EFFECTIVE ELASTIC CONSTANTS OF FIBER-REINFORCED POLYMER-MATRIX COMPOSITES WITH THE CONCEPT OF INTERPHASE

ARMĒTA POLIMĒRKOMPOZĪTA ELASTĪGĀS ĪPAŠĪBAS, IEVĒROJOT STARPSLĀNI STARP STIEGRU UN MATRICU

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Key words: interphase/interface, elastic modulus, glass/epoxy composites, identification method

Introduction

During the past several decades composite materials are finding increasing use in a variety of application such as aircraft, automobiles, sporting goods and electronics. Composites often show considerable advantages of stiffness and strength over homogeneous materials and the advantage is particularly evident when these properties are considered on a unit weight basis. Under these circumstances prediction of mechanical properties of a unidirectional fiber-reinforced composite has been an active research area.

In order to realize the optimum mechanical properties of a composite material, each of it constituents must be fully utilized. A large number of recent studies are dedicated to theoretical and numerical studies. The most usual approaches[1-5] disregard the existence of a layer between the fiber and the matrix developed during the preparation of composite materials, which as shown by Theocaris[6], plays an important role in the overall mechanical behaviour of the composite. This layer depends on the fiber, matrix and surface treatment of the fiber[7]. The properties of this layer differ distinctly from those of the fiber and the matrix. Therefore this layer is defined as an interphase.

The goal of this investigation is to study numerically the influence of interphase on the elastic properties of glass/epoxy composites. The major restriction to numerical modelling is the lack of reliable information on the mechanical and geometrical properties of the interphase. In the present paper it is proposed to identify volume content of interphase and elastic modulus of interphase. For the identification of interphase parameters (volume content of interphase and elastic modulus of interphase) a numerical-experimental method is employed. It is proposed to use the method of experiment design and the response surface approach to solve the identification problem. The response surface approximations are obtained using information on the behaviour of a structure in the reference points of the experiment design. The Finite Element modelling of the structure is performed only in the reference points. Therefore, a significant reduction in calculations of the identification functional can be achieved in comparison with the conventional methods of minimization. The functional to be minimized describes the difference between measured and numerically calculated parameters of the response of structure. By minimizing the functional the identification parameters are obtained.

Modelling

Model for Interphase

In the present analysis, it is assumed that the interphase has elastic properties, which are changing with the radial distance from the fibre boundary (see Fig.1.) [7]

$$E_i(r) = \left(\alpha E_f - E_m\right)\left(\frac{r_i - r}{r_i - r_f}\right)^n + E_m \qquad (1)$$

where $E_{i,f,m}$ is the Young's modulus of the interphase, fibre and matrix, respectively; $0 \leq \alpha \leq 1$, and $n = 2, 3, ...$

