Numerical study of the stress strain state during tests of polymer composite materials samples

E V Feklistova, A V Babushkin and A V Babushkina

Perm National Research Polytechnic University, Perm, 29, Komsomolsky prospekt, Perm, 614990, Russia

E-mail: cem.feklistova@mail.ru

Abstract. To date, a large number of experimental methods for determining the mechanical properties of composite materials is known. However, the results of these methods, i.e. their comparison features, are relative and give good repeatability in strict compliance with the sample production and experiment technology. In this case, the stress-strain state in the working area of sample structures should be numerically evaluated to determine the generally accepted characteristics. This paper constructs and develops the simplest models of the mechanical behavior of polymer composite material samples. The stress-strain state is numerically simulated in the working areas of samples with various geometric parameters and external loading features. Modeling is made using the ANSYS engineering analysis system. According to the results of calculations for each of the samples, the fields of stresses, deformations, and displacements under compression and tension are obtained for medium models: effective isotropic medium, effective anisotropic medium, and layered composite with effective anisotropic medium texture layers.

1. Introduction

When testing sample structures made of composite materials, non-trivial methods should be used to determine values similar to the basic ones: strength and stiffness. In addition, the standards often recommend using a very rough but simple model to determine these values. In this regard, the issue of evaluating the experimental characteristics of the mechanical properties of sample structures made of composite materials with the parameters of the calculated inhomogeneous deformation and stress fields becomes the most relevant. Moreover, input information for such simulation can be obtained during the basic tests of standard samples, defining the generally accepted characteristics in tension, compression and displacement.

Composite materials have a set of properties and features that differ from traditional structural materials. Hence, they open up wide opportunities for improving existing structures for a wide range of purposes and for developing new structures and technological processes [1].

Three-dimensional reinforcing agents are used for high-performance composite materials in such industries as aerospace, mechanical engineering, aircraft and shipbuilding, metallurgy, nuclear and thermal power industry. Multilayer carbon fiber fabrics are used as a reinforcing material of carbon plastics for difficult and harsh conditions of exposure to high-speed aerodynamic flows, vibration and high temperatures. A review of technological and structural aspects, mechanical behaviors, as well as the current state and prospects for the use of three-dimensional fabrics in polymer composites are given in [2, 3].
A stress riser in a structure leads to a detailed study of the stress and deformable state in the concentration spots under the conditions of elasticity, plasticity and creep. Since the limiting state and destruction occurs precisely in the spots of stress concentration, the assessment of how much a particular raiser will affect the bearing capacity of an element [4-6] is of importance here.

In the numerical study of composite materials, various methods are used, however, the finite element method is very popular [7, 8]. Its main idea is that any continuous quantity, such as temperature, shift or pressure, can be approximated by a discrete model built on a set of piecewise continuous functions defined on a finite number of subdomains. Discrete functions are determined using the values of a continuous quantity at a finite number of points of the area considered. Numerical modeling is used both for assessing the ultimate strength [9] of a structure, and for modeling destruction, using various mechanisms and criteria [10-12].

2. Main part

2.1 Mathematical model

The scientific content of this work is the development of methods for calculating and analyzing the stress-strain state in the working area of composite materials samples when implementing the composite materials structural-phenomenological approach. The paper considers the numerical FE implementation of a multilevel approach when analyzing the processes of mechanical behavior of composite materials with inhomogeneous components and a complex structure in the working areas of samples structures. Practice has shown that even with the simplest versions of this approach (from considering an isotropic medium to a layered isotropic and layered anisotropic, in this case), it becomes possible to further compare the predicted characteristics, characteristics obtained during basic standard tests, and verify the comparison values, obtained in the course of non-trivial tests of structural samples.

