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Comparative analysis of methods for calculating the physico-mechanical characteristics of multi-layered composite materials

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Abstract. The paper presents a comparative analysis of methods and results of calculating the physical and mechanical characteristics of single-layered and multi-layered polymer composite materials (PCM). The object of the study is a polymer composite which consists of epoxy binder and carbon fiber reinforcements. The principle of multiscale modelling is applied to determine the physical and mechanical characteristics of the composite. Within the framework of this study, a representative volume element (RVE), the structure of which corresponds the characteristics of real materials, is used. The initial data for the calculation in this case are physical and mechanical characteristics of anisotropic fibers (carbon fabric) and an isotropic binder, as well as the geometric model of the RVE. As a result of the calculation, the effective characteristics of a quasi-homogeneous anisotropic material suitable for numerical analysis of the composite structures are determined. A comparison of the results of determining the physical and mechanical characteristics of the polymer composite using ANSYS Material Designer and MSC Digimat software packages for various size of RVE model is carried out and ANSYS Workbench software is also used to perform the stress-strain conditions of RVE model to determine the physico-mechanical characteristics of polymer composites. Key words: layered polymer composite materials, epoxy binder, carbon fiber, finite element.

1 Introduction

Nowadays, there is a global trend of expanding the use of composite materials, especially in critical structures of space and aviation technology. By using composite materials can achieve the weight reduction and increase the performance characteristics of products [1,2].

When creating structures made of composite materials, it is important to have reliable data on their physical and mechanical characteristics. The mechanical properties of composites are influenced by such factors as characteristics, type (fiber, fabric, etc.) and the volume content of the reinforcements, orientation of fibers (layup), as well as the characteristics of the resin and the contact zone [3-5]. Experimental determination of the mechanical characteristics of PCM for the large number of structural variants is extremely time consuming and costly, therefore, computational and theoretical methods have now come

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to important [6-8]. Currently, methods for determining the mechanical characteristics of composites based on numerical modeling of the stress-strain state of representative volume element (RVE) of material, have been primarily developed. In this case, a relatively small volume element is allocated in the material (usually containing no more than a few dozen individual elements), the characteristics of which correspond to the average characteristics of the material as a whole. For this RVE, an analysis of stress-strain state, which occurs from the action of tensile, compressive and shear loads in various directions is carried out, which make it possible to determine the physical and mechanical characteristics of the material. Commercial finite element analysis packages such as ANSYS Material Designer and MSC Digimat can be used to perform such calculations [9,10]. However, the question of rational choice of the size of the RVE and finite elements remains in determining the characteristics of the polymer composites. As a rule, two approaches to numerical modeling of the mechanical characteristics of composite materials are used – micro-mechanical and macro-mechanical analysis. In micro-mechanical analysis, the object of research is a monolayer and modeling of stress-strain state is carried out at the fiber-matrix level, and in macro-mechanical analysis, the characteristics of a multi-layered polymer composite laminate are determined, but its individual layers are considered as an anisotropic quasi-homogeneous medium [10].

The purpose of this work is to select rational parameters for the computational and theoretical determination of the physical and mechanical characteristics of carbon fibered reinforced plastics (CFRP) which are used in the structural elements of the rear part of fuselage structure by numerical modeling methods.

2 Initial data for modeling calculation

As the initial data for modeling the physical and mechanical characteristics of CFRP, the characteristics of carbon fibers and epoxy resin presented in table 1, which are taken from the source of manufacturer's documents, are used [11,12].

Table 1. Physical and mechanical characteristics of constituent materials of CFRP.

Name of the characteristics	**Carbon fabric WL-Blatt 8.3520.80**	**Epoxy resin ED-20**
Young's Modulus in longitudinal direction, E_1 (GPa)	238	3.78
Young's Modulus in transverse direction, E_2 (GPa)	22	3.78
Shear Modulus, G_{12} (GPa)	9	1.4
Poisson's ratio	0.4	0.35
Type of fiber weaving	Twill	-
Linear density, tex	200	-

3 Computational and theoretical determination of the physical and mechanical characteristics of carbon fiber monolayer in MSC Digimat and Ansys material designer software packages

The MSC Digimat and ANSYS Material Designer software packages are used for the micro-mechanical analysis of the physical and mechanical characteristics of the polymer composites [13,14]. At the first step, the construction of a geometric model of the RVE was carried out. At the same time, it was assumed that the reinforcement of this material is carbon fabric of plane weave with a 2x2 periodicity cell. It was believed that the carbon fiber has an elliptical cross-section of 0.14x2 mm, and its content in composite is 60%. The thickness of the monolayer was assumed to be 0.26 mm. At the same time, all the space free from the reinforcement materials of RVE was filled with an epoxy binder, and the behaviour of contact between reinforcements and binder was considered ideal. Figures 1-a and 1-b show geometric and finite element models of RVE, built in ANSYS Material Designer software, which used tetrahedral mesh with a maximum element size of 0.06 mm.