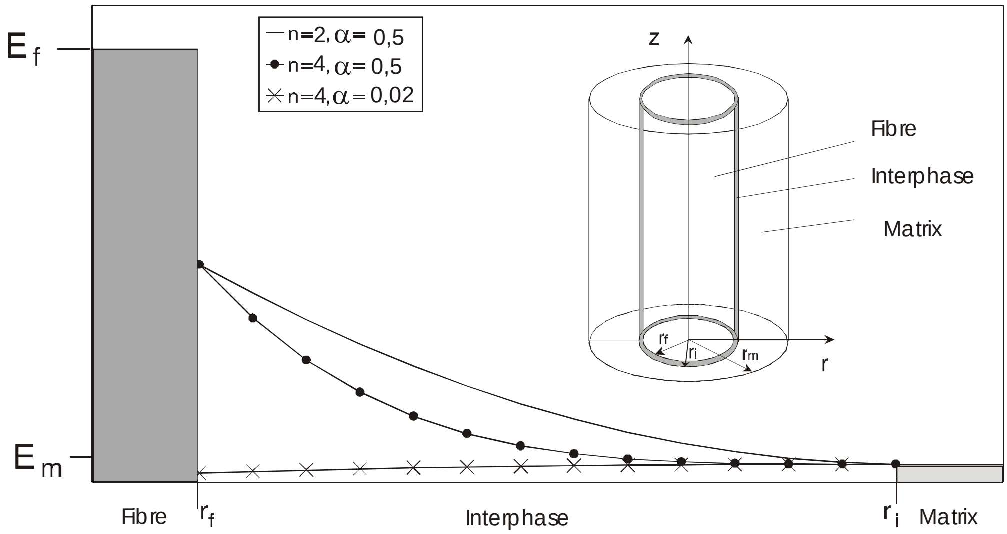

Fig.1. Model for interphase.

The effect of fibre/matrix interphase on the composite properties will be investigated by varying the parameters of Young's modulus and the interphase thickness. It will be used a square packing array of circular fibres, since this simple packing geometry is known to give satisfactory results [8].

Representative volume element (RVE)

In the present approach, the procedure for predicting the elastic constants of the composite from a representative volume element (RVE) is laid on a rigorous mechanics foundation by using strain energy equivalence principles in conjunction with finite element analysis [9]. First, the appropriate boundary conditions for the typical RVE under different loading are determined and applied to the finite element model. Than, the non-homogeneous strain fields obtained from the analysis are reduced to a volume – averaged strain by using Gauss theorem to integrate the surface displacements. The average stress is then determined by using the strain energy equivalence principle to relate the energy stored in the RVE to the external work done on it. The relevant composite modulus is than obtained as the ratio of average stress to the average strain. Sun and Vaidya [9] used such approach to obtain elastic constants of unidirectional composites (without taking into account the interphase). In the present investigation this approach is extended for unidirectional composites taking into account the interphase.

In a composite lamina the actual fiber distribution is quite random across the cross-section. For simplicity reasons, most micromechanical models assume a periodic arrangement [7-15]. The RVE has the same elastic constants and fiber volume fraction as the composite. The periodic fiber sequences commonly used are the square array and the hexagonal array. The RVE with square array is used in the present investigation (see Fig.2.).

In lamination theory the composite lamina is modelled as a homogeneous orthotropic medium with certain effective modulus that describe the average material properties of corresponding composite. To describe this macroscopically homogeneous medium, averaging the stress and strain tensor over the volume of the RVE derives macro-stress and macro-strain

$$\overline{\sigma}_{ij} = \frac{1}{V}\int_V \sigma_{ij}(x,y,z)dV\ ; \qquad \overline{\varepsilon}_{ij} = \frac{1}{V}\int_V \varepsilon_{ij}(x,y,z)dV \tag{2}$$

In [9] is shown, that the average stress and strain quantities defined in (2) ensure equivalence in strain energy between the equivalent homogeneous material U and the original heterogeneous material U^*

$$U = U^* \tag{3}$$

where

$$U = \frac{1}{2}\overline{\sigma}_{ij}\overline{\varepsilon}_{ij} \quad \text{and} \quad U^* = \frac{1}{2}\int_V \sigma_{ij}\varepsilon_{ij}dV$$

These average quantities will be used in present analysis to determine composite modulus.

