

# Prediction of elastic characteristics of spatially reinforced composite materials

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**Abstract.** Numerical prediction of elastic characteristics of spatially reinforced composite materials (SRCM) with various reinforcement schemes is carried out in the work. Idealized SRCM structures constructed using TexGen, as well as parametrized geometric models constructed manually, are considered. It is revealed that, in spite of TexGen algorithms improved in recent times, it is impossible to achieve the required volume fraction of fibers corresponding to a real composite when constructing models of complex spatial structure of SRCM, and besides, self-intersection of weft and sewing threads often occurs. To eliminate the identified errors, idealized, parametrized geometric models in the language APDL were developed. In the framework of the developed geometric models, it was possible to realize a more dense arrangement of filaments in the frame, which allowed to maintain the percentage of the volume fraction of the reinforcing cage for the structures under consideration. The effective elastic characteristics of SRCM calculated using the developed numerical models and obtained as a result of mechanical tests were compared.

## 1. Introduction

One of the promising technologies for creating composite materials with high physical and mechanical properties is the technology of spatial weaving of reinforcing skeletons. Spatially reinforced composite materials (SRCM) are used to create highly loaded structures of aerospace industry. To develop such materials, corresponding to different operational requirements, it is necessary to use methods for predicting their mechanical properties [1].

At present, an approach based on computer modeling of their geometric structure is widely used to predict the mechanical properties of SRCM. Using the constructed geometric models, the micromechanics problem for predicting the mechanical properties of a SRCM reduces to a set of boundary conditions for either the periodicity cell or the structure fragments. From the solution of these problems, the stress and strain fields in the fibers and the composite matrix are determined, averaging and subsequent comparison of which makes it possible to find its effective mechanical properties.

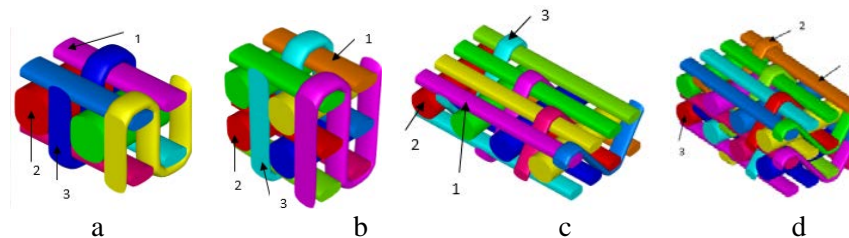
To construct geometric models of SRCM, special software packages are developed, originally designed for modeling textile composites with two-dimensional weaving. The most famous packages are WiseTex [2-5] and TexGen [6, 7]. Using these packages, it is possible to construct an idealized composite structure, which leads to errors in predicting mechanical properties. To obtain real models of the three-dimensional structure of the composite, various corrections of model structures are used based on the results of optical microscopy or tomography of composite materials [8-10].



In this paper, we propose an algorithm for automatically correcting the model structure of SRCM obtained using the TexGen software package. It is shown that it is possible to improve the accuracy of predicting the elastic mechanical characteristics of SRCM using the proposed algorithm, which allows to describe the enveloping of the contacting fibers more accurate and to exclude their intersection.

## 2. Problem formulation

The object of the study was woven spatially-reinforced composite material with four variants of weaving (Figure 1): variants 1 and 2 have rectilinear fibers in three directions; 3 and 4 have straight-line fibers in two directions. The structure of weaving of SRCM fibers is a system of three threads: warp, weft and sewing yarns (Figure 1). The volumes between the reinforcing carcass filaments are filled with a matrix. The volume fraction of reinforcing yarns in the structures under consideration was determined within the framework of morphological studies of SRCM and constituted for weaving variants: 51.7%; 52.8%; 50.9%; 60.5% respectively.



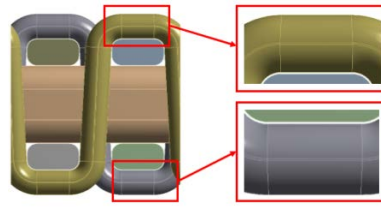
**Figure 1.** General view of geometric models of SRCM periodicity cells constructed with the help of TexGen, structures: a - 1; b - 2; c - 3; d - 4.