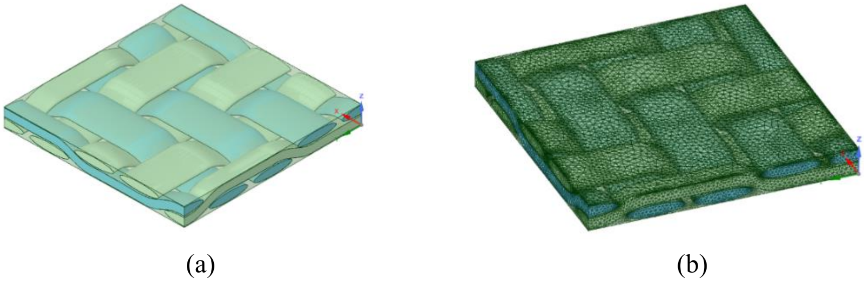
(a) (b)

Fig. 1. RVE model of monolayer: a) geometric, b) finite element models in ANSYS.

Further, finite element models were created for these geometric models of RVE, while a voxel mesh with a maximum size of 0.16x0.16x0.005 mm was used for MSC Digimat. When calculating the physical and mechanical characteristics of materials, periodic boundary conditions were used, which guarantee the periodicity of the fields of displacement with respect to the faces of the RVE. When determining the physical and mechanical characteristics of a carbon fiber monolayer in MSC Digimat, 2 models of RVE are considered, which consist of periodicity 1 cell (RVE 1x1), 4 cells (RVE 2x2), respectively (Fig.2).

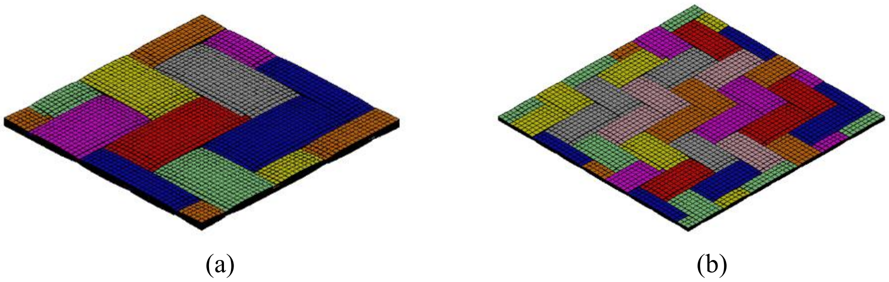
(a) (b)

Fig. 2. Finite element models of RVE of carbon fabric monolayer: a) 1x1, b) 2x2.

The calculation results show that the size of RVE has little effect on the values of physico-mechanical characteristics of the carbon fiber monolayer (table 2), therefore, in order to save computing resources, the RVE 1x1 model should be used.

Table 2. Physico-mechanical characteristics of CFRP RVE models obtained in MSC Digimat.

Parameters	**Size of RVE**	
	4x4	8x8
Elastic modulus of the monolayer RVE in the longitudinal direction E_1, GPa	51.65	51.22
Elastic modulus of the monolayer RVE in the transverse direction E_2, GPa	50.82	50.37

Elastic modulus of the monolayer RVE in the transverse direction E3, GPa	8.46	8.49
Poisson’s ratio, ν_{12}	0.072	0.071
Poisson’s ratio, ν_{13}	0.472	0.470
Poisson’s ratio, ν_{23}	0.471	0.469
Shear Modulus G_{12}, GPa	2.742	2
Shear Modulus G_{13}, GPa	2.525	2.504
Shear Modulus G_{23}, GPa	1.576	1.669
Density ρ, kg/m^3	1653.26	1655.32

In the ANSYS Material Designer software carried out the calculation of physical and mechanical characteristics of carbon fiber monolayer was carried out, however, in this case, due to the limitations of ANSYS Material Designer, modeling was carried out only for the 1x1 fabric periodicity cell. Analysis of the results shown in table 3 showed that the difference between the characteristics obtained using MSC Digimat and ANSYS Material Designer did not exceed 5%.

Table 3. Results of modeling of physical and mechanical characteristics of carbon fiber monolayers in MSC Digimat and ANSYS Material Designer modules.