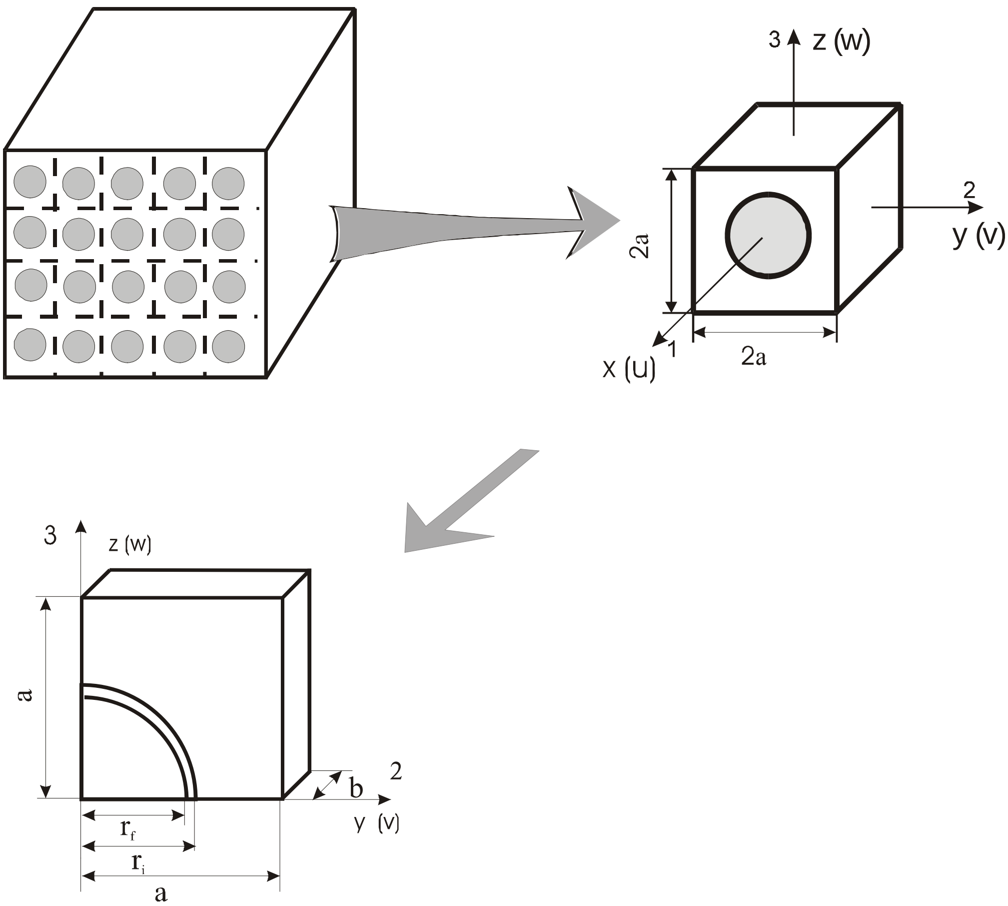

Fig. 2. RVE for square configuration.

The finite element analysis of the RVE yields the stress and strain fields within the heterogeneous material. The corresponding average quantities $\overline{\sigma}_{ij}$ and $\overline{\varepsilon}_{ij}$ can be obtained using equations (2). Alternatively, the average strain can be related to the boundary displacements of the RVE by using Gauss theorem. In this case, equation for average strains becomes [9]

$$\overline{\varepsilon}_{ij} = \frac{1}{V}\int_V \varepsilon_{ij}(x,y,z)dV = \frac{1}{2V}\int_S \left(u_i n_j + u_j n_i\right)dS \qquad (4)$$

where V is the volume of the RVE, S is the boundary surface of the RVE, u_i is the ith component of displacement and n_j, is the jth component of the unit normal to S.

The relationship given by equation (4) makes it possible to evaluate the volume-averaged strains using the boundary displacements, thus avoiding the volume integration.

Finite Element modelling

The RVE used in the Finite Element analysis (ANSYS 5.6) is shown in Fig. 3. Only a quadrant of the original RVE is modelled since there are two axes of symmetry in this problem (both normal loading and transverse loading). The interphase with a various elastic modulus $E_i(r)$ is modelled using a very fine Finite Element mesh (see Fig. 4 and Fig. 5).

