IDENTIFICATION OF STRAINS IN A MULTILAYER COMPOSITE PIPE

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Summary:
The paper presents the measurements and the analysis of deformations between layers and the outside surface of a multilayer filament wound composite pipe. The pipe was made through the hoop wrap of roving stripes hence ring-shaped samples were prepared for test purposes. Carbon fibers and glass fibers were used for winding. In the course of their manufacturing, strain gauges and fiber optic sensors were placed between the composite layers. Then, the strength tests were performed. The samples were subjected to the internal pressure of 30 MPa. During the tests peripheral deformations were measured on outside surfaces of individual layers of the structure.

Keywords:
filament wound composites, high pressure pipe, deformation measurement, FEM analysis

INTRODUCTION

The large-scale introduction of lightweight, high-pressure composite gas fuel tanks requires effective solutions to numerous problems. The optimization of manufacturing technology in order to reduce the mass, and hence the cost of production, which in turn enables the widespread use of such tanks, is one of the key routes. In view of
these requirements, it is necessary to reach for new qualitative concepts. These include mastering the design principles and, afterwards, producing a multilayer tank, which will allow for obtaining a strain state, substantially uniform possible along the radius. Due to the fact that the cylindrical section of the tank is the most stressed, the considerations are limited to a multilayer composite pipe. The main aim was to model a composite structure so that the state of the strain was as uniform as possible, giving a chance to reduce the weight of the composite, while providing the desired level of safety of use.

Bearing in mind the above-mentioned needs, samples for structural strength testing were manufactured in the form of rings with the internal diameter of 113 mm, the wall thickness of 8 mm and the height of 30 mm. The wall consisted of three layers: a steel liner, an epoxy - carbon composite layer and an epoxy - glass composite layer. Only the circumferential winding technology, which guarantees the highest strength parameters of the manufactured structures, was used to make the samples.

The issue of stress determination in an anisotropic pipe subjected to internal pressure has been repeatedly considered in the literature, but the obtained analytical models have not been used to optimize the layering. A N. Mitinskij in his work [1] analyzes stress distribution in a single thick-walled oak pipe. S G. Lekhnitskii, at work [2] derives equations describing the state of stress of different constructions, from plates and coatings to curved rods and tubes, with the anisotropy taken into account. Works [3, 4] concern computational procedures for composite structures, especially those used for tanks. V E. Verijenko considers the effort of the tank [5], whose wall consists of several layers with predefined boundary conditions (e.g. introduction of additional pressure) between them. It is also proposed to intentionally stretch the fiber in the winding process in order to produce the initial residual stress to minimize the gap between the composite and the liner. In the work [6] there was a tank constructed, reinforced with steel straps which were wound on a steel liner with the appropriate fixed tension. In some techniques, this is performed also by, for example, cooling [7] or introducing a vacuum in the liner.

1. TEST SAMPLES

The test samples were made in the form of rings consisting of three layers: the inner steel layer (S355) with the epoxy-carbon composite (CFRP) and the epoxy-glass composite (GFRP) wound around it. The sample cross-section and the component layers are shown in Figure 1.

During the production of the composites, the prepared 2 mm thick steel liners were placed on the core between the steel rings defining the width of the samples and then resin-saturated carbon fiber was wound on them. The CFRP layer was made 2 mm thick. After 24 hours, when the resin was pre-gelatinized, another 4 mm layer of glass fiber was wound. The samples were again left standing for 24 hours at 20 ° C and then they were cured for another 24 hours at 80° C.
The tensile force of 28 N was applied when winding the carbon fiber, and of 104 N for glass fiber.

The steel liner was used to produce the samples so that the stresses from the tensile force during winding remained on the boundary of the layers and were not transferred to the steel core. The liner was made with additional flanges, symmetrically on both sides. Cuts (grooves) were made in the flanges, through which electric wires were routed out from strain gauges and fiber optics sensors.

Five identical samples were prepared for the test purposes.

After having the samples produced and cured, they were removed from the core and prepared for stretching on a testing machine. When removing from the core, the rings did not show resistance, which means that the liner did not deform under the influence of the tensile force of the fibers during the winding. The significant tensile force in the glass fiber was transferred primarily by the pre-made carbon layer. The samples are shown in Figure 2.
At the next stage, the rings were successively loaded on the testing machine on a specially prepared stand (Figure 3).

![Test stand](image)

**Fig. 3. Test stand**

*Source: own elaboration*

The test apparatus was made of the conical die (1), which was pushed into the split ring (2) placed inside the composite ring (4). The copper pad (3) was inserted between the split ring and the composite ring, which improved the uniformity of the distribution of the internal pressure applied to the test sample. The vertical force from the head of the testing machine changed direction into the horizontal component as a result of the mutual contact of those elements. The cone had a convergence of 1: 7.15; which made it possible to achieve much greater force on the surface of the conical split ring. It consists of six equal parts, distributed symmetrically around the circumference of the sample. Owing to this, each piece slightly moved after loading, resulting in almost even loading on the inner surface of the sample under test.

Strain gauges (T) and fiber optic sensors (FBG) were mounted on the liner and on the CFRP layer during winding in order to measure circumferential deformations after application of the load in the composite samples tested. After having the composite structures cured, strain gauges were also applied on the outer surfaces of the samples. Tensometric sensors were stuck on five samples, while FBG sensors were applied on three samples.

The distribution and method of the signal output from the sensors are shown schematically in Figure 4.
2. TENSOMETR – TENSOMETER

During the tests, at the first phase the rings were loaded with an internal pressure of 5.5 MPa, then tempered and reloaded with a pressure of 30 MPa. The pre-load of the samples was aimed at aligning and matching all of the components of the test stand that worked together. The load flow diagram is shown in Figure 5.

