and *Dyneema® HB50* have an ultimate strength comparable to low carbon steel. The number of layers does not influence considerably the maximal value of stress obtained, but it should be emphasised that all curves, those presented and obtained but not shown here, have slightly different courses for the same material used. Composites made of preimpregnate based on CT 736 fabric of *Twaron®* fibres coated with phenolic resin modified with PVB have little ultimate strength in comparison to that made of *Dyneema®*, but it is still high, at a level of about 300 ÷ 400 MPa. In comparison to *Dyneema®* the elongation for *Twaron®* is decidedly minor (8 ÷ 14 times). This difference results from the fact that *Dyneema®* (ultra-high-molecular-weight polyethylene fibres) is a more ductile material, especially for single thin sheet.

The combination of the mentioned materials in the tension test (***Figure 8***) shows that the ultimate strength is lower than in the case of composite made of pure *Dyneema®*. As regards the two other materials, as shown in ***Figure 8***, the tensile curve cannot be evaluated correctly because each material behaves in a different way (different elastic limit, different strain at the same force). The property obtained is a typical average of the composites connected to each other. Observing the curves, it can be noticed that during the tensile test, both composites fail at different elongations. The participation of *Dyneema®* with regard to the thickness of the plate was mainly smaller, and the curves in ***Figure 8*** are similar those in ***Figure** 7* (pure *Twaron®*).

If *Twaron®* failure happens first, the second material at this load cracks in a short time as well (rapid decrease in stress follows because the initial cross-section of the specimen is suddenly changed). Taking into consideration *Dyneema® HB80* and *Dyneema® HB50,* other courses of the curves obtained can be seen (***Figures 5*** and ***6***). The first of them during tension is characterised by two straights (in approximation) before the maximal force peaks (the remark is noticed in *Twaron®* as well). For *Dyneema® HB50* it is observed the one range and subsequent final longer tension of the specimen- in this case the plastic failure of the material, occurs.

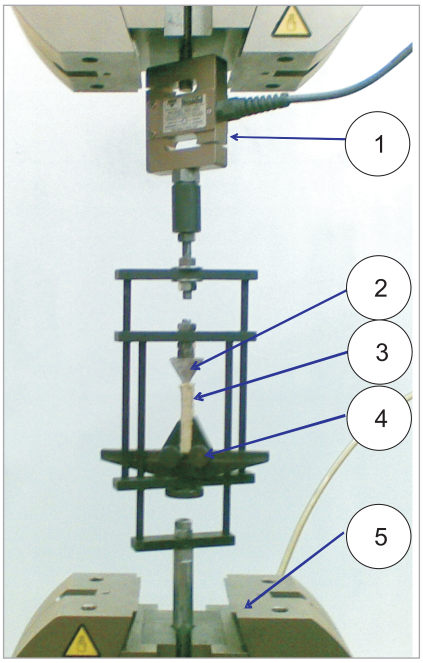

Figure 4. *Workstand for the delamination test; 1 - force gauge, 2 - intender, 3 - investigated specimen, 4 - holder, 5 - jaws of Intron machine.*

Bending test

For the same materials, given above, bending curves describing the dependence force as a function of the deflection measured in the middle of the specimen are presented in ***Figures 9 - 12***. Looking at the two diagrams concerning *Dyneema® HB80* and *Dyneema® HB50*, the different character of these curves can be observed; however, for both materials the greatest force causing breakage is below 10 dN. For the materials (*Dyneema® HB80*), visible drops and peaks of the bending force can be noticed. This can be explained by the curves presented - *Dyneema® HB80* is a thinner specimen (about 3 times) than in the case of *Dyneema® HB50.* During the bending test, by increasing the force, the exterior layers began to break in sequence. For thicker specimens (*Dyneema® HB50*) a different course on the diagram was observed – a slightly fluent one. The material behaved in a homogeneous manner (layers crept in the same time) and distinct breaks in the sheets could not be marked.

