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Modeling of Dependencies of Operational Properties of Three-Dimensional Reinforced Products from Composite Materials on Process-Dependent Parameters of Preform Production

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Summary

This article presents research and evaluation of practical methods for modeling the internal construction of composite materials such as fiber-polymer matrix, operational properties of items created using woven preforms, options for calculating their macromechanical properties on the basis of generation, and further analysis of meso-level models of three-dimensional reinforced structures.

INTRODUCTION

To calculate strength properties of structures from polymer composite materials having complex geometry, finite element analysis techniques may be used to determine averaged physical-mechanical properties of a representative elementary bulk reinforcement unit.

The design of products made from materials with a complex microstructure should be performed taking into account distribution of loads, and reinforcement diagram should ensure an even product, which involves development and optimization of the material directly with the design for every particular part.

The modern most common method for determining physical-mechanical characteristics of the material involves a series of measurements on test samples of structural materials. The design task with a wide range of possible design parameters involves a complex, time-consuming and costly series of experiments.

Thus, development of a systematic approach to optimal calculations of properties of composites with a given reinforcement diagram is very relevant today, as well as the task of designing preforms for composite products with specified properties. The major part of calculation procedures during designing of products made from composite materials is made with the help of finite-element packages, many thereof are characterized with built-in parametric optimization units that are optimally combined with end-to-end design technologies.

Insufficient impact resistance and tendency to interlayer cracking inherent in traditional layered composite materials is the main reason for the trend towards the use of three-dimensionally reinforced composite materials. In addition, automated production of preforms on specialized textile equipment will provide a significant reduction in the proportion of manual labor, increasing performance of the production process and quality of serial products [1-3].

The tasks to be solved when developing the technology of production of three-dimensional reinforced preforms and their introduction into production may be divided into the following groups:

1. Designing preforms with predefined parameters,
2. Development of methods for determining composition and structure of the preform, as well as a list of the parameters of the preforms required for their manufacture, control and identification;
3. Calculation of strength and technological parameters of preforms and products obtained on their basis;
4. Creation of specialized equipment for the technological cycle of creating preforms.

The results of the studies given in this paper are aimed to solve the problems of designing three-dimensionally reinforced preforms with specified characteristics and design prediction of their properties.

MATERIALS AND METHODS

As shown by previous experiments, under certain conditions, the addition of an insignificant mass fraction of the reinforcing filler in the form of weaving of the preform basic layers makes a significant contribution to the final properties of the article [4]. There are three levels of refining for numerical or analytical modeling of the mechanical behavior of woven composites:

a) At the *micro level*, individual strands of reinforcing material are modeled. This approach is resource-intensive and practically not used in KE modeling.

b) At the *meso level*, the constituent strands of woven CM are represented in the form of homogeneous volumes from a transversely isotropic material of a structure equivalent (with sufficient practical accuracy) in its parameters to the original one.

c) At the *macro level*, the woven composite material is modeled by three-dimensional finite elements. The material is assumed to be homogeneous, continuous, homogeneous. Strength characteristics are defined as the averaged values obtained for heterogeneous RVE structure studied at the mesolevel.

Calculation of rigidity and strength of the whole structure, taking into account all levels of the material structure, is a non-trivial task. Several approaches to its solution are considered in this study.

The macromechanical approach assumes each area of a construction with the same type of weaving as a continuous anisotropic material with averaged base ratios, taking into account some anisotropy of characteristics and material diversity of materials.

In this case, parameters of the macromechanical model may be determined in accordance with the results of tests for complex loading of elementary samples. The advantage of this approach refers to accounting of micromechanical characteristics and material features by averaging them during the transition to the macrolevel by measuring the integral material response in the experiment.

However, with this approach it becomes practically impossible to optimize the structure for reinforcing the material (weaving diagram), which negates all the advantages of bulk reinforcement, since performing numerous experiments for every new diagram of weaving is extremely resource intensive.

Using a representative volume cell method (Representative Volume Cell, RVC), provides for a transition from a micromechanical approach to a macromechanical approach, and involves several consecutive steps. First, a representative volumetric cell of the woven layer is modeled on the meso level, i.e. fiber and binder are modeled discretely. An example of modeling a three-dimensional woven composite RVC is shown in Figure 1.

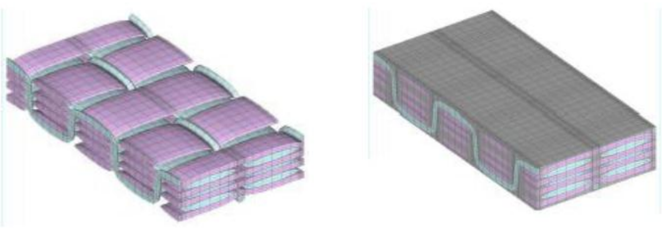


Figure 1. A representative bulk element RVC of bulk woven composite

Physical parameters of the fiber and binder, as a rule, are declared by the manufacturing companies as part of technical accompanying documentation. Further, on the basis of the unit cell, a representative volume element (Representative Volume Element, RVE) is determined. RVE stiffness matrix is calculated based on a unit cell. Microstresses in the cell (maximum stresses in the matrix and fibers) are also determined in these calculations, on the basis thereof the local strength is forecast. The specified element may be programmed through a user procedure in a typical computer analysis engineering environment (ANSYS, NASTRAN, ABAQUS). The product is calculated using a new element with the stiffness matrix specified in the meso level calculation and microvoltage recalculation matrix.