Parameter	**MSC Digimat**	**ANSYS Material Designer**	**Difference, %**
Elastic modulus of the monolayer RVE in the longitudinal direction E_1, GPa	51.65	52.93	2.47
Elastic modulus of the monolayer RVE in the transverse direction E_2, GPa	50.82	52.98	2.25
Elastic modulus of the monolayer RVE in the transverse direction E3, GPa	8.46	8.644	2.17
Poisson’s coefficient, ν_{12}	0.072	0.069	4.17
Poisson’s coefficient, ν_{13}	0.472	0.45	4.66
Poisson’s coefficient, ν_{23}	0.471	0.45	4.46
Shear Modulus G_{12}, GPa	2.742	2.707	1.27
Shear Modulus G_{13}, GPa	2.525	2.44	3.36
Shear Modulus G_{23}, GPa	1.576	2.44	2.28
Density ρ, kg/m^3	1653.26	1643.6	0.58

4 Computational and theoretical determination of the physical and mechanical characteristics of carbon fiber based on the analysis of the stress-strain state

At this step of the study, the influence of the RVE size on the accuracy of the computational and theoretical determination of the physical and mechanical characteristics of the monolayer was analyzed. For this purpose, a series of geometric models of RVE of various sizes was built in MSC Digimat software, which consists of one cell of periodicity of fabric (RVE 1x1), 4 cells (RVE 2x2) and 9 cells (RVE 3x3), shown in figure 3.

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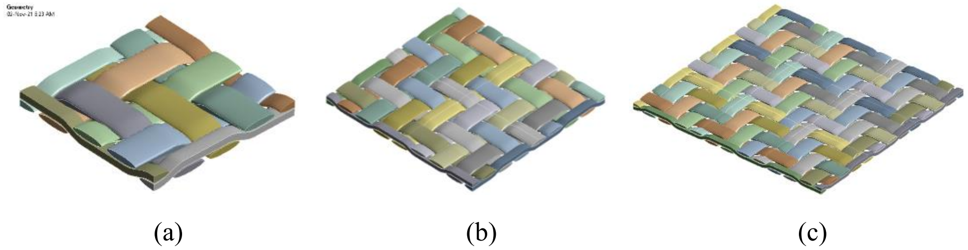

(a) (b) (c)

Fig. 3. RVE models for stress-strain calculation: a) 1x1, b) 2x2, c) 3x3.

The RVE models shown in figure 3 are imported into ANSYS Workbench and created finite element models based on tetrahedral mesh elements with different maximum element sizes. And then modeling of stress-strain of RVE monolayer was carried out. At the same time, for each their three mutually perpendicular directions, the one of the sides was assigned as fixed constraint, and a constant displacement of 0.03 mm was set on the opposite side of RVE.

Table 4. Results of modeling of physical and mechanical characteristics of CFRP monolayer RVE 1x1.

Parameter	**RVE 1x1**			
	Finite element size			
	matrix – 0.05 mm reinforcement – 0.02 mm	matrix – 0.05 mm reinforcement – 0.03 mm	matrix – 0.05 mm reinforcement – 0.04 mm	matrix – 0.05 mm reinforcement – 0.05 mm
Normal stress, MPa	4934.5	4724	4598.8	4568.4
Normal strain	0.146	0.147	0.1214	0.11521
Young's Modulus, E_1	33.79	32.14	37.88	39.65

Table 5. Results of modeling of physical and mechanical characteristics of CFRP monolayer RVE 2x2.

Parameter	**RVE 2x2**			
	Finite element size			
	matrix – 0.2 mm reinforcement – 0.06 mm	matrix – 0.2 mm reinforcement – 0.08 mm	matrix – 0.2 mm reinforcement – 0.1 mm	matrix – 0.2 mm reinforcement – 0.12 mm
Normal stress, MPa	1598.8	1581.0	1637.7	1291.1
Normal strain	0.0275	0.0356	0.0228	0.0189
Young's Modulus, E_1	58.14	44.41	71.82	68.32

Table 6. Results of modeling of physical and mechanical characteristics of CFRP monolayer RVE 3x3.

Parameter	**RVE 3x3**			
	Finite element size			
	matrix – 0.2 mm reinforcement – 0.06 mm	matrix – 0.2 mm reinforcement – 0.08 mm	matrix – 0.2 mm reinforcement – 0.1 mm	matrix – 0.2 mm reinforcement – 0.12 mm

Normal stress, MPa	2386.7	2301.5	2282.2	2343.4
Normal strain	0.0434	0.0425	0.0384	0.0427
Young's Modulus, E_1	54.99	54.15	59.43	54.88

5 Computational and Theoretical Determination of Physical and Mechanical Characteristics of Multi-Layered Cfrp Composites

During the micro-mechanical analysis, a multi-layered composite laminate loaded with tensile force was considered. It was assumed that the length and width of the plate are 1m, and the thicknesses of all layers are equal. To determine the characteristics of the laminate, the orientation of multi-layered composite ribs of the fuselage structure, obtained using the parametric optimization method in the work [18-20], were used (table.7).

