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Thin Wall and Thick Wall Filament Wound Polymeric Composite Tubes: Mechanical Characteristics Caused by Internal Hydraulic Pressure

Jovan Radulović[1)]

Two groups of so-called „thin wall" test tubes (wall thickness less than 2 mm) and two groups of so-called „thick wall" test tubes (wall thickness more than 2 mm) of the same internal diameter were produced by the filament winding technology using glass roving and a polyester resin system. The mentioned test tubes were exposed to the influence of internal hydraulic pressure and their mechanical characteristics were investigated. The radial deformations of four groups of filament wound test tubes were measured by strain gauges and internal hydraulic pressure was recorded by a piezoelectric pressure converter. The elastic characteristics i.e. elastic deformations and hydraulic pressures at the elastic limit were determined. The testing processes were ended by determining the final properties i.e. radial deformations and hydraulic pressure at the moment of burst of two groups of „thin wall" and two groups of „thick wall" test tubes.

Key words: **composites materials, polymers, polyester resign, glass fiber, filament winding, tubes, mechanical characteristics, pressure effects, hydralic pressure.**

Introduction

A great number of new materials with specific properties, which enabled an important breakthrough in engineering and technology, were developed in the last few decades.

Materials, in a broader sense, are solid or liquid matters used for production of various articles [1].

Material characteristics are defined as measuring values, by which the shape or the measure of material capability to react to external influence are characterized.

In accordance with the nature of external influences on a material, material characteristics can be classified into three groups: 1) chemical characteristics, 2) physical characteristics and 3) mechanical characteristics.

Mechanical properties refer to the material behaviour under mechanical stress i.e. under the influence of external mechanical forces.

Engineering materials, based on the structure and the nature of existing relations, can be approximately divided into four groups: 1) metal materials and alloys, 2) ceramics and glass, 3) polymer materials and 4) composite materials [2].

The term *composite* originally arose in engineering when two or more materials were combined in order to rectify shortcomings of particularly useful components [3].

Composite materials

Composite materials, usually formed of two or more materials, are characterized by new properties with regard to the starting components.

One of composite materials production technologies increasingly used is filament winding technology.

Filament-wound polymeric composites consist of a reinforcing agent and an impregnating agent.

The essential property and the advantage of filament winding technology over other composite materials production procedures is a fact that the reinforcing agent is placed in the direction in which stress during exploitation of a filament-wound part is expected to occur.

Filament-wound composite materials have a unique set of specific properties so, very often, they represent an only choice for numerous purposes [4].

In stress-strain diagrams of most materials, two regions can be observed:

- region in which material returns to its original state after stress removal i.e. elastic region of materials, and
- region in which material does not return to its original state after stress removal ie. plastic region of materials.

The point up to which a material exhibits elastic behaviour is called the elastic limit.

Elasticity is the property of a body or substance that enables it to resume its original shape or size when a distorting force is removed [5].

There is a statement that elasticity is the property of a substance that enables it to change its length, volume, or shape in direct response to a force affecting such a change and to recover its original form upon the removal of the force [6].

Most solid materials display elasticity up to a load point called the elastic limit [7].

Generally, up to the elastic limit, Hooke's (1635-1703) law holds,. stating that the stress applied to a material is proportional to the strain on that material [8].

A stress (σ)-strain (ε) diagram of materials which exhibits typical elastic and plastic behaviour is presented in Fig.1. Up to the elastic limit (E), material exhibits elastic

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[1)] Military Technical Institute (VTI), Ratka Resanovića 1, 11132 Belgrade, SERBIA behavior, and after the elastic limit (E), material exhibits plastic behavior.

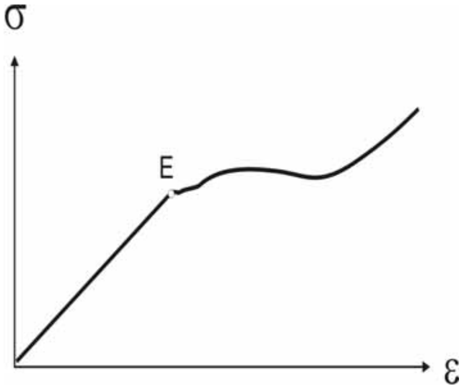

Figure 1. Stress-strain diagram of materials which exhibits typical elastic and plastic behaviour

This paper presents the mechanical characteristics of two groups of so-called „thin wall” filament wound composite polymeric hydraulically stressed tubes and two groups of so-called „thick wall“ ones.

Hydraulically stressed tubes, in this paper, imply tubes exposed to the influence of internal hydraulic pressure.

