Modeling of Mechanical Properties of the Polymeric Composite Reinforced with Braided Preform

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Abstract. Braided composite structures based on preforms are widely used in various industries. Owing to use of such preforms high speed and efficiency of the process of manufacturing of polymeric composite materials and structures on their basis can be provided. Knowledge of their properties in the design allows optimizing the production of structures with the specified parameters. The paper gives the review of three approaches to the description of physical and mechanical characteristics of the composite with braided fixtures – based on the classical theory of layered media, rod-based model, and the method of polynomial approximation. The necessary estimated dependencies were derived in order to predict the elastic and structural behavior of the composites under study at any reinforcement angle according to the known characteristics of predetermined angles. Synthesized design parameters, as distinct from the existing ones, allow predicting strength characteristics of the composite based on the braided hoses depending on the positioning and location of the material on the shape-generating surface. For the verification of theoretical results, a number of experimental studies have been carried out with the formation of samples of the material with the different reinforcing angles. Comparison of the analytical and experimental results allows drawing the conclusions that rod-based model gives the best results for the description of elastic behavior of the polymeric composite materials, whereas the obtained polynomial dependences are recommended for the structural behavior. The results of the work represent the basis for solving the problems of calculation of strength of the structures made of composite materials based on the braided preforms

1. Introduction

Structures made of polymeric composite materials (PCM) are successfully used in the aerospace, marine, automobile, construction and power industries [1, 2]. Among the various classes of PCM, special emphasis should be placed on the continuously reinforced PCM. These materials are capable of ensuring the maximum strength performance in the process of creation of the most advanced unique products and structures, as applied to critical structures and complex technical systems [3, 4]. The global trends in the use of cost-effective and environmentally safe technologies contribute to the
development of autoclave-free PCM manufacturing methods, such as RTM, RFI, and vacuum infusion [5]. The most effective application of the above methods can be provided by using the braided preforms (premixes) made of a continuous reinforcing filler [6]. Premix is a semi-finished product in the form of the “soft hose”, fabric or multilayer braid of the mandrel, whenever necessary, of the variable diameter. Significant advantages of the PCM manufacturing technology using braided preforms are as follows: shortening of the complex-shaped parts’ production cycle, reduction of production costs owing to mechanization of the process, decrease in the use of manual labor, and possibility of application in serial production [7].

Since the reinforcing element is the main component defining the mechanical properties of the PCM product, an important role is given to both the material of the preform and orientation of its structure in space.

2. Literature Review

The papers [8, 9] show that physical and mechanical characteristics in the longitudinal direction are decreasing with the increase in the angle of weaving of braided preforms. When the load is applied in the transverse direction, an increase in strength and tensile and compression moduli is observed. The paper [10] deals with computer systems, which allow determining the value of the optimal reinforcing angle of the braided preforms. The accuracy of such calculations is confirmed by the results of analysis of the images of braided structures with the specified parameters [11]. Despite the usefulness of these characteristics, they are not sufficient for solving the tasks of determination of stress-strain behavior, which are based on the elastic constants (elastic moduli, Poisson’s ratios etc.) and strength properties. Authors of the paper [12] studied the mechanical properties of braided structures on the basis of the micromechanical model. The braided premix was modeled as a structure consisting of threads with unidirectional layers. The model was described upon condition that properties of the material were calculated with the use of the principle of superposition to the two sublayers. The drawback of this work is that the results were obtained for the longitudinal modulus of elasticity and Poisson’s ratio only. The model for predicting elastic properties of the braided composites is proposed in the paper [13]. The model uses geometric characteristics of the premix, where the braided composite is considered as a set of three plates with inclined and longitudinal fibers. Bending of the fiber is taken into account in the initial calculations, and the contribution of the binder is then considered on the basis of the mixture rule. Most of the above papers use the classical theory of the laminated composites, based on the listing of characteristics of any structure according to the known physical and mechanical characteristics of the monolayer [14]. For example, the paper [15] reveals that the physical and mechanical properties of the conditional monolayers of the braided hose modeled by the structure ±φ depend on the angle between the yarns, which is not observed according to the theory of the laminated composites. Use of rod-based model of symmetrically reinforced composites [15, 16] is of interest for predicting the properties of the class of materials under study. The paper [17] gives the review of the possibility of using rod-based composite model to describe the physical and mechanical characteristics of the composite material with braided fixtures. Formally, the method for determining the elastic characteristics of the composites with reinforcement ±φ is based on the same fundamental properties of the monolayer as the classical theory of the layered media [15], so the use of the rod-based model [17] is limited by a number of assumptions of this theory.

