Розглянуто питання розрахунку електричних явищ в багатошарових композитних матеріалах на основі вуглецевих волокон. Запропоновано метод оцінки достовірності моделей композитного матеріалу для моделювання електричних явищ у композитних конструкціях. Метод засновано на порівнянні розрахункових та експериментальних значень електричного опору зразків матеріалу з певними схемами укладки шарів. Проведено експериментальне визначення електричного опору зразків одношарових і багатошарових композитів на основі двох типів вуглецевих армуючих матеріалів. Проведено розрахунок електричного опору композитів на основі зазначених матеріалів з використанням гомогенної моделі, а також шаруватої моделі композитного матеріалу, реалізованої із застосуванням методу скінченних елементів. Вихідні дані для моделювання у вигляді коефіцієнтів електропровідності шарів отримано за результатами експерименту. Проведено порівняння результатів розрахунку із застосуванням гомогенної і шаруватої моделей з результатами експерименту. На основу отриманих численних результатів, а також аналізу розподілу електричного потенціалу у моделях зразків, проведено оцінку меж застосування використаних моделей. За результатами аналізу, гомогенна модель дає прийнятні результати з похибкою 12 % для матеріалів, в яких спостерігається чергування шарів з різними кутами армування. Для матеріалу, в якому шари з одним кутом армування утворюють кластери, гомогенна модель дала похибку більшу за 50 %. Шарувата модель матеріалу в усіх розглянутих випадках забезпечує високу точність моделювання з похибкою меншою за 10 %. На основі проведеного аналізу надано практичні рекомендації до моделювання електричних явищ у композитних конструкціях

Ключові слова: композиційний матеріал, гомогенна модель, шарувата модель, електропровідність, метод скінченних елементів

PREDICTION OF THE ELECTRICAL RESISTANCE OF MULTILAYER CARBON FIBER COMPOSITES

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1. Introduction

Polymer composite materials are widely used in many industries, primarily due to their high specific strength and rigidity. However, today there is a trend of target use of not only high mechanical properties of composites, but also other properties, which can be controlled in wide ranges of values. Choosing appropriate reinforcing materials, types of semi-finished products, binding materials, as well as applying various methods of their modification, it is possible to obtain a material with a given set of properties.

One of the properties of carbon fiber composites, which can be used in a variety of products, is the ability of this material to conduct electric current. At the same time, the majority of carbon fibers have rather high values of specific electrical resistance, which allows using them in resistive components of heating equipment. There are also a number of methods for increasing the electrical conductivity of carbon fiber composite materials, such as modification of the binding material by adding nanoparticles, deposition of cur-rent-conducting coatings on reinforcing materials, and others. These methods can substantially expand the application of composites in the areas where high electrical conductivity is required. For example, the use of these methods can potentially solve the problems of lightning protection of aircraft carbon fiber structures, static elimination, electromagnetic shielding, and other problems associated with low electrical conductivity of carbon fiber materials.

Also a promising direction is the use of electrical conductivity of carbon fibers in self-diagnosing smart structures and structural health monitoring systems.

Thus, there is a need for reliable methods of modeling electrical phenomena in composite materials necessary for the development of new types of structures with improved properties.

Composites is heterogeneous in structure, which greatly complicates the modeling of its behavior, including electric current transmission. As a rule, composites is a layer structure in which individual layers have their own orientation. In this case, each layer is a reinforced material based on one

of the existing types of reinforcing materials in the form of unidirectional tapes, 2D or 3D fabrics, and others.

Depending on the type of problem solved, different models are used, many of which are based on material homogenization at a certain level. The following models of composite materials can be distinguished.

Microscale models are based on the presentation of the material as a heterogeneous medium consisting of a matrix and reinforcing fibers. Mesoscale models are used to model the behavior of fabric-reinforced materials. In these models, the representative element is a non-uniform material consisting of homogenized threads immersed in the binder matrix. Layered models are based on the representation of composite in the form of a packet of homogeneous orthotropic layers. And, finally, homogeneous models are based on the representation of composite as a homogeneous anisotropic material.

The first two models are used mainly for research purposes, as well as for predicting the properties of materials through the properties of components, fibers and matrices. The layered and homogeneous models are used in practical calculations of composite structures.

The use of the homogeneous model can significantly simplify calculations, but requires justification, because in some cases neglecting the real structure of composite can lead to a significant error of calculation. The possibilities of using the homogeneous model for studying mechanical phenomena in composites are well studied, but there is almost no information on the possibilities of using this model in electrical phenomena modeling.

Thus, the actual task is to develop an effective method for assessing the adequacy of different models for the study of electrical phenomena in multilayer composite materials and to determine the limits of their application.

2. Literature review and problem statement

Homogenization of composite within individual layers or within the entire packet is often used when modeling the behavior of composite structures in different operating conditions. The homogenization procedure is reduced to the definition of some so-called effective properties of the material, with which it behaves equally to a non-uniform material, taking into account certain assumptions.