Two groups of the mechanical characteristics of the mentioned, hydraulically stressed, tubes were obtained:

- one group represents elastic characteristics i.e. the properties of the examined tubes at the elastic limit, and
- another group represents the final properties, i.e. the characteristics of the tested tubes at the moment of burst.

„Thin wall” test tubes have a wall thickness less than 2 mm and „thick wall” test tubes have a wall thickness higher than 2 mm of the same internal diameter. The wall thickness of 2 mm was defined as a thickness criterion for the purpose of this paper. All test tubes, obtained by filament winding of glass fiber impregnated by a polyester resin system, were exposed to the influence of internal hydraulic pressure. The values of radial deformations were recorded during the whole process of exposing the mentioned test tubes to the action of internal hydraulic pressure i.e. from the start moment to the burst moment. The corresponding values of internal hydraulic pressure were recorded as well.

Based on the registered data, a diagram shows the dependence of radial deformations versus internal hydraulic pressure during the whole testing process.

The elastic characteristics of the examined tubes were obtained from the diagram of the dependence of internal hydraulic pressure versus radial deformations. The elastic characteristics i.e. radial deformations and the appropriate internal pressure of the mentioned test tubes at the elastic limit were obtained from the linear portion of the mentioned diagrams.

The final characteristics of the examined tubes i.e. data for radial deformations and internal hydraulic pressure at the burst moment of two groups of „thin wall” test tubes and two groups of „thick wall” test tubes were also presented.

Experimental part

Two groups of „thin wall” test tubes and two groups of „thick wall“ test tubes were produced by the filament winding technology. The reinforcing agent was a glass roving trade mark R 2117 (made by the ETEX glass fibre manufacturer, Baljevac/Ibar). The impregnating agent was a polyester resin system trade mark DUGAPOL H 230 (made by the DUGA polyester resin manufacturer, Serbia) with addittion of an inhibitor trade mark TBC (produced by the AKZO chemical producer, Holland). The tubes were wound on a cylindrical mandrel about 60 mm in diameter using the PLASTEX type PLA 500 machine (made by the PLASTEX-MANUHRINE machine manufacturer, France).

The winding angle is an angle which the reinforcing agent (fiber) forms regarding the longitudinal axis of the product.

In all test tubes, the first internal layer and the final outer layer were wound under the angle of 90^o.

For the purpose of this paper, the following abbreviations will be used:

„Thin61” - „thin wall” test tubes are thin test tubes with 1.70 mm wall thickness and medium layers 61^o winding angles,

„Thin45” - „thin wall” test tubes are thin test tubes with 1.70 mm wall thickness and medium layers 45^o winding angles,

„Thick61” - „thick wall” test tubes are thick test tubes with 3.45 mm wall thickness and medium layers 61^o winding angles,

„Thick45” - „thick wall” test tubes are thick test tubes with 3.45 mm wall thickness and medium layers 45^o winding angles.

Marks, wall thickness, number of layers and winding angles of „thin wall” test tubes and „thick wall” test tubes are presented in Table 1.

Table 1. Marks, wall thickness, number of layers and winding angles of „thin61”, „thin45”, „thick61” and „thick45” test tubes

Marks	Wall thickness (mm)	Number of layers and winding angles
„Thin61”	1.70	1 x 90°
		2 x 61°
		1 x 90°
„Thin45”	1.70	1 x 90°
		2 x 45°
		1 x 90°
„Thick61”	3.45	2 x 90°
		4 x 61°
		2 x 90°
„Thick45”	3.45	2 x 90°
		4 x 45°
		2 x 90°

The schematic representation of „thin wall” test tubes and „thick wall” test tubes with winding layers is presented in Fig.2.

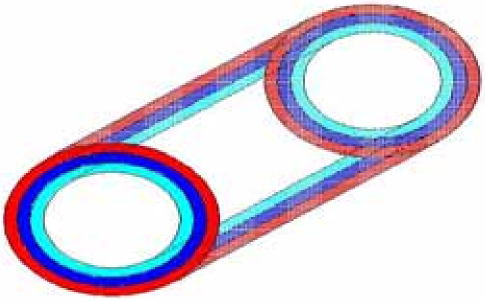

Figure 2. Winding layers of „thin wall” test tubes and „thick wall” test tubes

The elastic properties of „thin wall”test tubes and „thick wall” test tubes were experimentally determined by a device for monotonic increasing hydraulic pressure range

200 MPa, produced by the WALTER & BAI hydraulic equipment manufacturer, Germany, along with the protection equipment and the specific tool enabling an action of internal hydraulic pressure.