The experimental part of the paper uses a unique scientific installation “Testing and Diagnostic Equipment Set for Studying Structural and Functional Material Properties under Complex Thermomechanical Effects” http://ckp-rf.ru/usu/501309/" at the Center experimental mechanics. The mathematical model for calculations is the structural and phenomenological model of composite material deformation and fracture [13]. The results of our own experiments and known reference data [14] are used as comparison characteristics. The stresses, in the absence of bulk forces, should satisfy the equilibrium equations:

$$\sigma_{ij}(r)=0, \quad i,j=1,2,3$$  \hspace{1cm} (1)

Small deformations are associated with displacement by the Cauchy relation

$$\varepsilon_{ij}(r) = \frac{1}{2} (U_{ij}(r) + U_{ji}(r)), \quad i,j=1,2,3$$  \hspace{1cm} (2)

$$\sigma_{ij} = C_{ijmn}(r)\varepsilon_{mn}, \quad i,j=1,2,3$$  \hspace{1cm} (3)

Thus, equations 1 to 3 describe the boundary value problem of the mechanics of composites within the framework of the structural and phenomenological model. If the composite properties are considered effective, the system of equations 1-3 is rewritten as:

$$\sigma_{ij}^* = 0, \quad i,j=1,2,3$$  \hspace{1cm} (4)

$$\varepsilon_{ij}^* = \frac{1}{2} (U_{ij}^* + U_{ji}^*), \quad i,j=1,2,3$$  \hspace{1cm} (5)

$$\sigma_{ij} = C_{ijmn}^*\varepsilon_{mn}^*, \quad i,j=1,2,3$$  \hspace{1cm} (6)

Equations 4-6 are supplemented with boundary conditions in displacements or stresses on the body surface S:
The geometric relationships that establish the relationship between structural deformations and displacements are as follows:

\[ \varepsilon_{ij} = \langle \varepsilon_{ij} \rangle + \frac{1}{2} (u_{i,3} \delta_{j3} + u_{j,3} \delta_{i3}) \]  

Then the constitutive relations take the form:

\[ \sigma_{ij} = C_{ijmn} \varepsilon_{mn} \]  

Boundary conditions

\[ \langle \varepsilon_{ij} \rangle x_j \bigg|_{\Sigma} = u_i^0 \]  
\[ \langle \sigma_{ij} \rangle n_j \bigg|_{\Sigma} = S_i^0 \]  

are equivalent to specifying macrodeformations \( \varepsilon_i^* = \langle \varepsilon_{ij} \rangle \) or macrostresses \( \sigma_i^* = \langle \sigma_{ij} \rangle \).
Three types of tests are simulated: compression of sample strips, compression of holed samples, bending of a curved beam. The geometry and dimensions of the samples comply with test standards ASTM D3039, ASTM D3410, ASTM D5766, ASTM D6484 and ASTM D641. We use the results of our own research as the isotropic material properties, namely, data from tests — Young’s modulus and Poisson's ratio [14]; data for calculating an anisotropic material are taken from a reference book. The isotropic material properties are given in table 1 and the anisotropic material properties are presented in table 2.

| Table 1. Properties of isotropic material. |
|-------------------------------------------|
| $E$, Pa | $\nu$ |
| 66     | 0.3   |

| Table 2. Properties of anisotropic material. |
|---------------------------------------------|
| $E_x$, Pa | $E_y$, Pa | $E_z$, Pa | $\nu_{xy}$ | $\nu_{yx}$ | $\nu_{zx}$ | $G_{yz}$, Pa | $G_{zx}$, Pa | $G_{xy}$, Pa |
|----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|-----------|
| 58 \times 10^9 | 29 \times 10^9 | 6 \times 10^9 | 0.2 | 0.2 | 0.2 | 3 \times 10^9 | 2 \times 10^9 | 4 \times 10^9 |

For each of the samples, grid models are built (Figure 1), using a 20-node finite element SOLID 186, a three-dimensional structural solid element with 20 nodes. This type of element has a quadratic displacement behavior and is well suited for modeling both regular and irregular grids. The accuracy of the numerical study is achieved through a preliminary analysis for the convergence of the solution when the grid is clustered. The parameters of the grid model in terms of the number of nodes and the quality of the grid model are given in Table 3. The improved grid quality parameters of the sample models considered are justified by simplified geometry. The grid model is adopted near the stress concentrators (sample hole and bend). When carrying out the calculations, a structured grid is used. It has not only a more advantageous application in terms of efficient use of computing resources, but also the ability to quickly change the parameters of the grid model. It allows to quickly and conveniently control the grid creation, which is important especially in areas that have characteristic geometric features.

