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PREDICTION OF SPECIFIC ELECTRICAL RESISTIVITY OF POLYMERIC COMPOSITES BASED ON CARBON FABRICS

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Запропоновано підхід до прогнозування питомого електричного опору полімерних композитних матеріалів на основі вуглецевих тканин з використанням методу скінченних елементів та аналітичних залежностей для визначення питомої електропровідності ниток. Порівняння розрахункових та експериментальних значень питомого електричного опору композитних матеріалів на основі двох типів вуглецевих тканин показали достатню достовірність запропонованого підходу

Ключові слова: композитний матеріал, вуглецеве волокно, питомий електричний опір, метод скінченних елементів

Предложен подход к прогнозированию удельного электрического сопротивления полимерных композитных материалов на основе углеродных тканей с использованием метода конечных элементов и аналитических зависимостей для определения удельной электропроводности нитей. Сравнение расчетных и экспериментальных значений удельного электрического сопротивления композитных материалов на основе двух типов углеродных тканей показали достаточную достоверность предложенного подхода

Ключевые слова: композитный материал, углеродное волокно, удельное электрическое сопротивление, метод конечных элементов

1. Introduction

Polymeric composite materials based on carbon fabrics of different weaving have been widely used in the aerospace industry. In terms of indicators for specific strength and stiffness, carbon composites significantly outperform metals, however, they have substantially lower electrical conductivity. This must be taken into consideration when designing structural elements that may be exposed to direct and indirect effects from a lightning strike.

At present, there are many techniques to improve electrical conductivity of composite materials and structures made from them. For example, using carbon fibers with high enhanced electrical conductivity, introduction of conductive layers to composite structure, modification of a binding material employing current conductive nanoparticles, spraying of current conductive particles onto a reinforcing material or articles, etc. In addition to lightning protection systems, composites with enhanced electrical conductivity can be applied in heating elements, to shield the equipment and in other areas [1].

The application of the above methods makes it possible to create multifunctional composite materials that possess the required combination of mechanical, thermal-physical, and electrical characteristics.

Given the extending scope of application of composites in industry and increasing requirements to multifunctionality, it is a relevant task to develop reliable methods for determining their mechanical, thermal-physical, and electrical properties. At present, determining the electrical characteristics of composites is typically based on using experimental methods. These methods make it possible to obtain reliable results, but at the same time they are not effective enough when selecting the optimal structure of a composite that requires choosing from a large number of options. It is obvious that the existence of reliable calculation methods will make it possible to deal more effectively with the challenge of creating multifunctional composite materials.

2. Literature review and problem statement

The composite materials reinforced with continuous unidirectional carbon fibers have a relatively high conductivity along fibers. Specific electrical conductivity in this direction σ_ℓ can be quite reliably calculated using the rule of mixtures [2]

$$\sigma_\ell = \sigma_f \theta + \sigma_m (1-\theta), \quad (1)$$

where σ_f is the specific electrical conductivity of fibers; σ_m is the specific electrical conductivity of the matrix; θ is the volumetric fiber content.

In the direction transverse to reinforcing fibers, the electrical conductivity of unidirectional composites can be several orders of magnitude lower. According to the model proposed in [3], a composite is the system of condensers and resistive elements, representing, respectively, the gaps and contact zones between adjacent reinforcing fibers. Given the complexity of the mechanism of electrical conductivity in the examined case, empirical models that are typically based on the percolation theory have been practically applied.

A significant increase in the specific conductivity of a material occurs when the volumetric content of reinforcing fibers θ_c exceeds the so-called percolation threshold. The simplest empirical dependence to calculate specific conductivity of a composite across fibers σ_t in the case of $\theta > \theta_c$ takes the form [4]

$$\sigma_t = \sigma_f (\theta - \theta_c)^t, \quad (2)$$

where t is a certain empirical parameter.

Paper [4] applies FEM numerical simulation in a two-dimensional statement using two models for the arrangement of fibers. Electrical conductivity values are calculated based on the Monte-Carlo method. Based on a more realistic model that takes into consideration the chaotic arrangement of fibers in a matrix, the authors obtained the value of percolation threshold as θ_c=0.6.

Authors of paper [5] built a refined model for forecasting specific electric conductivity of composites with respect to temperature and pressure of molding. The proposed model demonstrates a rather high reliability, confirmed by the conducted experimental research.