Axial loading is modelled by a force P_1 acting on the face $x = b$ (see Fig.3), while transverse loading corresponds to a force P_2 acting on the face $y = a$ or $z = a$. For such loading conditions, the boundary conditions of the RVE also correspond to lines of symmetry. Thus, normal displacements of the boundaries of the quadrant are restricted to those that cause the boundary to displace only parallel to the original boundary. The displacement constraints applied to the FE model are

$$\begin{array}{lll} u(0,y,z)=0 & v(x,0,z)=0 & u(x,y,0)=0 \\ u(b,y,z)=\delta_1 & v(x,a,z)=\delta_2 & u(x,y,a)=\delta_3 \end{array} \qquad (5)$$

where u,v and w denote displacements in x, y and z directions, respectively. The displacements δ_1, δ_2 and δ_3 are solutions obtained from FE analysis of the RVE subjected to a load at the boundary.

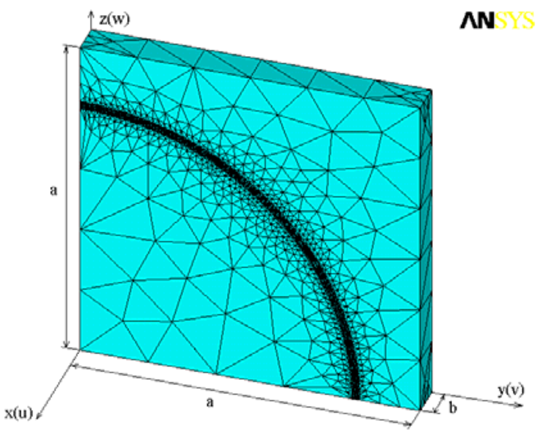

Fig. 3. Finite element mesh for RVE.

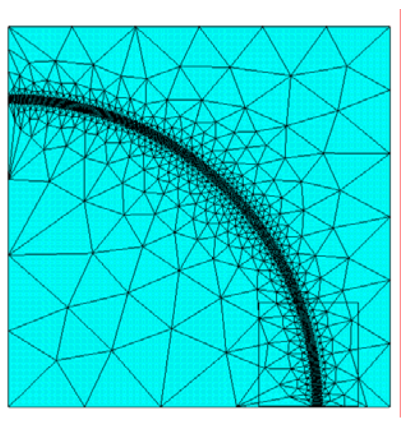
Fig. 4. Finite element mesh for RVE with zoom for interphase

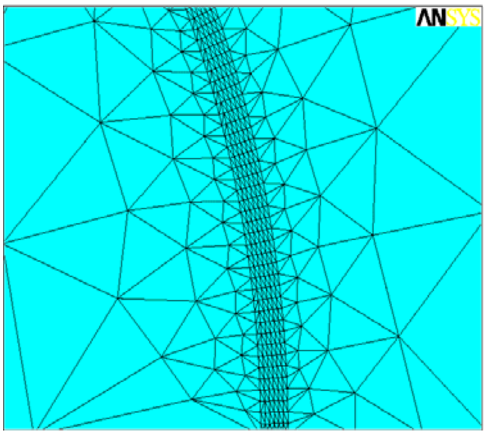

Fig. 5. Details of Finite Element mesh for interphase (zoom from Fig. 4.).

Axial loading (longitudinal elastic modulus)

For the case of an axial loading, P_1, the average longitudinal strain calculated from equation (4), reduces to the conventional definition of strain

$$\bar{\varepsilon}_{11} = \frac{1}{V}\int_S u_1 n_1 dS = \frac{\delta_1}{b} \tag{6}$$

The strain energy stored within the RVE is given by

$$U = \frac{1}{2}\bar{\sigma}_{ij}\bar{\varepsilon}_{ij}V = \frac{1}{2}\bar{\sigma}_{11}\bar{\varepsilon}_{11}V \tag{7}$$

External work done on the RVE by the applied load P_1 is given by

$$W = \frac{1}{2}P_1\delta_1 \tag{8}$$

Using the principle of strain energy equivalence between stored energy and external work

$$\frac{1}{2}P_1\delta_1 = \frac{1}{2}\bar{\sigma}_{11}\bar{\varepsilon}_{11}V \tag{9}$$