The technology of manufacturing SRCM includes the preparation of a woven fiber skeleton with the possibility of changing the parameters of the weave and subsequent impregnation with a reactive plastic binder under pressure in a rigid form (RTM). In the process of impregnation, the parameters of the fiber skeleton can be unevenly altered by the volume of the billet. All this leads to heterogeneity of mechanical properties of SRCM in the finished product. The solution of the problem of prediction of elastic characteristics makes it possible to evaluate the influence of the fiber framework parameters on the mechanical properties of SRCM.

For the prediction, geometric models of fragments of the spatial structures of SRCM were constructed using the TexGen software package (Figure 1) and corrected further using the developed algorithm. Further for the fragments, elastic problems with periodic boundary conditions were solved, and averaging was performed, obtained fields of structural stresses and deformations. By comparison of the averaged (macroscopic) stresses and deformations found, the effective elastic characteristics of the SRCM were found.

## 3. Construction of geometric models of the structure of SRCM

The initial data for constructing geometric models of the cells of periodicity were the cross-sectional area of the filaments and the distance between their centers. They were determined on the basis of the given parameters of the linear density of filaments and the density of laying on the base and weft. When constructing geometric models, the following assumptions were used: solid threads, the interphase layer between the matrix and the filaments is absent, the technological dispersion in the area of contact between the fibers of the warp, weft and sewing threads, a guaranteed interlayer of the matrix was set (Figure 2).



**Figure 2.** General view of the geometric model with a guaranteed interlayer of the matrix between the filaments.

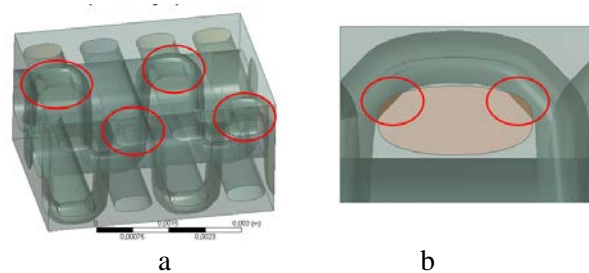
Assuming an ideal packing of fibers in a complex filament, its conditional cross-sectional area  $S$  can be determined by specifying the linear density of the complex yarn  $T$ , the density of the yarn material  $\rho$ , and the degree of volume filling of the filaments in the yarn  $k$  can be determined using formula:

$$S = \frac{T}{\rho k} \quad (1)$$

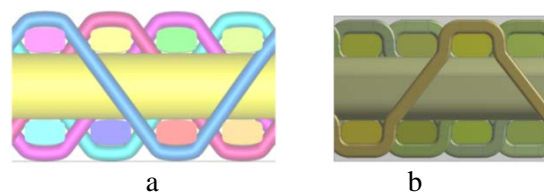
Initially, cells of the periodicity of four different versions of idealized structures were constructed for the SRCM under consideration using the TexGen software package (Figure 1). The structures differ in the straightness of the fibers in the directions, in the number of layers, and in the volume fractions of the reinforcing carcass and threads along the directions

Subsequent studies have shown that, despite the improved TexGen algorithms recently, it is impossible to achieve a volume fraction of fibers corresponding to the real material when constructing geometric models of SRCM structures. In addition, self-intersections of weft and sewing threads appear in the construction of models (Figure 3), which in turn leads to errors when the geometric model is divided into finite elements, and also affects the accuracy of the results of numerical calculations.

To eliminate these shortcomings, an algorithms for constructing idealized parametrized geometric models of SRCM structures were developed. The algorithms took into account the deformability, density, volume fractions of threads along directions. With the help of developed algorithms implemented in the language APDL ANSYS, it was possible to implement a more dense arrangement of threads in the frame and eliminate their self-intersections. As a result, the SRCM periodicity cells (Figure 4) were obtained with a volume fraction of fibers corresponding to the real composite material. Further, predictions of the elastic characteristics of the SRCM with four variants of fiber weaving were made.