Article [6] used a three-dimensional model of a material to determine the conductivity tensor of unidirectional composites. The proposed model makes it possible to take into consideration the impact from damage of reinforcing fibers on the values of specific electrical conductivity.

Papers [4–6] considered composites reinforced with unidirectional fibers only, and thus the results obtained cannot be directly used for woven materials with a more complex structure. However, the results of these studies can be employed as a basis for determining the characteristics of filaments in the woven material by using the proposed empirical formulae. For unidirectional composites with fibers of circular cross-section, the mean values of empirical parameters in formula (2) are θ_c=0.6, t=3.

There are several other empirical formulae presented in [4–6] for the prediction of specific conductivity of a composite material reinforced with continuous fibers. However, the practical application of many of them requires the availability of a large number of parameters of the material, which can be obtained only after examining the microstructure of the finished composite [6]. Therefore, the use of refined dependences is hardly effective at the stage of structure selection.

The electrical resistivity of composites based on woven reinforcing materials will depend on the characteristics of filaments, weaving type, and local volumetric content of reinforcing fibers in filaments. When predicting the mechanical, thermal-physical, and other properties of such materials, the method of a single cell is applied (Unit Cell Approach), based on the isolation of a representative element form the bulk of a material. That typically includes the homogenization of filaments, which are represented as conditionally homogeneous bodies with effective properties.

The mentioned approach is used in paper [7] for the prediction of thermal conductivity coefficients of a composite based on the fabric with plain weaving by employing the FEM. In this case, effective characteristics of filaments in different directions should be determined using any microstructural models. This approach was also applied in work [8] for composites with three-dimensional reinforcement. Despite the fact that these studies address the thermophysical properties of a material, the material models that their authors employed can be adapted to calculate specific electric resistance. At the same time, the authors considered an idealized cell of a material excluding the impact of the technological process in its geometry, which might influence results of the simulation.

To predict the electrical characteristics of composites based on woven fabrics, the method of equivalent electrical circuits is exploited [9]. A given method is also used to calculate electrical characteristics of the complex-reinforced composites based on unidirectional layers in paper [10]. The resistance of circuit elements is assigned depending on the characteristics of filaments used or unidirectional layers. This method makes it possible to operatively synthesize rational schemes for weaving the fabrics in order to achieve the required magnitudes of electrical conductivity. At the same time, the limitation of this method is insufficient reliability of modeling and a limited possibility to use this model to predict other properties of the material.

Paper [11] proposed a mathematical model to predict specific conductivity of woven composites that takes into consideration patterns in fabric weaving and demonstrates improved reliability compared to the equivalent circuit method. A constraint of the model is its insufficient universality in terms of application to materials based on woven reinforcements.

It should be noted that the above papers also consider the idealized cell of a composite material. At the same time, the molding process may change its structure under the influence of vacuum pressure that can affect the results of simulation. This is especially relevant for the composites based on fabrics with spatial reinforcement, which are sufficiently compliant at transversal compression. This phenomenon can be accounted for by the preliminary simulation of the deformation of reinforcing material during molding process, which may be implemented, for example, by using the FEM.

Work [12] deals with the modelling of performance of plain and twill weave fabrics at different types of deformation. In this paper, filaments are modeled as a totality of fibers, which in turn are treated as elastic beams. Based on this model, the authors investigated behavior of the material at shear in the plane of the fabric, at bending and torsion, using the FEM. With some modifications, the proposed model can be adapted to simulate the process of compression of three-dimensional fabrics under vacuum pressure.

At the same time, a given model requires significant computational resources, due to a large number of finite elements, as well as the existence of a large number of contacts. The specified feature restricts the use of the mentioned method at the stage of choosing the rational scheme for weaving a fabric.

Thus, at present there are no general methods for predicting electrical resistivity of composite materials based on woven and braided reinforcements that would take into consideration all essential factors. These factors include the variety of schemes for filament weaving, actual values of volumetric content of a reinforcing material, as well as a change in the thickness of a fabric and in the orientation of filaments in the forming process of a composite product.

