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Filament Wound Composite Tubes: Experimental and Numerical Simulations Results

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This study conducts a failure analysis of filament wound glass reinforced plastic (GRP) pipes made of E glass/polyester under the closed-ended internal pressure. Good agreement was found in comparing the levels of the hydraulic burst pressure of specimens of filament wound tubes made of polyester resin/glass fiber and obtained experimentally and the properties of the tube model, i.e. the values of the pressure at which the initial failure of the tube model occurred, obtained by computation and based on the strength theory for orthotropic laminate composite materials. The hydraulic burst pressure of filament wound tube specimens was obtained using the tool of a specific design, and the calculation of the tube model properties was done by applying the finite element method, the initial failure criterion and the experimentally obtained mechanical properties of the filament wound composite material polyester resin/glass fiber. A successful verification of the computation method of the tube model shows that the mentioned strength theory may be applied with enough reliability to filament wound elements of constructions.

Key words: **composite materials, polymers, filament winding, pipe, hydraulic pressure, experimental results, strength analysis, fracture mechanics, numerical simulation, finite element method,.**

Introduction

BESIDES energy and IT issues, materials represent the most important element of continual progress in the technology field. One of the essential factors in the development of elements of construction is the choice of materials. A correct choice implies the use of materials assessed as suitable for functional demands. Due to increasingly specific and diverse demands with regard to elements of construction, there is a problem of materials which will satisfy exploitation requirements.

Filament wound composite pipes made of GRP have many potential advantages over pipes made of conventional materials, such as their resistance to corrosion; high strength, light weight and good thermal insulation properties. Continuous filaments are an economical and excellent form of fiber reinforcement and may be oriented to match the direction of stress loaded in a structure.

Rousseau et al. [1] conducted parametric studies of the influence of winding patterns on the damage behavior of filament wound structures. Beakou et al. [2] used the classical laminated theory to analyze the effect of variable scattering on the optimum winding angle of cylindrical composites. Kabir [3] made the finite element analysis of composite pressure vessels having a load sharing metallic liner with a 3-D laminated shell element of the commercial FEM code, NISA-II.

With developments in the manufacture of filament wound pipes, there is a growing interest in application of filament wound fiber-reinforced cylindrical composite structures. Plastic composites offer many cost advantages over metals due to their considerably higher strength-to-weight ratios.

Owing to their anisotropic nature, fiber reinforced composite material properties may be tailored by varying laminate fiber orientations. This is beneficial as the stiffness or strength of a structure can be maximized. Alternatively, the weight or cost can be minimized. Thin-walled filament-wound E-glass fiber-reinforced polyester tubes were tested under internal pressure to determine their burst strength.

The finite element method, based on the Mindlin plate and the shell theory, is used in this application in conjunction with the initial failure criteria in order to obtain the failure load of layered composite tubes under internal pressure.

Composite materials

Engineering materials, based on structure and nature of bonds, may be approximately divided into four groups: 1) metal materials, 2) ceramics and glass materials, 3) polymer materials and 4) composite materials. There are estimations that composite materials will be primary ones in solving the mentioned problems. Composite materials, in short, consist of a reinforcing agent and an impregnation agent, and sometimes additives are present as well. The reinforcing agent is the holder of mechanical properties, while the impregnation agent binds the reinforcements into a compact entity. Additives improve specific properties of composite materials (fire resistance, price, etc.). Composite materials have a unique set of special properties so they can replace standard construction materials and also present the only choice for the production of elements of new constructions [4].