In the flexure test, *Twaron®* in comparison to *Dyneema®* had decidedly greater stiffness because not only the forces used for bending were higher but the thickness of specimens was smaller as well. For the two material combined with each other, the bending force decreased, but curves

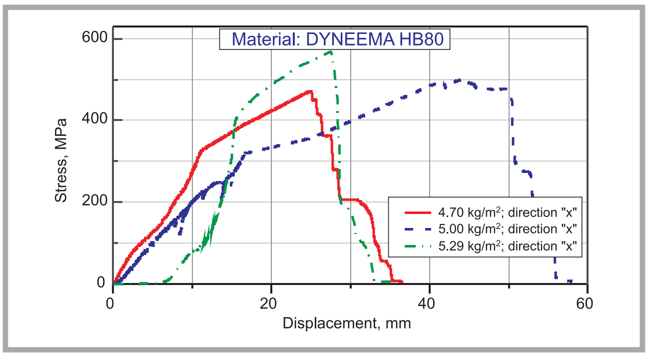

***Figure 5.** Stress versus displacement for composites made of Dyneema® HB80 in the tensile test.*

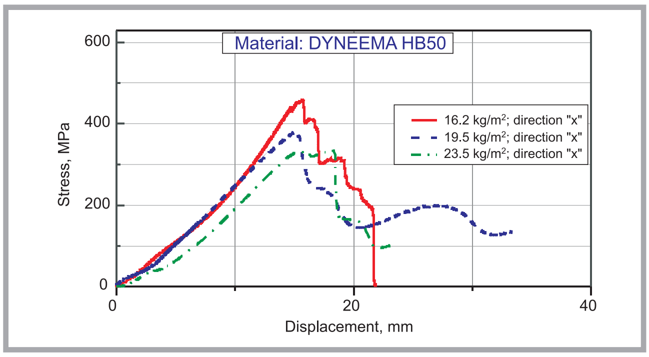

***Figure 6.** Stress versus displacement for composites made of Dyneema® HB50 in the tensile test.*

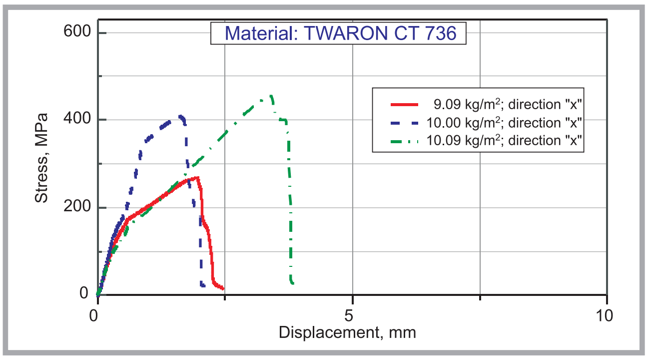

***Figure 7.** Stress versus displacement for composites made of preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB in the tensile test.*

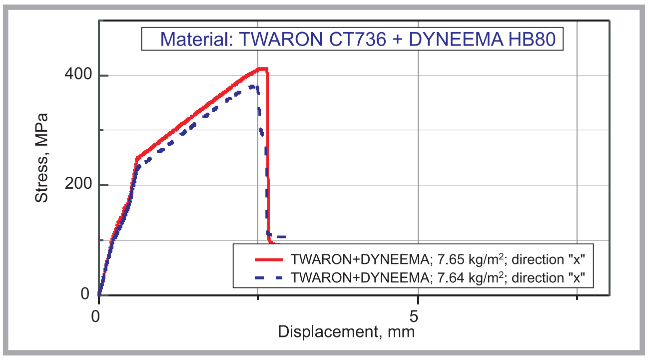

***Figure. 8.** Stress versus displacement for hybrid composites made of preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB and Dyneema® HB80 in tensile test.*