In order to predict electrical resistivity of a composite material when choosing a rational scheme for weaving a fabric, it is necessary to devise a method for accounting for the impact of forming pressure on the geometry of a fabric and the volumetric fiber content. This would make it possible to exploit at a given stage the original scheme of weaving without resorting to the fabrication of experimental samples and to their microstructural analysis in order to build a model of the unit cell of a material. In doing so, to ensure operative prediction of the characteristics of a material, preference should be given to the model based on the homogenization of a reinforcing material by using known empirical formulae to calculate electrical conductivity of filaments in different directions.

3. The aim and objectives of the study

The aim of present work is to develop a method for the prediction of electrical resistivity of composite materials based on carbon fabrics that would take into consideration the actual fabric structure by modelling the performance of a material when molding a structure. Given this, the method could be used when selecting a rational scheme for weaving a fabric in order to obtain the material with preset properties.

To accomplish the aim, the following tasks have been set:

– to devise a method for accounting for the deformation of a reinforcing material during molding process when predicting electrical resistivity of composite materials;

– to obtain numerical values of electrical resistivity for composite materials based on the carbon fabric of twilled weaving and weft-knitted carbon fabric;

– to derive experimental values of electrical resistivity of the examined materials in order to estimate reliability of simulation results.

4. Modeling of composites based on carbon fabrics

To model and to subsequently experimentally estimate simulation validity, we use in this work two types of a reinforcing material: carbon fiber of the brand Kordcarbon 200 (Fiberpreg CZ, Czech Republic), twilled weaving 2×2, as well as the spatial weft-knitted carbon fabric with the “elastic” type weave. The weft-knitted carbon fabric was fabricated at the Institute for Problems in Materials Science named after I. N. Frantsevich of the National Academy of Sciences of Ukraine (Kyiv, Ukraine). The fabric of twilled weaving utilizes filaments of the brand Toray 3K (TORAY INDUSTRIES, Inc., Japan). The number of filaments along the warp and the weft is the same. The weft-knitted carbon fabric utilizes filaments of the brand Ural-100 (OAO “SvetlogorskKhimvolokno”, Belarus) for weaving the base, and filaments of the brand T-700 (TORAY INDUSTRIES, Inc., Japan) for the weft.

Specifications of filaments are given in Table 1.

When building the 3D models of fabrics, the filaments were modeled as homogeneous solid bodies. When determining the cross section of a filament, we took into account local volumetric content of fibers in the region taken by a filament in the finished composite. Based on an analysis of the available images of the microstructure of materials, manufactured under vacuum pressure, the local volumetric fiber content in filaments was taken to be equal to $\theta_{local}=0.72$. Fiber cross-sectional area was calculated based on the adopted local volumetric content, linear density of the filament and volumetric density of the fiber derived from technical specifications. 3D models of the examined fabrics are shown in Fig. 1, 2.

Table 1

Characteristics of the used filaments

Filament type	Linear density, tex	Fiber volumetric density, g/cm^3	Fiber elasticity module E, GPa	Electrical resistivity of fiber ρ, 10^{-6}·Ohm·m
Toray 3K	200	1.76	210	18
Ural-100	100	1.75	90	15
T-700	800	1.75	230	18

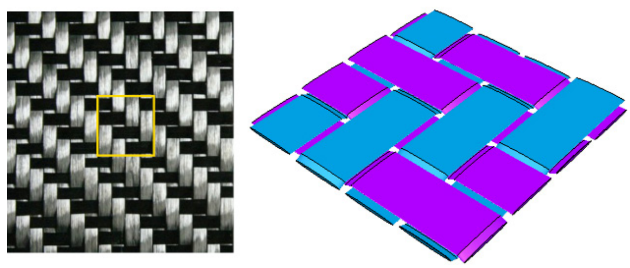

Fig. 1. Representative element of the carbon fabric of twilled weaving

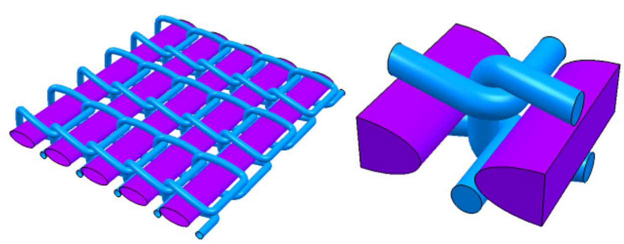

Fig. 2. CAD-model of a weft-knitted carbon fabric and a representative element for predicting electrical resistivity