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For the production of composite materials by the filament winding technology, a reinforcing agent in the form of continuous fibers (glass, carbon, aramide, etc.) and an impregnation agent in the form of liquid resin (polyester, epoxy, etc.) are used. The basis of this technology includes winding of resin-impregnated fibers into a tool and hardening of the wound structure. Basically developed for the army industry, this technology enables the fiber to be placed into the direction of the load that may be expected during exploitation of construction elements. Owing to this unique capability, the mechanical properties of fibers in the longitudinal direction can be maximally exploited. From all the above said, it is clear that the filament winding technology is used for creating new materials with distinct anisotropy according to the direction in which the fiber is placed. In other words, different directions result in a material with different mechanical properties. Thus produced composite materials have the highest percent of fibers of all composite materials and small density. This fact is important for loaded elements of construction, which also need to have small mass. Since polymers are sometimes reinforcing agents, and often impregnation agents, it is believed that there are more than 5.000 polymer composite materials [4-7].

This paper has three objectives:

- The first objective is the experimental determination of the hydraulic burst pressure of the tube samples, produced by the filament winding technology using glass fiber impregnated with polyester resin. The tube samples were produced using the same fiber and resin that were used for the production of flat test specimens, the experimentally determined mechanical properties of which will be used for the calculation of the tube model properties [4]. The experimentally tested tube samples have the same structure of winding i.e. they have the same number of layers and angles of winding as the calculated tube models. For the experimental determination of the hydraulic burst pressure of tube samples a tool of specific construction was used.
- The second objective is modeling a tube which is produced by filament winding technology, i.e. the calculation of the hydraulic pressure that causes the initial failure of the tube model. The calculation is based on the strength theory of layered composite materials with orthotropic properties. Four winding structures of the tube are chosen. The winding structure includes the number of layers and angles under which the reinforcing agent were wound according to the longitudinal axis of the tube.
- The third objective is the comparison of the calculation-acquired pressure values which cause the initial failure of tube models and the experimentally obtained values for the hydraulic burst pressure of wound tubes, i.e. the verification of the procedure for tube modeling and the calculation of properties for the tube model.

The strength analysis and the failure criteria

The strength analysis of fiber reinforced composite structures until the initial failure is significantly more complex than the calculation of structures of isotropic materials. In the strength theory for isotropic materials, the load function is equalized with a single parameter (for example, tensile strength of the material).

In strength theories for anisotropic materials, the load function has more than one strength parameter. Theories of failure of composite structures are load functions and appropriate properties of material strength. The complexity of the failure analysis for composite structures originates from the fact that material consists of thin orthotropic layers (lamina), and each layer of a reinforcing agent (fibers) and an impregnation agent (resin).

In most theories of failure for composite multi-layered materials, or laminate, squared load functions are used. Goldenblant and Kopnov have suggested that the strength function F may be expressed as tensor-polynomial approximations [8]:

$$F = \left(F_{ij}\sigma_{ij}\right)^{\alpha} + \left(F_{ijk1}\sigma_{ij}\sigma_{k1}\right) + \left(F_{ijklmn}\sigma_{ij}\sigma_{k1}\sigma_{mn}\right)^{\gamma} - 1 \quad (1)$$

where:

$F_{ij}, F_{ijk1}, F_{ijk1mn}$ - strength tensors of 2, 4 and 6th progression,
α, β and γ - materials constants,
$\sigma_{ij}, \sigma_{ijk1}, \sigma_{ijk1mn}$ - load tensors of 2, 4, and 6th progression.

For the initial failure determination, different criteria are used and two most significant failure criteria for laminate are the resin failure criteria and the fiber failure criteria. It is believed that the resin failure criteria is the most complex in the laminate failure. The most commonly used initial failure criteria for fiber reinforced composite materials are based on the tensor-polynomial formulation.

For the case of $\alpha = \beta = \gamma = 1$, the tensor-polynomial approximation includes the formation of a polynomial as a scalar function of the load components, which may be written in the most basic form as:

$$F_i\sigma_i + F_{ij}\sigma_i\sigma_j + F_{ijk}\sigma_i\sigma_j\sigma_k + ... = 1\,,\ i, j, k = 1, 2, ...6 \quad (2)$$

where:

$\sigma_i, \sigma_j, \sigma_k$ - load tensor components,
F_i, F_{ij}, F_{ijk} - components for the tensors of the strength failure of unidirectional material, which were 2, 4, and 6th progression.