Internal hydraulic pressure was measured with a piezoelectric converter of pressure trade mark 601H range 100 MPa, manufactured by the KISTLER measuring device manufacturer, Germany.

Two one-axis strain gauges trade mark HBB 10/120 LA 11, manufactured by the HOTTINGER BALDWIN MESSTECHNIK, Gmbh strain gauges manufacturer, Germany, were glued to the outer surfaces of test tubes using adhesive trade mark X 60, produced by same manufacturer.

The mentioned two one-axis strain gauges were positioned at the middle of the tube length, one opposite another, transversal to the longitudinal axis of a tube in order to register radial deformations.

A test tube with glued two one-axis strain gauges for the registration of radial deformations is presented in Fig.3.

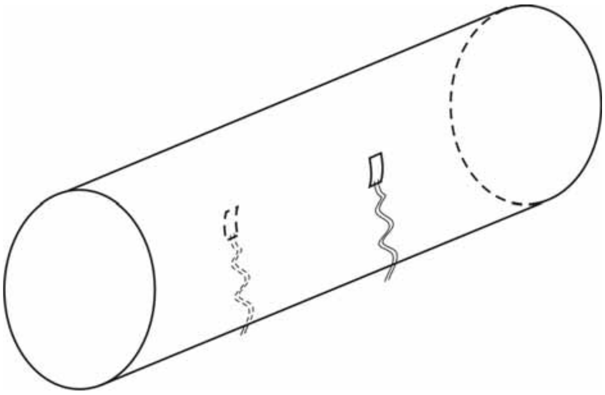

Figure 3. Test tubes with glued two one-axis strain gauges for the registration of radial deformations

A digital oscilloscope NICOLET 4094 B with additional equipment, produced by the NICOLET INSTRUMENTS measuring equipment manufacturer, USA, was used for the simultaneous detection of the internal hydraulic pressure and radial deformations.

Experimental results and the analysis

Data obtained during the whole test process i.e. internal hydraulic pressure and radial deformations, caused by the corresponding values of internal hydraulic pressure, are presented by figures [9].

It is well known that a linear dependence on a stress-strain diagram denotes the elastic region of materials. By analogy, a point on the internal hydraulic pressure-radial deformations diagram dependence, at which a change of slope occurrs, denotes the elastic limit of test tubes.

The elastic characteristic i.e. internal hydraulic pressure and radial deformation at the elastic limit for two so-called „thin wall" test tubes and two so-called „thick wall" test tubes are presented by figures. The values of radial deformation 1 and radial deformation 2 are obtained by two mentioned one-axis strain gauges and an arithmetic mean value, based on two single radial deformation values.

The arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thin61/1" are presented in Fig.4.

The arithmetic mean values of radial deformation versus internal hydraulic pressure test tube „thin61/2" are presented in Fig.5.

The arithmetic mean values of radial deformation versus internal hydraulic pressure test tube „thin61/3" are presented in Fig.6.

The arithmetic mean values of radial deformation versus internal hydraulic pressure test tube „thin45/1" are presented in Fig.7.

The arithmetic mean values of radial deformation versus internal hydraulic pressure test tube „thin 45/2" are presented in Fig.8.

The arithmetic mean values of radial deformation versus internal hydraulic pressure test tube „thin 45/3" are presented in Fig.9.

The arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick61/1" are presented in Fig.10.

The arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick61/2" are presented in Fig.11.

The arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick45/1" are presented in Fig.12.

The arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick45/2" are presented in Fig.13.

The arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick45/3" are presented in Fig.14.

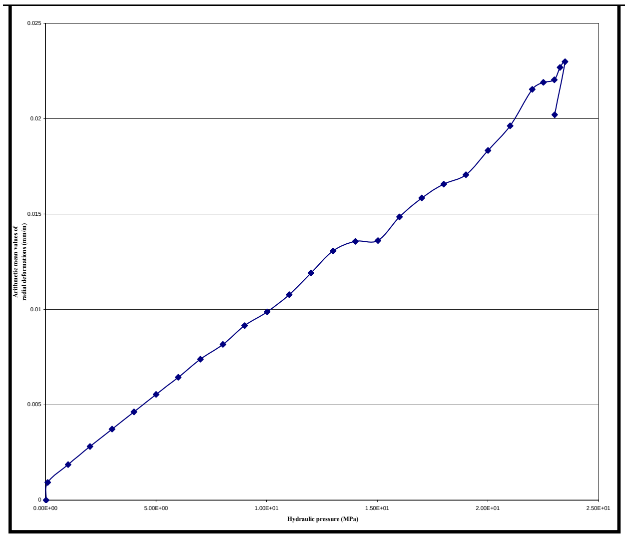

Figure 4. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thin61/1"