When predicting the properties of the material based on a fabric with spatial weaving, it is required to take into consideration its deformation in a composite part manufacturing process, which manifests itself by a change in the thickness of the fabric. Thus, when fabricating experimental samples, we observed a decrease in the thickness of the utilized weft-knitted carbon fabric from 1.53 to 1.02 mm. To account for this phenomenon, we simulated a process of fabric deformation under the action of vacuum pressure by using the FEM. When modeling, a representative element of the fabric was pressed between the two absolutely rigid plates (Fig. 3). In this case, the filaments were modeled as conditionally homogeneous bodies with a longitudinal elasticity module equal to the elasticity modulus of fibers multiplied by the local volumetric content, and transverse modulus of elasticity and modulus of elasticity at shear were taken close to zero. The resulting deformed mesh of finite elements was imported to the CAD system to build a model of the representative element of a material, which was subsequently used to predict electrical resistivity.

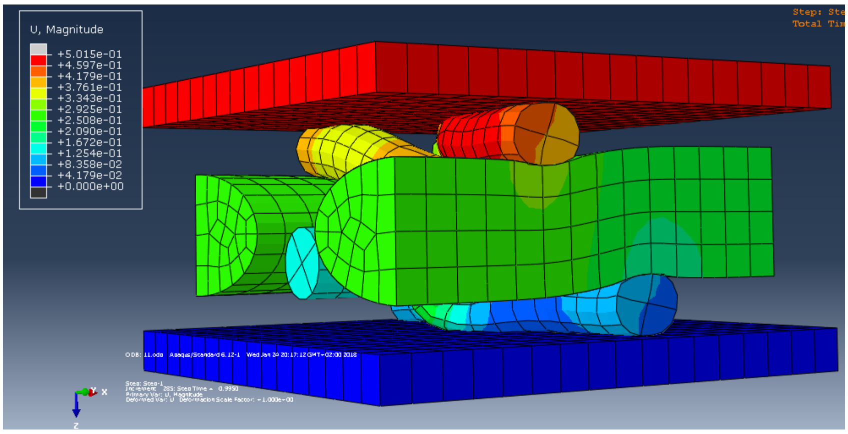

Fig. 3. Simulation of deformation process of a representative element of the fabric under vacuum pressure

The problem on predicting electrical resistivity was solved using the Abaqus system. The type of analysis is coupled thermal-electric. A general approach to the calculation implies the following (Fig. 4). At the opposing ends of a representative element of the composite material we assigned the difference in potentials U. Upon calculation, we determined the resulting current I that passes the cross-section as the mean value of current density ECD in the cross-section, multiplied by the cross-sectional area of the representative element.

$$I = ECD \cdot a \cdot b, \tag{3}$$

where ECD is the mean electric current density, derived during simulation; a, b – cross-section dimensions of the representative element.

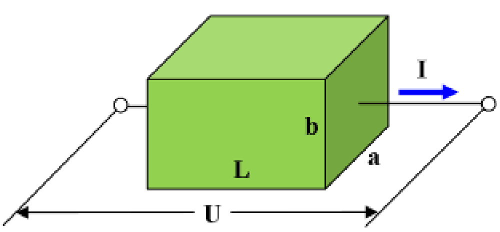

Fig. 4. Schematic for determining electrical resistivity: U – difference in potentials; I – current; a, b, L – width, height, and length of the representative element, respectively

The electrical resistivity of a material is determined from formula (4)

$$\rho = \frac{Rab}{L} = \frac{Uab}{IL}, \tag{4}$$

where L is the length of a representative element.

With respect to formula (4), we finally obtain

$$\rho = \frac{U}{ECD \cdot L}. \tag{5}$$

The material of homogenized filaments was taken to be orthotropic; in this case, tensor components of the filament electrical conductivity were assigned in local coordinate systems with axis 1, directed along the fibers (Fig. 5). Specific electrical conductivity in direction 1 – σ_{11} was calculated using formula (1), and in directions 2 and 3, respectively, σ_{22} and σ_{33} – by using formula (2), where we accepted, as the volumetric content of fiber, a local volumetric fiber content in a filament θ_{local}. The matrix was taken to be an isotropic material with specific electrical conductivity $\sigma=10^{-12}$ S/m.

To enable an interaction between the interacting filaments, as well as fibers and matrix, for the contacting surface pairs we assigned a perfect electrical contact (Electrical Conductance).

