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Characterization of Filamentwound Polymeric Composite Materials

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The mechanical properties of a composite material - glass fiber/polyester resin, obtained by the filament winding technology, are presented in this paper. The filament winding technology produces cylindrical parts; since the methods of investigation of mechanical properties of composite materials define the usage of flat specimens, a new method of production of flat sheets by filament winding was developed first and then a procedure for obtaining defined specimens by machining flat sheets. The paper presents strength, elastic modulus and Poisson's ratio, obtained by the tension and compression parallel and perpendicular to the fibre direction, flexural strength, interlaminar strength, shear strength and shear modulus of mentioned filamentwound composite material.

Key words: **composite materials, polymeric materials, filament winding technology, mechanical characteristics, polyester resin, glass fiber.**

Introduction

CHARACTERIZATION, in this paper, implies determination of mechanical characteristics of filamentwound polymeric composite materials. For optimizing structures made of composite materials, knowing mechanical properties is of essential importance [1].

Mostly axisymmetric i.e. cylindrical and, to a smaller extent, ball parts are produced by the filament winding technology.

Determination of mechanical characteristics of unidirectional (all fibres are placed in one direction) and crossply composite fiber-resin materials is defined by appropriate methods of investigation which all define the using of flat specimens. From cylindrical and ball products, obtained by the filament winding technology, it is not possible to get flat specimens by machining.

To obtaine flat specimens it was necessary first to develop a new method of producing flat sheets by filament winding. After that, a procedure was developed for obtaining defined specimens by machining flat sheets. At the end, the investigation of the produced flat specimens resulted in defining the mechanical characteristics of filamentwound composite materials of acceptable reliability.

Materials

Materials are solid (or liquid) substances used for production of various articles.

Material characteristic is defined as a measurable value by which the shape or the measure of material capability to react to external influence are characterized.

Mechanical properties refer to material behaviour under influence of external mechanical forces.

Composite materials are formed of two or more materials. Newly-formed materials are characterized by new properties, when compared to basic materials. Composites materials mostly consist of a reinforcing agent and a corresponding impregnation agent which bonds the reinforcing agent into a compact entity.

Owing to a fact that composite materials possess a unique set of characteristics, they are a right choice for production of new construction elements.

It is considered that there are more than 5,000 composite polymeric materials [2].

Filament winding technology

Filament winding technology shortly spoken consists of winding a reinforcing agent already impregnated by an impregnating agent on a mandrel followed by curing the wound structure. Reinforcing agents can be glass fibres, carbon fibres, graphite fibres, aromatic polyamide fibres (aramide), novoloid fibres, etc. Impregnating agents can be polyester resins, epoxy resins, phenolic resins and other thermoreactive resins.

Based on theoretical considerations and practical experience on investigation and development of polymeric composite materials obtained by the filament winding technology, it is known that the characteristics of the mentioned materials depend on reinforcing agents and impregnating agents and on the tecnological parameters of the production process as well.

Mechanical properties of composite materials depend on the applied reinforcing agent and the filament structure. The filament structure implies a number of layers and a filament angle in relation to the longitudinal axis of the cylinder.

The filament winding technology is mostly used for production of axisymmetric ie. cylindrical, and less often, ball parts. The essential advantage of this technology, compared to other technologies of production of construction materials (including other composite materials) is a fact that a reinforcing agent is placed in the direction in which stresses during exploitation of composite parts are expected to occur. In this way, the properties of fibres in the longitudinal direction are exploited to a great

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extent, so reinforcing agents are carriers of mechanical characteristics of composite materials.

A reinforcing agent is in a shape of roving (roving is a bundle of nontwisted fibres, theoretically of endless length). A roving possesses extremely high mechanical characteristics in the longitudinal direction i.e. in the fibre direction. It can be stated that a roving has extremely low mechanical characteristics in the perpendicular direction, if any.

It is, therefore, clear that the material produced by the filament winding technology has highly expressed anisotrophy, according to the direction in which fibres are placed.

Characteristics of filamentwound polymeric composite materials can be rarely found in expert literature for the following reasons:

- extremely versatility of reinforcing agents and impregnating agents,
- mix ratio of components of an impregnating resin system, recommended by manufacturers of resin systems, must be very often changed and adjusted to technological parameters for producing specified parts,
- this technology, initially developed for military applications is still used in areas which are protected in an appropriate way (army, space, energy programs),
- a growing tendency of protection od intelectual achievement.

The opinion of Epitectus - that materials of themselves affect us little, but it is the way we use them which influences our lives [2] - is valid for the filament winding technology in its full sense.

Filamentwound polymeric composite materials have a unique set of different properties and because of that, in many cases, elements of construction, made by the filament winding technology, are the only possible solutions for fullfilling specific functional demands.

These materials have extremely high values of mechanical characteristics in the fibre direction (strength and modulus of elasticity) and a low density value i.e. they are characterized by extremely high specific strength (relation of strength and density) and specific modulus (relation of modulus and density), which are very important for a production of highly stressed construction parts, which must have low mass. Besides this, they have excellent toughness, considerable resistance to corrosion, elevated temperature, abrasion, fatigue and chemical attack. Composite materials of glass fibre/polyeseter resin type are characterized by important dimensional stability, affordable prices, simplicity of processing, fabricating and handling, and some particular formulations have extremely high corrosion and fire resistance [3, 4].

For the determination of mechanical characteristics of unidirectional and crossply composite fiber-resin materials there are coresponding methods of investigation and all of them define the usage of flat specimens.