Detailed results of the research based on the finite element modeling are given in a number of works, for example, in [18, 19]. The main problem of modeling of the braided composites with regard to numerical implementation is the complexity of description of the weaving structure. Full description of weaving of the reinforcing material leads to the higher computational requirements for the system resources. The most rational method in terms of optimizing the requirements for design resources is the simultaneous use of the analytical and finite-element models of the composite deformation [20, 21].

The paper [22] proposes the experimental method for determining the breaking characteristics at uniaxial stretching of the braided hoses, which differs from the standard sample preparation for the tests. Based on this, the effect of weaving on the breaking characteristics of braided fabrics is established. The
paper [23] experimentally shows that the degree and nature of hose deformation in the braided structures has a pronounced effect on the axial stiffness and strength of the composite. Results of experimental studies of the material samples of two types of braided hoses with different reinforcing angles are given in [17]. The program of experimental studies includes the tensile, bending and compression tests. It is shown that, in contrast to the use of the theory of the layered media, application of the rod-based model allowed reducing the amount of the required experimental data. The deficiency of experimental studies for each braided composite with the different reinforcing materials is that for each type of braided PCM microstructure the results may differ significantly [24, 25].

In connection with the above, the studies of methods for calculating the physical and mechanical characteristics of the composite based on braided hoses depending on the positioning and location of the material on the shape-generating surface are considered relevant. To achieve this objective, the following problem was solved: derivation of computational and empirical parameters for predicting the characteristics of the composite on the basis of braided hoses depending on the degree and nature of deformation of the hose, i.e. the angle between the yarns.

3. Research Methodology

It is necessary to experimentally determine five physical and mechanical characteristics for the composite with the reinforcing angle of \( \varphi = 45^\circ \) and two other PCM with the angle of laying subject to the condition \( \varphi = 45^\circ \pm \Delta \varphi \) (for example, \( \varphi = 30^\circ \) and \( \varphi = 60^\circ \)) [15]. The use of rod-based model [17] allowed reducing the number of the required experimental elastic constants to four. To do this, it is sufficient to know them for two PCM: with the laying of \( \varphi = 45^\circ \) and any other pattern (for example, \( \varphi = 30^\circ \)). Both of these models are built on the use of physical and mechanical characteristics of the unidirectional monolayer, which cannot be considered the main structural unit of PCM based on the braided hoses [16]. In addition, properties of the material under consideration depend on the reinforcing angle due to the change in the volumetric content of fibers in the composite [6, 7]. Consequently, any theoretical dependence should include the experimental points, and predicted values of the characteristics in the intervals between them will not necessarily correspond to reality. This is especially true for the modeling of structural behavior, which requires the use of any of the numerous strength criteria; i.e. it is advisable to know in advance, which of them most adequately describes the behavior of the real material under the load.

Analysis of the experimental and theoretical data shows that a number of mechanical characteristics of anisotropic materials can be described by the dependences below [15, 26, 27]

\[
R = a_1 \cos^4 \varphi + a_2 \sin^2 \varphi \cos^2 \varphi + a_3 \sin^4 \varphi
\]

\[
\frac{1}{R} = \frac{\cos^4 \varphi}{a_1} + \frac{\sin^2 \varphi \cos^2 \varphi}{a_2} + \frac{\sin^4 \varphi}{a_3}
\]

where \( R \) – modeled characteristic; \( a_1, a_2, a_3 \) – certain coefficients.

Use of such empirical relations allows synthesizing the formulas for calculation of the elastic and structural behavior of the PCM under study, provided that their numerical values are known in three independent points, i.e. for three reinforcing angles. In this case, it is advisable that experimental data at these points differ as much as possible or, at least, the confidence intervals do not intersect [15].