Taking account (6), from (9) follows

$$\bar{\sigma}_{11} = \frac{P_1}{a^2} \tag{10}$$

The longitudinal modulus is given as follows

$$E_1 = \frac{\bar{\sigma}_{11}}{\bar{\varepsilon}_{11}} = \frac{P_1 b}{a^2\delta_1} \tag{11}$$

Transverse loading (transverse elastic modulus)

For the case of a transverse loading, P_2, the average transverse strain calculated from equation (4), is as follows

$$\bar{\varepsilon}_{22} = \frac{1}{V}\int_S u_2 n_2 dS = \frac{\delta_2}{a} \tag{12}$$

The strain energy stored within the RVE is given by

$$U = \frac{1}{2}\bar{\sigma}_{ij}\bar{\varepsilon}_{ij}V = \frac{1}{2}\bar{\sigma}_{22}\bar{\varepsilon}_{22}V \tag{13}$$

External work done on the RVE by the applied load P_2 is given by

$$W = \frac{1}{2}P_2\delta_2 \tag{14}$$

Using the principle of strain energy equivalence between stored energy and external work

$$\frac{1}{2}P_2\delta_2 = \frac{1}{2}\bar{\sigma}_{22}\bar{\varepsilon}_{22}V \tag{15}$$

Taking account (12), from (15) follows

$$\bar{\sigma}_{22} = \frac{P_2}{ab} \tag{16}$$

The transverse modulus is given as follows

$$E_2 = \frac{\bar{\sigma}_{22}}{\bar{\varepsilon}_{22}} = \frac{P_2}{b\delta_{22}} \tag{17}$$

Poisson's ratios are as follows

$$\nu_{12} = -\frac{\bar{\varepsilon}_{22}}{\bar{\varepsilon}_{11}} = -\frac{\delta_2 b}{\delta_1 a}; \qquad \nu_{23} = -\frac{\bar{\varepsilon}_{33}}{\bar{\varepsilon}_{22}} = -\frac{\delta_3}{\delta_2} \tag{18}$$

Identification

Parameters of Identification

Identification of interphase parameters is performed from the experimentally measured elastic properties of composite material. The parameters to be identified are volume content of interphase and elastic modulus of interphase. It is assumed that elastic modulus of interphase is constant.

$x_1 = \mu_i$ volume content of interphase
$x_2 = E_i$ elastic modulus of interphase

Identification functional and minimization problem

The functional to be minimized describes deviation between the measured transverse elastic modulus of composite $E_{Eksp}\Big|^{(T)}$ and numerically calculated transverse elastic modulus $E_{Model}\Big|^{(T)}$.

$$\Phi(x_1, x_2) = \frac{\left((\Psi_{Model})^2 - (\Psi_{Eksp})^2\right)^2}{(\Psi_{Eksp})^4} \tag{19}$$

Here $\Psi_{Eksp} = E_{Eksp}\Big|^{(T)}$, $\Psi_{Model} = E_{Model}\Big|^{(T)}(x_1, x_2)$

Identification problem is formulated as follows

$$\Phi(x_1, x_2) \Rightarrow \min$$

The lower $x_1^{\min}, x_2^{\min}$ and the upper x_1^{max}, x_2^{max} bounds of the identification parameters determine so called domain of interest.

Method of Experiment Design

Let us consider a criterion for elaboration of plans of experiment, which is to be independent on the mathematical model of the object. Initial information for elaboration of the plan is the number of variables *n* and the number of experiments *k*. The main principles in the proposed approach are as follows [18]

1) the number of levels in the domain of experiments for each variable is equal to the number of the experiments and for each level only one experiment is performed;
2) the reference points (points of experiments) in the domain of experiments are distributed as regular as possible.