Thus, the entire structure is divided into zones with the same type of weaving (the same representative volume cell), then a representative volumetric element is constructed for every cell and the product is calculated in terms of its stiffness and strength, in accordance with the principles of multi-level modeling of composite structures [5].

Methodological principle of material homogenization through modeling and analysis of representative volume elements is as follows:

1) For a material with a periodic structure, a heterogeneous representative element is modeled, boundary conditions are imposed that ensure equivalence of the strain tensor in the strain element, which is characteristic for the corresponding homogeneous element of the simplified model.

2) For the model of the representative element, the medium stiffness tensor is determined, which is used to specify elastic characteristics of anisotropic material in a simplified homogeneous model of the entire product.

The following main tasks are distinguished in the course of creating mathematical models created within the framework of this work on the method of homogenization:

- construction of practically applicable geometric and finite element models of the periodicity cell;
- development of an algorithm for taking into account boundary conditions of periodicity for KE model of the periodicity cell;
- determination of effective mechanical characteristics of KE test with the possibility of their further application in modeling of structures made from this material at the macro-scale level, in particular, for determining properties of preforms and designing preforms with predetermined properties.

Software environment TexGen was used, that allows creating three-dimensional models for various types of woven CM was used to create a three-dimensional solid model of a representative volumetric element (RVE) of a test composite 3D reinforcement material. As an example, the process of creating a representative volumetric element of a multilayered woven structure is shown below.

Figure 2 shows a layer of woven composite 3-D weave material of 25x25 cells in a periodic structure. The corresponding RVE model is shown in Figure 3. The weave is formed by 7 layers of orthogonally oriented strands sewn across the entire thickness. Weaving parameters are presented in Tables 1 and 2.

Table 1. Geometric parameters of weaving.

Width of basic strands wx, m	1•10
Distance between basic strands, sy, m	1,575•10-3
Width of weft strands, wy, m	1•10-3
Distance between weft strands, sx, m	1,65•10-3
Width of edge strands	0,5•10-3
Thickness of strands, t, m	0,15•10-3

Table 2. Dimensions of the cell under study

dx, m	3,3•10-3
dy, m	3,15•10-3
dz, m	1,5675•10-3

When modeling, it is assumed that the sections of the strands are ellipses. Nevertheless, in the presence of appropriate experimental data, the shape of the sections may be refined.

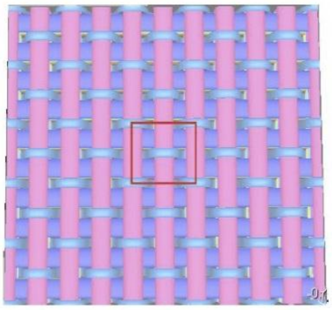


Figure 2. Woven composite of three-dimensional weaving with distinguished representative element

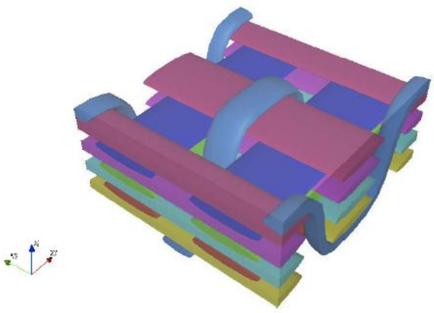


Figure 3. Geometric model of RVE. Isometry

The definition of the conditions of periodicity is an approximate approach to modeling mechanical properties of materials with a repetitive structure, consisting in using a basic representative element whose boundaries are superimposed on conditions that ensure the equivalence of average deformations tensor in the element versus deformations obtained in the corresponding homogeneous element for a simplified model. These conditions connect the displacements of nodes on the boundary of a representative element by the following relation: $u_i^{\beta} - u_i^{\alpha} = \bar{\varepsilon}_{ij} \cdot (x_j^{\beta} - x_j^{\alpha})$, in vector form: $\vec{u}^{\beta} - \vec{u}^{\alpha} = \bar{\varepsilon} \cdot \Delta\vec{x}$,

where: $u_i^{\alpha}, u_i^{\beta}$ -components of displacement vectors for 2 respective points designated as α and β, on the boundary of RVE, $\bar{\varepsilon}_{ij}$ - components of average deformations tensor (describing deformations of equivalent homogeneous element), x_j^{α}, x_j^{β} - coordinates of points.

The model of virtual nodes is used to determine the average deformation tensor. The displacements given in the virtual nodes correspond numerically to the average deformations, and the resulting reactions to the components of the average deformation tensor multiplied by the volume of the representative element.

The applied algorithm for imposing boundary conditions is constructed in accordance with the following principles:

a) Selecting the main node, for example, corresponding to the lower left corner of the representative element;
b) Sorting out the remaining nodes with the specification of communication equations for their own displacements with the movements of the main node.

With this option of setting periodicity conditions, the identity of KE grid on opposite faces is not required (figure 4):

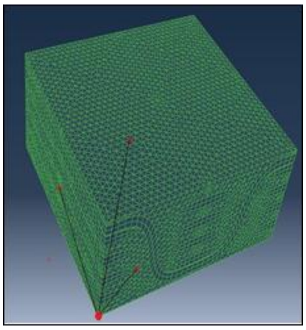


Figure 4. Imposition of communication equations on surface nodes of KE model of RVE

The basic finite element analysis programs contain modules for determining boundary conditions for periodicity. In the Mechanical unit of Ansys Workbench package, a symmetric modeling tool is provided that enables setting the following condition types in semi-automatic mode (without any need to define analytical dependencies):

a) Mirror symmetry;
b) Skew (inverse) symmetry;
c) Linear periodicity.