A minimum progression of the tensor-polynomial function (equation 2) depends on material anisotropy. It has been detected that in materials which own an orthotropic symmetry the tensor-polynomial function can be reduced into the second progression. For such multi-layered composite materials a squared form of tensor-polynomial criteria of failure can be used in a form of:

$$F_i\,\sigma_i + F_{ij}\,\sigma_i\sigma_j = 1\,,\ i, j, k = 1, 2, ...6 \quad (3)$$

Normal and shear components of strength tensors of the second progression $\left(F_{ij}\right)$ as well as all components of tensors differencies of strength of the first progression $\left(F_i\right)$, in most of the anisotropic material failure theories, are defined in the following method:

$$F_i = X_t^{-1} - C_c^{-1} \text{ and } F_{ij} = \left(X_t X_c\right)^{-1} \quad i < 3 \quad (4)$$

$$F_i = Y_t^{-1} - Y_c^{-1} \text{ and } F_{ij} = \left(Y_t Y_c\right)^{-1} \quad i < 3 \quad (5)$$

where:

X_t - tensile strength in the direction of fibers,
X_c - compression strength in the direction of fibers,
Y_t - tensile strength transversal to the direction of fibers,

Y_c - compression strength transversal to the direction of fibers.

From the several criteria for the resin failure, the criterion of the greatest deformation is chosen and applied. By using the appropriate relations, a general term for the initial failure, for the greatest deformation criterion, has the following values for the components F_i and F_{ij}:

$$F_1 = \left(X_t^{-1} - X_c^{-1} \right) - \upsilon_{TL} \left(Y_t^{-1} Y_c^{-1} \right) \tag{6}$$

$$F_2 = -\upsilon_{TL} E_L E_T^{-1} \left(X_t^{-1} - X_c^{-1} \right) + \left(Y_t^{-1} - Y_c^{-1} \right) \tag{7}$$

$$F_{11} = \left(X_t X_c \right)^{-1} + \upsilon_{TL} \left(X_t^{-1} - X_c^{-1} \right)\left(Y_t^{-1} - Y_c^{-1} \right) + \upsilon_{TL}^2 \left(Y_t Y_c \right)^{-1} \tag{8}$$

$$\begin{aligned} F_{22} = {} & -\upsilon_{TL} E_L^2 E_T^2 \left(X_t X_c \right)^{-1} + \\ & + \upsilon_{TL} E_L E_T^{-1} \left(X_t^{-1} - X_c^{-1} \right)\left(Y_t^{-1} - Y_c^{-1} \right) + \left(Y_t Y_c \right)^{-1} \end{aligned} \tag{9}$$

$$\begin{aligned} F_{12} = {} & -\upsilon_{TL} E_L E_T^{-1} \left(X_t X_c \right)^{-1} - \\ & -1/2\left(1 + \upsilon_{TL}^2 E_L E_T^{-1} \right)\left(X_t^{-1} X_c^{-1} \right)\left(Y_t^{-1} - Y_c^{-1} \right) - \\ & - \upsilon_{TL} \left(Y_t Y_c \right)^{-1} \end{aligned} \tag{10}$$

where:

υ_{TL} - Poisson's coefficient at tension and compression,

E_L - module of elasticity in the direction of fibers under tension and compression,

E_T - module of elasticity transversal to the fibers under tension and compression.

The strength analysis of the model of filament wound tubes, which is based on the strength theory of layered composite materials with orthotropic properties, was conducted using the finite element method (FEM) and the software package MSC/NASTRAN [9,10]. This software package, besides the analysis of load conditions for certain layers, enables the determination of the loading level. In this case, it is the internal hydraulic pressure when the initial failure of any layer occurs. The tube is modeled by using the finite elements of multi-layered shells for the determination of load conditions of layered composite materials with orthotropic properties and the failure criterion based on the greatest deformation for the initial failure. Every finite element consists of same number of layers which the appropriate tube has, which is calculated. The loading levels i.e. the pressure levels inside the tube models at which the initial failure occurs inside the individual layers, are calculated from the working load, which are obtained through the FEM analysis, the failure strength of the materials and the above mentioned initial failure criterion.