The plan of experiment is characterized by the matrix of the plan B_{ij}. For example, the plan of experiment with the fifteen reference points (k = 15) and two variables (n = 2) is given as follows

$$B^T = \begin{vmatrix} 8 & 2 & 15 & 1 & 13 & 3 & 5 & 7 & 12 & 11 & 9 & 4 & 14 & 6 & 10 \\ 15 & 7 & 11 & 12 & 8 & 3 & 9 & 1 & 13 & 2 & 10 & 14 & 4 & 5 & 6 \end{vmatrix} \tag{20}$$

The points of the experiment (reference points) for this matrix of the plan (n = 2) are presented in Fig. 6. The domain of the experiments is determined as $x_j \in \left[x_j^{\min}; x_j^{\max}\right]$. Thus, in this domain the reference points, where the experiments must be performed, are calculated by the expression

$$x_j^{(i)} = x_j^{min} + \frac{1}{k-1}\left(x_j^{max} - x_j^{min}\right)\left(B_{ij} - 1\right) \qquad (21)$$

Here $i = 1, 2,..., k$ and $j = 1, 2,..., n$.

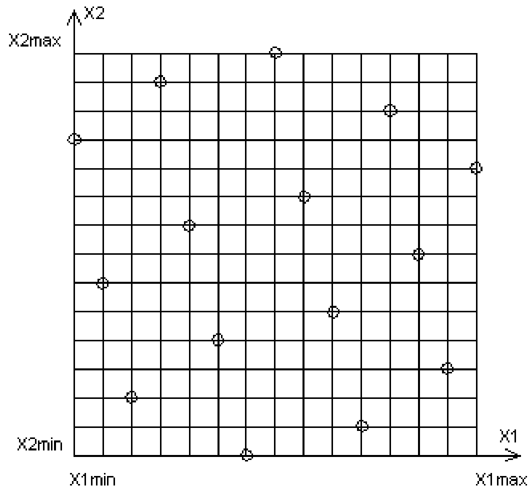

Fig. 6. Experiment design for n = 2 and k = 9

Approximation of Response Surface

Information about the behaviour of the object can be obtained by the physical experiment or by the computer solution in the reference points. This information can be represented as a table of data, where the response function $y(\mathbf{x})$ of the object is to be in relationship to the variables $x_1, x_2, ..., x_n$. The goal is by using the data of experiments (in our case data are obtained by the Finite Element solution in the reference points) to obtain the relation $y(\mathbf{x})$ in the mathematical form or so called equation of regression. The details of this procedure and corresponding program RESINT were described in [18].

Numerical results

Example 1

The Finite Element predictions of the elastic modulus are compared with analytical solutions and available experimental data. The results for boron/ aluminium composite with the input data

$$E_f = 379.3 \text{ GPa}, \quad \nu_f = 0.1, \quad E_m = 68.3 \text{ GPa}, \quad \nu_f = 0.3, \quad \mu_f = 0.47$$

are given in *Table 1*. In the present model interphase is introduced with the volume fraction μ_i =0.03 (volume fraction of matrix is $\mu_m = 0.5$) and with same elastic properties as for matrix $E_i = E_m$, $\nu_i = \nu_m$

Table1. Elastic modulus for boron/aluminium composite

Elastic Constants (Gpa)	Sun& Vaidya[9]	Sun& Chen[12]	Chamis[13]	Whitney& Riley[14]	Hashin& Rosen[15]	Experi-ment[16]	Present (FEM model with interphase)
E_1	215	214	214	215	215	216	215.5
E_2	144	135	156	123	139.1(131.4)	140	144.1
ν_{12}	0.19	0.19	0.20	0.19	0.195	0.29	0.193
ν_{23}	0.29	-	0.31	-	0.31(0.28)	-	0.292

Example 2

The properties of the constituent materials (Nicalon fiber and barium magnesium aluminosilicate (BMAS) matrix) are listed as follows

$$E_f = 200 \text{ GPa}, \ \nu_f = 0.3, \qquad E_m = 106 \text{ GPa}, \ \nu_m = 0.23,$$

The fiber volume content is 60%. The interphase elastic modulus is constant and changes in the range between 0.345 and 34.5 Gpa. Its volume content considered in the range between 0.0156 and 0.165. Results of the present approach are compared to the solution of N. J. Pagano *et al.*[17] and are given in *Table 2*.