To determine the periodicity cell of a flat structure, impose the condition of linear periodicity on two pairs of lateral faces. The software environment SwiftComp, by virtue of its functional focus on the calculation of composites at the meso level, automatically calculates these conditions.

To check the convergence and determine the sufficient characteristic size of the finite element, test KE models (Figures 5-7) of different degrees of detail have been designed (two layers of elements for thickness of strands for the first option, and three for the second option). The following finite element types have been used to design a grid:

1) Hexagonal (hex) and wedge (wedge) for strands;
2) Tetrahedral (tet) for the matrix, due to its complex geometric form.

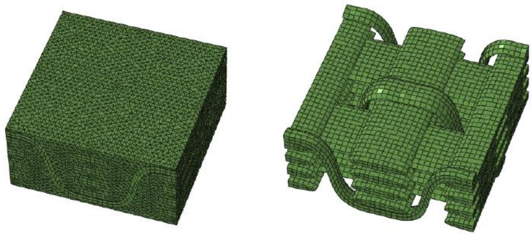


Figure 5. “Rough” (29 thousand nodes) KE model of RVE.

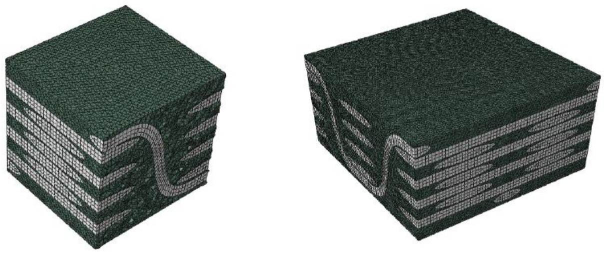


Figure 6. Detailed (162 thousand nodes) KE model

Dimensions of KE models are given in table 3.

Table 3. Characteristics of KE models under study

№	Typical size of element, m	Number of nodes	Number of elements
1	1·10-4	29167	105336
2	5·10-5	162367	636112

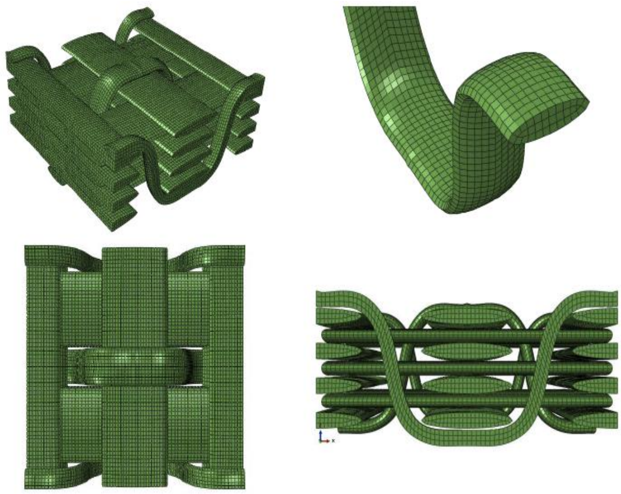


Figure 7. KE grid for RVE strands

As described above, the material of the reinforcing strands shall be taken into account in the model as orthotropic. Positioning of the local basis is based on the bending of the fiber (“tracking” coordinate system), local SKs are automatically generated in TexGen software. The distribution of the orientation vectors of local SKs in the cells of the fiber grid is shown in Figure 8:

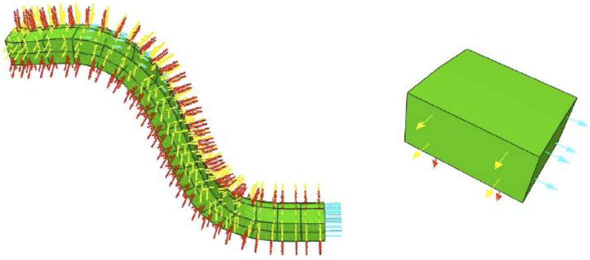


Figure 8. Axis of strand material properties orientation

Homogeneous material with the following characteristics has been used to verify boundary conditions:

a) Module of elasticity E = 2·1011 Pa;
b) Poisson ratio ν = 0,3.

The components of the rigidity tensor obtained for RVE should be close to analytically calculated from the generalized Hooke's law:

$$\sigma_x = \lambda e + 2G\varepsilon_x,$$

$$\sigma_y = \lambda e + 2G\varepsilon_y,$$

$$\sigma_z = \lambda e + 2G\varepsilon_z,$$

$$\tau_{xy} = 2G\varepsilon_{xy}, \tau_{xz} = 2G\varepsilon_{xz}, \tau_{yz} = 2G\varepsilon_{yz},$$

where $e = \varepsilon_x + \varepsilon_y + \varepsilon_z$ is bulk deformation, $\lambda = \frac{\nu E}{(1+\nu)(1-2\nu)}$.