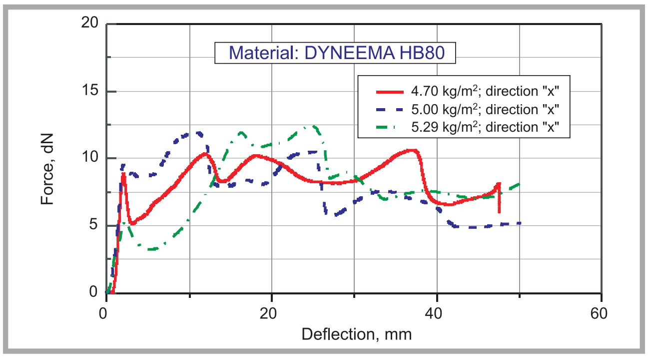

***Figure 9.** Force versus displacement for composites made of Dyneema® HB80 in the bending test.*

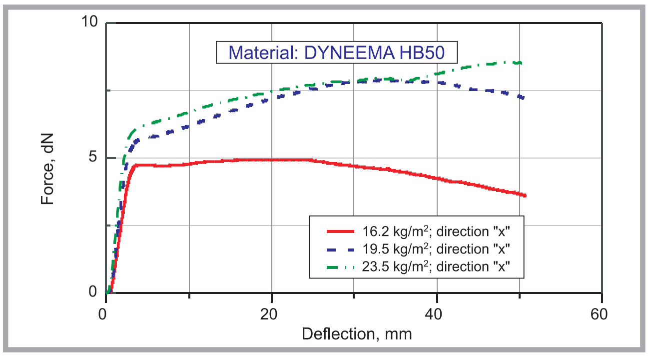

***Figure 10.** Force versus displacement for composites made of Dyneema® HB50 in the bending test.*

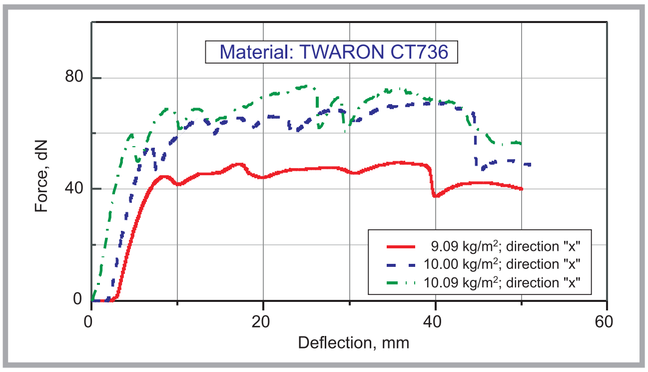

***Figure 11.** Force versus displacement for composites made of preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB in the bending test.*

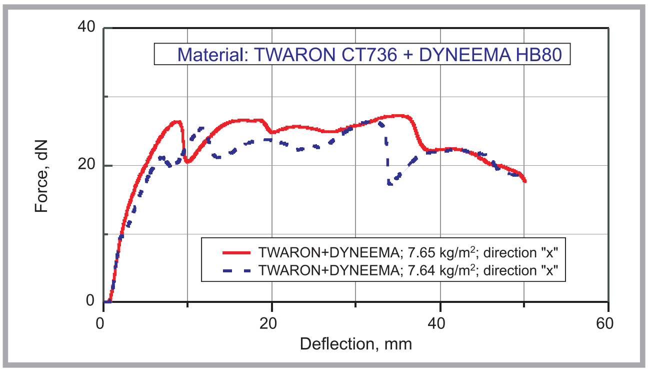

***Figure 12.** Force versus displacement for hybrid composites made of preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB and Dyneema® HB80 in the bending test.*

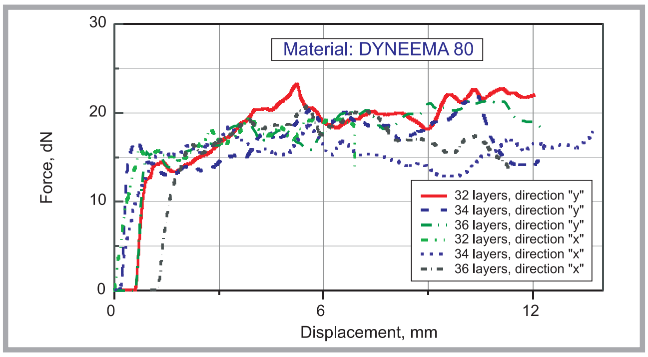

Figure 13. *Force versus displacement for composites made of Dyneema® HB80 in the delamination test.*