To build the mesh, we used triangular elements with linear approximation. The required accuracy of calculation with an accuracy of 1 % was achieved by sequential reducing the size of the finite elements. The mean size of the finite elements was reduced two-fold until the difference between the preceding and current value of mean electric current density is less than the specified error.

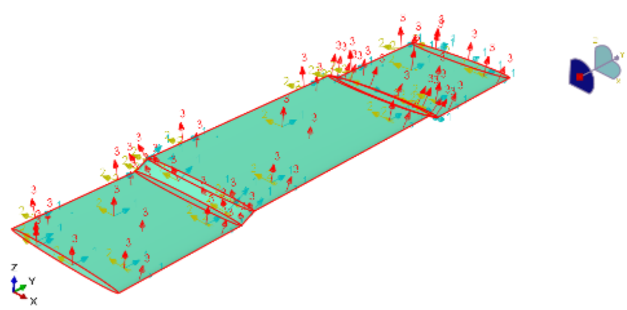

Fig. 5. Assigning a local coordinate system for a filament

5. Experimental determining of electrical resistivity

To conduct experimental study, we fabricated specimens based on the examined fabrics and an epoxy binding material consisting of the resin LH-289 and the hardener H-286 (HAVEL COMPOSITES, Czech Republic).

Specimens based on the fabric Kordcarbon 200 were manufactured by hand layup using 9 layers of the fabric with the subsequent vacuum molding at a temperature of 70 °C. Specimens from one layer of the weft-knitted carbon fabric were manufactured by the method of vacuum infusion. Curing of the binding material occurred at a temperature of 40 °C. The specimens in the form of strips with dimensions 150×15 mm were cut from the finished plates by a skive.

To conduct the experiment, we produced a batch of 5 specimens based on the fabric Kordcarbon 200 and two batches of specimens based on the weft-knitted carbon fabric, cut out in the direction of the base and the weft, 6 specimens per batch.

We measured electrical resistance using a universal RLC meter at a current frequency of 1 kHz. A certain effect of current frequency on the magnitude of electric resistance manifested itself at a frequency above 100 kHz. This effect was not examined in present work.

When measuring electrical resistance, surface of the samples in the measuring zone was scraped with sandpaper for removing the top layer of a binding material and was then degreased. During measurements, the samples were placed in clamps, shown in Fig. 6.

Fig. 6. Measurement of electrical resistance of experimental samples

For samples based on the carbon fabric of twilled weaving, we measured electrical resistance only in the direction of the base, given the same density of weaving in the directions of the base and the weft. For the weft-knitted carbon fabric, resistance was measured in the direction of the base and the weft.

Following the measurement of electrical resistance, electrical resistivity of the material for each specimen ρ was calculated from formula

$$\rho = \frac{RA}{L}, \tag{6}$$

where R is the electrical resistance of the specimen; A is the cross-sectional area of the specimen; L is the length of the specimen.

Experimental values of resistivity were calculated as the arithmetic mean for all specimens in the batch. In addition, we calculated, for each batch, a variance coefficient for the experimental value using a known formula.

It is obvious that the magnitude of electrical conductivity of a material is substantially affected by the volumetric fiber content in the composite. Upon manufacturing the specimens, the volumetric fiber content was determined by measuring their density and the known density of the fiber and the matrix. To calculate experimental value of the volumetric fiber content, we used formula

$$\theta_e = \frac{\rho_c - \rho_r}{\rho_f} 100\,\%, \tag{7}$$

where ρ_c is the density of the composite material; ρ_r is the density of the binder; ρ_f is the density of the fiber.

The density of fibers, taken from specifications, is given in Table 1. Density of the used binder, according to specifications, is ρ_r=1.3 g/cm^3.

To compare, we calculated values of the volumetric content based on the CAD-built models of fabrics, which were derived from formula

$$\theta_p = \frac{V_{\text{filament}}\theta_{\text{local}}}{V_{\text{total}}}, \tag{8}$$

where V_{filament} is the volume of filaments, computed based on the CAD-model of the representative element of a material; V_{total} is the total volume of the representative element.