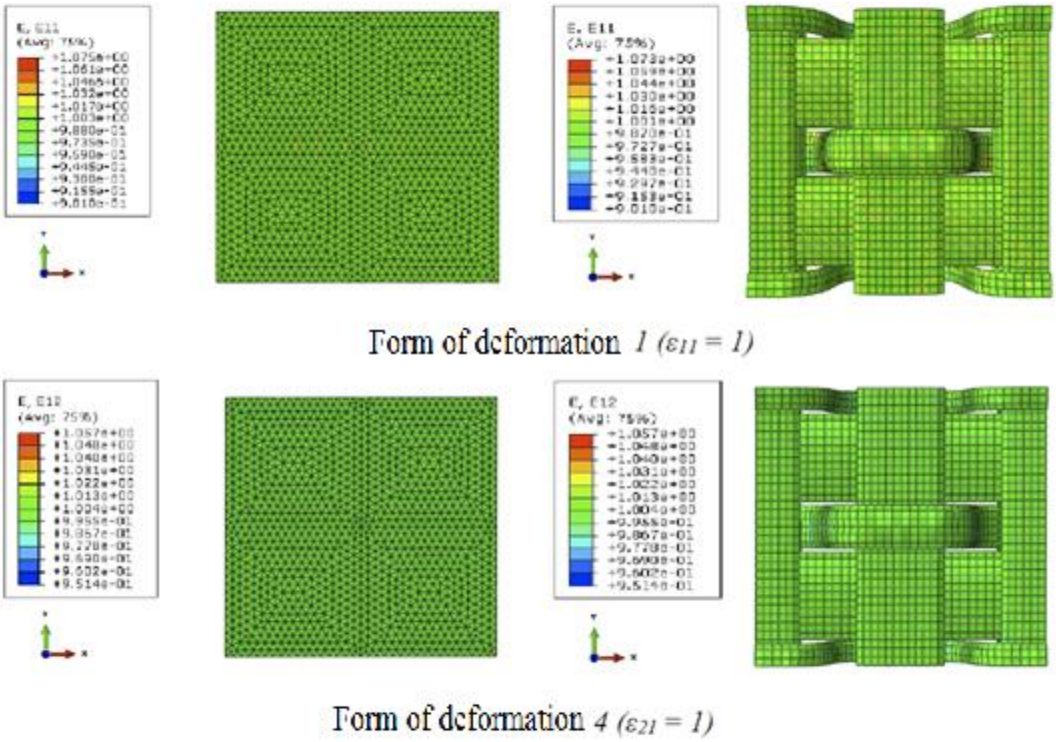
For deformations we have: $\varepsilon_x = \frac{1}{E}\left(\sigma_x - \nu(\sigma_y + \sigma_z)\right)$

The definition of the components of the medium rigidity tensor of RVE is performed in the following sequence:

a) Elementary forms of deformation are successively realized by setting single units in virtual nodes;
b) The reactions in these nodes are determined, stresses from unit deformations equal to the corresponding components of the medium rigidity tensor.

The ratios of the stiffness tensor components are given in Tables 4-6 (in Tables 5-6 after the values of the tensor components, deviations from corresponding values calculated analytically are given in parentheses). Maximum discrepancy is 1.3% for model 1 and 0.74% for model 2, which may be considered acceptable. Figure 9 below shows deformation fields for the 1st (stretching) and 4th (shift) deformation forms. The numbering of the components of stress and strain tensors is as follows:

1	x
2	y
3	z
4	xy
5	xz
6	yz



Form of deformation

Figure 9. Forms of deformations for test model 1 with test isotropic material

Table 4. Elements of matrix of stiffness tensor calculated analytically, Pa.

	1	2	3	4	5	6
1	$2{,}6923\cdot10^{11}$	$1{,}1538\cdot10^{11}$	$1{,}1538\cdot10^{11}$	0	0	0
2	$1{,}1538\cdot10^{11}$	$2{,}6923\cdot10^{11}$	$1{,}1538\cdot10^{11}$	0	0	0
3	$1{,}1538\cdot10^{11}$	$1{,}1538\cdot10^{11}$	$2{,}6923\cdot10^{11}$	0	0	0
4	0	0	0	$1{,}5385\cdot10^{11}$	0	0
5	0	0		0	$1{,}5385\cdot10^{11}$	0
6	0	0	0	0	0	$1{,}5385\cdot10^{11}$

Table 5. Elements of matrix of stiffness tensor obtained by calculation methods from calculation of RVE for a test model 1, Pa.

	1	2	3	4	5	6
1	$2{,}6847\cdot10^{11}$ (0,3%)	$1{,}1467\cdot10^{11}$ (0,61%)	$1{,}1389\cdot10^{11}$ (1,3%)	0	0	0
2	$1{,}1467\cdot10^{11}$ (0,61%)	$2{,}6847\cdot10^{11}$ (0,3%)	$1{,}1389\cdot10^{11}$ (1,3%)	0	0	0
3	$1{,}1389\cdot10^{11}$ (1,3%)	$1{,}1389\cdot10^{11}$ (1,3%)	$2{,}6589\cdot10^{11}$ (1,2%)	0	0	0
4	0	0	0	$1{,}5381\cdot10^{11}$ (0,03%)	0	0
5	0	0		0	$1{,}5327\cdot10^{11}$ (0,38%)	0
6	0	0	0	0	0	$1{,}5327\cdot10^{11}$ (0,38%)

Table 6. Elements of matrix of stiffness tensor obtained by calculation methods from calculation of RVE for a test model 2, Pa.