The first information obtained from the calculation of the hydraulic pressure that causes the initial failure of the tube model is the coefficient of initial failure (Failure Index – F.I.). This coefficient presents the relation between the failure strength of a composite material and the working loads inside the tubes, as a result of the action of the internal hydraulic pressure. It is common for the value of the hydraulic pressure that acts within the tube to accept the value that actually causes the tube to burst. In case such information is unavailable, any other estimated value is taken into account. After determining the coefficient of the initial failure, the relation between the hydraulic pressure which is taken into account and the above mentioned coefficient is calculated and by this method the calculated pressure of the initial tube failure is obtained. It practically presents the pressure that causes the initial failure, i.e. the first burst of any layer inside the tube.

If for a value of the hydraulic pressure that acts within the tube one takes the hydraulic pressure that causes the burst of the tube, and if the calculation for the coefficient of the initial failure yields a value of 1.0 that would mean that the calculation perfectly corresponds to the experiment. If the calculated value for the coefficient of the initial failure is different from 1.0, then it presents the difference between the calculation and the experiment.

Experimental part

The following was used for the tube production: a system of polyester resin of DUGAPOL H230, by the manufacturer "DUGA" - Belgrade, and R 2117 glass roving, by the manufacturer "ETEKS" – Baljevac on Ibar.

The tubes were produced with the filament winding technology using a PLASTEX machine, PLA 500 type, produced by the manufacturer PLASTEX – MANUHRIN, France.

The 400 mm long samples were cut from the tube by machining, and only a layer of pure resin was removed from the outer surface, so that the final layer of the glass fiber remained undamaged.

The markings of four groups of tube samples, as well as the winding structure (from the inside toward the outside), the internal diameter, the outer diameter and the wall thickness are presented in Table 1.

Table 1: Group markings, structure, internal diameter, outer diameter and wall thickness of the tube samples

Group markings	**Winding structure**	**Internal diameter** (mm)	**Outer diameter** (mm)	**Wall thicness** (mm)
A	1 x 90° 2 x 61° 1 x 90°	64.20	67.60	1.70
B	1 x 90° 2 x 45° 1 x 90°	64.20	67.60	1.70
C	2 x 90° 4 x 61° 2 x 90°	64.20	71.10	3.45
D	2 x 90° 4 x 45° 2 x 90°	64.20	71.10	3.45

The strain gauges 10/120 XA 11 are glued on the outer surface of the tube samples using X60 glue, both made by the same the manufacturer HOTTINGER BALDWIN MESSTECHNIK GmbH, Germany.

Thus completed tube samples are mounted on the tool of specific construction for testing the hydraulic burst pressure of tubes.

For the experimental determination of the sample tube properties, the WALTER & BAI, Germany equipment for a hydraulic pressure range of 200 MPa was used, along with the protection equipment, the tools for testing the hydraulic burst pressure of tubes and a piezoelectric converter of pressure 601H range 100 MPa, from KISTLER, Germany.

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

Results of the tests and structural analysis

Computation results of the of tube model

The calculation procedure of the tube model includes the following sequences:

1. Definition of mechanical properties of filament wound composite material – polyester resin/glass fiber [1]:
   - tensile strength in the direction of fibers = 694.7 MPa,
   - tensile module of elasticity in the direction of fibers = 10.95 GPa,
   - tensile Poisson’s coefficient in the direction of fibers = 0.296,
   - tensile strength transversal to the direction of fibers = 9.72 MPa,
   - tensile module of elasticity, transversal to the direction of fibers = 3.51 GPa,
   - tensile Poisson’s coefficient, transversal to the direction of fibers = 0.13,
   - compression strength in the direction of fibers = 409.3 MPa,
   - compression module of elasticity, in the direction of fibers = 1.171 MPa,
   - compression Poisson’s coefficient, in the direction of fibers = 0.312,
   - compression strength, transversal to the direction of fibers = 11.05 MPa,
   - compression module of elasticity, transversal to the direction of fibers = 767.1 MPa,
   - compression Poisson’s coefficient, transversal to the direction of fibers = 0.181,
   - bending strength = 1,097.9 MPa,
   - interlaminal strength = 44.3 MPa,
   - shear strength = 11.06 MPa,
   - shear module of elasticity = 6.55 MPa.
2. Definition of dimensions and structure of wounded tube samples:
   - internal diameter = 64.2 mm
   - length = 400 mm
   - outer diameter (of group A tubes) = 67.60 mm
   - number and angles of winding of the layers:
   - for example, group A tubes: 1 x 90°
     2 x 61°
     1 x 90°
3. Importation of terms for orthotropic.
4. Definition of the network of nodes for the tubes of mentioned dimensions. The chosen network has nodes with medium density, which, on the one hand, offers sufficient accuracy, and, on the other hand, simplifies calculations or, in other words, the tube models consist of about 4000 finite elements type multi-layered shells (“laminate”). Four-node finite elements of multi-layered shells that satisfy the critical “patch tests” with an accuracy of 2 % were used.
5. Definition of terms of testing. Since the tube sample relies on tool pieces for testing with both of its ends, that means there are no axial, but only radial deformations, and the data about tubes loaded with the internal hydraulic pressure are entered into the program as well.

The properties of four tube models, loaded with the internal pressure, are calculated. The four tube models have the same length and internal diameter. The only difference is in the structure of winding, as well as in the thickness of layers themselves. The models of the composite tube made of finite elements are shown in Fig.1, and the distribution of the coefficients of the initial failure (Failure Index – F.I.) is shown in Fig.2.

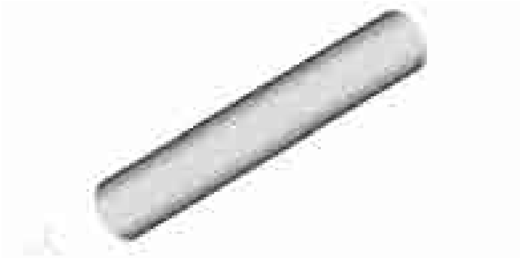

Figure. 1. Model of the composite tube made of finite elements

Figure 2. Distribution of the coefficients of the initial failure

The analysis of load conditions, with the application of the FEM, was conducted by using certain values of hydraulic pressure. For example, a 23.0 MPa hydraulic pressure was used for the calculation of the group A tube samples. The choice of this pressure was based on the experimentally calculated mean arithmetic value of the hydraulic burst pressure of the group A tube sample, which is 22.34 MPa. The choice may be completely random, but the fact that the experimental value of the burst pressure was already known contributed to its use. The calculated coefficient value of the initial failure (F.I.) for the group A tubes was:

$$F.I.= 0.96$$

By combining the existing data for the strength and the coefficient of the initial failure, according to the calculated analysis, the calculated pressure of the initial failure for the group A tubes is:

$$23.0/0.96 = 23.96 \text{ MPa}.$$

The calculation analysis also determined that the initial failure occurs in the internal layer at the angle values under 90°, in all four groups of tubes.

The markings of the four groups of tube samples, the chosen hydraulic pressure, the coefficient of the initial failure and the calculated hydraulic pressure of the initial failure are given in Table 2.

Table 2. Group markings of tubes, the chosen hydraulic pressure, the coefficient of the initial failure and the calculated hydraulic pressure of the initial failure

Characteristic	Group markings			
	A	B	C	D
Chosen hydraulic pressure (MPa)	23.0	18.0	49.0	38.0
Coefficient of failure index (F.I.)	0.96	0.70	1.02	0.74
Calculated hydraulic pressure of the initial failure (MPa)	23.9	25.7	48.0	51.3

For A and C tube groups which have middle layers wound at an angle of 61° the calculated coefficients of the initial failure are very close to the value of 1.0. This fact shows that the structure which has the above mentioned angles of winding should be an almost ideal match of the theoretically predicted burst pressures of the tube and those obtained in practice.