From cylindrical and ball products, obtained by the filament winding technology, it is not possible to get flat specimens by machining, which is a procedure applied for products made from other construction materials (for example metals) or produced by other technologies.

In order to produce flat specimens, it was first necessary to develop a new method of producing flat sheets by the filament winding technology. The essence of fabricating flat sheets by the filament winding technology is to use a mandrel of a specific design and to determine particular technological parameters of the given procedure.

The next step is to develop a procedure for machining flat sheets for the production of flat specimens. Flat specimens were produced by machining flat sheets using appropriate tools and particular machining parameters [5].

Methods of investigation

Standard ASTM D 3039 specifies the test method for tensile properties of fiber-resin composites [6].

Standard ASTM D 3410 specifies the test method for compressive properties of unidirectional or crossply fiber-resin composites [7].

Standard ASTM D 790 specifies the test method for flexural properties of unreinforced and reinforced plastics and electrical insulation materials [8].

Standard ASTM D 2344 specifies thetest method for apparent interlaminar shear strength of parallel fibre composites by the short-beam method [9].

Standard ASTM D 3518 specifies the test method for in-plane shear stress-strain response of unidirectional reinforced plastics [10].

All mentioned standards specify the use of flat specimens.

Besides the use of flat specimens, standard ASTM D 2344 specifies a procedure for determining interlaminar shear strength using ring (bow) specimens.

The density of the mentioned composite materials is determined according to SRPS G. S2. 510 /method B/ [11], and the glass fibre content by the gravimetric method, based on the organic phase burning.

Practical part

The unidirectional flat sheets, crossply flat sheets and tubes were produced using a system of polyester resin DUGAPOL H 230, made by the polyester resin manufacturer "DUGA", Beograd, and glass roving R 2117, made by the glass fibre manufacturer "ETEX", Baljevac/Ibar.

The polyester resin system DUGAPOL H 230 consists of the polyester resin DUGAPOL H 230, hardener N and accelerator N.

The polyester resin DUGAPOL H 230 is a medium reactive, unsaturated polyester resin of medium reactivity.

The hardener N is the 50 % solution of methyl ethyl keton peroxide in toluene.

The accelerator N is the 6 % solution of cobalt naphtenate in dimethyl phtalate.

To adjust the reactivity and the viscosity of the system polyester resin DUGAPOL H 230/hardener N/accelerator N for the production of flat sheets and tubes by the filament winding technology, an inhibitor terc. butyl catehol was added.

The glass roving R 2117, based on boralumosilicate nonalkaline glass fibre, is of 1160 tex linear density [12]. The tensile breaking force of the applied glass roving R 2117 is 393 N [13].

An essential condition for the production of parts by the filament winding technology is the isotensoid condition.

The starting idea for a flat sheet production comprised two activities:

a) development of a procedure for the production of flat sheets by the filament winding technology,
b) development of a procedure for the production of determined flat specimens by machining filamentwound flat sheets.

The first attempt to produce filamentwound flat sheets was done using a winch-shaped mandrel i.e. a tool which has the central axle with four radially placed perpendicular carriers. Between these carriers there were four plates over which impregnated glass fibres were wound. This attempt was unseccesful because the obtained sheets were flat near the supporting points but deformed in the middle i.e. in the areas far from the supporting points and the isotensoid condition was not fullfilled either.

Another attempt was an attempt to wind a single specimen for an appropriate investigation on a mandrel of similar design. Neither this attempt was succesful because the woundstructure was not flat and compact, nor the isotensoid condition was fullfilled.

A completely new conception of solving this problem i.e. design of a mandrel for filament winding of flat sheets was successful. A massive sheet with carefully chosen parameters (thickness, width, length, radius at edges, technological gaps), and appropriate technological parameters of the filament winding technology enabled the production of flat sheets with fullfilling the isotensoid condition.

The construction of this mandrel is shown in Fig.1. The gaps in the mandrel, 8 mm in width and 6 mm in depth, were filled with a few plastic bars of appropriate dimensions.

For filament winding of tubes, a cylindrical mandrel of appropriate dimensions was used.

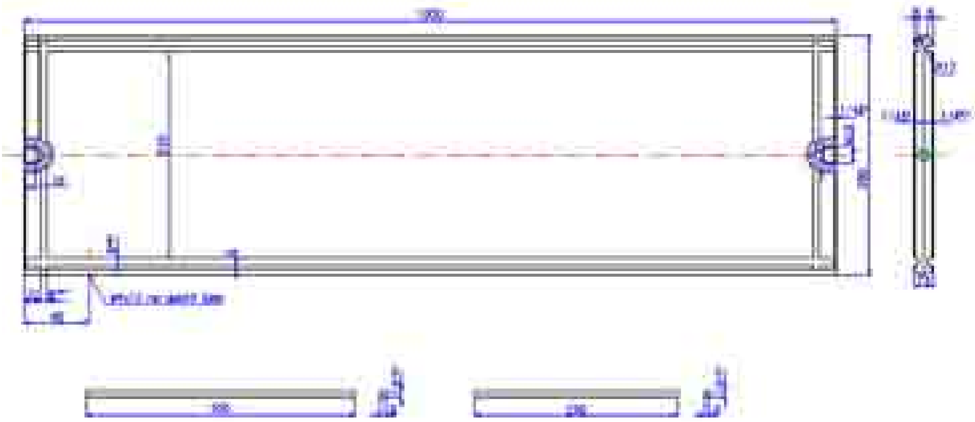

Figure 1. Mandrel for filament winding of flat sheets

Flat sheets and tubes were wound using the filament winding machine PLASTREX type PLA 500, manufactured by the PLASTEX-MANUHRIN, France.