	1	**2**	**3**	**4**	**5**	**6**
1	$2{,}6879 \cdot 10^{11}$ (0,16%)	$1{,}1497 \cdot 10^{11}$ (0,35%)	$1{,}1453 \cdot 10^{11}$ (0,74%)	0	0	0
2	$1{,}1497 \cdot 10^{11}$ (0,35%)	$2{,}6880 \cdot 10^{11}$ (0,16%)	$1{,}1453 \cdot 10^{11}$ (0,74%)	0	0	0
3	$1{,}1453 \cdot 10^{11}$ (0,74%)	$1{,}1453 \cdot 10^{11}$ (0,74%)	$2{,}6733 \cdot 10^{11}$ (0,71%)	0	0	0
4	0	0	0	$1{,}5382 \cdot 10^{11}$ (0,02%)	0	0
5	0	0	0	0	$1{,}5359 \cdot 10^{11}$ (0,17%)	0
6	0	0	0	0	0	$1{,}5356 \cdot 10^{11}$ (0,17%)

The resulting stiffness tensor components for heterogeneous RVE with mechanical characteristics of the material mentioned above for the two models considered are given in Tables 7 and 8. A comparison of the results is shown in Table 9, from which it follows that maximum discrepancy is 1.14%. Thus, the calculation for a more detailed KE model (containing 5 times more nodes) did not lead to a significant difference in the results. From this it can be concluded that the characteristic size of the finite element taken in model 1 of 0.06 parts of RVE thickness is sufficient to obtain effective stiffness characteristics for homogenization of woven CM. This conclusion is relevant in view of the significant requirements for computational resources required by calculations of this kind. The obtained effective stiffness characteristics of a woven CM may be further used to determine elastic constants of an anisotropic material in the construction of simplified homogeneous models of structures.

Table 7. Elements of matrix of stiffness tensor components for heterogenous RVE for test model 1, Pa.

g	**1**	**2**	**3**	**4**	**5**	**6**
1	$1{,}6006 \cdot 10^{10}$	$3{,}9896 \cdot 10^{9}$	$4{,}0407 \cdot 10^{9}$	0	0	0
2	$3{,}9896 \cdot 10^{9}$	$1{,}7305 \cdot 10^{10}$	$3{,}8332 \cdot 10^{9}$	0	0	0
3	$4{,}0407 \cdot 10^{9}$	$3{,}8332 \cdot 10^{9}$	$8{,}5278 \cdot 10^{9}$	0	0	0
4	0	0	0	$4{,}9701 \cdot 10^{9}$	0	0
5	0	0	0	0	$4{,}1386 \cdot 10^{9}$	0
6	0	0	0	0	0	$4{,}0167 \cdot 10^{9}$

Table 8. Elements of matrix of stiffness tensor components for heterogenous RVE for test model 1, Pa.

	1	**2**	**3**	**4**	**5**	**6**
1	$1{,}6169 \cdot 10^{10}$	$4{,}0063 \cdot 10^{9}$	$4{,}0872 \cdot 10^{9}$	0	0	0
2	$4{,}0063 \cdot 10^{9}$	$1{,}7470 \cdot 10^{10}$	$3{,}8637 \cdot 10^{9}$	0	0	0
3	$4{,}0872 \cdot 10^{9}$	$3{,}8637 \cdot 10^{9}$	$8{,}5900 \cdot 10^{9}$	0	0	0
4	0	0	0	$4{,}9881 \cdot 10^{9}$	0	0
5	0	0	0	0	$4{,}1354 \cdot 10^{9}$	0
6	0	0	0	0	0	$4{,}0142 \cdot 10^{9}$

Table 9. Divergence between calculated effective stiffness characteristics

	1	**2**	**3**	**4**	**5**	**6**
1	1,01%	0,42%	1,14%	0	0	0
2	0,42%	0,95%	0,79%	0	0	0
3	1,14%	0,79%	0,73%	0	0	0
4	0	0	0	0,36%	0	0
5	0	0	0	0	0,08%	0
6	0	0	0	0	0	0,06%

Table 10. Properties of reinforcing fibers.

Name	**HTS45**	**IMS65**	**Pycap-C**
Fiber material	Carbon	Carbon	Aramid
Use	A part of fabric	Sewn strand	Weaving strand
Filament diameter, µm	7	5	7,6
Number of filaments	12K	24K	450
Weight per meter, tex	800	830	29
E_1, GPa	240	290	170
E_2, GPa	16	19,3	11,3
G_1, GPa	100	121	68
G_2, GPa	6,4	7,7	4,4
ν_1	0.2	0.2	0,25
ν_2	0.25	0.25	0.3

Mathematical models of textile structures suitable for performance of theoretical calculations shall take into account physical-mechanical properties of fibers and resins actually used in practice. The averaged characteristics of epoxy binders used for processing by closed impregnation technologies have been selected to perform a calculation of the matrix material parameters:

E = 3500 MPa, ν = 0.35,

where E – modulus of elasticity, ν – Poisson ratio.