For B and D groups tubes which have middle layers wound at an angle of 45° the calculated coefficients of the initial failure are different from the value of 1.0, but, based on experience, this deviation is considered acceptable.

Results of the experimental tests of tube samples and the analysis

The tube samples were exposed to the effects of the internal hydraulic pressure, and the hydraulic pressure and axial deformations were registered. The increase of the internal hydraulic pressure was even and this pressure loaded the tube samples until they burst.

A tool of specific construction for testing the hydraulic pressure, with an installed tube sample, is shown in Fig.3. It is considered that the tube sample is clinched on both ends.

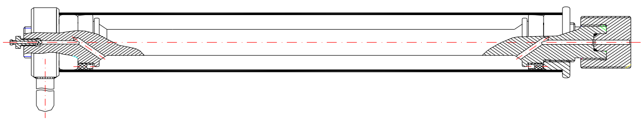

Figure 3. Tool for testing the hydraulic burst pressure with a tube sample

Fig.4 shows a tube sample from the group A with glued two-axis strain gauges.

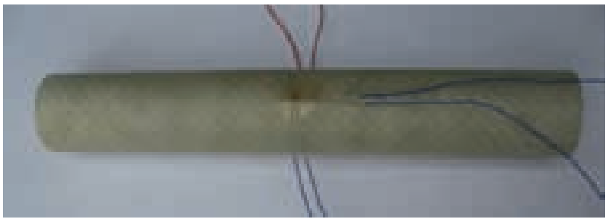

Figure 4. Tube sample from the group A with glued two-axis strain gauges

Fig.5 shows the above mentioned tube sample with glued two-axis strain gauges which are installed onto the tool for testing the hydraulic burst pressure.

Figure 5. Above mentioned tube sample with glued two-axis strain gauges installed onto the tool for testing the hydraulic burst pressure

Fig.6 shows a tube sample from a group after the testing of internal hydraulic burst pressure.

Figure 6. A group A tube after the testing of the internal hydraulic burst pressure

The single values of the hydraulic burst pressure (X_i) for the tube samples from A, B, C, and D groups are shown in Table 3 along with the appropriate arithmetic mean values and standard deviations $\left(\bar{X} \pm \sigma\right)$.

Table 3. Values for the hydraulic burst pressure of tube samples

Group marings	Hydraulic burst pressure (MPa)	
	Single values (X_i)	**Arithmetic mean values and stadard deviations** $\left(\bar{X} \pm \sigma\right)$
A/1	23.08	22.34 ± 0.90
A/2	22.50	
A/3	23.49	
A/4	21.56	
A/5	21.10	
A/6	22.31	
B/1	19.04	18.04 ± 0.91
B/2	17.83	
B/3	17.25	
C/1	50.23	49.13 ± 1.54
C/2	48.04	
D/1	36.01	38.53 ± 2.81
D/2	41.56	
D/3	38.02	

Based on the data given in Table 3, the conclusion is that there is a slight deviation of individual results of tests from the arithmetic mean value of the hydraulic burst pressure, i.e. standard deviations are completely acceptable for all four groups of tubes; therefore, these arithmetic mean values will be used in any additional analysis. The values of the hydraulic pressure and the axial deformations at the moment of burst of A/4 and B/3 tube are given in Table 4.

