Study of the stressed state in the layers of the composite material of the construction element

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Abstract. Numerical analysis was used to estimate influence of orientation of composite material layers on strain changes in a constructive element. A finite element method was used to conduct a strain-stress state analysis. A cylindric shell with a radius of 300 mm, a height of 600 mm and a wall thickness of 1.56 mm was examined. The shell consisted of eight differently oriented carbon fiber layers, that were impregnated with epoxy resin. Plate Laminate type elements were used to imitate composite layers orientation and to create a model of cylindric shell walls. Lower base of the cylinder had rigid fasteners and the upper base was under external loading. During strain-stress state analysis of composite layers were examined following loading types: axial tension, bend, torsion, internal pressure. Numerical analysis revealed that tension distribution in layers of composites depends on layer orientation and the cylindric shell loading type. Moreover, this paper defines estimated fatigue life of the shell under pulsatory load. It was determined that characteristics of fatigue strength of the constructive element depend on loading type.

1. Introduction
Combination of different materials in composite materials leads to a creation of a new material with properties different from properties of its components. Required characteristics can be attained by varying matrix and reinforcement materials and their ratio and by applying specific supplemental reagents. In comparison with noncomposite constructive materials, composites have a range of advantages [1-6]:
- Relatively low density;
- High specific strength and high specific modulus;
- High chemical endurance and corrosion resistance;
- Composites can be reused for production of new articles;
- Fiber-reinforced composite materials have high fatigue characteristics;
- Possibility to control strength due to appropriate reinforcement orientation;
- Specific properties (radio-wave transparency, thermostability etc).

Thus, composite materials have a wide range of useful and unique properties and combination of these properties produces constructions with high weight perfection.

However, constructive materials also have a range of disadvantages:
Most of the composite materials have a high cost in comparison with metal alloys;
Low interlaminar strength and modulus;
Polymer composites have low compressive strength that complicates joint of items with fasteners;
Lack of yield zone, fragile destruction;
Necessity of labor protection and recycling while composites production.

2. Relevance of the study
Due to unique properties composites are used in science, engineering and industry (buildings, mechanical engineering, metallurgy, chemical industry, energy industry, electronics, household appliances, clothing and footwear industry, medicine, sports etc) [7-8].

Because of wide use of composites in industry properties of composite materials under different types of loading are especially relevant. This paper aims to examine influence of composite layer orientation on strain change.

3. Purpose and objectives of the study
The article provides results of stress state analysis of different types of load of short compartment of closed cylindrical shell with a height of 600 mm and a radius of 300 mm (Figure 1). The shell is made of composite material, which contains layers. Layer orientation is presented in figure 2 [9-10].

![Figure 1. Cylindrical shell.](image1)

![Figure 2. Layer orientation angles.](image2)

Composite material properties correspond to properties of a plate impregnated with epoxy resin and made of 8-layer unidirectional carbon fiber with each layer thickness of 0.195 mm. The analyzed composite material has following characteristics:
- Young's modulus $E_1=147000$ MPa;
- Transversal elastic modulus $E_2=E_3=7580$ MPa;
- In-plane shear modulus $G_{12}=3960$ MPa;
- Interlayer shear modulus $G_{13}=3960$ MPa;
- Interlayer shear modulus $G_{23}=3000$ MPa;
- In-plane Poisson's ratio $\mu_{12}=0.33$;
- Interlayer Poisson's ratio $\mu_{13}=0.33$;
- Interlayer Poisson's ratio $\mu_{23}=0.38$;
4. Theoretical part

A static analysis of the construction was conducted with Finite element analysis software to analyze stress state of the smooth cylindrical shell [11-14].

For modelling of composite characteristics was used a two-dimensional orthotropic material, which specified characteristics of the composite layers in 2 orthogonal directions. Composite layer orientation of 0° coincides with the cylinder longitudinal axis.

Cylindrical plane Laminate type elements were used to imitate composite layers orientation and to create a model of the cylindric shell walls (Figure 2). Laminate type elements reproduce internal strength factors and were exposed to diaphragm, shear, transverse and bending loading.