Filament winding of flat sheets was realized with a tension force of 15 N per band of glass fibre (two rovings in a band) and with a speed of winding which was 40 % of a maximum possible speed of winding. The mandrel of shown dimensions and described technological parameters enabled the production of flat sheets with fullfiling an essential condition for the fabrication of parts by the filament winding technology i.e. the isotensiod condition.

Flat specimens were obtained by machining flat sheets on the milling machine ALG-100, manufactured by the PRVOMAJSKA, Yugoslavia. The machining of flat sheets to determined thickness was realised using the facing cutter at a speed of 560 rpm and a horizontal speed of 71 mm/min. Flat sheet cutting was realised by a circular of 80 mm in diameter with diamond edges at a speed of 250 rpm and a horizontal speed of 10 mm/min.

Poisson's coefficient i.e. Poisson's ratio represents the relation of the deformation in the longitudinal direction and the deformation in the transverse direction. To determine the Poisson's coefficient of a composite material in the longitudinal and the transversal directions, related to the fibre direction, it was necessary to make the flat specimens with the direction of fibres in the direction of applied forces (tensile and compresive) and the flat specimens with the direction of fibres perpendicular to the direction of applied forces. Cured filamentwound flat sheets so-called "longitudinal specimens" and so-called "transversal (perpendicular) specimens" were produced by machining. In "longitudinal specimens" glass fibres are placed in the direction of the longer dimension of specimens i.e. in the direction of external forces. In "transversal specimens" glass fibres are placed perpendicularly to the longer dimension of specimens i.e. perpendicularly to the direction of external forces.

Longitudinal flat specimens and transversal flat specimens for the tensile and compressive investigation, flat specimens for flexural strength and flat specimens for interlaminar shear strength were obtained from unidirectional flat sheets.

Flat specimens for shear investigation were produced from crossply flat sheets.

Rings of appropriate thickness and width were produced from tubes by machining in the lathe.

Ring specimens for the investigation of interlaminar shear strength were obtained from these rings using particular tools and the mentioned circular with diamond edges.

Dural tabs were glued at the end parts of specimens for tensile, compressive and shear investigation using epoxy adhesive Araldite 2011, manufactured by the Vantico, Switzerland.

Deformations in longitudinal and perpendicular directions were registered by strain gauges.

For a simultaneos registration of deformations in longitudinal and perpendicular directions in the tensile investigation of "longitudinal specimens" two-axis strain gauges CEA-06-125WT-120 manufactured by the VISHAY MEASUREMENT GROUP, Germany, were used.

The two-axis strain gauges HBB 10/120 XA 11 manufactured by the HOTTINGER BALDWIN MESSTECHNIK GmbH, Germany, were used for the tensile investigation of "transversal specimens" and for the determination of shear characteristics.

Two one-axis strain gauges HBB 1,5/120 LY 11 manufactured by the HOTTINGER BALDWIN MESSTECHNIK GmbH, Germany, were glued at available surfaces of "longitudinal specimens" and "transversal specimens" for the determination compressive characteristics.

All strain gauges were glued to specimens by adhesive HBB 60 manufactured by the HOTTINGER BALDWIN MESSTECHNIK GmbH, Germany.

The specimens, prepared in the described manner, were subjected to tensile and compressive forces and during these investigations, stresses and deformations in longitudinal and transversal directions, related to the direction of applied forces, were registered.

Tensile, compressive, flexural, interlaminar and shear characteristics of flat specimens were investigated by the dynamometer ZWICK type 1644, manufactured by the ZWICK, Switzerland.

The digital osciloscope NICOLET type 4094 B with belonging equipment, manufactured by the NICOLET INSTRUMENTS, USA, simultaneosly registered force and deformation signals in longitudinal and perpendicular directions.

A tool, in accordance with standard ASTM D 3410 and completed with two additional steel disks (to prevent slipping of specimens) was used for investigating compressive characteristics.

For the investigation of flexural strength, a tool in accordance with standard ASTM D 790 and adapted to the dynamometer ZWICK 1644, was used.

For the investigation of linear density of glass roving and density of composite material, an analytical balance METTLER was used. For the investigation of the breaking tensile force of glass roving the above mentioned dynamometer ZWICK was used.

For the investigation of the glass fibre content in the composite material, a furnace INSTRUMENTARIA, Yugoslavia, and the above mentioned analytical balance METTLER were used.

Results of investigation and discussion

The composite material glass fiber/polyester resin has a density of 1. 97 g/cm^3 and the glass fiber content is 74.7 %.

Using flat specimens the following characteristics of the filamentwound composite glass fibre/polyester resin were determined:

– tensile strength, tensile modulus of elasticity and Poisson's coefficient longitudinal i.e. parallel with fibre direction,
– tensile strength, tensile modulus of elasticity and Poisson's coefficient perpendicular i.e. normal to fibre direction,
– compressive strength, compressive modulus of elasticity and Poisson's coefficient longitudinal i.e. parallel with fibre direction,
– compressive strength, compressive modulus of elasticity and Poisson's coefficient perpendicular i.e. normal to fibre direction,
– flexural strength,
– interlaminar shear strength,
– shear strength and modulus of elasticity at shear.

A statistical analysis of the obtained results was done. The arithmetic mean $\left(\bar{X}\right)$ and the standard deviation (σ) were calculated.