Table 4. Hydraulic pressure and the axial deformations at the moment of burst of A/4 and B/3 tube

Group marings	**Hydraulic pressure** (MPa)	**Axial deformations** (mm/m) x 10^{-4}
A/4	21.56	1.559538
B/3	17.23	0.850888

Comparison of the experimental and computation results of the test

The calculated hydraulic pressure of the initial failure of the tube model of the group A is 23.9 MPa (Table 2), while the experimentally determined hydraulic burst pressure of the same group is relatively the same and its value is 22.3 MPa (Table 3). The results are similar regarding the tubes from group C, i.e. The calculated hydraulic pressure of the initial failure for the tube model is 48.0 MPa (Table 2), and the experimental hydraulic burst pressure of tube samples from the same group is 49.1 MPa (Table 3). Based on this information, it may be concluded that there is a good match of the calculated estimation of the tube model and the experimentally determined values of the hydraulic burst pressure of these tube samples.

The calculated hydraulic pressure of the initial failure for the tube model that belongs to the group B is 25.7 MPa (Table 2), while the experimentally determined hydraulic burst pressure is 18.0 MPa (Table 3), and the difference between them is about 30 %. The results are similar to the tubes from the group D, because its calculated hydraulic pressure of the initial failure for the model tubes is 51.3 MPa (Table 2), and the experimentally determined hydraulic burst pressure is 38.5 MPa (Table 3), and the difference between them is about 25 %. However, based on experience, it is estimated that this deviation may be tolerated because the calculation, in this case, determines the level of load that produces the initial failure of one of the layers, while experiments determine the effective burst. Therefore, the matching of the calculated and experimentally determined values for the hydraulic burst pressure is acceptable even with this tubes.

The above information shows that the tubes which have middle layers wound at an angle of 61° are sufficiently appropriate for the calculated load with hydraulic pressure, while the tubes with middle layers wound under an angle of 45° are less suitable for the defined loading.

Real condition, that there were no axial deformation, was correctly applied in the calculating process of model tubes, because at the moment of burst of the tube samples A/4 and B/3, caused by hydraulic pressure, an extremely small axial deformation was registered (10^{-4} mm/m), which is negligible.

Conclusions

This paper explains the production of tubes by the filament winding technology using glass fiber impregnated with polyester resin, the process of testing the tube samples under the effect of the internal hydraulic pressure, as well as the procedure of analyzing the strength of tubes made of composite material, which is a result of internal research in establishing the calculation procedure and the experimental verification.

The conclusions, from everything that is mentioned, are:

1. Hydraulic burst pressure of the tube samples was experimentally determined (the same structure of winding as with tube models), produced by the filament winding technology of the same materials that are used in the production of test specimens, the mechanical properties of which are applied for the computation of model tubes (polyester resin and glass fiber).
2. Modeling of filament-winded tubes with four different winding structures is conducted based on the strength theory for composite materials with orthotropic properties, applying the method of finite elements and the initial failure criterion with the usage of the experimentally determined mechanical properties of the filament wound composite material of polyester resin/glass fiber, or in other words, the calculation of the hydraulic pressure of the initial failure for model tubes was completed.
3. Successful verification of the strength computations for tube samples was conducted. An exceptionally good matching of the computations of the estimated hydraulic pressure of the initial failure of tube models and the experimentally determined hydraulic burst pressure of the tube samples that have middle layers wound under an angle of 61° was achieved. The tubes with their middle layers wound under an angle of 45° have an acceptable deviation between the computation hydraulic pressure of the initial failure of the tube model and the experimentally determined hydraulic burst pressure of the tube samples.
4. Strength theory for composite materials with orthotropic properties can be used for computing model properties of filament wound elements of constructions, if mechanical properties of the composite material are given.
5. This investigation proposes the complete methodology including computation and the experimental strength analysis of tubes obtained by the filament winding technology using glass fiber impregnated with polyester resin under internal pressure.