6. Results of calculation and measurement of electrical resistivity of materials

Table 2 gives results of comparison of the calculated and experimental values of volumetric fiber content in the composite, derived from formulae (7) and (8). The results obtained can be considered quite satisfactory. Divergence between the theoretical and experimental values for the weft-knitted carbon fabric was 8.1 %. Thus, simulation a deformation of the reinforcing material allowed us to obtain a rather realistic value for the volumetric fiber content in the composite.

Table 2

Comparison of calculated and experimental values of volumetric fiber content in samples

Reinforcing material	Experimental value of the volumetric fiber content θ_e, derived from formula (7)	Calculated value of the volumetric fiber content θ_p, derived from formula (8)	Divergence of calculated and experimental values, %
Fabric Kord-carbon 200	0.62	0.64	3.2
Weft-knitted carbon fabric	0.37	0.34	8.1

Fig. 7–9 show the distribution of density of electric current at a difference of potentials of U=1 V for carbon fabrics with twilled weaving and weft-knitted carbon fabric. The matrix is not shown in the Figures.

By analyzing the obtained electrical current density distribution, one can note that for the carbon fabric of twilled weaving the current passes almost entirely along the filaments oriented in the longitudinal direction. In this case, the transverse filaments are practically not engaged in passing the current. For the weft-knitted carbon fabric, passing the current in the direction of the weft results in an uneven distribution of current density along the filament of the weft, due to their electric interaction with filaments of the base. However, when passing the current towards the fabric's base, maximum current density is observed in the contact area of the base filaments. Thus, resistivity in this direction should be defined mainly by the conductivity of filaments in the transverse direction.

Based on the obtained distributions, we calculated the mean density of electrical current passing through the surface of a representative element of the fabric with the applied potential as the arithmetic mean of electrical current density in the nodes of elements. Employing the obtained values, we calculated resistivity of materials using formula (5).

Results of the calculation of electrical resistivity of the examined materials, results of the experiment, variance coefficients of experimental values, as well as variances in the calculated values and experimental values, are given in Table 3.

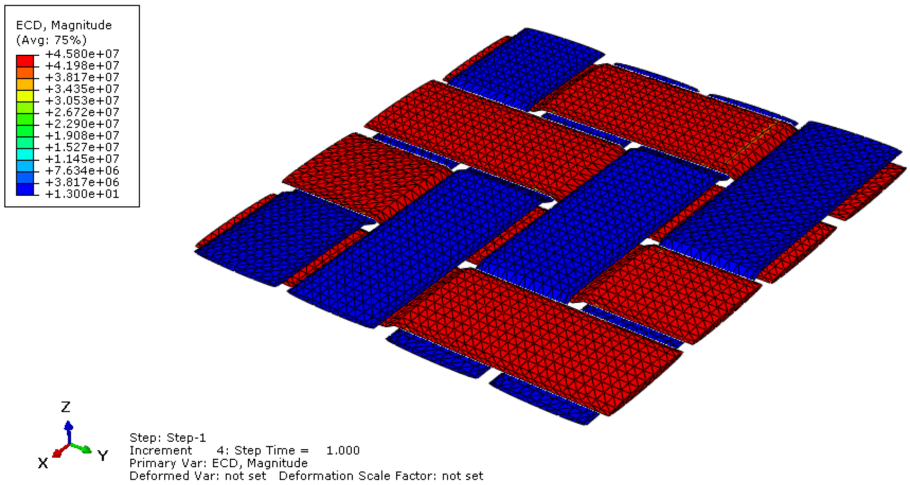

Fig. 7. Electrical current density distribution in filaments of the carbon fabric of twilled weaving