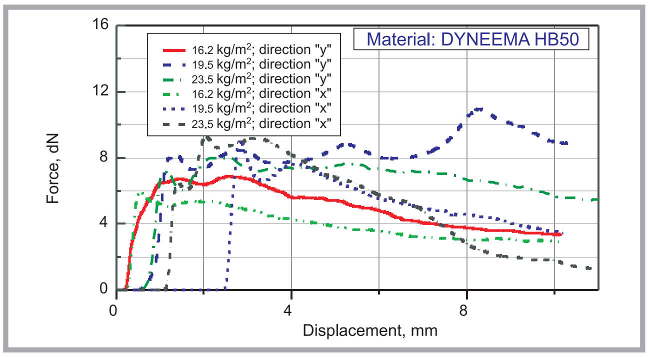

Figure 14. *Force versus displacement for composites made of Dyneema® HB50 in the delamination test.*

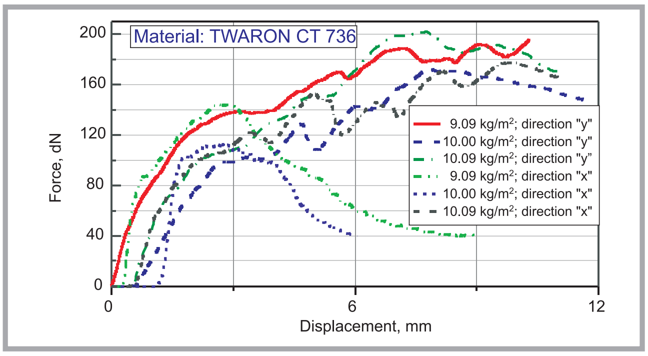

Figure 15. *Force versus displacement for composites made of preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB in the tensile test.*

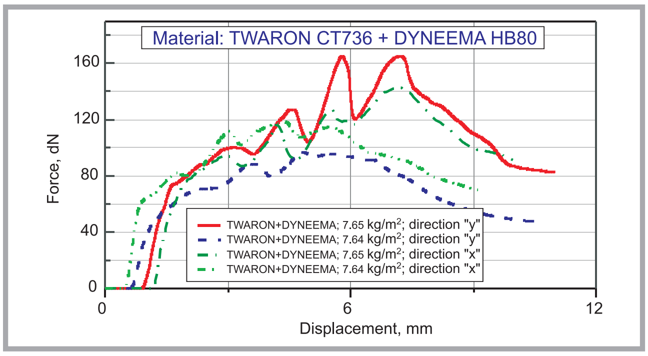

Figure 16. *Force versus displacement for hybrid composites made of preimpregnate based on CT 736 fabric of Twaron® fibres coated with phenolic resin modified with PVB and Dyneema® HB80 in the tensile test.*

obtained are alike (***Figure 12***). The dispersion of all curves in the greatest force for this test (as well as delamination test) can result in the quality connection of separate sheets (in some cases - pure connections).

Delamination test

This study was performed for at least six specimens taken from the plate in two orthogonal directions. The repeatability for each series was satisfactory as the curves received were similar. The forces versus displacement of the intender for the materials discussed are plotted in ***Figures 13 ÷ 16.*** The investigation shows that the delamination loading for *Twaron*® is incomparably greater (about 8 or 12 times) than in the case of *Dyneema*®. As observed, the direction of the taking of specimens for this kind of material does not influence the results received. As regards the curves of the other two materials, it can be remarked that for *Dyneema*®, the force increases to a certain value and next drops or remains at the same level. This takes place in a different way for *Twaron*®, where delamination loading mostly still grows during the entering of the intender into material (***Figure 15***). The characters of all curves presented in the delamination testing, taking into consideration the same material and number of layers remaining, are almost similar, but values of the forces dependent upon the displacement can be different (not in all cases). The maximal forces obtained in first step of the delamination test (in dependence upon the number of sheetsused) for a given material have similar values (50% in most cases).