The graphs (Figures 6 - 8) of the circumferential deformations as a function of time for the sensors placed on individual layers of the composite were constructed on the basis of the obtained measurement data.

It was found during the test that some of the fiber-optic sensors and strain gauges were damaged in the sample preparation process. This could have been due to the fact that, for example, during the winding, considerable tension forces were applied to the roving stripes that directly pressed the sensors.
Fig. 6. Values of circumferential strains on the liner

Source: own elaboration

Fig. 7. Values of circumferential strains on the CFRP layer

Source: own elaboration

Fig. 8. Values of circumferential strains on the GFRP layer

Source: own elaboration
The finite element numerical calculations were performed in the Abaqus 6.14 / Standard system, using the Static General solver in order to compare the experimental results with theoretical values.

In the beginning, the stand model together with the ring was discretized. The C3D8R higher order elements were used for discretization (Figure 9).

![Fig. 9. The discrete model of the test stand](image)

Models of materials determined by analytical homogenization (for elliptic inclusions) were used for the calculations [8, 9]. It was assumed that the material (CFRP and GFRP) had an orthotropic structure with transverse isotropy. The designated properties are summarized in Table 1.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Epoxy-carbon composite</th>
<th>Epoxy-glass composite</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_1$ [GPa]</td>
<td>161,52</td>
<td>54,62</td>
</tr>
<tr>
<td>$E_2 = E_3$ [GPa]</td>
<td>14,28</td>
<td>15,32</td>
</tr>
<tr>
<td>$G_{12}$ [GPa]</td>
<td>5,22</td>
<td>5,96</td>
</tr>
<tr>
<td>$G_{23}$ [GPa]</td>
<td>5,05</td>
<td>5,50</td>
</tr>
<tr>
<td>$v_{12} = v_{13}$ [-]</td>
<td>0,30</td>
<td>0,24</td>
</tr>
<tr>
<td>$v_{23}$ [-]</td>
<td>0,41</td>
<td>0,39</td>
</tr>
</tbody>
</table>

Half of the geometric model was prepared and symmetry conditions were assumed so as to speed up the calculations. In addition, the inner part of the die was omitted during discretization, since it did not affect the quality of the calculations. On the other hand, its stiffness was increased deliberately and a friction value of 0.2 was introduced between the cooperating elements. A vertical force of the same value as in the experiment was applied to the die.
Then the calculations were performed. The results of the calculations are presented in the form of the distribution of circumferential strains for the whole structure as well as for individual constituent layers (Figures 10-12).

**Fig. 10.** Distribution for circumferential strains for the composite with the liner  
*Source: own elaboration*

**Fig. 11.** a) distribution for circumferential strains for the composite with the liner b) for the liner the thickness distribution  
*Source: own elaboration*

**Fig. 11.** a) distribution for circumferential strains for the EW composite b) for the ES composite the thickness distribution  
*Source: own elaboration*
Table 2 summarizes and compares the resulting deformation values obtained from the calculations and the experiment.

**Table 2. Comparison of results of the test and the FEM analysis**

<table>
<thead>
<tr>
<th>Sample number</th>
<th>Strains on the liner [‰]</th>
<th>Strains on the CFRP layer [‰]</th>
<th>Strains on the GFRP layer [‰]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>–</td>
<td>1,38 (FBG)</td>
<td>–</td>
</tr>
<tr>
<td>2.</td>
<td>1,25 (FBG)</td>
<td>1,49 (FBG)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td>1,08 (T)</td>
<td>1,40 (T)</td>
<td>–</td>
</tr>
<tr>
<td>3.</td>
<td>1,58 (T)</td>
<td>1,45 (FBG)</td>
<td>–</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,38 (T)</td>
<td>–</td>
</tr>
<tr>
<td>4.</td>
<td>–</td>
<td>–</td>
<td>1,40 (T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,69 (T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,41 (T)</td>
</tr>
<tr>
<td>5.</td>
<td>–</td>
<td>–</td>
<td>1,33 (T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,27 (T)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1,06 (T)</td>
</tr>
<tr>
<td>Test results (average)</td>
<td>1,30</td>
<td>1,43</td>
<td>1,36</td>
</tr>
<tr>
<td>FEM results</td>
<td>1,71</td>
<td>1,67</td>
<td>1,49</td>
</tr>
<tr>
<td>Difference</td>
<td>23,9%</td>
<td>14,4%</td>
<td>8,7%</td>
</tr>
</tbody>
</table>

*Source: own elaboration*

### 3. SUMMARY AND CONCLUSIONS

Based on the tests and simulations carried out, it can be clearly stated that:

- despite the large number of scientific studies in the field of production and research on tubular composite structures, the issue of their strength remains one of the fundamental unresolved tasks and therefore requires further work and is within the scope of the current research area;
- the original stand for testing strength of wound composite structures with ring geometry was made using a testing machine;
- the methodology for measurement of strains (including between layers of the composite structure) was developed using two systems: resistance tensometry and Fiber Bragg Grating;
- the strain values obtained on the experimental basis correlate well with the theoretical values received by the FEM method, especially for composite materials; therefore, this method can be successfully applied to the calculations of such structures with complex geometry;
— through experiment it was proven that different types of strain gauges can be used, where fitting sensors requires high precision during winding of structures;
— by comparing the results of both analyzes it can be concluded that it is sufficient to measure the strain on the outer surface of the structure in the case the calculations are to be verified by means of experimental method.

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