The model is loaded and fixed by two Rigid elements placed on two sides of the model. Rigid element independent nodes are placed on the cylinder axis, dependent nodes are placed on arcs of the upper and lower bases of the cylinder. Independent nodes relate to dependent nodes by degrees of freedom. Thus, cylinder faces retain their shape after being deformed.

The dependent node of the lower bases of the cylinder is fixed by six degrees of freedom. Thus, the shell is fixed.

The load allocation was made according to the Bernoulli-Euler Beam Theory. The upper base of the cylinder was exposed to external loading. This leads to stress field distortion near the cylinder base but do have a crucial influence on tension distribution in central section of the shell.

Four types of tension were examined to analyze stress state (figure 3):

- Axial tension $F_z=1 \times 10^5$ N;
- Bend $M_x=2 \times 10^7$ N×mm;
- Torsion $M_z=2 \times 10^7$ N×mm;
- Internal pressure $\Delta p=0,1$ MPa.

![Figure 3. The finite element model and loading conditions of the cylinder](image-url)}
where \( \sigma_x, \sigma_y \) are normal stresses, \( \tau_{xy} \) is shear stress in areas perpendicular to \( X \) and \( Y \) axis of the finite element.

To exclude the influence of the boundary and loading conditions on the results of the analysis of the stress state examination of the shell elements was held in \( 275 \text{ mm} \leq z \leq 375 \text{ mm} \).

Table 1 presents equivalent tensile stress peak values in composite layers after applying different types of loading.

**Table 1. Maximum Equivalent Stress Values in the Composite Layers.**

| Type of Loading       | Maximum Equivalent Stress, MPa |
|-----------------------|--------------------------------|
|                       | Layer 4, 5 (0°)                |
|                       | Layer 1, 8 (–45°)              |
|                       | Layer 3, 6 (45°)               |
|                       | Layer 2, 7 (90°)               |
| Tension               | 91.29                          |
| Bend                  | 121.64                         |
| Torsion               | 7.48                           |
| Internal Pressure     | 16.91                          |

Estimation of characteristics of the composite material cylindrical shell was conducted according to traditional method that includes following stages [15-20]:

- Creation of finite element model;
- Definition of boundary conditions;
- Assignation of a loading cyclogram;
- Analysis of strain-stress state, search of the most loaded (critical) construction areas;
- Processing tension cyclograms with cycle counting algorithm for each critical area and obtaining of asymmetric cycle with extremums of \( \sigma_{\text{max}}, \sigma_{\text{min}} \);
- Using formulas below equate asymmetric cycles to equal in fatigue damage zero-to-tension stress cycles:

\[
\sigma_{0i} = \begin{cases} 
\frac{\sigma_{\text{max}} \times (\sigma_{\text{max}} - \sigma_{\text{min}})}{2}, & \text{if } \sigma_{\text{max}} \geq 0 \\
\sqrt{2 \times (0.6 \times \sigma_{\text{max}} - 0.4 \times \sigma_{\text{min}})}, & \text{if } \sigma_{\text{max}} < 0, \sigma_{\text{max}} > 0 \\
0, & \text{if } \sigma_{\text{max}} \leq 0 
\end{cases}
\]

where \( \sigma_m = \frac{\sigma_{\text{max}} + \sigma_{\text{min}}}{2} \) is average strain per cycle;

- According to linear damage accumulation hypothesis define extremum of a zero-to-tension stress cycle which is equivalent to loaded area fatigue damage:

\[
\sigma_{0\text{max}} = \left( \sum (n_i \times \sigma_{0i}^m) \right)^{1/2}
\]

where \( n_i \) is a quantity of zero-to-tension stress cycles with maximum value \( \sigma_{0i} \); \( m \) is a fatigue curve coefficient;

- Selection of standard specimen basic fatigue curves that are described by equations:

\[
N\sigma_g^m = A_g
\]

where \( A_g \) is fatigue curve parameter, which depends on properties of material and construction characteristics; \( \sigma_g \) is the sample tension in gross section;

- Calculating estimated fatigue life with a ratio below:
\[ N_c = \frac{A_g}{\sigma_{0\text{max}}} \times k_{tg}^m \]  

(5)

where \( k_{tg}^m = 3.02 \) is a stress concentration coefficient (calculated in gross section).