Tensile characteristics

The tensile characteristics of the filamentwound composite material glass fibre/polyester resin were determined in accordance with standard ASTM D 3039.

For the determination of the tensile characteristics longitudinal to the fibre direction, a specimen shown in Fig.2 was used.

Figure 2. Specimen for the tensile investigation parallel to the direction of fibres ("longitudinal specimen")

The results of the investigation of tensile strength were obtained by the investigation of 7 single specimens, and the tensile modulus of elasticity and Poisson's coefficient were obtained by the investigation of 4 single specimens. This refers to the tensile investigation of the longitudinal and the perpendicular specimens and the results are shown in Tables 1 and 2, respectively.

Table 1. Tensile characteristics of the longitudinal specimens

Tensile strength (MPa)			Modulus of elasticity (MPa)			Poisson's coefficient		
X_i	$\bar{X}$	σ	X_i	$\bar{X}$	σ	X_i	$\bar{X}$	σ
699.0 649.1 744.1 739,3 653.1 683.1 695.4	694.7	37.4	10.695 10.598 11.470 11.033	10.949	394	0.284 0.301 0.310 0.290	0.296	0.011

On the basis of the analysis of the obtained results shown in Table 1, the following can be seen:

– uniformity of single values of the tensile strength longitudinal ie. paralel to the fibre direction because the standard deviation is only 5.4 % of the arithmetic mean (σ=5.4 % $\bar{X}$),
– uniformity of single values of the modulus of elasticity of the longitudinal specimens because the standard deviation is only 3.6 % of the arithmetic mean (σ=3.6 % $\bar{X}$),
– uniformity of single values of the Poisson's coefficient longitudinal ie. paralel to the fibre direction because the standard deviation is only 3.4 % of the arithmetic mean (σ=3.4 % $\bar{X}$).

For the determination of tensile characteristics perpendicular to the fibre direction, a specimen shown in Fig.3 was used.

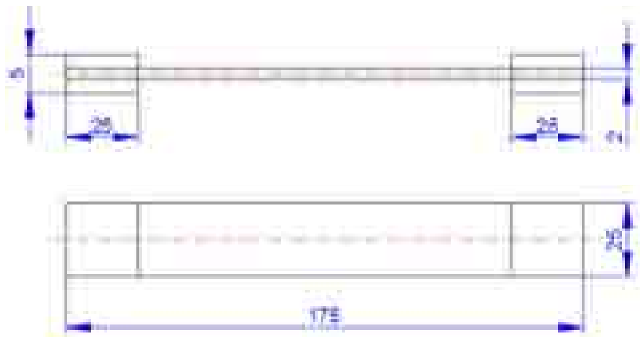

Figure 3. Specimen for the tensile investigation perpendicular to the direction of fibres ("transverse specimen")

Table 2. Tensile characteristics of the perpendicular specimens

Tensile strength (MPa)			Modulus of elasticity (MPa)			Poisson's coefficient		
Xi	$\bar{X}$	σ	Xi	$\bar{X}$	σ	Xi	$\bar{X}$	σ
9.62 10.98 9.93 9.57 8.21 11.31 8.41	9.72	1.16	3.85 3.38 3.65 3.53	3.51	0,31	0.0012 0.0014 0.0015 0.0012	0.0013	0.00015

On the basis of the analysis of the obtained results shown in Table 2, it can be concluded:

– uniformity of single values of the tensile strength, the tensile modulus of elasticity and the Poisson's coefficient of perpendicular specimens is somewhat lower than the uniformity of single values of the same characteristics of longitudinal specimens but still acceptable,
– standard deviation of the tensile strength perpendicular to the fibre direction is 11 % of the arithmetic mean (σ=11 % $\bar{X}$),
– situation is similar with the Poisson's coefficient i.e. the Poisson's coefficient during the tension of perpendicular specimens is 11.0 % of the arithmetic mean (σ=11.0 % $\bar{X}$),
– deviation of single results of the investigation of the modulus of elasticity perpendicular to the fibre direction is acceptable because the standard deviation is 8.8 % of the arithmetic mean (σ=8.8 % $\bar{X}$).

A possible explanation of the phenomena observed during the tension of perpendicular specimens i.e. when the direction of tensile stress is transversal to the direction of fibres lies in smaller or bigger disruption of the wound structure occuring during the cutting of perpendicular specimens from unidirectional flat sheets. It is supposed that cutting glass fibres transversal to the fibre direction can cause more or less damage to the specimen structure, thus causing the deviation of single values of the examined properties.

As far as the tensile breaking force of the reinforcing agent i.e. glass roving is concerned, it can be estimated that the obtained values of the mechanical properties of flat filamentwound specimens, notably the tensile strength in the fibre direction, were expected.

Great differences in the obtained results of investigation of the same characteristics of the same material but of different orientation of the reinforecing agent, with respect to the direction of tensile stress confirm an extreme anisotrophy of composite materials produced by the filament winding technology.

Compressive characteristics

The compressive characteristics of the filament wound composite material glass fibre/polyester resin were determined in accordance with standard ASTM D 3410.

For the determination of the compressive characteristics longitudinal and perpendicular to the fibre direction, a specimen shown in Fig.4 was used.

The results of the investigation of compressive strength were obtained by investigating 7 single specimens, while the compressive modulus of elasticity and the Poisson's coefficient were obtained by investigating 3 single specimens. This refers to the compressive investigation of the longitudinal and perpendicular specimens and the results are shown in Tables 3 and 4, respectively.