Methods for determining the electrical properties of composites using microscale models are discussed in [1]. The presented methods allow modeling both continuous fiber-reinforced composites and dispersion-filled materials. Mesoscale model of carbon fiber reinforced composites is successfully applied in [2]. Prediction of the specific electrical resistance of the material is carried out using the finite element method, taking into account structural changes in the fabric during forming.

The above-mentioned methods allow predicting the electrical properties of composite layers, if the fiber and matrix properties are known. To model the behavior of multilayer materials, it is necessary to use models that in one way or another take into account the transmission of electric current between the material layers.

In [3–5], the method of equivalent electric circuit is used to predict the electrical conductivity of a composite. The approach proposed in [3] allows creating various types of weaving and assigning electrical conductivity, depending on the electrical conductivity and direction (warp, weft or z-direction) of threads. The advantage of this method is accounting of mechanisms of electric current transmission between individual threads in woven materials and between individual layers. In [4], this method is used to model knitted fabrics made of carbon fibers.

The equivalent electrical circuit method is used in [5] to model the dynamic behavior of composite material as a result of lightning strike.

With all the advantages, this method has limitations when used for woven materials with complicated weaving schemes, and it is also difficult to apply to practical calculations of composite structures.

Layered models of composite material, according to which each layer is accepted as conditionally homogeneous material, are widely used in strength calculations of composite structures. Similar models are also used to model electrical phenomena in composites. In [6], the so-called equivalent layer model is used for modeling electromagnetic phenomena in composite plates. The layered model of composite material is also used for developing structural health monitoring methods to assess the impact of delamination damages on the electrical resistance of structures [7, 8].

In [9], the layered model of composite material is used to model the effects of lightning strike. Modeling of lightning strike into the composite panel is also considered in [10]. In this paper, the rotation operation of the electrical conductivity tensor is used to obtain the properties of the panel layers in the global coordinate system.

The main drawback of the layered model is the need to use a large number of finite elements for calculation. The thickness of composite layers is tenths of a millimeter, and the total number of layers in real structures may be several dozen.

The use of the homogeneous model of the material can significantly reduce the number of finite elements, but raises questions about the reliability of electrical phenomena modeling. The general method of homogenization of the layered material for solving thermoelectric problems is given in [11]. Assessment of modeling reliability is carried out by comparing the temperature distribution in the ring-shaped plate, caused by ohmic heating obtained by calculation and experimentally. The qualitative picture of the temperature distribution, obtained by FEM modeling, satisfactorily coincides with the result of thermography, but this approach does not allow for an adequate quantitative assessment of modeling reliability.

Thus, to date, there are no reasonable recommendations for the application of a particular model for modeling the behavior of composite structures in the transmission of electric current. Adequate assessment of application limits of models requires a method based on comparing the values of electrical resistance of composites with different reinforcement schemes in the form of strips obtained by calculation from experimental results.

3. The aim and objectives of the study

The aim of the study is to assess the applicability of homogeneous and layered models for modeling electrical phenomena in layered carbon fiber composites.

To achieve the aim, the following objectives were set:
– to carry out experimental studies to determine the electrical resistance of the materials, for which to pre-select parties of specimens with necessary lay-up sequences;

– to obtain the calculated results of electrical resistance of composite specimens with different structures using the homogeneous and layered model of the material;

– to compare the calculated and experimental results for single-layer and multilayer materials, on the basis of which to identify the conditions and limits of application of different models of composite material during calculations.

4. Experimental determination of specific resistance of composites

It is proposed to assess the reliability of modeling of electrical phenomena in composites by comparing the results of calculating the electrical resistance of multilayer strip specimens with the experimental results.

In order to assess the possibility of material homogenization both at the level of individual layers and at the level of the entire packet, it is proposed to apply two types of specimens. The specimens of the first type with the structure [+φ] consist of layers with one reinforcement angle and are used to assess the adequacy of the homogeneous layer model. Cross-ply specimens with the structure [±φ], where φ is the reinforcement angle, are made with different lay-up sequences and are used to assess the possibility of homogenization of the entire packet of layers.

Experimental studies are conducted to obtain the values of electrical resistance of carbon fiber materials for further evaluation of the reliability of applied calculation methods.

Two types of reinforcing material (RM) were used, namely: Kordcarbon 200 2×2 twill-woven carbon fabric (Fiberpreg CZ, Czech Republic), UD 3K-300-150 carbon fiber tape (SLG Group). Passport specifications of the materials are given in Table 1.

For carrying out experimental tests, series of specimens (Table 2), based on the above reinforcing materials and the binder consisting of LH-289 epoxy resin and H-286 hardener (HAVEL COMPOSITES, Czech Republic) were made. All of the specimens based on UD 3K-300-150 reinforcing material consist of 12 layers, the specimens based on Kordcarbon 200 – 8 layers of reinforcing material.

All the specimens were made by the hand lay-up method, followed by forming in a vacuum bag at a temperature of 70 °C. Each party consisted of 5 specimens representing rectangular plates with 100 mm and 15 mm sides.