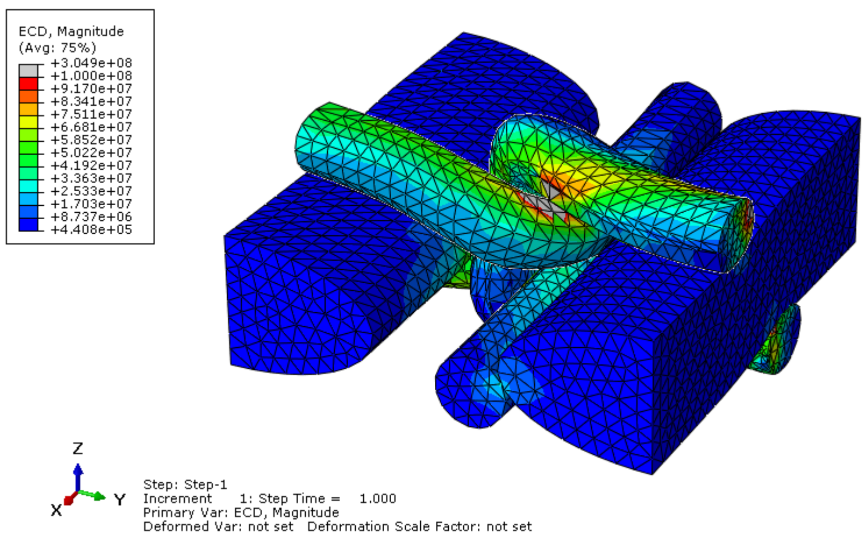

Fig. 8. Electrical current density distribution in filaments of the weft-knitted carbon fabric when passing current in the direction of the base

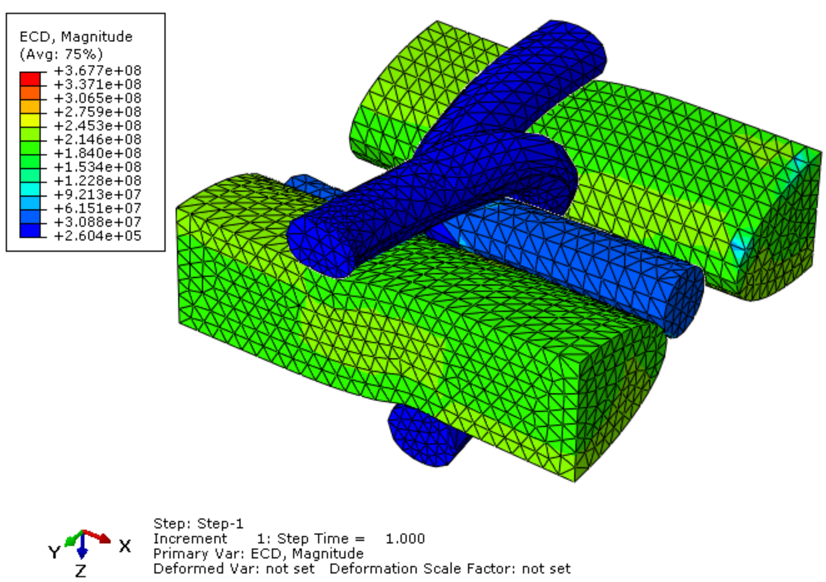

Fig. 9. Electrical current density distribution in filaments of the weft-knitted carbon fabric when passing current in the direction of the weft

Table 3

Calculated and experimental results of determining specific electric resistance

Reinforcing material		Electrical resistivity, 10^{-6} Ohm·m		Variance coefficient of experimental value, %	Difference between calculated and experimental values, %
		Calculated	Mean experimental		
Kordcarbon 200		70.8	78.9	15.2	10
Weft-knitted carbon fabric	For base	1,681	2,476	3.8	32
	For weft	78.5	88.5	7.4	11

Thus, we obtained calculated and experimental values of electrical resistivity of materials based on the carbon fabric of twilled weaving and the weft-knitted 3D carbon fabric, which makes it possible to estimate the reliability of simulation results.

7. Discussion of results of predicting specific electric resistance

The results obtained show that in all the examined cases, the calculation yields lower values of specific electric resistance compared with experiment. A similar pattern was also noted in papers [9, 11] and is explained by applying the idealized model of a material. For the carbon fabric of twilled weaving, divergence between the experiment is 10 %, at a variance coefficient of the experimental value of 15.2 %. In the direction of fibers of the weft of the weft-knitted carbon fabric, divergence between the experiment is 11 % at a variance coefficient of 7.4 %.

The largest divergence of 32 % observed for resistivity of the weft-knitted carbon fabric in the direction of the base. This can be explained by the fact that actual samples undergo destruction of part of the fibers when weaving a fabric, which is ignored in the calculation. Resistivity of the weft-knitted carbon fabric in the direction of the base is defined almost completely by the passage of current through the ground filaments. At the same time, the utilized weft-knitted carbon fabric did demonstrate a damage to part of the ground fibers, which may explain the divergence in results in the direction of the base. In addition, the damage to fibers can to some extent affect characteristics in the weft direction because ground fibers soil are also involved in conducting the current in a given direction.