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Mokronamotane kompozitne cevi: Eksperimentalni i rezultati numeričkih simulacija

Ova istraživanja se bave analizom loma kompozitnih cevi od (GRP) staklenih vlapana pod dejstvom unutrašnjeg pritiska u cevi čija su oba kraja zatvorena. Poređenjem vrednosti hidrauličkog pritiska prskanja mokronamotanih uzoraka cevi poliestarska smola/stakleno vlakno, dobijenih eksperimentalnim putem, i osobine modela cevi tj. vrednosti opterećenja pri kome se javlja inicijalni lom modela cevi, dobijenog proračunom na osnovu teorije čvrstoće ortotropnih višeslojnih kompozitnih materijala konstatovano je dobro slaganje. Hidraulički pritisak prskanja mokronamotanih uzoraka cevi određen je korišćenjen alata specifične konstrukcije, a proračunavanje osobina modela cevi je izvršeno primenom metode konačnih elemenata, kriterijuma loma i eksperimentalno određenih mehaničkih karakteristika mokronamotanog kompozita poliestarska smola/stakleno vlakno. Uspešna verifikaija proračuna modela cevi pokazuje da navedena teorija čvrstoće može sa dovoljnom pouzdanošću da se primeni za mokronamotane elemente konstrukcije.

Ključne reči: **komopozitni materijali, polimerni materijali, mokro namotavanje, cev, hidrualični pritisak, proračun čvrstoće, mehanika loma, numerička simulacija, metoda konačnih elementa, eksperimentalni rezultati.**

Трубы из смешанных материалов с мокрым наматыванием: экспериментальные результаты и результаты цифровых моделирований

Настоящие исследования занимаются анализом излома смешанных труб (ГРП) из стекляных волокон под влиянием внутреннего давления в трубе, закрытой с обоих сторон. Сравниванием значений гидравлического давления при разрыве мокронаматываных образцов труб из полиэстарских смол/ стекляных волокон, полученых экспериментальным способом, и особенности модели трубы т.е. значения нагрузки при котором появляется начальный излом модели трубы, полученого расчётом на основании теории прочности ортотропных многослоистых смешанных материалов, констатировано хорошее согласовывание. Гидравлическое давление при разрыве мокронаматываных образцов труб определено пользованием инструментов удельной конструкции, а расчёт свойств модели трубы сделан применением метода конечных элементов, критерия излома и экспериментальным способом определённых механических характеристик мокронаматываных смешанных материалов полиэстарских смол/ стекляных волокон. Удачное подтверждение расчёта модели трубы показывает, что приведённую теорию прочности с достаточной надёжностью возможно употребить для мокронаматываных элементов конструкции.

Ключевые слова: смешанные материалы, полимерные материалы, мокрое наматывание, труба, гидравлическое давление, расчёт прочности, механика излома, цифровое моделирование, метод конечных элементов, экспериментальные результаты.

Les tubes composites à filament enroulé: résultats des essais et des simulations numériques

Cette étude s'occupe de l'analyse de la défaillance des tubes composites de fibres en verre (GRP) sous l'influence de la pression intérieure dans le tube dont les deux bouts sont fermés. On a constaté bon accord en comparant les valeurs de la pression hydraulique de la défaillance chez les échantillons des tubes en résine polyester / fibre en verre , obtenus par la voie expérimentale et les caractéristiques du modèle de tube, à savoir les valeurs de charge où se produit la défaillance initiale du modèle de tube, obtenue par le calcul basé sur la théorie de solide des matériaux composites orthotropes laminaires. La pression hydraulique de la défaillance des échantillons des tubes à filament enroulé a été obtenu par l'emploi des outils de construction spécifique et le calcul des caractéristiques du modèle des fibres a été réalisé par la méthode des éléments finis, le critère de défaillance et les propriétés mécaniques des composites à filament enroulé résine polyester/fibre en verre, obtenus expérimentalement. La vérification réussie du calcul du modèle des tubes démontre que la théorie de solide peut être appliquée pour les éléments de construction à filament enroulé avec satisfaisante fiabilité.

Mots clés: matériaux composites, matériaux polymériques, filament enroulé, tube, pression hydraulique, calcul à résistance, mécanique de la défaillance, simulation numérique, méthode des éléments finis, résultats des essais.