Measurement of electrical resistance was carried out using the AM-3018 universal digital RLC meter at a frequency of 1 kHz. A certain influence of current frequency on the resistance was found at a frequency exceeding 100 kHz. This effect is not studied in the work.

When measuring the electrical resistance, the surface of the specimens in the measurement zone was sandpapered to remove the surface layer of the binder and degreased. In the process of measuring, the specimens were placed in clamps, as shown in Fig. 1. It should be noted that for fabric-based specimens, electrical resistance was measured only in the warp direction because this fabric has the same weaving density in the warp and weft directions. After measuring the electrical resistance, the specific resistance of the material for each specimen ρ was calculated by the formula

$$\rho = \frac{RA}{L}, \tag{1}$$

where R, A, L are the electrical resistance, cross-sectional area and length of the specimen, respectively.

The experimental value of specific resistance was determined as the arithmetic mean for all specimens in the party. Each party consisted of 6 specimens. Also, the variation coefficient of the experimental value was calculated for each party.

Fig. 1. Experimental determination of electrical resistance of the composite specimen

The parties of the specimens based on UD 3K-300-150 with numbers 1, 2, as well as specimen parties 6, 7 on the basis of Kordcarbon 200, were used to determine the components of the matrix of electrical conductivity of the layers. The experimental values of the coefficients of the matrix of electrical conductivity for the materials used are given in Table 3.

The obtained properties of the materials were used later when calculating the electrical resistance of specimen parties 3–5.

Table 1

Properties of reinforcing materials

Type of RM	Surface density, g/m^2	Fiber volume density, g/cm^3	Fiber specific electrical resistance ρ, 10^{-6} Ohm·m
Kordcarbon 200	200	1.76	18
UD 3K-300-150	150	1.75	20

Table 2

Structure of experimental specimens

Specimen party number	Reinforcing material	Structure
1	UD 3K-300-150	$[0_{12}]$
2		$[90_{12}]$
3		$[45_{12}]$
4		$[45_3/-45_3]_s$
5		$[45/-45]_{3s}$
6	Kordcarbon 200	$[0_8]$
7		$[30_8]$
8		$[45_8]$

Table 3

Experimental values of the coefficients of electrical conductivity of the layers

Conductivity matrix component	UD 3K-300-150 layers		Kordcarbon 200 layers	
	Values, cm	Variation coefficient, %	Values, cm	Variation coefficient, %
σ_{11}	16,946	7.1	12,556	4.8
σ_{22}	15.4	8.5		

4. Prediction of electrical resistance of laminated composites

4. 1. Method of homogenization of laminated material

The matrix of the components of the electrical conductivity of the material in the general case binds the current density vector $\vec{j}$ with the electric field vector $\vec{E}$.

$$\vec{j} = \sigma\vec{E}.$$

In the two-dimensional case of an anisotropic medium, the connection between the components of the current density vector with the components of the electric field vector has the form

$$j_x = \sigma_{xx}E_x + \sigma_{xy}E_y;$$
$$j_y = \sigma_{xy}E_x + \sigma_{yx}E_y, \tag{2}$$

where σ_{xx}, σ_{xy}, σ_{yy} are the components of the electrical conductivity tensor; j_x, j_y, E_x, E_y are the projections of the current density and electric field vectors on the coordinate axes, respectively.

For the case of orthotropic material, whose orthotropy axes coincide with the axes of the coordinate system x, y, the mixed components of the electrical conductivity tensor $\sigma_{xy}=0$.

For the composite layer in the axes of the local coordinate system 1, 2, the connection between the components of the current density vector and the components of the electric field vector has the form

$$j_1 = \sigma_{11}E_1; \quad j_2 = \sigma_{22}E_2, \tag{3}$$

where j_1, j_2, E_1, E_2 are the components of the current density and electric field vectors in the coordinate axes 1, 2, respectively (Fig. 2).
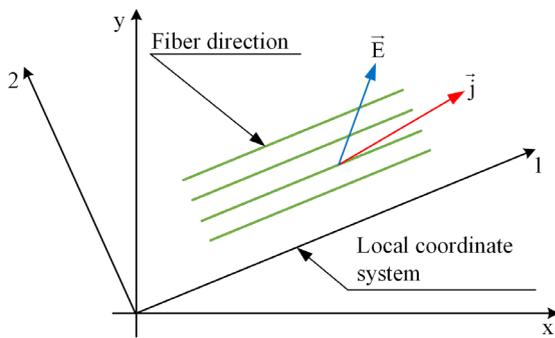

Fig. 2. Local coordinate system of the composite layer

The components of the electrical conductivity tensor of the layers σ_{11}, σ_{22} can be determined experimentally or by microscale and mesoscale models, depending on the type of reinforcing material.