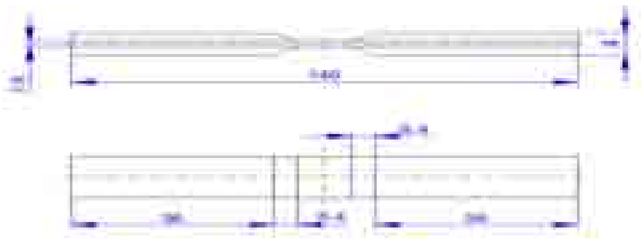

Figure 4. Specimen for the compressive investigation parallel and perpendicular to the direction of fibres

Table 3. Compressive characteristics of the longitudinal specimens

Compressive strength (MPa)			Modulus of elasticity (MPa)			Poisson's coefficient		
X_i	$\bar{X}$	σ	X_i	$\bar{X}$	σ	X_i	$\bar{X}$	σ
412.2 403.2 396.8 423.1 430.2 388.3 411.6	409.3	14.6	1.178.4 1.115.9 1.219.5	1.171.3	52.1	0.323 0.307 0.308	0.312	0.009

On the basis of the analysis of the results obtained by the investigation of longitudinal specimens by compressive stress, the following can be seen:

– uniformity of single results of the investigation of the compressive strength ie. σ= 3.6 % $\bar{X}$,
– uniformity of single results of the investigation of the modulus of elasticity ie. σ= 4.4 % $\bar{X}$,
– uniformity of single results of the investigation of the Poisson's coefficient ie. σ= 2.9 % $\bar{X}$.

Table 4. Compressive characteristics of the perpendicular specimens

Compressive strength (MPa)			Modulus of elasticity (MPa)			Poisson,s coefficient		
Xi	$\bar{X}$	σ	Xi	$\bar{X}$	σ	Xi	$\bar{X}$	σ
12.14 10.61 10.40 12.33 9.75 11.35 10.74	11.05	0.94	785.6 796.8 718.8	767.1	42.3	0.173 0.172 0.199	0.181	0.015

On the basis of the analysis of the compressive results of the investigation of specimens in which fibres are perpendicular to the stress direction, the following can be seen:

– uniformity of single results of the investigation of the compressive strength ie. σ= 8.5 % $\bar{X}$,
– uniformity of single results of the investigation of the modulus of elasticity ie. σ= 5.5 % $\bar{X}$,
– uniformity of single results of the investigation of the Poisson's coefficient ie. σ= 8.3 % $\bar{X}$.

The compressive investigation of the same properties of the same material resulted in great differences depending on the direction of the reinforcing agent, in relation to the external compressive stress, as it was obtained in the case of tensile stress. This is attributed to extreme anisotrophy of the filamentwound composite material.

Flexural characteristic

The flexural strength of the filamentwound composite material glass fibre/polyester resin was determined in accordance with standard ASTM D 790.

This standard describes the determination of flexural

strength using flat specimens in two methods:
- method I, i.e. so-called three-point bend test or, shortly, 3-PBT,
- method II, i.e. so-called four-point bend test or, shortly, 4-PBT, which has variety 1 and variety 2.

Method I of standard ASTM D 790 defines the determination of flexural strength by the investigation at three points - a flat specimen (bar) rests on two supports and is loaded by means of the loading nose midway between the supports (L), as shown in Fig.5.

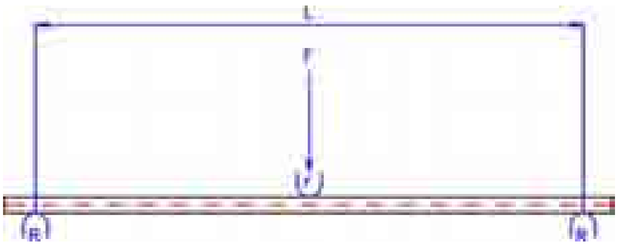

Figure 5. Scheme of the investigation of flexural strength at three points in accordance with method I of standard ASTM D 790

Method II of standard ASTM D 790 defines the determination of flexural strength by the investigation at four points - a flat specimen, which rests on two supports, is loaded at two points by two loading noses, each at an equal distance from the adjacent support points, as shown in Fig.6. This method has two varieties:
- variety 1 when the distance between the loading noses (LS) is 33 % of the distance between the supports (L),
- variety 2 when the distance between the loading noses (LS) is 50 % of the distance between the supports (L).

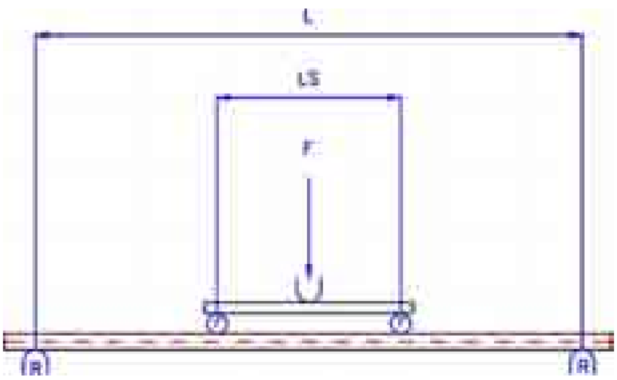

Figure 6. Scheme of the investigation of flexural strength at four points in accordance with method II of standard ASTM D 790

For the flexural investigation, a flat specimen shown in Fig.7 was used.

Figure 7. Specimen for the investigation of flexural strength

The flexural strength was determined using a specimen of the given dimensions and the corresponding tool, in accordance with the mentioned standard, which was adapted for the ZWICK dynamometer.