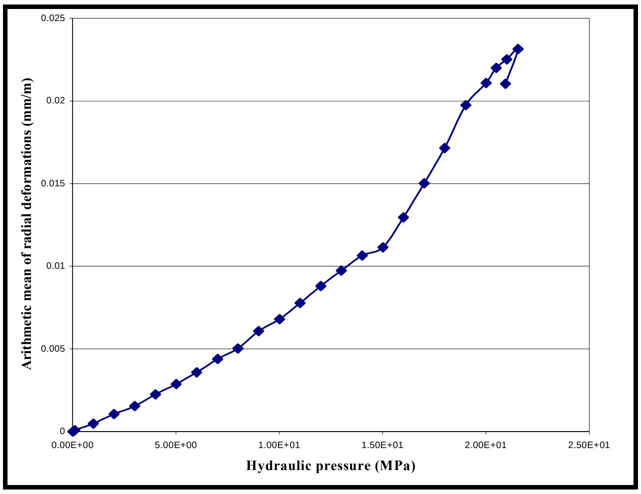

Figure 5. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thin61/2"

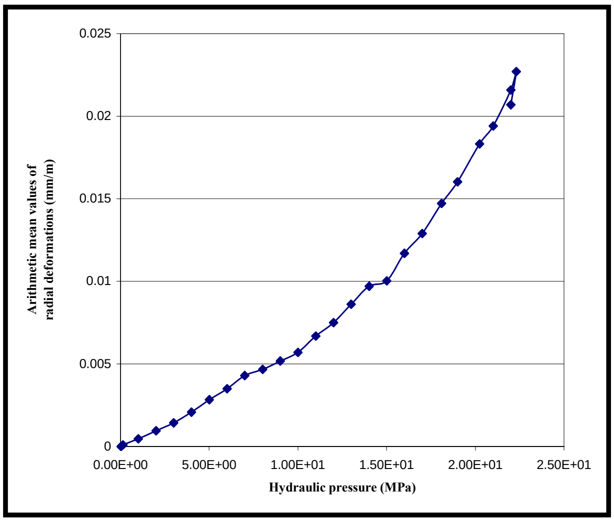

Figure 6. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thin61/3”

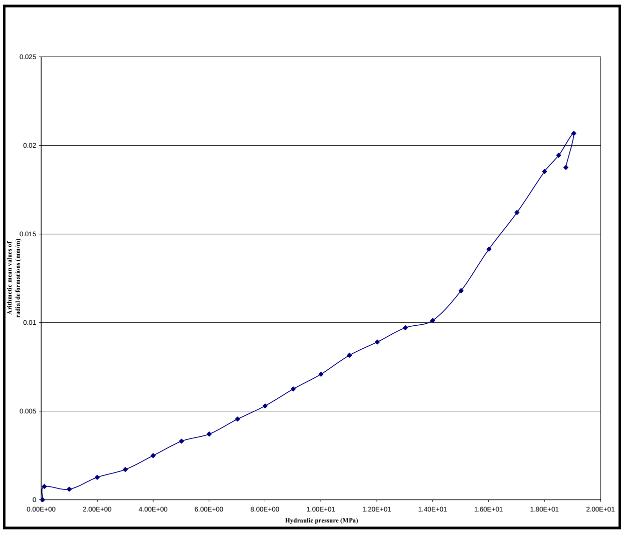

Figure 7. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thin45/1”

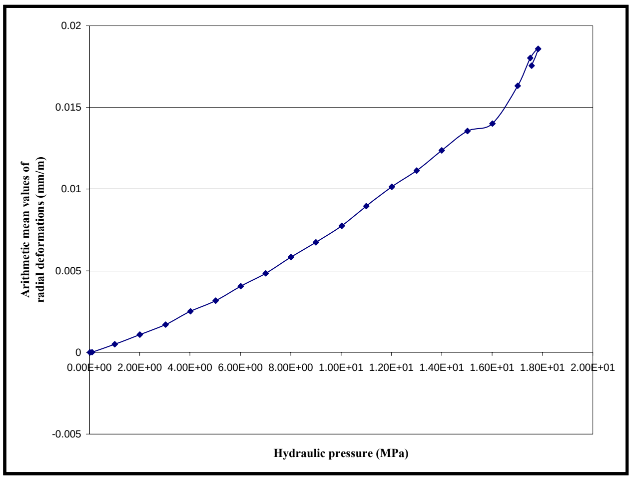

Figure 8. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thin 45/2”