If the components of the electrical conductivity tensor of the i-th layer in the local coordinate system 1, 2 are known, then the components of the electrical conductivity tensor of this layer in the global coordinate system x, y can be found according to the rotation rule of the vectors:

$$j_{xi} = j_{1i}\cos\varphi_i - j_{2i}\sin\varphi_i;$$
$$j_{yi} = j_{1i}\sin\varphi_i + j_{2i}\cos\varphi_i.$$

Then, taking into account the formulas (3), we have

$$j_{xi} = E_{1i}\sigma_{11i}\cos\varphi_i - E_{2i}\sigma_{22i}\sin\varphi_i;$$
$$j_{yi} = E_{1i}\sigma_{11i}\sin\varphi_i + E_{2i}\sigma_{22i}\cos\varphi_i. \tag{4}$$

The components of the electric field vector in the axes of the local coordinate system 1, 2 are found by the formulas of vector rotation by the opposite angle

$$E_{1i} = E_x\cos\varphi_i + E_y\sin\varphi_i;$$
$$E_{2i} = -E_x\sin\varphi_i + E_y\cos\varphi_i. \tag{5}$$

Substituting the formulas (5) in (4) we obtain:

$$j_{xi} = \left(\sigma_{11i}\cos^2\varphi_i + \sigma_{22i}\sin^2\varphi_i\right)E_x +$$
$$+\left(\sigma_{11i} - \sigma_{22i}\right)\sin\varphi_i\cos\varphi_i E_y;$$
$$j_{yi} = \left(\sigma_{11i} - \sigma_{22i}\right)\sin\varphi_i\cos\varphi_i E_x +$$
$$+\left(\sigma_{11i}\sin^2\varphi_i + \sigma_{22i}\cos^2\varphi_i\right)E_y. \tag{6}$$

The expressions standing at the electric field components represent the components of the electrical conductivity tensor of the layer, turned through φ.

For the multilayer material, we assume that each layer conducts current separately and consider the packet of layers as a parallel connection (Fig. 3).

If the packet of layers is in the electric field with the field vector components E_x, E_y, Ey, then the total current in the x, y directions will be equal to the sum of currents for each layer

$$I_x = \sum_{i=1}^{n} j_{xi}\delta_i a; \quad I_y = \sum_{i=1}^{n} j_{yi}\delta_i b.$$

Then the components of the average current density vector through the laminate will be equal to

$$j_x = \frac{\sum_{i=1}^{n} j_{xi}\delta_i}{\delta_\Sigma}; \quad I_y = \frac{\sum_{i=1}^{n} j_{yi}\delta_i}{\delta_\Sigma}. \tag{7}$$

Taking into account the formulas (6) and introducing the relative thickness of the layers

$$\psi_i = \frac{\delta_i}{\delta_\Sigma},$$

we finally get

$$j_x = E_x \sum_{i=1}^{n} \left(\sigma_{11i} \cos^2 \varphi_i + \sigma_{22i} \sin^2 \varphi_i \right) \psi_i +$$

$$+ E_y \sum_{i=1}^{n} \left(\sigma_{11i} - \sigma_{22i} \right) \sin \varphi_i \cos \varphi_i \psi_i;$$

$$j_y = E_x \sum_{i=1}^{n} \left(\sigma_{11i} - \sigma_{22i} \right) \sin \varphi_i \cos \varphi_i \psi_i +$$

$$+ E_y \sum_{i=1}^{n} \left(\sigma_{11i} \sin^2 \varphi_i + \sigma_{22i} \cos^2 \varphi_i \right) \psi_i. \tag{8}$$
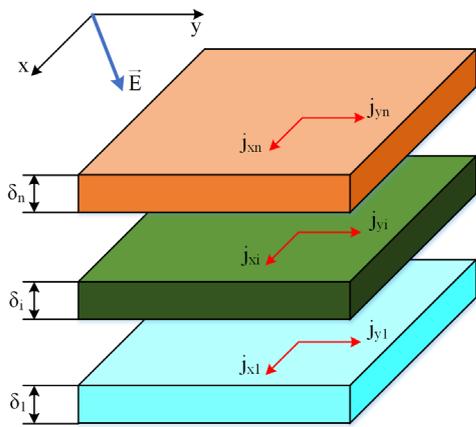

Fig. 3. Determination of total currents in the layered packet

Comparing (2) with (8) we obtain the necessary expressions for effective coefficients of the matrix of electrical conductivity of the laminated material:

$$\sigma_{xx} = \sum_{i=1}^{n} \left(\sigma_{11i} \cos^2 \varphi_i + \sigma_{22i} \sin^2 \varphi_i \right) \psi_i;$$

$$\sigma_{xy} = \sum_{i=1}^{n} \left(\sigma_{11i} - \sigma_{22i} \right) \sin \varphi_i \cos \varphi_i \psi_i;$$

$$\sigma_{yy} = \sum_{i=1}^{n} \left(\sigma_{11i} \sin^2 \varphi_i + \sigma_{22i} \cos^2 \varphi_i \right) \psi_i. \tag{9}$$

For the orthotropic material, the mixed electrical conductivity σ_{xy} is zero. Then the value of the specific electrical resistance of the material in the directions of the x, y axes can be defined as:

$$\rho_x = \frac{1}{\sigma_{xx}}; \quad \rho_y = \frac{1}{\sigma_{yy}}.$$

Subsequently, these values were compared with the results of the experiment and FEM calculations using the layered model.