Table 7. Optimized lay-up angle of multi-layered composite ribs of fuselage structure.

Number of ribs	**Lay-up angles**	
	Round part	**Vertical part**
1	$[0/\pm30/\pm60/\pm10]_2$	-
2	$[\pm30/\pm60/\pm90/\mp50/\mp 30]_2$	$[+35/+30/-65/-50/\mp40/+30/+35/-30/-45/+50]_2$
3	$[0/0/\pm50/\pm65]_2$	$[-40/0/0/\mp55/\mp48/+35]_2$
4	$[\pm6/\pm6/\pm12/\mp12/\mp10]_2$	$[\mp3/0/0/\mp82/\mp24/\mp52]_2$

For the computational and theoretical determination of elastic properties of multi-layered composite laminate, both the classical laminate theory (CLT) [15-17] and Siemens NX software package were used. The geometric and finite element models of the composite plate used in Siemens NX software are shown in figure 4.

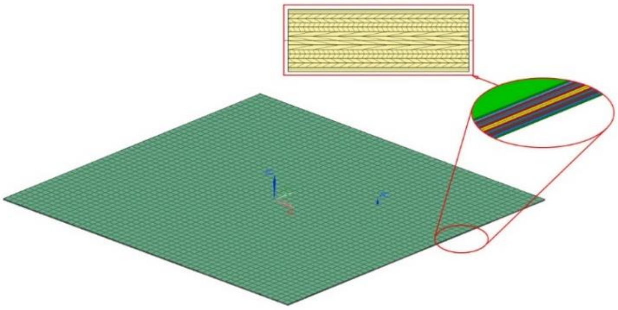

Fig. 4. Modeling of multi-layered composite laminate in Siemens NX (lay-up scheme of round part of rib no.1 $[0/\pm30/\pm60/\pm10]_2$).

The physical and mechanical characteristics of multi-layered composite ribs of fuselage structure obtained on the basis of classical laminate theory and using Siemens NX software are shown in table 8. The results show that the difference between the characteristics of multi-layered composite laminate is no more than 3.5%.

Table 8. Result of modeling of physical and mechanical characteristics of multi-layered composite fuselage ribs (CLT– classical laminate theory, NX –Siemens NX software).

Number of ribs	Part	Calculation method	Parameter					
			E_1	E_2	E_3	G_{12}	ν_{12}	ν_{13}
1	round	CLT	38.44	38.44	8.82	12.96	0.3125	0.3125
		NX	37.63	37.63	8.82	12.71	0.3116	0.3116
2	round	CLT	30.78	30.78	8.82	16.99	0.449	0.449
		NX	30.18	30.18	8.82	16.63	0.45	0.45
	vertical	CLT	17.93	17.93	8.82	14.23	0.679	0.679
		NX	-	-	-	-	-	-
3	round	CLT	36.21	36.21	8.82	14.22	0.352	0.352
		NX	35.46	35.46	8.82	13.93	0.35	0.35
	vertical	CLT	28.09	28.09	8.82	12.21	0.498	0.498
		NX	-	-	-	-	-	-
4	round	CLT	49.72	49.72	8.82	5.22	0.11	0.11
		NX	48.7	48.7	8.82	5.04	0.108	0.108
	vertical	CLT	43.6	43.6	8.82	9.74	0.22	0.22
		NX	42.66	42.66	8.82	9.56	0.22	0.22

6 Conclusion

The influence of the size of RVE and finite elements on the result of modeling of physical and mechanical characteristics based on the analysis of the stress-strain state of RVE is analyzed. A comparison of the results of the calculation of physical and mechanical characteristics in ANSYS Material Designer and MSC Digimat are well similar with each other (an error of no more than 5%), and the direct calculation of physical and mechanical characteristics based on the modeling of the stress-strain state of the RVE requires the use of models with a number of cells of periodicity of at least 3x3. At the same time, the resutls of determining the physical and mechanical characteristics of multilayer packages made for the structrual ribs of the tail section of light aircraft made of polymer composite, obtained using an analytical method based on classical laminate theory, and numerical method using the Siemens NX software will lead to a difference in results of no more than 3%.

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