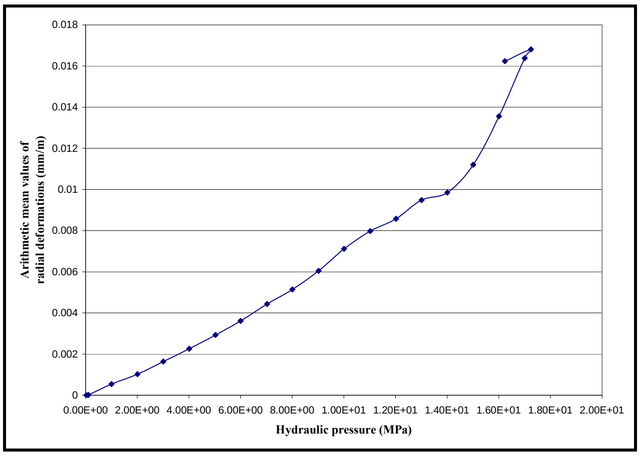

Figure 9. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thin 45/3”

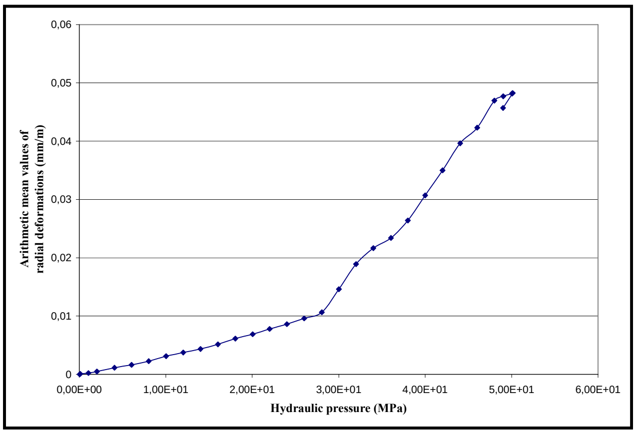

Figure 10. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick61/1”

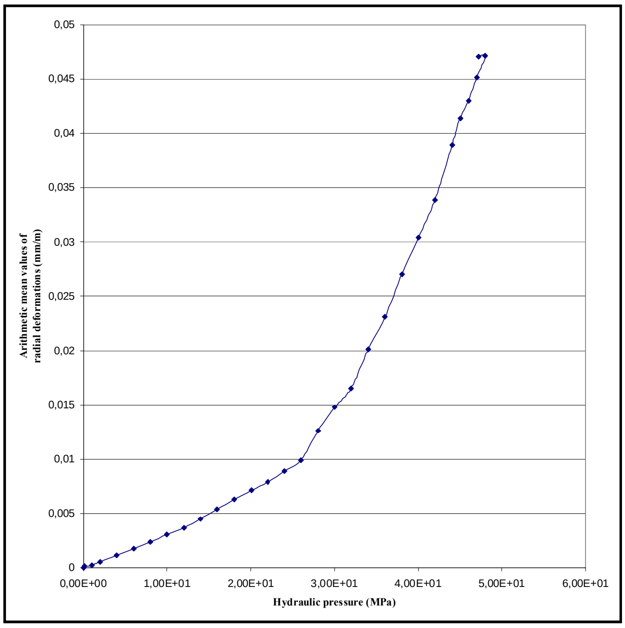

Figure 11. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick61/2”

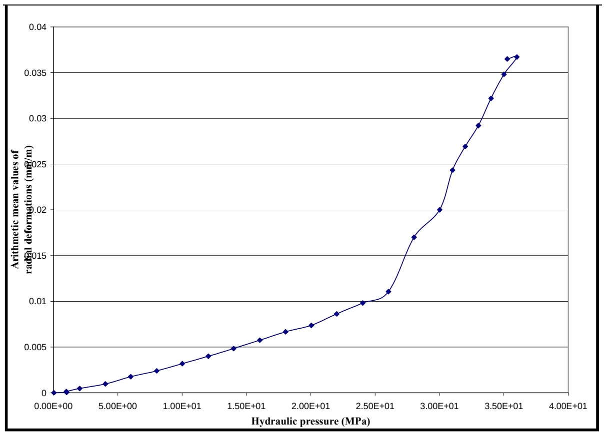

Figure 12. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick45/1"