4. 2. Prediction of electrical resistance of layered composites by the finite element method

To assess the reliability of the homogeneous model, calculations of electrical resistance of the specimens based on carbon fiber tape using the layered model were performed. During the modeling of the composite packet, each layer was considered as a homogeneous orthotropic material with its own coordinate system.

The general view of the three-dimensional model of the specimen is shown in Fig. 4. The length, width and thickness of the specimens were taken as averages for each party.
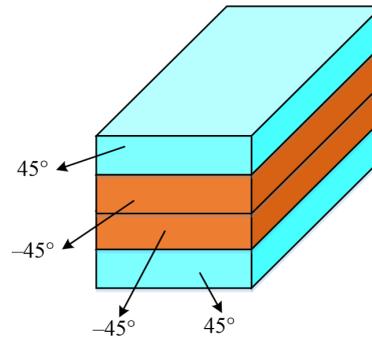

Fig. 4. FEM modeling of the multilayer composite

Carbon fabric specimens were not modeled in the CAE system, due to the weaving pattern (twill 2×2) and identical type of fibers in the warp and weft direction. Hence, the electrical conductivity is the same in both directions, and taking into account the rotation matrix, the components of the electrical conductivity tensor are constant for various cross-ply structures of the composite.

The calculation of the specific resistance of the composite was performed using CAE of the Abaqus system. Type of calculation – coupled thermal-electric under stationary process conditions. In general, the essence of the approach is as follows. At the opposite ends of the modeled composite specimen, the potential difference U was set. After the calculation, the resulting current I passing through the cross section was the product of the cross-sectional area and the mean current density ECD in the cross-section at the ends of the specimens (Fig. 5).

$$I = ECD \cdot b \cdot h, \tag{10}$$

where ECD is the mean current density obtained by modeling; b, h are the specimen width and thickness, respectively.
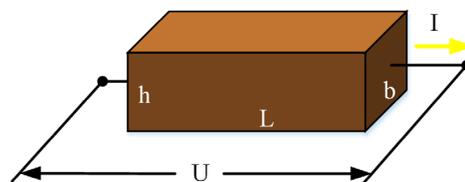

Fig. 5. Determination of specific electrical resistance:
U — potential difference; I — current; b, h, L — specimen width, height and length, respectively

The specific electrical resistance of the specimen is determined by the following formula

$$\rho = \frac{Rbh}{L} = \frac{U}{ECD \cdot L}. \tag{11}$$

The material of the homogeneous layers was taken orthotropic, and the components of the electrical conductivity tensor were given in the coordinate system of the material in such a way that the angle between the direction of the axis 1 and the longitudinal axis of the specimen is φ or $-\varphi$.

To provide a connection between the composite layers, the ideal electric contact (Electrical Conductance) for the contacting surface pairs was set.

Rectangular elements with quadratic approximation were used to construct a grid. The required accuracy of calculation

with an error of 0.5 % was achieved by successively reducing the size of finite elements. Their average size was reduced until the difference between the previous and current average values of current density is less than the specified error.

5. Results of calculation of electrical resistance of specimens

At the first stage of the study, the values of electrical resistance for specimens with the structures [45] and [30] were compared. When calculating the materials with such structures, all layers were combined into one cluster corresponding to the homogeneous model of the material. It should be noted that materials with such structures have a general case of anisotropy (mixed component of the conductivity matrix $\sigma_{xy} \neq 0$), so the distribution of the electric potential and current density will be non-uniform in the plane of the specimens (Fig. 6). Because of this, the comparison of the calculation and experimental results for such specimens is based on the values of electrical resistance.

The results of the comparison of the calculated and average experimental values of the electrical resistance of the specimens are given in Table 4.

Table 4

Results of comparison of experimental and calculated values of electrical resistance for single-layer materials

Reinforcing material and structure	Electrical resistance, Ohm		Variation coefficient of experimental value, %	Relative difference between experimental and calculated values, %
	Calculated	Experimental		
UD 3K-300-150 [45_{12}]	138.4	172.4	13.2	19.73
Kordcarbon 200 [45_8]	0.425	0.481	4.5	12.3
Kordcarbon 200 [30_8]	0.425	0.447	3.2	4.6

At the second stage of the study, the results of the calculated values obtained using the layered and homogeneous model were compared with the experimental results for the structures [$45/-45$]$_{3s}$ and [$45_3/-45_3$]$_s$ based on UD 3K-300-150. The results are presented in Table 5.