**Figure 3.** Intersection of filaments at bending points: a - isometry; b - side view.



**Figure 4.** A geometric model of structure 3 constructed using: a - TexGen; b - APDL.

Prediction of elastic characteristics was carried out for two types of periodic cells of SRCM with four variants of weaving of fibers, named further: 1, 2, 3, 4 (Figure3).

#### 4. Peculiarities of the numerical solution of the problem for the fragment of the structure of SRCM

To predict the effective elastic characteristics of SRCM, the problems of elastic deformation of fragments of the constructed model structures with periodic boundary conditions were solved. The solution was implemented using the ANSYS software. Discretization of the investigated fragments was carried out using the spatial finite elements of SOLID186. The minimum size of the finite element, for all structures, was set equal to the thickness of the guaranteed interlayer of the binder between the filaments and was 0.01 mm. The degree of sampling was chosen on the basis of the estimated convergence of the numerical solution with respect to the maximum stresses. The total number of finite elements amounted to 4-8.5 million elements for structure 1-4. In Figure 5, as an example, a fragment of the finite element model of the textile framework and the representative volume of SRCM for the structure variant 3 is given.



**Figure 5.** General view of the finite element model of the SRCM fragment (a) and the SRCM fiber skeleton (b) for the third variant of the structure 3.

Carbon filaments were modeled as a unidirectional fiber composite having a transversely isotropic symmetry system. In each finite element belonging to a carbon filament, local coordinate systems were assigned corresponding to the principal axes of symmetry of the material. Between the interacting threads in the model, the ideal contact condition was specified.

The SRCM structures under consideration are orthotropic and are characterized by nine independent elastic constants: Young's moduli  $E_x$ ,  $E_y$ ,  $E_z$ , Poisson's ratios  $\nu_{xy}$ ,  $\nu_{yz}$ ,  $\nu_{xz}$ , and shear moduli  $G_{xy}$ ,  $G_{yz}$ ,  $G_{xz}$ . For each fragment, six boundary-value problems were solved numerically: stretching along the X, Y, Z axes to determine effective Young's moduli and Poisson's ratios and a net shift in the planes XY, XZ, YZ to determine the shear moduli.

The elastic characteristics of carbon filaments were calculated from the models for a unidirectional fibrous composite [11], the properties of the polymer binder were taken from experimental data (Table 1).

**Table 1.** Material properties used in the calculation.

Material	$E_x$ , GPa	$E_y$ , GPa	$E_z$ , GPa	$\nu_{xy}$	$\nu_{yz}$	$\nu_{xz}$	$G_{xy}$ , GPa	$G_{yz}$ , GPa	$G_{xz}$ , GPa
Carbon thread	240	14	14	0.014	0.24	0.014	6.93	12.84	6.93
*		3.10			0.34			1.15	

#### 5. Results

The resulting effective elasticity characteristics of SRCM for the considered variants of structural models constructed with the help of the TexGen software complex without correction and corrected according to the developed algorithm realized in the language APDL are presented in Table 2. Analysis

of calculation results showed that the elastic moduli of SRCM for structure models, constructed using the corrective algorithm (APDL), are usually higher than those obtained based on the original TexGen models. This is due to a denser layout and the absence of fiber intersections in the model structure of SRCM, obtained as a result of the adjustment.