![Figure 1. Mesh models of the sample - strip (a), sample with a hole (b), curved beam (c).](image)

| Table 3. Parameters of mesh models. |
|-------------------------------------|
| Parameter | Mesh structure model | Mesh model of a sample with a hole | Curved Beam Mesh Model |
|-----------|----------------------|-----------------------------------|------------------------|
| Number of nodes | 143022 | 139592 | 297077 |
| Amount of elements | 31122 | 30944 | 64872 |

When numerically modeling, the second stage after the grid is built should set the boundary conditions (Figure 2). For samples with or without a hole for the bottom surface, the boundary condition for limiting
the displacement along three coordinates is set, while, for the opposite surface, the condition of tension or compression by 100 Pa is set. For a curved beam sample, the lower planes of the surfaces have a displacement restriction in two coordinates; and displacement is allowed along the third coordinate. A load of 100 Pa is applied to the upper part of the sample for compression or tension.

Figure 2. Boundary conditions of sample - strip (a), sample with hole (b), curved beam (c).

For each of the above plates, as well as the curved beam, a calculation is made under compression and tension by 100 Pa. According to the results of calculations for each of the samples, the fields of stresses, strains and displacements under compression and tension are given for the medium models: effective isotropic medium, effective anisotropic medium, and layered composite with effective anisotropic medium texture layers (Figure 3).

Figure 3. Fields of distribution of equivalent stresses in compression of strip specimens (a-c), compression of specimens with a hole (d-f), curved beam (g-i) for models of the medium: effective isotropic medium (a, d, g), effective anisotropic medium (b, e, h) and a layered composite with texture layers of an effective anisotropic medium (c, f, i).
3. Conclusion
Thus, this paper constructs a boundary value problem of deformation and fracture of composite materials to determine the complex stress-strain state in the working areas of samples of medium models: effective isotropic medium, effective anisotropic medium, and layered composite with effective anisotropic medium texture layers. To determine the fields of stresses, deformations and displacements under compression and tension, the deformation of sample structures is numerically simulated. Numerical modeling is performed using the ANSYS engineering analysis system. Three types of tests are simulated: compression of sample strips, compression of holed samples, and bending of a curved beam. Sample geometry and dimensions comply with ASTM test standards. According to the results of calculations for each of the samples, the fields of stresses, deformations and displacements under compression are obtained.

Acknowledgements
This work was carried out in Perm National Research Polytechnic University using the equipment of the Centre of Collective Usage «Center of experimental mechanics» http://www.ckp-rf.ru/ckp/353547/ with the use of the results obtained in the study supported by The Russian Foundation for Basic Research (project No. 18-01-00763).

References
[1] Lubin J 1988 Reference book on composite materials (Moscow: Mechanical Engineering) 584
[2] Sharma P, Mali H S, Dixit A Mechanical behavior and fracture toughness characterization of high strength fiber reinforced polymer textile composites *Iranian Polymer Journal* 2020
[3] Asenjan M S, Sabet S A R, Nekoomanesh M 2020 *Iran Polym J* 29 301–307
[4] Senthil K, Arockiarajan A, Palaninathan R, Santhosh B, Usha K M 2013 *Compos Struct* 106 139-149
[5] Bespalov V A, Gotselyuk T B, Kovalenko N A, Olegin I P 2015 *Omsk Scientific Bulletin* 3 (143) 329-333
[6] Ataş A, Soutis C 2013 *Compos. Part B* 54 20–27
[7] Zenkevich O , Chang I 1967 The finite element method in the theory of structures and in mechanics of continuous media ( New York) 240
[8] Segerlind L 1979 Application of the finite element method (Moscow: MIR) 392
[9] Aidi B, Case S W 2015 *Compos Mater* 22 837–855
[10] Bian T, Guan Z, Liu F 2018 *Archive of applied mechanics* 1-20
[11] Guo Z, Zhu H, Li Y, Han X, Wang Z 2016 *Compos. Mater* 23 12091218
[12] Kumar D, Roy R, Kweon J-H, Choi J-H 2016 *Compos. Mater*. 23 397419
[13] Wildeman V, Sokolkin Yu, Tashkinov A 1998 The mechanics of inelastic deformation and fracture of composite materials (Moscow: Nauka) 288
[14] Babushkin A V , Babushkina A V, Strungar E M, Staroverov O A, Lobanov D S, Temerova M S, Feklistova E V 2019 *Procedia Structural Integrity* 17 658-665