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Influence of fiber type and the layer thickness on the stress distribution in composite pipe

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Abstract: *In this work authors presented distribution of circumferential stress in wound composite structures made from different layers. The cylindrical shape specimens were made from layers which have different elastic moduli. Manufactured specimens underwent strength test to obtain distribution of circumferential stress as a function of radius. Circumferential strain on outside surface was measured by fiber optic strain gauge. In order to verify the experimental results were made microscopy specimens, obtained material properties by homogenization method and calculated the strain using analytical approach. In the end, authors compared results obtained from both methods.*

Keywords: *: composite, glass fiber, carbon fiber, material properties, strength test*

1. Introduction

Introducing large-scale lightweight, high-pressure composite tanks for gaseous fuels, requires effective solutions for many problems. One of the key problems is to optimize the manufacturing technology in order to reduce the weight, and hence production costs, this will make possible in the future to use the composite tank on large scale. Therefore, it is necessary to look for new ideas. One of them is to manufacture multilayer tanks, this solution allows to obtain uniform circumferential stress in of wall thickness. The most effort part of tank is cylindrical part, thus discussion is limited to aspects of the multilayer composite pipe. The main purpose is to model such state of effort of composite pipe to obtain so uniform stress state as possible, which would give an opportunity to reduce the weight of the composite, while providing the desired level of safety.

This issue has long been the subject of discussion in the literature, but satisfactory solution was never found. A N. Mitinskij in his work [6] analyzes the stress distribution in the single walled oak pipe. S G. Lekhnitskii in [4] derived equations that describe the state of effort for different structures, from plates and shells on the curved rods and tubes, taking into account the anisotropy of material. Works [2, 7] involve computational procedures for composite structures, especially used for tanks. V E. Verijenko considered effort of tank, which wall contained of several layers and boundary conditions between them. It is also suggested to increase value of the fiber tension in the winding process, in order to obtain residual stress, than the gap between the composite and liner can be reduced. In some techniques, this is accomplished for example by cooling [5] or by creation of vacuum in the liner.

In view of these requirements, multilayer composite cylindrical specimens were wound from continuous fibers and loaded by internal hydrostatic pressure. Fiber optic strain gauges measure circumferential strain on outside plane and using constitutive equations stress was calculated.

2. Specimens

The specimens used in experiment, were made by circumferential wound fiber on core, because unidirectional fiber orientation provide the highest value of stiffens and strength. The wall of specimens contained from two layers, where each layer were wound from material with different elastic modulus. The specimens differ from each other by thickness value of particular layers. The specimens were made in two stages: in first stage carbon fiber were wound, in second stage glass fiber were wound from which the outside layer was created.

Fig. 1. Composite specimens used in the experiment

Bands of used roving of glass and carbon fibers before they were wound on a core they were drowned through a bath of liquid resin impregnated. The bath of the resin and the core are heated continuously during winding, thus the resin does not lose its ability to flow. To get a good stiffness of a composite matrix the authors used epoxy resin and hardener Epolam 5015 Epolam 2016 produce by Axson company.

After preparation, the specimens were stand alone in ambient temperature (21°C) for 24 hours. In the next phase, the rings were cured for an additional 24 hours. at 60°C. After this treatment the specimens were removed from the mold by means of a press, and purified from the residue and resin burrs.

The geometric dimensions of the specimens and their parameters are given in Table 1.

Tab. 1. Thickness of specimens used in experiment

Specimen	Specimens thickness [mm]	Thickness of carbon composite layer[mm]	Thickness of glass composite layer [mm]
1	5,76	5,76	0
2	5,81	2,47	3,34
3	5,77	1,23	4,54
4	5,44	0	5,44

3. Experimental set-up

In order to investigate the deformation of the structure under the influence of the applied internal pressure, the appropriate device to the hydraulic pulsator (MTS – 809 on fig. 2) has been manufactured. The device was constructed from a piston which push wedges on the composite specimen.

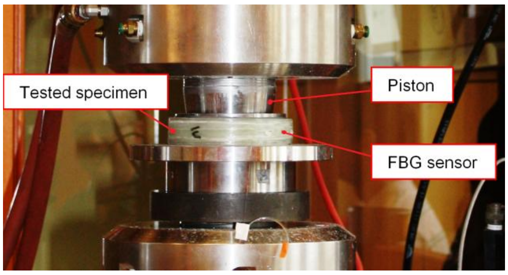

Fig. 2. The specimen mounted in the test machine

By the action of the axial force of the test machine and the mutual contact of the elements on the conical surface, it was possible to produce a controlled and uniform pressure to the inner surface of the specimens.

Measurement of deformation under the action of the internal pressure was performed by means of optical sensors (Fiber Bragg Gratings – FBG) glued on the outer surface of the specimens.

Before testing composite samples, experimental set–up has been calibrated. For this purpose we loaded the reference specimen (made from steel) with optical strain gauges that were glued on the circumference of the sample. Based on Hooke's low circumferential stress was calculated from the measured strain. Using the known issues in the strength of materials, so-called Lame task, it was possible to determine the value of pressure acting on inner surface of the specimen. These method are discussed more detail in [2].

On prepared and calibrated set–up the tests were carried on manufactured composite rings. Fiber optic sensors were glued to composite ring shaped specimens and loaded by ingrowing force until brake. After tests, signals from force sensor and FBG were analyzed and summarized in Figure 3.