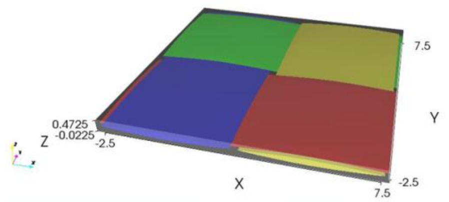
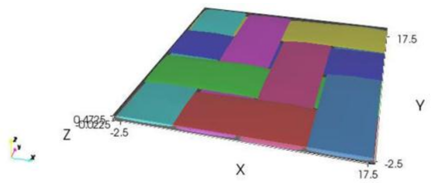
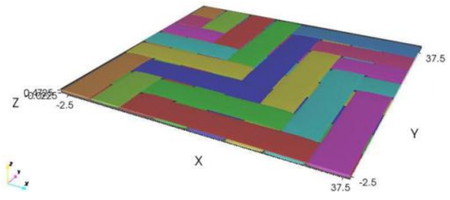
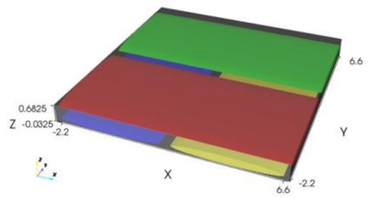
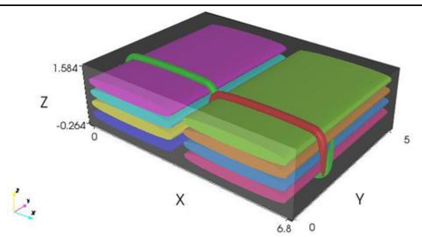
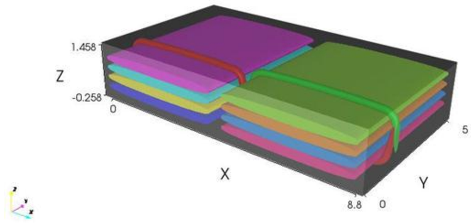
The properties of the test reinforcing fillers used for preforms in the form of fabric strands, sewn strands and weaving strands are given in Table 10:

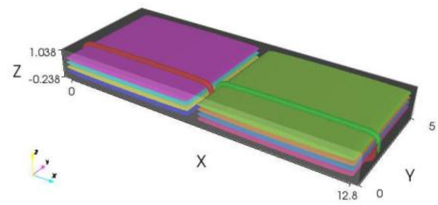
Mathematical models of a representative cell of the following textile structures have been created for a study:

a) Preform on the basis of fabric from HTS45 fiber, fiber width 4.7 mm, fabric thickness 0.45 mm, fiber orientation 0°/90°, weaving options: fabric, twill 2/2, twill 4/4 (models 1 - 3);
b) Non-woven preform on the basis of IMS65 fiber, 0°/90° orientation, fiber width 4 mm, weaving is not taken into account (model 4).
c) Sewn preform on the basis of IMS65 fiber, 0° orientation; fiber width 3, 4, 6 mm, Rusair-C fiber weaving (models 5 - 7) every 5 mm.
d) Sewn preform on the basis of IMS65 fiber, 0° orientation, fiber width 4 mm, Rusair-S fiber weaving, every 3, 10, 15 mm (models 8-10);

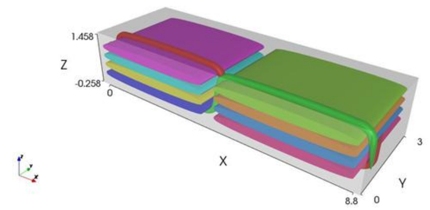
Visual representation of created mathematical models is given in Table 11:

Table 11. Visual representation of preform mathematical models

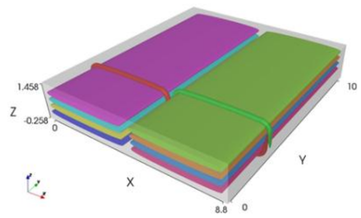
	
Model 1. Preform on the basis of HTS45, fabric weaving	Model 2. Preform on the basis of HTS45, weaving Twill 2/2
	
Model 3. Preform on the basis of HTS45, weaving Twill 4/4	Model 4. Preform on the basis of IMS65, without regard to weaving
	
Model 5. Preform on the basis of IMS65, 0°, stitch width 3 mm	Model 6. Preform on the basis of IMS65, 0°, stitch width 4 mm



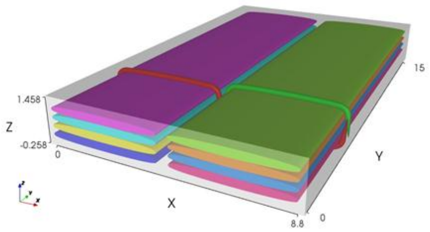
Model 7. Preform on the basis of IMS65, 0°, stitch width 6 mm



Model 8. Preform on the basis of IMS65, 0°, stitch width 4 mm, weaving interval 3 mm



Model 9. Preform on the basis of IMS65, 0°, stitch width 4 mm, weaving interval 10 mm



Model 10. Preform on the basis of IMS65, 0°, stitch width 4 mm, weaving interval 15 mm

Results of studies of operational characteristics of composites by means of developed mathematical models

Homogenization of the material properties on the periodicity cell to obtain the reduced stiffness constants of the equivalent orthotropic material was performed in SwiftComp software. The results of the calculation are given in Table 12.