Table 5

Results of comparison of the calculated values of specific electrical resistance obtained using the homogeneous and layered model for multilayer materials

Structure	Specific electrical resistance, 10^{-6} Ohm·m			Relative error of the layered model, %	Relative error of the homogeneous model, %
	Layered model (FEM)	Homogeneous model	Experimental mean (variation coefficient, %)		
[$45/-45$]$_{3s}$	140	117	131 (6.4)	6.9 %	11.7
[$45_3/-45_3$]$_s$	244.2		243.7 (4)	0.2 %	52

The obtained results indicate that the homogeneous model gives a significant error for the structure [$45_3/-45_3$]$_s$, where the layers 45 and $-45°$ form clusters as compared to the structure [$45/-45$]$_{3s}$, where the layers 45 and $-45°$ alternate with each other. The fact that the homogeneous model does not sufficiently accurately describe the first of these structures is also evidenced by the distribution of electrical potential in the specimens obtained as a result of FEM modeling and shown in Fig. 7, 8. It is seen from these figures that the distribution of electric potential for the structure [$45_3/-45_3$]$_s$ is essentially heterogeneous.

Thus, the comparison of the calculated results with the experimental results shows that the use of the homogeneous model of the material is not always appropriate, which requires the appointment of application limits.
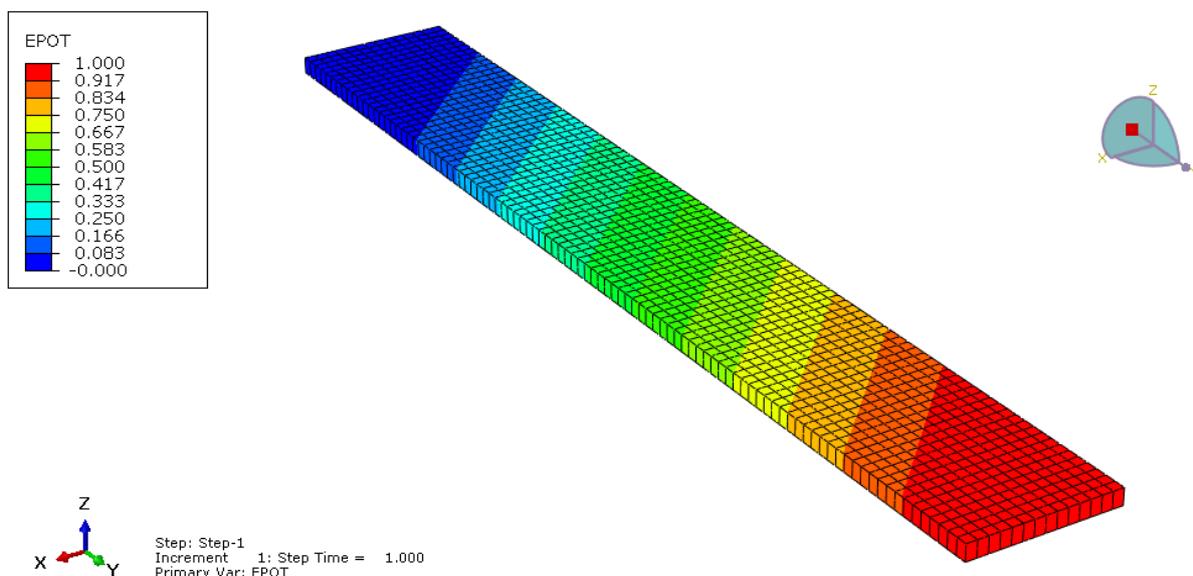