These differences can come out of the right preparation of specimens (even tolerance) or place of taking them from the plate or the precise setting of the specimen in the holders (the intender during the test could be covered by the middle of specimens or be parallel along the edges of the composite material). Additionally, in some cases it might occur that the intender runs into the edges of the sheet but not into the resin (***Figure 17.a***). To prevent this possibility, perhaps the initial penetration of the intender should be applied (***Figure 17.b***).

Hardness test

This test was conducted on a Brinnel machine using a ball of 5 mm diameter as an intender. Results of this investigation are shown in ***Table 1*** (see page 66). It appears that *Twaron*® is the harder material by about 50%, but both materials have very low hardness (at least 10 times lower than carbon steel). On the basis of the results obtained, it cannot be stated how the number of layers influences the

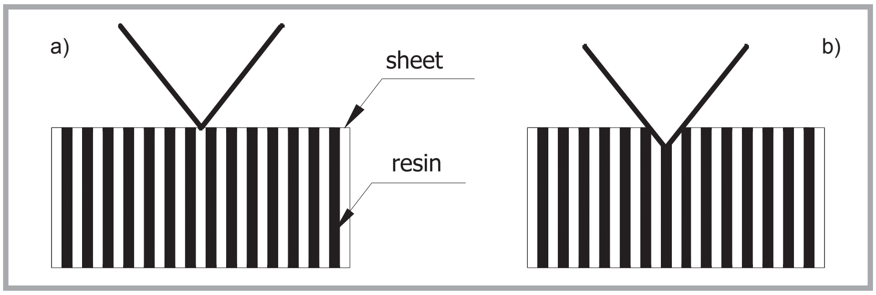

Figure 17. *Typical possibility of the intender entering into specimen investigated in the delamination; Testing, coming across a) sheet and b) resin.*

***Table 1.** Results of measurement of material hardness.*

Type of raw material		Surface weight, kg/m^2	Average value, Brinnel scale
Twaron® CT 736 prepreg + Dyneema® HB 80	**measured Twaron®**	7.65 (approx. 60% of layers of Twaron prepreg)	12.9
	measured Dyneema®		10.7
	measured Twaron®	7.64 (approx. 50% of layers of Twaron prepreg)	15.5
	measured Dyneema®		11.1
Dyneema® HB 50		23.50	7.6
		16.20	8.5
		19.50	6.7
Twaron® CT736		10.00	12.0
Twaron® CT 736 prepreg		9.09	14.0
		10.09	16.3
Dyneema® HB 80		4.70	9.1
		5.00	9.2
		5.29	9.6

hardness. On the one hand, the values of material hardness in comparison to a similar material (manufactured in other conditions) do not differ considerably, but on the other, the thickness of each composite investigated might have an influence marked differences (Authors of the empirical investigation did not know exactly how each composite material had been produced or which kind of resin had been applied).

The hardness of material presented can be applied to the V_{50} - standard (it states the dependence of the penetration of the projectile upon material hardness).

Final remarks and conclusions

This research was performed for composite materials for the purpose not only of the determination of a certain material property but also for verification of the repeatability of the same material. Considering the tensile test, different stress-strain curves for *Dyneema® HB80* and *Dyneema® HB50* were observed; however, for *Twaron®* with regard to its structure, it is characterised by short elongation. In the case of the results obtained in the bending test, it can be seen that *Dyneema® HB50* behaved as a homogenous material (in comparison to *Twaron®* or *Dyneema® HB80,* where the breaking of a specimen took place in the external sheets). The material hardness for all composites studied was comparable (difference in many units in the Brinnel scale), although *Twaron®* turned out to be harder. Assessing the delamination test, it was noticed that for *Dyneema® HB50* the curves were slightly different (after obtaining the delamination of the specimen, the force decreased further).

Acknowledgment

The research was carried out within the framework of Innovative Economy – National Cohesion Strategy as a Key Project No. POIG 01.03.01-10-005/08 entitled: „MODERN BALLISTIC BODY ARMOUR AND COVERS FOR TRANSPORTATION MEANS AS WELL AS FOR BUILDINGS MADE ON THE BASIS OF TEXTILE COMPOSITES", supported by the European Regional Development Fund - ERDF

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Received 26.04.2011 Reviewed 14.11.2011

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