The direction of the loading noses was perpendicular to the direction of glass fibres.

The flexural strength results for both methods were obtained by investigating 7 single specimens.

Different radii of the support (R) and the radii of the loading noses (r) were used in method I and method II, in accordance with the recommandations defined in standard ASTM D 790.

In method I, the following parameters were used:
- the radius of the support R = 3 mm and the radius of the loading nose r = 3 mm and
- the radius of the support R = 6 mm and the radius of the loading nose r = 16 mm.

In method II, the following parameters were used:
- the radius of the support R = 3 mm and the radius of the loading nose r = 3 mm and
- the radius of the support R = 6 mm and the radius of the loading nose r = 6 mm.

For the combination of the radius of the support R = 3 mm and the radius of the loading nose r = 3 mm the parameter 3/3 is used in the further text.

For the combination of the radius of the support R = 6 mm and the radius of the loading nose r = 16 mm, the parameter 6/16 is used in the further text.

For the combination of the radius of the support R = 6 mm and the radius of the loading nose r = 6 mm the parameter 6/6 is used in the further text.

The results of the investigation of flexural strength, in accordance with method I (3-PBT) of standard ASTM D 790 are shown in Table 5.

Table 5. Flexural strength according to method I

Flexural strength (MPa)					
Parameter 3/3			Parameter 6/16		
X_i	$\bar{X}$	σ	X_i	$\bar{X}$	σ
1,110.8 1,085.6 1,121.3 1,099.3 1,076.2 1,094.1 1,098.2	1,097.9	15.0	1,194.1 1,184.1 1,205.1 1,211.2 1,210.7 1,201.9 1,220.5	1,202.1	12.8

The results of the investigation of flexural strength, according to variety 1 (LS= 33 % L) of method II (4-PBT) of standard ASTM D 790 are shown in Table 6.

Table 6. Flexural strength according to variety 1 of method II

Flexural strength (MPa)					
Parameter 3/3			Parameter 6/6		
X_i	$\bar{X}$	σ	X_i	$\bar{X}$	σ
871.8 867.0 824.7 888.2 868.5 880.3 858.4	865.5	20.4	908.9 912.0 928.1 951.0 895.9 890.1 898.9	912.0	21.3

The results of the investigation of flexural strength, according to variety 2 (LS= 50 % L) of method II (4-PBT) of standard ASTM D 790 are shown in Table 7.

Table 7. Flexural strength according to variety 2 of method II

Flexural strength (MPa)					
Parameter 3/3			Parameter 6/6		
X_i	$\bar{X}$	σ	X_i	$\bar{X}$	σ
678.0 666.1 678.0 660.1 689.9 670.2 680.0	674.6	10.0	811.9 826.8 756.0 792.1 779.9 797.1 790.2	793.3	22.5

The analysis of the results of the investigation of flexural strength resulted in the following:

– very good uniformity of single values determined by method I with the parameter 3/3 (σ = 1.4 % $\bar{X}$) and parameter 6/16 (σ= 1.1 % $\bar{X}$),
– very good uniformity of single values determined by method II (σ = 2.4 % $\bar{X}$ for both variety 1 and variety 2}.
– higher values of flexural strength are obtained with method I than with method II,
– with method I, higher values of flexural strength are obtained with the parameter 6/16 ie. 1202.1 MPa than with the parameter 3/3 ie. 1097.9 MPa,
– value of flexural strength obtained with method I with the parameter 6/16 (1202.1 MPa) is highest of all determined values of this characteristic,
– method I gave higher values with variety 1 than with variety 2,
– method II gave higher values with the parameter 6/6 than with the parameter 3/3, regardless of the variety,
– for the parameter 3/3, the highest values of flexural strength are obtained with method I (1097.9 MPa), lower with method II, variety 1 (865.5 MPa) and the lowest ones with method II, variety 2 (674.6 MPa).

Interlaminar characteristics

Interlaminar shear strength, by definition, represents a measure of integrity and „homogeneity“ of composite materials.

Interlaminar shear strength of the filamentwound composite material glass fibre/polyester resin was determined in accordance with standard ASTM D 2344.

In this investigation, the direction of external stress was perpendicular to the direction of glass fibres.

The interlaminar shear strength of the mentioned composite material, in accordance with standard ASTM D 2344, was determined using a flat specimen and a ring specimen:

– flat specimen rests on two supports with a radius of 1.85 mm and is loaded with the loading nose with a radius of 3.2 mm – variety A (designation introduced for the purpose of this paper),
– ring specimen rests on two sharp edges and is loaded with the loading nose with a radius of 3.2 mm – variety B (designation introduced for the purpose of this paper).

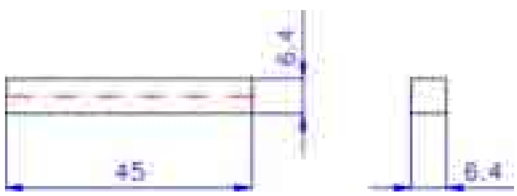

Figure 8. Flat specimen for the investigation of interlaminar shear strength

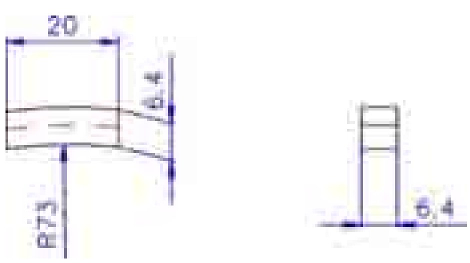

Figure 9. Ring specimen for the investigation of interlaminar shear strength

For the investigation of interlaminar shear strength, a flat specimen (shown in Fig.8) and a ring specimen (shown in Fig.9) were used.