Table 12 - The reduced stiffness constants for an equivalent orthotropic material

	E1, Pa	E2, Pa	E3, Pa	G12, Pa	G13, Pa	G23, Pa	v12	v 13	v 23
1	6,78E+10	6,78E+10	9,35E+09	6,95E+09	2,93E+09	2,93E+09	0,06	0,36	0,36
2	8,30E+10	8,30E+10	1,07E+10	9,55E+09	3,81E+09	3,81E+09	0,04	0,34	0,34
3	8,60E+10	8,61E+10	1,08E+10	9,84E+09	3,78E+09	3,78E+09	0,03	0,34	0,34
4	9,20E+10	9,20E+10	1,05E+10	8,09E+09	3,18E+09	3,18E+09	0,03	0,36	0,36
5	8,49E+09	1,52E+11	6,64E+09	4,31E+09	2,43E+09	3,15E+09	0,01	0,21	0,23
6	1,04E+10	1,47E+11	8,29E+09	5,16E+09	2,37E+09	2,86E+09	0,02	0,37	0,32
7	1,10E+10	1,47E+11	8,21E+09	5,85E+09	2,35E+09	2,74E+09	0,02	0,38	0,32
8	1,17E+10	1,47E+11	8,55E+09	5,35E+09	2,49E+09	2,98E+09	0,02	0,37	0,32
9	1,13E+10	1,52E+11	8,42E+09	8,61E+09	2,41E+09	2,79E+09	0,02	0,37	0,32
10	1,13E+10	1,53E+11	8,36E+09	8,59E+09	2,38E+09	2,76E+09	0,02	0,37	0,32

Based on the data given in the table, the dependencies of the rigidity characteristics of the preform have been analyzed from three variable values:

a) type of weaving (bending degree of the bearing strands);
b) degree of compression of the thread in weaving (stitch width of the weaving machine);
c) weaving intervals (the distance between the lines of weaving).

The diagram of dependence of the reduced modulus of elasticity and modulus of the interlayer shift of the monolayer on the type of weaving is shown in Figures 10-11:

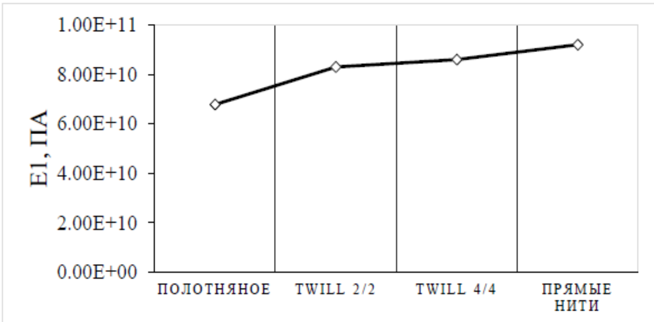


Figure 10 Dependence E1 on the type of weaving

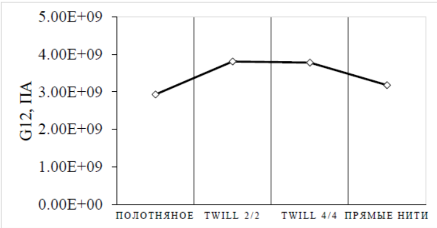


Figure 11 Dependence G23 on the type of weaving

As shown in the figures, the shape of strands significantly (up to 40%) affects the stiffness when stretching the pack in the plane of the layers. The diagram of dependence of the reduced moduli of elasticity of a monolayer (due to the features of TexGen software, in the given mathematical models, the axis along the fibers corresponds to the axis 2, across the fibers is axis 1), and the modulus of the monolayer shift on the stitch width of the weaving machine are shown in Figures 12-14:

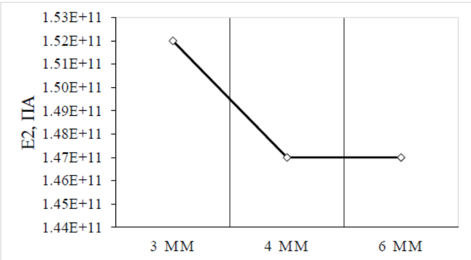


Figure 12– Dependence of the modulus of elasticity along fibers on the stitch width

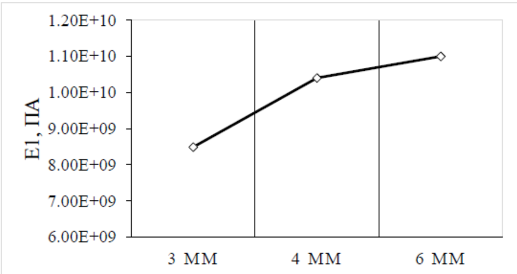


Figure13 Dependence of the modulus of elasticity across fibers on the stitch width

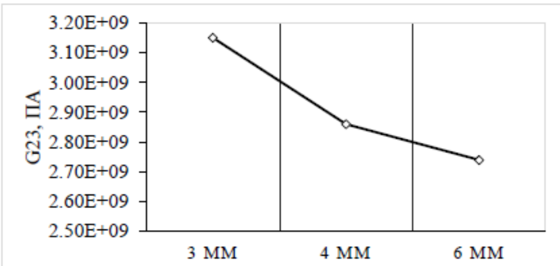


Figure 14 Dependence of inter-layer shift modulus on the stitch width

As shown in the diagrams, the maximum stitch width has an effect on the modulus of elasticity across the fibers (up to 30% in the range under consideration) and shift modulus (up to 15%). The diagram of the dependence of the reduced moduli of elasticity of a monolayer and monolayer shift modulus on the frequency of weaving is shown in Figures 15-17:

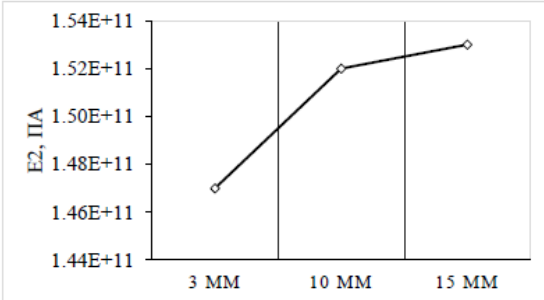


Figure 15 Dependence of the modulus of elasticity along fibers on the weaving interval