Taking into account the similar nature of dependences (1) and (2) on the angle \( \varphi \), we shall formulate the general empirical equation for the prediction of PCM properties as

\[
R^\alpha = a_1 \alpha \cos^4 \varphi + a_2 \alpha \sin^2 \varphi \cos^2 \varphi + a_3 \alpha \sin^4 \varphi
\]

where \( \alpha \) – certain power exponent.
For example, suppose that the values of $R_{30}$, $R_{45}$, $R_{60}$, corresponding to the target value for PCM with the reinforcement of 30°, 45° and 60° are found by experiment. Then, to calculate the coefficients $a_1$, $a_2$, $a_3$, appearing in (3), we obtain the system of three equations:

\[
\begin{align*}
9a_1^\alpha + 3a_2^\alpha + a_3^\alpha &= 16R_{30}^\alpha; \\
a_1^\alpha + a_2^\alpha + a_3^\alpha &= 4R_{45}^\alpha; \\
a_1^\alpha + 3a_2^\alpha + 9a_3^\alpha &= 16R_{60}^\alpha.
\end{align*}
\] (4)

The solution of this system is given by

\[
\begin{align*}
a_1^\alpha &= 3R_{30}^\alpha - 3R_{45}^\alpha + R_{60}^\alpha; \\
a_2^\alpha &= -4R_{30}^\alpha + 10R_{45}^\alpha - 4R_{60}^\alpha; \\
a_3^\alpha &= R_{30}^\alpha - 3R_{45}^\alpha + 3R_{60}^\alpha.
\end{align*}
\] (5)

When we substitute these expressions in (3), after certain transformations we obtain the formula below for predicting the physical and mechanical characteristics

\[
R^\alpha = R_{45}^\alpha + \cos 2\varphi \left[ R_{30}^\alpha - R_{60}^\alpha + 2\cos 2\varphi \left( R_{30}^\alpha + R_{60}^\alpha - 2R_{45}^\alpha \right) \right]
\] (6)

Using this ratio, we can describe the dependence of any PCM property on the angle of yarn laying in the braided hose. Accordingly, instead of values of $R_{30}$, $R_{45}$ and $R_{60}$ it is necessary to substitute the experimental values of the modeled characteristic at the points $\varphi=30^\circ$, $\varphi=45^\circ$, and $\varphi=60^\circ$.

For example, for the case $\alpha=1$

\[
\begin{align*}
E_x &= E_{45} + \cos 2\varphi \left[ E_{30} - E_{60} + 2\cos 2\varphi \left( E_{30} + E_{60} - 2E_{45} \right) \right]; \\
\mu_{xy} &= \mu_{45} + \cos 2\varphi \left[ \mu_{30} - \mu_{60} + 2\cos 2\varphi \left( \mu_{30} + \mu_{60} - 2\mu_{45} \right) \right]; \\
F_x &= F_{45} + \cos 2\varphi \left[ F_{30} - F_{60} + 2\cos 2\varphi \left( F_{30} + F_{60} - 2F_{45} \right) \right],
\end{align*}
\] (7)

where $F_x$, $F_{30}$, $F_{45}$, $F_{60}$ – ultimate tensile/compressive strength along the $x$ axis and its values for PCM with the reinforcement of 30°, 45° and 60°.

Taking into account the available statistics on the coefficients of variation of the elastic and strength properties of PCM [15, 27], we can assume that synthesized dependence (6) describes the real properties of PCM with the sufficient degree of accuracy and about the same error as the formulas obtained on the basis of the classical theory of the layered media [15] or with the use of rod-based model [17].

4. Results

In order to verify the developed model for predicting the mechanical characteristics of composites based on the braided hoses, batches of samples of PCM were manufactured with the use of vacuum-autoclave molding and tested. Braided hoses of 120/4 grade on the basis of carbon yarns were impregnated with the binder EDT-69N 52%. The samples with different angles of the yarn laying were made of the filler, with two layers in a sample. The samples for tensile, compression and bending tests were cut from each panel. Tensile and bending tests were carried out on INSTRON tensile tester, and compression tests on the testing machine 1932-U10. Results of mechanical tests were subjected to statistical processing [27]. Figures 1–4 show the comparison of experimental findings with the theoretical values of elastic strength properties of PCM. Theoretical values of mechanical characteristics were calculated by formula (6) of the proposed model and formula obtained on the basis of the classical theory of the layered media [15] and with the use of the rod-based model [17].
Figure 1. Dependence of the modulus of elasticity on the angle of yarn laying in the braided hose

Figure 2. Dependence of the Poisson’s ratio on the angle of yarn laying in the braided hose

Figure 3. Dependence of the ultimate tensile strength on the angle of yarn laying in the braided hose

Figure 4. Dependence of ultimate compressive strength on the angle of yarn laying in the braided hose
Therefore, mathematical support of calculations of the physical and mechanical characteristics of PCM based on premix, depending on the degree and nature of the hose deformation, i.e. angle between yarns, is synthesized.