This fact may indicate inadequate choice of the brand of ground fibers for weaving a fabric. The use of more flexible fibers with a less permissible radius of bending or filaments with a lower linear density will make it possible to prevent a significant damage to fibers at weaving.

Moreover, the calculation result might have to some extent been affected by the value of specific conductivity of filaments in the transverse direction, derived from formula (2). This value is very sensitive to the local volumetric content of fiber in the filament, which is difficult to predict accurately.

It should also be noted that when calculating the weft-knitted carbon fabric the volumetric fiber content was determined based on the results of modeling the performance of fabric under the action of vacuum pressure. Experimental values of the volumetric fiber content were not employed in the calculation. This corresponds to the case of applying the proposed approach at the stage of choosing a brand of the filaments and a fabric weaving scheme when the exact values of volumetric content are unknown. Given the aforementioned, reliability of the simulation can be considered satisfactory.

That conclusion is also confirmed by comparing the results obtained in this work with the results of similar studies by other authors. Thus, a deviation between the calculated values of electrical resistance and the results of experiment in paper [11] for different types of fabrics ranges from 12 to 74 %.

Improvement of accuracy of calculation can be achieved by taking into consideration the damage to part of the reinforcing fibers when weaving a fabric, as well as applying more accurate models to determine the values of lateral specific conductivity of filaments.

Thus, present work proposes an approach to predicting the magnitude of electrical resistivity of composites based on carbon fabrics. The proposed approach is based on using the FEM in combination with known analytical dependences and empirical formulae for determining specific conductivity of filaments in different directions. Benefits of the proposed approach include its universality and the possibility to account for the deformation of a reinforcing material in the molding process. At the same time, the proposed approach does not make it possible to take into consideration a damage to part of the reinforcing fibers, which is often observed when weaving a fabric and can affect the values of electrical resistivity of the material. In further research, it might be possible to account for a fiber damage based on existing methods, proposed, for example, in [5] using statistical data.

The proposed approach could be applied when solving a task on the rational choice of a filament brand and a fabric weaving scheme in order to obtain a composite material with the preset electrical properties. This will reduce the amount of experimental research and improve efficiency of utilizing composites in the structures that operate under conditions of passing electric current.

Thus, the approach we propose could be used effectively when solving such tasks as:

– development of multi-functional composite materials with the optimum combination of mechanical, thermal-physical, and electrical characteristics;

– estimation of effectiveness of aircraft lightning protection systems that have design elements made of carbon plastics;

– development of heating elements based on carbon fibers in aircraft anti-icing systems and in forming tooling with internal heat sources for molding the products from composites, etc.

Further development of the present research is the simulation of thermomechanical phenomena that occur in composite materials when passing electric current. That would make it possible to estimate ohmic heating and related thermal stresses in the elements of structures made of conductive composites.

8. Conclusions

1. We have proposed an improved approach to forecasting electrical resistivity of composite materials, based on the combined application of FEM and empirical dependences for

the calculation of characteristics of filaments. The approach takes into consideration a deformation of the reinforcing material during molding by modeling the performance of a fabric under vacuum pressure. That makes it possible to use the proposed approach when selecting a scheme for weaving a fabric when actual structure of the material is unknown.

2. The proposed approach was verified using the example of two types of carbon fabrics: carbon fabric of twilled weaving and 3D weft-knitted carbon fabric. The calculation accounted for a deformation of the weft-knitted carbon fabric, which manifested itself in the form of a reduction in its thickness from 1.53 to 1.02 mm. The value of volumetric fiber content, calculated based on the results of modeling, differs from the experimental value by 8.1 %, indicating sufficient reliability of modeling.

3. The calculated values obtained were compared with the results of experiment. According to a preliminary estimation, under conditions of available experimental data, the simulation results can be considered quite satisfactory. For a material based on the carbon fabric of twilled weaving, divergence between the calculated value and the experimental value is 10 %. For the direction of weft fibers of the weft-knitted carbon fabric, divergence between the experiment does not exceed 11 %. The largest divergence of 32 % was observed in the direction of the base of the weft-knitted carbon fabric, which can be explained by a damage to the ground fibers when weaving a fabric. Given the impact of variety of factors whose accurate determining is difficult at the stage of selecting a scheme for weaving the fabrics, the results obtained can be considered quite satisfactory.

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