Table 2. Transverse elastic modulus for a unidirectional composite

Interphase volume content	Interphase modulus (Gpa)	Transverse elastic modulus (Gpa)	
		N. J. Pagano	Present FEM
0.0156	34.5	148.031	148.909
	3.45	109.741	109.649
	0.345	45.148	45.337
0.08	34.5	131.901	131.996
	3.45	58.332	56.660
	0.345	22.891	22.148
0.165	34.5	115.995	114.515
	3.45	37.123	31.901
	0.345	14.624	9.47

Example 3

The effect of interphase on the composite properties will be investigated by varying the parameters of Young's modulus and thickness of interphase. It is assumed, that elastic modulus of interphase is non-constant and changes according to

$$E_i(r) = \left(\alpha E_f - E_m\right)\left(\frac{r_i - r}{r_i - r_f}\right)^n + E_m$$

The properties of the constituent materials are selected as follows

$\mu_f = 0.5$ - volume content of fiber

$E_f = 59387$ $[N/mm^2]$, $\nu_f = 0.22$ - elastic properties of fiber

$E_m = 3140$ $[N/mm^2]$, $\nu_m = 0.34$ - elastic properties of matrix

Results of FEM calculation of transverse elastic modulus $E_{FEM}\Big|^{(T)}$ for different volume content μ_i and Young's modulus $E_i(r)$ of interphase are presented in *Table 3*.

Table 3. Transverse elastic modulus for different volume content μ_i and Young's modulus $E_i(r)$ of interphase

Volume content of interphase		$\mu_i = 0.029$	$\mu_i = 0.04$
n	α	Transverse elastic modulus $E_{FEM}\Big\|^{(T)}$	
2	0.5	10397.3	10580.7
4	0.02	9357.6	9369.8
4	0.5	10236.8	10349.1
4	1	10326.4	10473.9
$E_{Eksp}\Big\|^{(T)}$ =10994 $[N/mm^2]$			

Example 4

Identification of interphase parameters (volume content and elastic modulus of interphase) is obtained using FEM, the method of experiment design and response surface approach. The properties of the constituent materials are selected as follows

$\mu_f = 0.5$ - volume content of fiber

$E_f = 59387$ $[N/mm^2]$, $\nu_f = 0.22$ - elastic properties of fiber

$E_m = 3140$ $[N/mm^2]$, $\nu_m = 0.34$ - elastic properties of matrix

The plan of experiment with 15 reference points for two variables ($x_1 = \mu_i$ and $x_2 = E_i$) is selected. The lower $x_1^{\min}, x_2^{\min}$ and the upper $x_1^{\max}, x_2^{\max}$ bounds (domain of interest) for identification are chosen as follows

$0.02 \le x_1 \le 0.08$
$3140 \le x_2 \le 59387$

Calculated values of identification parameters in points of experiment design are presented in *Table 4*. In all 15 reference points the transverse elastic modulus $E_{FEM}\Big|^{(T)}$ is calculated (using FEM).

Table 4. Reference points of experiment design and calculated values of the transverse elastic modulus $E_{FEM}\Big|^{(T)}$ in these points

No.	$x_1 = \mu_i$	$x_2 = E_i\ [N/mm^2]$	$E_{FEM}^{ASs}\Big|^{(T)}\ [N/mm^2]$
1	0.0500	59387	11110
2	0.0243	27246	10200
3	0.0800	43316	12160
4	0.0200	47334	10120
5	0.0714	31263	11730
6	0.0286	11175	10150
7	0.0371	35281	10620
8	0.0457	3140	9456
9	0.0671	51352	11710
10	0.0629	7158	10560
11	0.0543	39299	11200
12	0.0329	55369	10530
13	0.0757	15193	11510
14	0.0414	19211	10630
15	0.0586	23228	11200