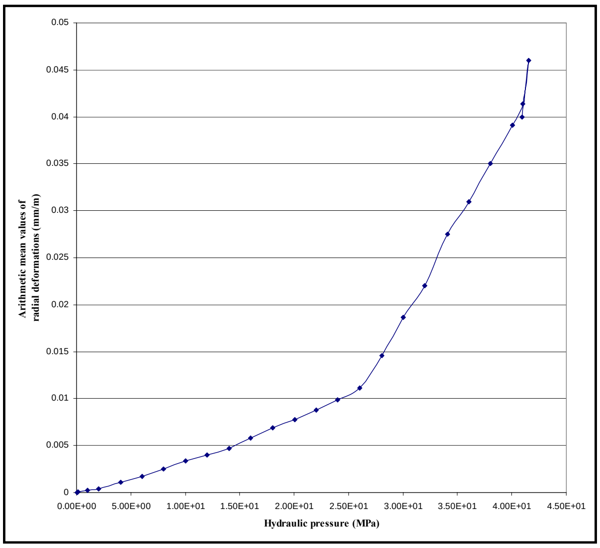

Figure 13. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick45/2"

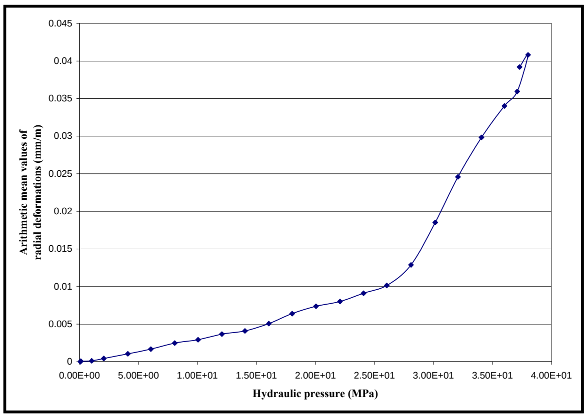

Figure 14. Arithmetic mean values of radial deformations versus internal hydraulic pressure test tube „thick45/3"

For the presentation of the obtained data, the following abbreviations will be used in the tables of this paper:

I.H.P.–internal hydraulic pressure of a single test tube,

A.M.V.-arithmetic mean values of the radial deformations of a test tube, based on two mentioned single values of radial deformations,

A.M.V. of R.D.-arithmetic mean values of the radial deformations of a group of test tubes,

A.M.V. of I.H.P.-arithmetic mean values of the internal hydraulic pressure of a group of test tubes.

The marks and elastic characteristics (values of internal hydraulic pressure and arithmetic mean of radial deformations at the elastic limit) of single tested samples are presented in Table 2.

Table 2. Marks and elastic characteristics of single tested tubes

Single tube marks	Elastic characteristic	
	I.H.P. (MPa)	A.M.V. (mm/m) x10^{-2}
„Thin61/1"	14.0	1.36
„Thin61/2"	14.0	1.06
„Thin61/3"	14.0	0.97
„Thin45/1"	14.0	1.01
„Thin45/2"	15.0	1.35
„Thin45/3"	14.0	0.98
„Thick61/1"	28.0	1.06
„Thick61/2"	26.0	0.99
„Thick45/1"	26.0	1.10
„Thick45/2"	26.0	1.11
„Thick45/3"	26.0	1.01

The marks and elastic characteristics (values of the arithmetic mean of internal hydraulic pressure and the arithmetic mean of radial deformations at the elastic limit) of the „thin wall" test tubes group mark „"thin61", the „thin wall" test tubes group mark „thin45", the „thick wall" test tubes group mark „thick61" and the „thick wall" test tubes group mark „thick45" are presented in Table 3.

Table 3. Marks and elastic characteristics of the „thin wall" test tubes groups and the „thick wall" test tubes groups

Group tube marks	Elastic characteristic	
	A.M.V. of I.H.P. (MPa)	A.M.V. of R.D. (mm/m) x10^{-2}
„Thin wall" tubes group „thin61"	14.0	1.13
„Thin wall" tubes group „thin45"	14.3	1.11
„Thick wall" tubes group „thick61"	27.0	1.03
„Thick wall" tubes group „thick45"	26.0	1.07

The marks and final characteristics (values of internal hydraulic pressure and the arithmetic mean of radial deformations at the burst moment) of single tested samples are presented in Table 4.