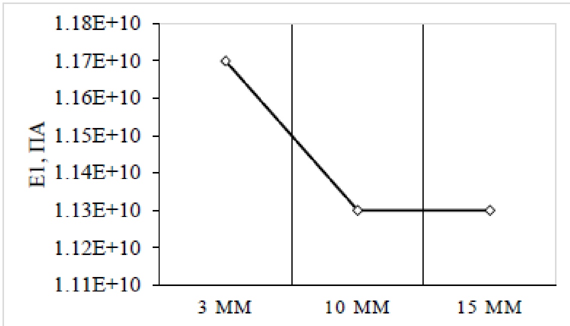


Figure 16 Dependence of the modulus of elasticity across fibers on the weaving interval

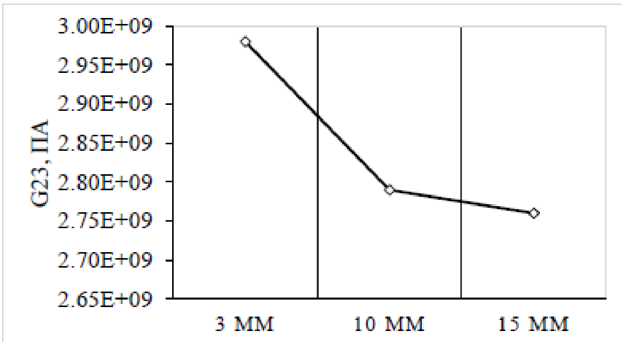


Figure 17 Dependence of the shift modulus on the weaving interval

The diagrams above show that weaving interval for a given geometry and selected materials of microstructure to a lesser extent affects its rigidity. Based on the diagrams above, the weaving interval has a maximum influence (close to 8%) on the interlayer shift module.

CONCLUSION

In the course of this work, the following tasks to study and evaluate practical methods for modeling the internal design of composite materials have been solved:

1) The scope and principles of the numerical experiment have been specified;
2) The review of specialized software on the market for implementation of profile calculations has been performed;
3) The method and main principles of construction of computational mathematical models have been given;
4) A series of mathematical models of textile structures has been created;
5) Simulation modeling of the mechanics of composites at the mesolevel has been made;
6) Conclusions on the influence of individual parameters of the textile structure of the preform on the final properties of the product have been presented.

Summarizing the data of theoretical studies performed in this paper, we can make the following conclusions:

a) To improve the performance of composite products, it is recommended to use preforms with minimally curved, preferably straight strands. In this regard, the preforms obtained by strand sewing are preferable to the fabric ones, giving a benefit in hardness of up to 40%.
b) Maximum stiffness in the interlayer shift is achieved by introducing a number of transverse bonds within a layer. Weaving Twill 2/2 is optimal for the fabric structures used.
c) Tensile rigidity along fibers and at interlayer shift shows the best values with the maximum compressed strand. Stiffness in tension across the fibers is maximal with a minimally compressed strand, and here the coefficient of influence is stronger (up to 30% in the considered range).
d) The increase in the weaving density slightly reduces tensile modulus along the fibers, but more significantly (up to 8% in the range under consideration) the stiffness and strength at interlayer shift increase.
e) It has been substantiated that direction of laying, as well as nature of the process of obtaining the preform structure, have a significant effect on the physical and mechanical properties of composite materials.

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REFERENCES

[1] Gareev A.R. Development and research of three-dimensionally-reinforced carbon plastics on the basis of core structures of the filler: thesis of the Candidate of Technical Sciences: 05.16.06/Gareev A.R.; [Place of defense: Research Institute of Structural Materials]. - Moscow, 2015. - 113 p.

[2] Donetskiy K.I., Raskutin A.E., Khilov P.A., Lukyanenko Yu.V., Belinis P.G., Korotygin A.A. Volumetric textile preforms used in the manufacture of polymer composite materials (review) //The WORKS OF VIAM, - 2015.-No.9. -p. 13.

[3] Gorbatkina Yu.A., Strength of the interface in compounds of dispersed-filled epoxy binder with fiber/Yu.A. Gorbatkina, V.G. Ivanova-Mumzhieva, A.S. Putyatin, T.M. Ulyanov//Mechanics of composite materials. - 2007. P. 43. No.1.

[4] Mikheev P.V., Orlov M.A., Shatalov R.L., Verkhov E.Yu. Influence of the preform weaving with aramid strands on the shift characteristics of the final product from CF composite material//System technologies - No.3 (16), 2015, p.37-42.

[5] Yu. I. Dimitrienko, A.P. Sokolov, Multiscale modeling of elastic composite materials, Mathematical modeling, 2012, Volume 24, No. 5, 3-20.

[6] Nelyub, V.A., Borodulin, A.S., Kobets, L.P., Malysheva, G.V. Capillary hydrodynamics of oligomer binders 2016 Polymer Science - Series D, 9(3), p. 322-325

[7] Nelyub, V.A. Determination of adhesion interaction between carbon fiber and epoxy binder 2015. Polymer Science - Series D, 8(1), p. 6-8

[8] Nelyub, V.A., Borodulin, A.S., Kobets, L.P., Malysheva, G.V. A study of structure formation in a binder depending on the surface microrelief of carbon fiber, 2016. Polymer Science - Series D, 9(3), p. 286-289