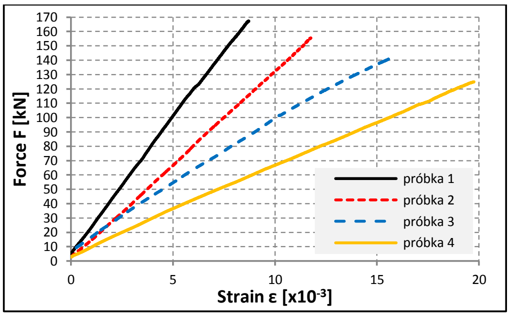

Fig. 3. Applied force in function of circumferential strain

4. Material properties determination

In order to determine the actual mechanical properties of materials (composites) used in the experiment, the microstructure was examined to determine the fiber volume content of the matrix. This is a key parameter for projecting material properties because the strength of the composite depend mainly on the fiber volume fraction.

In order to determine the volume fraction of the fibers in cross-sections of composite specimens, metallographic sections were made and then the samples were subjected to microscopic analysis. Examples of cross sections are shown in fig. 4: (for composite epoxy resin – glass fiber CFRP and for composite epoxy resin – carbon fiber – CFRP). After measuring the areas occupied by fibers from few specimens and performed the statistical analysis the volume fraction was determined for different composite materials (values given in table 2).

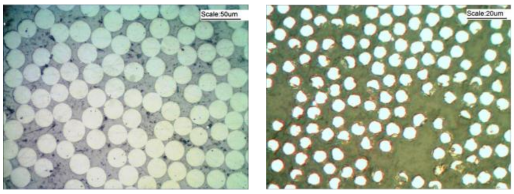

Fig. 4. Microscope photography of GFRP (left), CFRP (right).

After obtained the content of the fiber, the material properties were determined, in this purpose homogenization method was used. In this calculations following assumptions were made:

- the fibers have a circular cross section,
- fibers in matrix are arranged in a hexagonal manner,
- fibers and matrix are isotropic materials.

The presented method is based on the homogenization solution of Eshelby, extended on cyclic boundary conditions for the representative cell as a calculation method discussed in the work [1]. Based on materials parameters of the fibers and the matrix (table. 2), it was possible to calculate the effective properties of composites (table. 3).

Tab. 2. Physical and material properties of fiber and matrix

Properties	Glass fiber	Carbon fiber	Epoxy resin
Density ρ [g/cm^3]	2,6	1,79	1,12
Tensile strength R_m [MPa]	3400	4800	73
Elastic modulus E [GPa]	73	240	2,9
Poisson ratio ν [–]	0,21	0,28	0,35
Volume fiber content [%]	39,3	47,4	–

Tab. 3. Material properties for CFRP and GFRP

Properties	GFRP	CFRP
E_1 [GPa]	36,46	96,47
$E_2 = E_3$ [GPa]	9,12	8,17
G_{12} [GPa]	3,3	2,92
G_{23} [GPa]	3,2	2,79
ν_{12} [–]	0,29	0,28
ν_{23} [–]	0,43	0,46

5. Analytical approach

In order to determine the distribution of circumferential and radial stresses, the well-known Lame issue was used, expanded with the coefficients for the materials with anisotropic properties. Assuming the model of elastic material, the distribution of the circumferential stress in the pipe is given by a multilayered [3]:

$$\sigma_\theta^{(m)} = \frac{q_{m-1} c_m^{k_m+1} k_m}{1-c_m^{2k_m}} \left[\left(\frac{r}{a_m}\right)^{k_m-1} + \left(\frac{a_m}{r}\right)^{k_m+1} \right] - \frac{q_m k_m}{1-c_m^{2k_m}} \left[\left(\frac{r}{a_m}\right)^{k_m-1} + c_m^{2k_m}\left(\frac{a_m}{r}\right)^{k_m+1} \right] \quad (1)$$

and the radial stress distribution:

$$\sigma_r^{(m)} = \frac{q_{m-1} c_m^{k_m+1}}{1-c_m^{2k_m}} \left[\left(\frac{r}{a_m}\right)^{k_m-1} - \left(\frac{a_m}{r}\right)^{k_m+1} \right] + \frac{q_m}{1-c_m^{2k_m}} \left[-\left(\frac{r}{a_m}\right)^{k_m-1} + c_m^{2k_m}\left(\frac{a_m}{r}\right)^{k_m+1} \right] \quad (2)$$

where:

q_{m-1} – internal pressure for mth layer
q_m – external pressure for mth layer
r – radius surface concentric with the inner and outer surfaces,
c_m – the ratio of the inner to the outer radius for the mth layer
$k_m = \sqrt{\frac{E_2}{E_1}}$ – factor determining the elasticity of the material.

The above formulae, geometrical and material properties were implemented to the computing environment "Mathematica". Thus it was possible to calculate the value of deformation of the combination of layers shown in table 1.

In order to verify the analytical and experimental approach, in table 4 are presented obtained strain measure on the outer surfaces of the specimens and calculated in Mathematica.

Tab. 4. Comparison results obtained from analytical and experimental method

Specimen thickness [mm]	CFRP layer thickness [mm]	GFRP layer thickness [mm]	Volume content of CFRP layer [%]	F_{max} [kN]		
				Strain [-]		Difference [%]
				Experimental approach	Analytical approach	
5,76	5,76	0	100	0,00898	0,00874	3
5,81	2,47	3,34	43	0,01275	0,01161	10
5,77	1,23	4,54	21	0,01321	0,01518	15
5,44	0	5,44	0	0,01911	0,01979	4

6. Conclusions

From the analysis of conducted simulations and experiment, the authors found good correlations for both methods. The main conclusions can be summarized as following:

- most of specimens were damaged suddenly, without yield point, all layers of the material broke at the same time of experiment, otherwise only for specimen 1,

- volume fiber content have significantly influenced the strength of composite structure,
- maximum 30% volume fiber content have significantly improved the composite strength, more than 30% of carbon fiber content make slight increase of composite strength and substantial cost of production.

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