Table 4. Marks and and final characteristics of single tested tubes

Single tube marks	Final characteristic	
	A.M.V. of I.H.P. (MPa)	A.M.V. of R.D. (mm/m) x10^{-2}
„Thin61/1"	23.49	2.30
„Thin61/2"	21.56	2.31
„Thin61/3"	22.31	2.28
„Thin45/1"	19.04	2.06
„Thin45/2"	17.83	1.86
„Thin45/3"	17.25	1.69
„Thick61/1"	50.23	4.82
„Thick61/2"	48.04	4.71
„Thick45/1"	36.01	3.67
„Thick45/2"	41.56	4.60
„Thick45/3"	38.02	4.08

The marks and final characteristics (values of the arithmetic mean of internal hydraulic pressure and the arithmetic mean of radial deformations at the burst moment) of the „thin wall" test tubes group mark „thin61", the „thin wall” test tubes group mark „thin45”, the „thick wall” test tubes group mark „thick61” and the „thick wall” test tubes group mark „thick45” are presented in Table 5.

Table 5. Marks and final characteristics of the „thin wall” test tubes groups and the „thick wall” test tubes groups

Group tube marks	Final characteristic	
	A.M.V. of I.H.P. (MPa)	A.M.V. of R.D. (mm/m) x10^{-2}
„Thin wall“ tubes group „thin61”	22.4	2.30
„Thin wall“ tubes group „thin45”	18.0	1.87
„Thick wall“ tubes group „thick61”	49.1	4.76
„Thick wall“ tubes group „thick45”	38.5	4.12

The data analysis of the mentioned figures points out:

- elastic limit for the tubes mark „thin61” is about internal hydraulic pressure of 14.0 MPa,
- elastic limit for the tubes mark „thin45” is about the internal hydraulic pressure region from 14.0 MPa to 15.0 MPa,
- elastic limit for the tubes mark „thick61” is about the internal hydraulic pressure region from 26.0 MPa to 28.0 MPa,
- elastic limit for the tubes mark „thick45” is about the internal hydraulic pressure of 26.0 MPa,
- radial deformations at the elastic limit for all tested tubes samples i.e. the tubes mark „thin61”, mark „thin45”, mark „thick61” and mark „thick45” is about 0.01 mm/m.

- The analysis of the final data investigation i.e. at the moment of burst of the tested tubes samples pointed out:

- tubes mark „thin61” have radial deformations about 2.1x10^{-2} mm/m and hydraulic pressure about 22.3 MPa,
- radial deformations of the tubes mark „thin45” are about 1.9x10^{-2} mm/m and hydraulic pressure is about 18.0 MPa,
- tubes mark „thick61“ have radial deformations about 4.8x10^{-2} mm/m and hydraulic pressure about 49.1 MPa and
- hydraulic pressure of the tubes mark „thick45” is about 38.5 MPa while the value of the final radial deformations is about 4.1x10^{-2} mm/m.

Conclusions

From the analysis of all results presented by figures, it can be concluded:

1. Mechanical characteristics of two groups of so-called „thin wall” test tubes and two groups of so-called „thick wall” test tubes, caused by the influence of internal hydraulic pressure, are determined.
   The test tubes were produced by the filament winding technology using glass roving impregnated by a polyester resin system
2. Radial elastic deformations i.e. radial deformations at the elastic limit of all four groups of filament wound composite polymeric test tubes are about 0.01 mm/m.
3. Elastic limit of the „thin wall” tubes mark „thin61” and mark „thin45” is about the internal hydraulic pressure level of 14.0 MPa, while this parameter at the „thick wall” tubes mark „thick61” and mark „thick45” is about a level of 26.0 MPa.
4. Final radial deformations of the „thin wall” tubes mark „thin61” are about 0.021 mm/m, and those of the „thin wall” tubes mark „thin45” are about 0.019 mm/m. At the „thick wall” tubes mark „thick61”, the final radial deformations are about 0.048 mm/m, while at the „thick wall” tubes mark „thick45” this parameter is near 0.041 mm/m.
5. Hydraulic pressure at the burst moment of the „thin wall” tubes mark „thin61” and mark „thin45” are 22.3 MPa and 18.0 MPa, respectively.
   The „thick wall” tubes mark „thick61” have hydraulic burst pressure about 49.1 MPa, while at the test tubes of the same kind mark „thick45” this parameter is 38.5 MPa.

Literature

[1] ASHBY,F.M.: *Materials selection in mechanical design*. Butterworth-Heinemann, Oxford, 1999.

[2] KELLY,A.: *Concise Encyclopedia of Composite Materials*, Pergamon Press, Oxford, 1989.