Load block of the cylindrical shell is presented by a pulsed tension or stress load \( F_z = 1 \times 10^5 \) N.

Fatigue curves are presented in figure 4, fatigue curve equations and the shell fatigue values are presented in table 2.

![Fatigue life of carbon fiber reinforced epoxy.](image)

**Figure 4.** Fatigue life of carbon fiber reinforced epoxy.

**Table 2.** Estimated fatigue life.

| Loading type    | Fatigue curve equation | Estimated fatigue life \( N_c \), cycles |
|-----------------|------------------------|------------------------------------------|
| Pulsed tension  | \( N\sigma_{50}^{50,29} = 9.92 \times 10^{149} \) | 2.37 \times 10^{160} |
| Pulsed stress   | \( N\sigma_{51}^{51,38} = 5.17 \times 10^{134} \) | 1.91 \times 10^{149} |

**5. Practical implications**

This paper proves necessity of selection an appropriate layer orientation of composites according to construction loading type.

This analysis results can be used in estimation of article characteristics.

**6. Conclusion**

Numerical analysis of the cylindrical shell revealed that tension distribution in composites with different layer orientation depends on construction loading type. Composites with layer orientation angle of 0° are effective in peripheral area fiber bend. Composites with layer orientation angle of 45° and of -45° are effective in torsion. Composites with layer orientation angle 90° are effective in internal pressure.

Moreover, analysis results reveal that fatigue life of the cylindrical shell under pulsed tension is significantly higher than under pulsed stress.
References
[1] Ananin S, Ananeva E and Markin V 2007 Composite materials: Manual (Barnaul: ASU) p 94
[2] Yuskaev V 2006 Composite materials: Manual (Sumy: SSU) p 199
[3] Vasilev V, Protasov V and Bolotin V 1990 Composite materials: Handbook (Moscow: Mechanical engineering Press) p 512
[4] Adaskin A, Krasnovskij A 2017 Materials science and technology of metallic, non-metallic and composite materials (Moscow: Forum) p 167
[5] Zotov A 2015 Composite materials. Classification, composition, structure and properties (Moscow: Faktorial Press) p 161
[6] Kobelev A 2016 Technology of composite materials (Moscow: KnoRus) p 185
[7] Timofeeva M, Dolomatov M. Composite materials and their application in industry (Moscow: SINTEG) p 287
[8] Bataev A, Bataev V 2002 Composite materials: structure, preparation, application: Manual (Novosibirsk: NSTU) p 384
[9] Solomonov Y 2009 Methods of calculating cylindrical shells from composite materials (Moscow: FIZMATLIT) p 264
[10] Bakulin V, Gusev E and Markov V 2008 Methods of optimal design and calculation of composite structures. Optimal design of structures made of composite and traditional materials vol 1 (Moscow: FIZMATLIT) p 256
[11] Shimkovich D 2003 Construction Design in MSC.Visual NASTRAN for Windows (Moscow: DMK Press) p 448
[12] Rychkov S 2013 Construction Modeling in Femap with NX Nastran (Moscow: DMK Press) p 784
[13] Rydakov K 2011 FEMAP 10.2.0. Geometry and Finite Element Modeling of Constructions (Kyiv: Igor Sikorsky Kyiv Polytechnic Institute Press) p 317
[14] Adegova L and Zinovev B 2015 Fundamentals of the finite element method: Manual (Novosibirsk: SGUPS) p 131
[15] Belov V, Rudzei G, Kaluta A and Adegova L 2011 J. All-Russian J. Polyot 42–46
[16] Rudzei G and Adegova L 2014 J. of Transsib Railway Studies 2 86–94
[17] Belov V, Rudzei G, Kaluta A and Adegova L 2014 J. All-Russian J. Polyot 8 24–30
[18] Adegova L 2014 J. Sci. Bulletin of NSTU 3 160–170
[19] Adegova L 2015 J. Sib. Transport Univ. Herald pp 49–53
[20] Adegova L 2015 J. News of Higher Educational inst. Construction 3 92–98