Having information about values in all 15 points of experiment design the approximating function for the transverse elastic modulus $E_{FEM}\Big|^{(T)}$ can be determined. For this the software code RESINT is used and approximating function is built (correlation $C = 99$ %)

$$E_{Model}\Big|^{(T)}(x_1, x_2) = 8986 + 1815 z_1 + 428 z_2 + 72.26 \frac{1}{z_2} + 219.9 z_1^2 - 253.1 z_2^2 - 159.1 \frac{z_1}{z_2}$$

where

$$z_1 = 0.16667 + 16.667 x_1 \qquad z_2 = 0.000016839 x_2$$

Identification of volume content of interface $x_1 = \mu_i$ and elastic modulus of interface $x_2 = E_i$ is carried out by minimization functional

$$\Phi(x_1, x_2) \Rightarrow \min$$

where

$$\Phi(x_1,x_2)=\frac{\left((\Psi_{Model})^2-(\Psi_{Eksp})^2\right)^2}{(\Psi_{Eksp})^4}$$

Here $\Psi_{Eksp}=E_{Eksp}\Big|^{(T)}$, $\Psi_{Model}=E_{Model}\Big|^{(T)}(x_1,x_2)$

Results of the identification and corresponding Finite Element solution of the transverse elastic modulus $E_{FEM}\Big|^{(T)}$ are given in *Table 5*.

Table 5. Results of identification

No.	$x_1=\mu_i$	$x_2=E_i\ [N/mm^2]$	$E_{FEM}\Big\|^{(T)}\ [N/mm^2]$	$E_{Eksp}\Big\|^{(T)}\ [N/mm^2]$
1	0.0685	10000	10990	10994
2	0.0582	15000	11000	
3	0.0539	20000	11000	
4	0.0498	30000	10990	
5	0.0479	40000	10980	
6	0.0469	50000	10980	

CONCLUSIONS

A method, based on classical elasticity theory, is proposed for the calculation of effective elastic constants of unidirectional composites. The interphase influence on the properties of composites was predicted using a FEM model based on RVE. The average Young's modulus of the interphase was identified combining the results of the experiments with the numerically calculated values.

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Ručevskis S., Reichhold J. Armēta polimērkompozīta elastīgās īpašības, ievērojot starpslāni starp stiegru un matricu
Rakstā tiek apskatīta starpslāņa ietekme uz armēta kompozīta materiāla elastīgajām īpašībām. Izmantojot klasisko elastības teoriju, tiek veidots kompozīta vienības šūnas modelis, ievērojot starpslāni starp stiegru un matricu. Starpslāņa elastīgās īpašības tiek aprakstītas ar matemātiska modeļa palīdzību. Iegūtie rezultāti ir salīdzināti ar citu autoru pētījumiem, kā arī ar eksperimenta rezultātiem.

Ruchevskis S., Reichhold J. Effective elastic constants of fiber-reinforced polymer-matrix composites with the concept of interphase
In this paper we discuss the effect of an interphase on the mechanical properties of unidirectional fiber composites. Classical elasticity theory has been applied to the simplified model of a composite unit cell in which the concept of interphase between fiber and matrix is taken into account. This interphase has its own set of properties, based on mathematical model. Obtained results are compared with the results of other author investigations and with the results of experiment.

Ручевскис С., Реицхолд Е. Упругие свойства армировенных полимерных композитов с учетом промежуточного слоя между волокном и матрицей.

В работе исследуется влияние промежуточного слоя между волокном и матрицей на механические характеристики однонаправленно армированного композитного материала. Для решения поставленной проблемы применён метод конечных элементов. При этом рассмотрена пространственная задача теорий упругости. Проведён сравнительний анализ полученных результатов с данными иследований других авторов, а также результатами эксперимента.