Fig. 6. Distribution of electric potential in the specimen with carbon fiber tape [45] structure
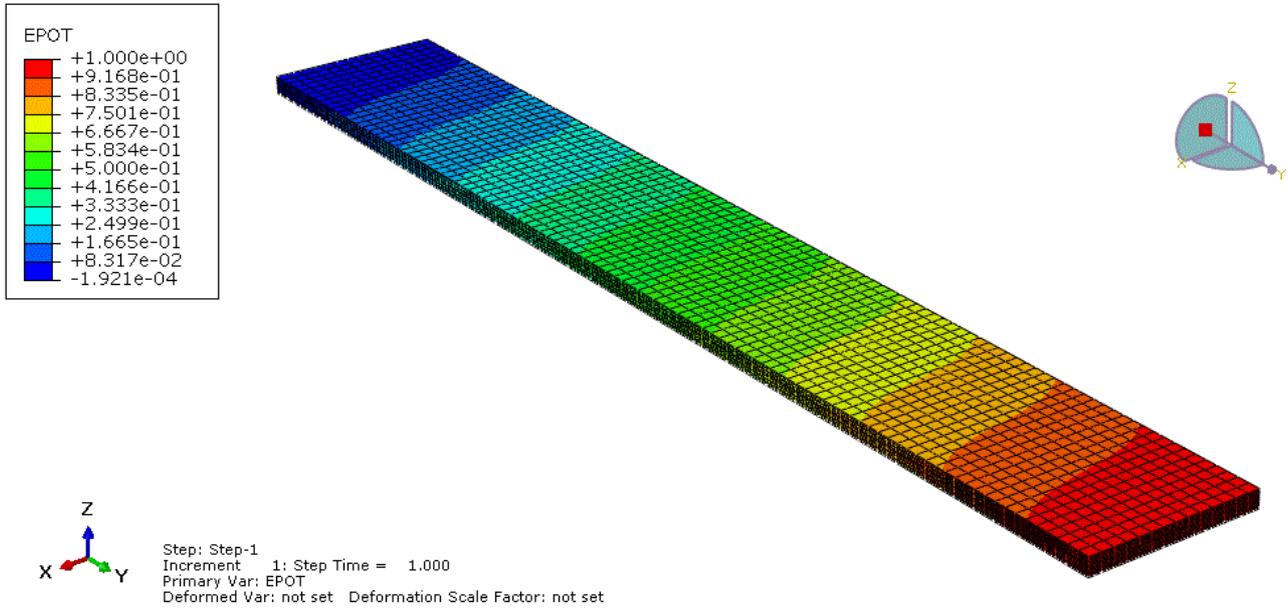
Fig. 7. Distribution of electrical potential in the specimen with the structure $[45/-45]_{3s}$
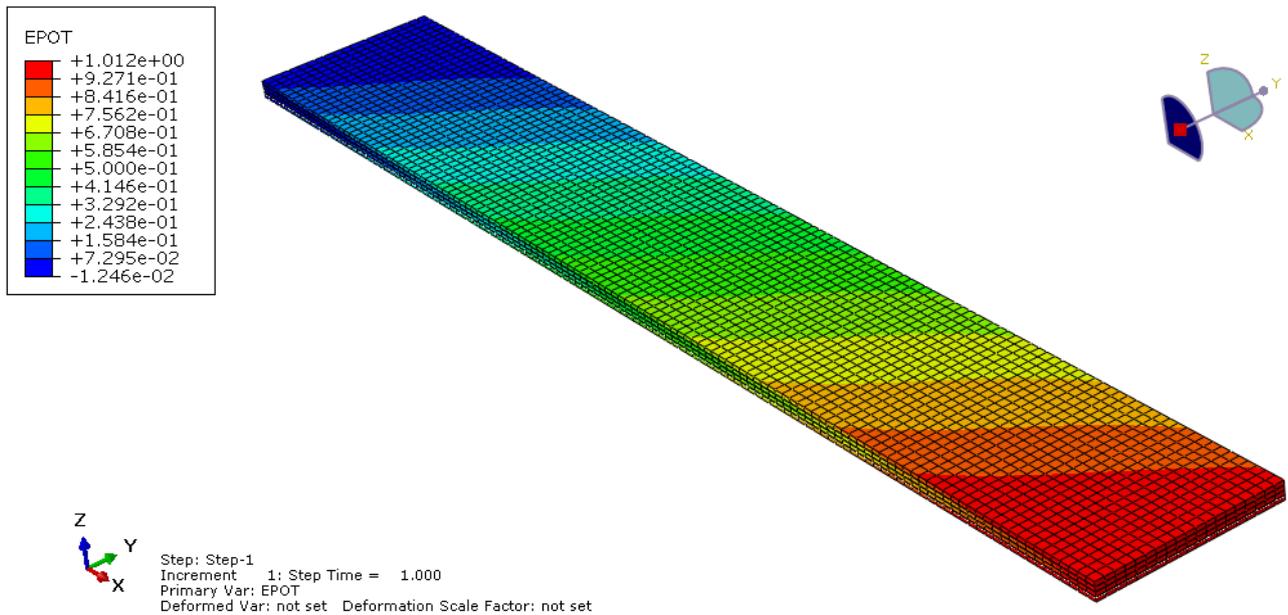

Fig. 8. Distribution of electric potential in the specimen with the structure $[45_3/-45_3]_s$

6. Discussion of the results of reliability assessment of modeling of the electrical resistance of composites

By analyzing the deviation of the calculated results from the experimental results for single-layer materials with the structures [30] and [45], we can assume that the homogeneous model of the layer does not accurately describe the current flow mechanism in real materials. For example, for woven materials, when the current flows along the warp and weft fibers, there is a continuous path of current flow. It is important to note that for the same material, but turned at a certain angle, the current flow will be due to the presence of electric contact between the warp and weft fibers. In this case, the resistance of the material will depend not only on the electrical conductivity of the fibers, but also on the quality of this contact.

These considerations explain the fact that the resistance of Kordcarbon 200 fabric specimens with the structures [30]

and [45] is slightly higher than the resistance of specimens of the same material with the structure [0]. But according to the formulas (9), with the same values of the components σ_{11}, σ_{22}, the values of the components of the electrical conductivity matrix in the coordinate system, turned at a certain angle, do not depend on the value of this angle, and such a material will behave as isotropic in the transmission of current.

For these reasons, the model of the equivalent electric circuit that takes into account not only the electrical conductivity of the fibers but also the resistance of the contact between them can be considered more reliable for the composite layer on the basis of woven material. However, the use of this model is complicated for complex-shaped structures and at the moment is not implemented in existing universal CAE packages.