The results of the determination of interlaminar shear strength, obtained by the investigation of 10 flat and 10 ring specimens, are shown in Table 8.

Table 8. Interlaminar shear strength of the flat specimens (variety A) and the ring specimens (variety B)

Interlaminar shear strength (MPa)					
Variety A			Variety Б		
X_i	$\bar{X}$	σ	X_i	$\bar{X}$	σ
45.9 37.7 49.1 44.4 45.1 44.9 50.9 37.4 43.3 34.2	44.3	4.5	43.4 41.9 47.0 43.1 41.0 46.9 46.0 41.1 41.3 43.2	43.5	2.4

The analysis of the results of interlaminar shear strength showed the following:

– uniformity of single values of investigation (σ= 10 % $\bar{X}$ for variety A) and (σ= 5 % $\bar{X}$ for variety B),
– values of the arithmetic mean of the interlaminar shear strength of the flat specimens (44.3 MPa) are very similar to those obtained for the ring specimens (43.5 MPa) .

Shear characteristics

The shear strength and the shear modulus of the filamentwound composite material glass fibre/polyester resin were determined in accordance with standard ASTM D 3518. The determination of the mentioned shear properties is based on the uniaxial tension of the flat specimens which contain layers at 45°, in relation to the direction of tensile stress.

The specimens for determining shear characteristics are of the same dimensions as the longitudinal specimens for the tensile investigation (Fig.2).

The determination of shear properties, in accordance with standard ASTM D 3518, is specific and will be briefly described.

In accordance with the mentioned standard, shear strength is calculated using the following equation:

$$S = P/2 \cdot b \cdot d$$

where:

S – shear strength, MPa,
P – maximum load of the tensile load-deformation curve for a specimen with 45° layers, N,
b – specimen width, mm,
d – specimen thickness, mm.

The results of the determination of shear strength, obtained by the investigation of 8 single specimens, are shown in Table 9.

Table 9. Shear strength

Shear strength (MPa)		
X_i	$\bar{X}$	σ
12.16 11.96 11.68 11.43 10.87 10.96 10.45 8.89	11.06	1.04

On the basis of the analysis of the results of the investigation of shear strength it can be concluded that the standard deviation is 9 % of the arithmetic mean and can be accepted.

In accordance with standard ASTM D 3518, shear modulus of elasticity is calculated using the following equation:

$$G_{12} = \Delta\tau'_{12} / \Delta\chi'_{12}$$

where:

G_{12} – modulus of elasticity of shear i.e. shear modulus of unidirectional composite, MPa,

$\Delta\tau'_{12} / \Delta\chi'_{12}$ – slope of the plot of the unidirectional shear stress-shear strain curve within the linear portion of the curve.

Shear stress is calculated using the following equation:

$$\tau'_{12} = \sigma' / 2$$

where:

τ'_{12} – shear stress i^{th} point of the unidirectional shear stress-shear strain curve, MPa,

σ' – longitudinal stress for a specimen with 45^o layers, MPa.

In accordance with standard ASTM D 3518, longitudinal stress for a specimen with 45^o layers is calculated using the following equation:

$$\sigma' = P' / b \times d$$

where:

σ' – longitudinal stress for a specimen with 45^o layers, MPa,

P' – tensile load of i^{th} point for a specimen with 45^o layers, N,

b – specimen width, mm,

d – specimen thickness, mm.

Shear strain is calculated using the following equation:

$$\chi' = Y' - X'$$

where:

χ' – hear strain at i^{th} point of the unidirectional shear stress-shear strain curve,

Y' – longitudinal strain at i^{th} point of the tensile load-tensile deformation specimen with 45^o layers,

X' – transverse strain at i^{th} point of the tensile load-tensile deformation specimen with 45^o layers.

Shear stress and shear strain dependance is presented in Fig.10.

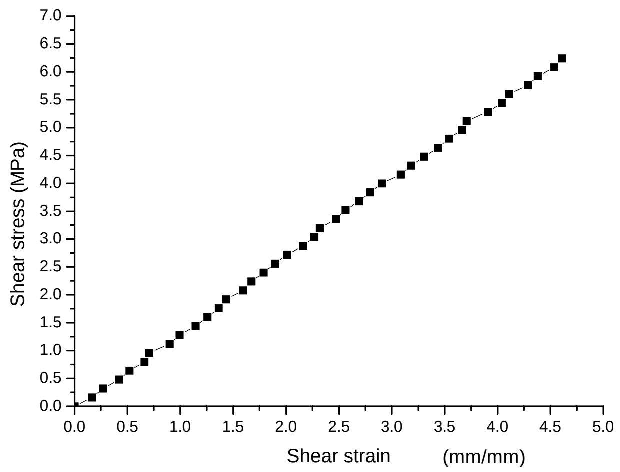

Figure 10. Shear deformation- shear stress relation

The results of the determination of modulus of elasticity at shear ie. shear modulus, obtained by the investigation of 5 single specimens, are shown in Table 10.

Table 10. Shear modulus

Shear modulus (MPa)		
X_i	$\bar{X}$	σ
6.56 7.13 5.97 7.10 6.19	6.59	0.52

On the basis of the analysis of the results of the investigation of shear modulus it can be concluded that the standard deviation is 8 % of the arithmetic mean and is of acceptable values.