[3] RADULOVIĆ,J.: *Characterization of Filamentwound Polymeric Composite Materials*, Scientific Tehnical Review, ISSN 1820-0206, 2008, Vol.LVIII, No.1, pp.66-75,

[4] RADULOVIĆ,J.: *Influence of Internal Cyclic Pressure on Filamentwound Composite Tube Quality*, Scientific Tehnical Review, ISSN 1820-0206, 2010, Vol LX, No.1, pp.54-60,

[5] http://www.thefreedictionary.com/_/misc/HarperCollinsProducts.aspx?English

[6] http://dictionary.reference.com/browse/elasticity

[7] <ahref="http://www.thefreedictionary.com/elasticity">elasticity

[8] <ahref="http://www.thefreedictionary.com/Hooke%27s+law">Hooke's law

[9] RADULOVIĆ.J.: *Elastic Characteristics of Hydraulically Stressed Filament Wound Composite Polymeric Tubes,* 5th International Scientific Conference on Defensive Technologies, Belgrade, OTEH 2012, Proceedings, pp.610-613.

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Tankozidne i debelozidne mokronamotane polimerne kompozitne cevi: mehaničke karakteristike izazvane unutrašnjim hidrauličkim pritiskom

Dve grupe tzv. „tankozidnih“ ispitnih cevi (debljine zida manje od 2 mm) i dve grupe tzv. „debelozidnih“ ispitnih cevi (debljine zida veće od 2 mm) istog unutrašnjeg prečnika su urađene tehnologijom mokrog namotavanja staklenog vlakna impregnisanog sistemom poliestarske smole. Pomenute ispitne cevi su bile izložene dejstvu unutrašnjeg hidrauličkog pritiska i određene su mehaničke karakteristike. Radijalne deformacije četiri grupe namotanih ispitnih cevi su izmerene pomoću mernih traka, a unutrašnji hidraulički pritisak je zabeležen pomoću piezoelektričnog pretvarača pritiska. Određene su elastične karakteristike tj. radijalne deformacije i hidraulički pritisak na granici elastičnosti. Procesi

ispitivanja su završeni određivanjem radijalnih deformacija i hidrauličkog pritiska u momentu prskanja dve grupe tankozidnih i dve grupe debelozidnih ispitnih cevi.

Ključne reči: **kompozitni materijali, polimerni materijali, poliesterska smola, stakleno vlakno, mokro namotavanje, cev, mehaničke karaktristike, uticaj pritiska, hidraulični pritisak.**

Тонкостенные и толстостенные полимерные влажнообмотанные трубы из композиционных матепиалов: механические свойства вызваны внутренним

Две группы так называемых "тонкостенных" пробирок (толщина стенки менее 2 mm) и две группы так называемых "толстостенных" пробирок (толщина стенки более 2 mm) того же внутреннего диаметра, были сделаны технологией влажных обмоток стекловолокном, армированным системой полиэфирной смолы. Вышеупомянутые пробирки подвергали воздействию внутреннего гидравлического давления и тогда определены их механические свойства. Радиальные деформации четырёх групп пробирок проката измеряют с использованием тензодатчиков, а внутреннее гидравлическое давление регистрировали с использованием пьезоэлектрических преобразователей давления. Определенны упругие особенности, т.е. радиальные деформации и гидравлическое давление до предела упругости. Процессы тестирования завершены задаванием радиальных деформаций и гидравлического давления во время распыления двух групп тонкостенных и двух групп толстостенных пробирок.

Ключевые слова: **композиционные материалы, полимеры, полиэфирная смола, стекловолокно, влажные обмотки, трубы, механические характеристики, влияние давления, гидравлическое давление.**

Les tubes à parois minces et les tubes à parois épais à filament enroulé en polymère composite: les caractéristiques mécaniques causées par la pression hydraulique interne

Deux groupes des tubes d'essai soi-disant «à parois minces» (épaisseur du paroi inférieure de 2 mm) et deux groupes des tubes d'essai soi-disant «à parois épais» (épaisseur du paroi supérieur de 2mm) du même diamètre interne ont été produits au moyen da le technologie du filament enroulé en fibre de verre imprégné par le système de la résine polyester. Les tubes d'essai citées ont été exposées à l'influence de la pression hydraulique interne et on a déterminé leurs caractéristiques mécaniques. Les déformations radiales de quatre groupes des tubes d'essai enroulées ont été mesurées à l'aide des jauges à ruban tandis que la pression hydraulique interne a été déterminée par le convertisseur piézoélectrique de pression. On a déterminé les caractéristiques élastiques c'est-à-dire les déformations radiales et la pression hydraulique à la limite de l'élasticité . Le processus des essais ont été terminés par la détermination des déformations radiales et de la pression hydraulique au moment de l'éclatement de deux groupes de tubes à parois minces et deux groupes de tubes d'essai à parois épais.

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