**Table 2.** Calculated effective elastic properties of SRCM.

Geometric model	$E_x$ , GPa	$E_y$ , GPa	$E_z$ , GPa	$\nu_{xy}$	$\nu_{yz}$	$\nu_{xz}$	$G_{xy}$ , GPa	$G_{yz}$ , GPa	$G_{xz}$ , GPa
Var. 1 <i>APDL</i>	59,98	44,28	6,931	0.074	0.260	0.273	3,39	2,83	2,71
Var. 1 <i>TexGen</i>	62,40	42,30	7,00	0,081	0,301	0,28	3,24	2,90	2,55
Var.2 <i>APDL</i>	61,01	43,88	7,23	0.079	0.254	0.260	3,33	2,84	2,76
Var. 2 <i>TexGen</i>	60,10	42,50	7,01	0,082	0,302	0,283	3,35	2,95	2,61
Var. 3 <i>APDL</i>	57,01	55,72	7,16	0.042	0.278	0.291	3,26	2,67	2,71
Var. 3 <i>TexGen</i>	48,70	46,82	6,55	0,054	0.313	0,326	2,63	2,45	2,45
Var.4 <i>APDL</i>	68,06	64,74	8,361	0.355	0.252	0.248	3,78	3,41	3,34
Var. 4 <i>TexGen</i>	68,01	63,50	8,05	0,356	0.243	0,226	2,91	3,35	3,45

The calculated effective elastic properties of SRCM were compared with the experimental estimates of the mechanical properties of the composite obtained from the OX stretching tests of the variants of structures 1 and 3 and the shear tests in the OXY plane of the variants of structures 2 and 4 (Table 3). The comparison showed that for models corrected using the developed algorithm (APDL), the error in predicting the elastic characteristics is several times smaller than in the initial models obtained with TexGen. The maximum prediction error is observed for the  $G_{xy}$  shear modulus and is no more than 10% for the developed geometric models (APDL), and for the TexGen initial models is 30%.

**Table 3.** Comparison of the calculated and experimental elastic characteristics of SRCM.

Geometric model	$E_x^{calc}$ , GPa	$\nu_{xy}^{calc}$	$G_{xy}^{calc}$ , GPa	$\frac{(E_x^{calc} - E_x^{exp})}{E_x^{exp}}, \%$	$\frac{(\nu_x^{calc} - \nu_x^{exp})}{\nu_x^{exp}}, \%$	$\frac{(G_x^{calc} - G_x^{exp})}{G_x^{exp}}, \%$
Var. 1 <i>APDL</i>	59,98	0.074	3,39	1,67-	5,4+	-“-
Var. 1 <i>TexGen</i>	62,4	0.081	3,24	2,24+	12,5+	-“-
Var.2 <i>APDL</i>	61,01	0.079	3,33	-“-	-“-	7,9+
Var.2 <i>TexGen</i>	60,10	0,082	3,24	-“-	-“-	5,27+
Var. 3 <i>APDL</i>	57,01	0.042	3,26	3,52+	4,76+	-“-
Var. 3 <i>TexGen</i>	48,70	0,054	3,26	14,58-	25,93+	-“-
Var.4 <i>APDL</i>	68,06	0.355	3,78	-“-	-“-	9,96-
Var.4 <i>APDL</i>	68,01	0,356	2,91	-“-	-“-	30,56-

## 6. Conclusion

When constructing geometric models of SRCM, it is important to ensure the volume fraction of fibers in general and in the directions of reinforcement corresponding to the values in a real composite material. The initial models obtained with the help of the TexGen software package may have inaccuracies in the laying and intersection of weft and sewing threads at the bending points. This leads to a decrease in the volume fraction of the fibers, to errors in the finite-element discretization of the geometric models of the SRCM, and reduces the accuracy of predicting the elastic properties. An algorithm for correcting the geometric structure of the SRCM for the TexGen software package implemented in the language APDL ANSYS is proposed. A selective comparison of the experimentally obtained elastic characteristics of SRCM with predictive results for geometric models of the structure constructed in TexGen and corrected by the proposed algorithm showed good agreement.

A further direction of research in the construction of geometric models and predicting the effective elastic properties of PACM is to take into account the deformation of threads in the composite at various technological stages of its production.

## Acknowledgments

The work was carried out with the financial support of the state represented by the Ministry of Education and Science of Russia within the framework of the federal target program "Research and development in priority areas of development of the scientific and technological complex of Russia for 2014-2020" on the topic: "Development of experimental technologies for the automated production of large-sized details of advanced aviation engines made of thermoplastic composite materials". Unique identifier of applied scientific research RFMEFI57717X0261.

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