For multilayer structures there is a significant influence of the lay-up sequence of layers on the specific electrical resistance, as evidenced by the results of the specific resistance

for the structures $[45/-45]_{3s}$ and $[45_3/-45_3]_s$. This effect is explained by the presence of a transversal connection (in the thickness of the specimen) between the layers with an opposite reinforcement angle, which increases the number of paths for electric current flow (Fig. 9).
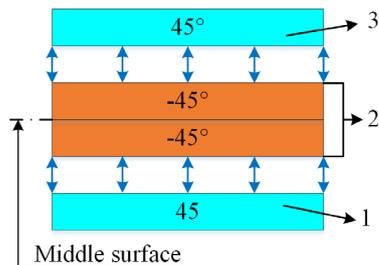

Fig. 9. Transversal connection between the layers, where numbers 1, 2 and 3 indicate the clusters of the layers, and arrows are the directions of current transmission between the clusters

For the structure $[45_3/-45_3]_s$ it is possible to distinguish 2 contact surfaces between the clusters 1–2 and 2–3 (Fig. 9), and for the structure $[45/-45]_{3s}$ the number of contact surfaces is 10. Based on the results of the experiment, the specific conductivity is 2.4 times greater for the structure $[45/-45]_{3s}$ compared with $[45_3/-45_3]_s$. A similar trend is also observed in the results obtained using the layered model. The relative error of the homogeneous model is about 12 % for the structure $[45/-45]_{3s}$ and 52 % for the structure $[45_3/-45_3]_s$. This indicates that this model can only be used for packets that have alternating layers with different angles of reinforcement.

In general, the layered model gives better results in all cases, but its significant disadvantage is a considerable increase in the number of finite elements to achieve acceptable accuracy of calculations, which complicates its use for real composite structures.

Summing up, the following practical recommendations can be made for modeling electrical phenomena in composites.

The use of homogeneous models of composites requires justification depending on the required accuracy of calculations, the size and complexity of the structure, and the presence of irregular zones in it.

Homogenization of the material of individual layers at the moment is the only choice for the practical calculations of electrical phenomena in real composite structures. However, it should be borne in mind that it does not always accurately model the behavior of real material, in particular woven reinforcement materials, because it does not take into account the mechanism of current transmission through the contact between individual threads. As a result, such a model may give some error in the direction of reducing the electrical resistance, especially in the case of poor contact between the fabric threads caused by the shortcomings of the manufacturing process.

Homogenization of the material at the layer packet level is advisable only for packets that have an alternation of layers with different reinforcement angles. A compromise solution can be the use of combined models that represent the homogeneous model with sites with separate modeling of layers in irregular zones where significant gradients of electrical potential (openings, connections, etc.) can be observed.

It is also important to note that the electrical conductivity of laminated composites is largely influenced by the transversal electrical conductivity between the layers. High values of interlayer conductivity reduce the error caused by homogenization of the material.

On the other hand, the results of the study indicate the need for high interlayer electrical conductivity in the structures operating in conditions of electric current transmission. This can be achieved by using high-pressure forming (autoclave forming) to provide high volumetric fiber content in the composite. Other solutions are the modification of the binder by introducing conductive nanomaterials in the form of carbon nanotubes, graphene nanoparticles, metal nanowires and others.

7. Conclusions

1. The paper proposes the method for assessing the reliability of methods for modeling electrical phenomena in composite structures, which consists in comparing the calculated and experimental results of determining the electrical resistance of multilayer specimens with certain structures. Specimen parties contain specimens with one angle of reinforcing layers and cross-ply specimens with different lay-up sequences. This allows estimating the error caused by homogenization of the material at the level of both the layer and the entire packet. Thus, the method allows evaluating the application limits of this or that model to achieve acceptable calculation accuracy.

2. The calculation of electrical resistance of the specimens of composite material with different structures on the basis of two types of carbon fiber reinforcing materials is carried out. The calculations are made using the homogeneous model of the material, as well as the layered model implemented with the help of FEM. As input data, the experimentally obtained conductivity coefficients of the layers were used. The components of the matrix of electrical conductivity of the homogenized material were determined using the obtained calculated dependencies. The calculated electric resistance values, obtained using the layered model, depend on the lay-up sequence of the layers. So, for the material, in which the layers alternate between $+45°$ and $-45°$, and the material, where the indicated layers form clusters, the layered model gives the value of the specific electrical resistance of $140 \cdot 10^{-6}$ Ohm·m and $244.2 \cdot 10^{-6}$ Ohm·m, respectively. At the same time, the value of the electric resistance obtained on the basis of the homogeneous model, which does not take into account the lay-up sequence of the layers, is $117 \cdot 10^{-6}$ Ohm·m. This phenomenon can be explained by the fact that the homogeneous model does not take into account current transmission between the layers.

3. Comparison of the calculated and experimental results for single-layer and multilayer materials was performed, on the basis of which the conditions and limits of application of the homogeneous model of composite material during calculations were found. For the material on the basis of carbon fiber tape, the homogeneous model provides acceptable results (an error of about 10 %) for packets that have an alternation of layers with different reinforcement angles. This can be explained by rather low transversal electrical conductivity.

The layered model of the material provides high-precision modeling for composites of any structure, but requires a significant amount of finite elements.

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