5. Discussion

It is necessary to note some discrepancies in the experimental values of properties, revealed in the course of their analysis using the layered PCM and rod-based models proposed in [15, 17].

Firstly, one of the fundamental conditions of PCM mechanics, which follows from the theorem on the existence of elastic potential, namely, $E_x \mu_y = E_y \mu_x$ [26], is not satisfied. In particular, for the considered type of the filler $E_{30} \mu_{60} \neq E_{60} \mu_{30}$. Therefore, the curve $E_x(\phi)$ constructed according to the model of laminated PCM will not necessarily pass through the point $E_x = E_{60}$. Besides, determination of the monolayer elastic properties using the model of laminated PCM [15] may give in this case physically incorrect (negative) values of the elastic moduli. This in principle does not allow using the model of laminated PCM [15] to predict the elastic behavior of PCM based on the braided hoses.

Secondly, reconstruction of the monolayer strength characteristics according to the model of laminated PCM [15] at the obtained relations between the values of tensile and compressive strength $F_{xp}$ and $F_{xc}$ for the different angles of laying also leads to inadequate results. In this case, the monolayer strength limits are complex numbers (the only exception is the case of PCM compression). Estimation of the strength properties within the framework of the laminated PCM model according to the criterion of maximum stresses, or according to the rod-based model, is not strict and does not allow calculating all the necessary strength characteristics.

These results can be explained by errors in the manufacturing of samples, as well as traditionally wide spread in properties of the polymeric PCM [28, 29]. However, more significant in this aspect is the effect mentioned in [10, 11] of the angles of yarn laying in the hose on the volumetric content of the reinforcing material $\theta$, and hence on the composite properties, whereas the model of laminated PCM [15] is built on the assumption of the invariance of the monolayer properties. At the same time, it should be noted that mechanical characteristics obtained during the tests for different variants of the yarn orientation in the hose agree quite well with the conclusions of [10, 11] that the minimal value $\theta$ is observed at $\phi = 45^\circ$.

Taking into account the good convergence of the theoretical and experimental data, it can be considered quite reasonable to use the rod-based model from [17] for the description of the composite class under study. However, it is advisable to limit the scope of its application by predicting the elastic behavior only.

The proposed empirical dependence (6) and corresponding method for predicting the mechanical characteristics of PCM, reinforced with the braided hose, describes the actual behavior of the composite with sufficient accuracy and agrees well with the test results. As shown by numerical experiments, it is advisable to take the power exponent $\alpha = 1$ for engineering calculations. In certain cases, for example, when determining the Poisson’s ratio, the best results are given by $\alpha = -1$. However, it should be noted that in the interval of $\phi$ varying from $30^\circ$ to $60^\circ$ the choice between two values $\alpha = 1$ or $\alpha = -1$ does not play a fundamental role. In both cases, the elastic and strength properties of PCM are almost identical in magnitude. The further increase or decrease of the value $\alpha$ is irrational, since it does not bring more clarity in the calculations within the specified interval of the angles of yarn laying in the hose.

According to the available experimental data, it is not possible to assess the validity of the model of the layered media to describe the mechanical behavior of the considered PCM. It can be explained by the fact that the values of elastic properties (first of all, Poisson’s ratio $\mu_{xy}$) obtained during the tests did not allow to set physically admissible properties of the conventional monolayer. However, taking into account the similarity of the basic principles of the rod-based model [17] and model of laminated PCM [15], the latter should not be considered completely incorrect. Its further experimental studies are required.
Conclusions
The paper gives the review of three approaches to the description of physical and mechanical characteristics of the composite with braided fixtures, based on the classical theory of layered media, rod-based model, and the method of polynomial approximation. The necessary estimated dependencies and equations were derived in order to predict the elastic and structural behavior of the composites under study at any reinforcement angle according to the known characteristics of predetermined angles $\pm 30^\circ, \pm 45^\circ$ and $\pm 60^\circ$

For the verification of theoretical results, a number of experimental studies have been carried out with the formation of samples of the material with the different reinforcing angles. Comparison of the analytical and experimental results allows drawing the conclusions that rod-based model gives the best results for the description of elastic behavior of PCM, whereas the obtained polynomial dependences are recommended for the structural behavior.

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