It is very hard to bring the mechanical characteristics of filamentwound flat specimens and the mechanical characteristics of filamentwound parts into a simple relation, and even harder to compare them for many reasons, to mention only the most important ones:

- there is an essential difference between the geometry of specimens (flat sheets) and the geometry of parts (cylinders or balls),
- specimens contain layers with only one winding angle (or only 0^o, or only 90^o or only 45^o) while parts, generally spoken, contain more layers with different winding angles,
- specimens are exposed to the action of only one type of stress (tension, compression) while parts, in practice, are exposed to the action of several types of stresses,
- specimens are exposed to the action of uniaxial external force (longitudinal or perpendicular) while parts are exposed to the action of multiaxial forces,
- dimensions of specimens are defined by standards, while the dimensions of parts depend on functional demands.

Conclusions

1. A procedure for the production of flat sheets by the filament winding technology is developed.
2. A procedure for the production of specimens, for determining mechanical characteristics is developed by machining filamentwound flat sheets.
3. Mechanical characteristics of the filamentwound composite material glass fibre/polyester resin produced by the filament winding technology were determined, in accordance with appropriate defined standards.

In the fibre direction, the (longitudinal) tensile strength is 694.7 MPa, the modulus of elasticity 10.949 MPa and the Poisson's coefficient is 0.296.

In the perpendicular direction, the tensile strength is 9.72 MPa, the modulus of elasticity is 3.51 MPa and the Poisson's coefficient is 0.0013.

At compression in the fibre direction, the (longitudinal) strength is 409.3 MPa, the modulus of elasticity is 1.171 MPa and the Poisson's coefficient is 0.312.

At compression perpendicular to the fibre direction, the strength is 11.05 MPa, the modulus of elasticity is 767.1 MPa and the Poisson's coefficient is 0.181.

The flexural strength, according to method 3-PBT, is 1.097 MPa. According to method 4-PBT, the flexural strength is 865.5 MP (variety 1), i.e 674.6 MPa (variety 2).

The interlaminar strength is 44.3 MPa (flat specimen method) and 43.5 MPa (ring specimen method).

The shear strength is 11.06 MPa and the modulus of elasticity at shear is 6.59 MPa.

The investigation results are uniform and acceptable since the standard deviation is up to 10 % of the arithmetic mean.

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Karakterizacija mokronamotanih polimernih kompozitnih materijala

Mehaničke karakteristike kompozitnog materijala stakleno vlakno/poliestarska smola, dobijenog tehnologijom mokrog namotavanja, navedene su ovom radu. Tehnologijom mokrog namotavanja izrađuju se cilindrični proizvodi, a pošto metode ispitivanja mehaničkih karakteristika kompozitnih materijala definišu korišćenje ravnih epruveta, prvo je osvojen postupak namotavanja ravnih ploča, a zatim i postupak dobijanja propisanih epruveta mašinskom obradom pomenutih ploča. Prikazani su rezultati ispitivanja zatezne čvrstoće, modula elastičnosti i Poasonovog koeficijenta pri zatezanju u pravcu i poprečno na pravac vlakana, zatezne čvrstoće, modula elastičnosti i Poasonovog koeficijenta pri pritiskanju u pravcu i poprečno na pravac vlakana, savojne čvrstoće, interlaminarne čvrstoće, smicajne čvrstoće i modula smicanja pomenutog mokronamotanog kompozitnog materijala.

Ključne reči: **kompozitni materijali, polimerni mateirjali, mokro namotavanje, mehaničke karakteristike, poliestarska smola, stakleno vlakno.**

Характеристики мокронамотанных полимерных композитных материалов

В настоящей работе приведены механические характеристики композитного материала стекловолокно/смола из полиэстра, полученного технологией мокрого наматывания. Впрочем, технологией мокрого наматывания изготавливаются цилиндрические произведения, а так как методы исследования механических характеристик композитных материалов определяют пользование плоских колб, сначала овладелось поступком наматывания плоских листей, а потом и поступком вырабатывания заданных колб машинной обработкой упомянутых листей. Здесь показаны результаты исследований затязной прочности модуля упругости и коэффициента Поиссона при затяжке в направлении и поперечно на направления волокон, затязной прочности, модуля упругости и коэффициента Поиссона при сжатии в направлении и поперечно на направления волокон, прочности на изгиб, межламинарной прочности, прочности на сдвиг и модуля изгиба упомянутого мокронамотанного композитного материала.

Ключевые слова: **композитные материалы, полимерные материалы, мокрое наматывание, механические характеристики, смола из полиэстра, стекловолокно.**

La caractérisation des matériaux composites polymères filament enroulés

Les propriétés mécaniques du matériel composite fibre de verre/résine polyester, obtenu par la technologie du filament enroulé, sont considérées dans ce travail. On a produit les pièces cylindriques par la technologie du filament enroulé. Etant donné que les méthodes d'essai des propriétés mécaniques des matériaux composites définissent l'utilisation des spécimens plats, on a d'abord développé le procédé du filament des plaques plates et ensuite le procédé pour obtenir les spécimens définis par le traitement mécanique des plaques. On a présenté les résultats des essais sur la résistance à la tension, module d'élasticité et coefficient de Poison à la pression parallèle et perpendiculaire aux fibres, résistance à la flexion, résistance interlaminaire, résistance au cisaillement et module du cisaillement du matériel composite filament enroulé.

Mots clés: **matériaux composites, matériaux polymères, filament enroulé, caractéristiques mécaniques, résine polyester, fibre de verre.**