ORIGINAL SCIENTIFIC PAPER OPEN ACCESS

Finite element modelling of laminated composite: effects of different ply orientations

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ARTICLE INFO

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DOI: 10.5937/engtoday2202029C

UDC: 621(497.11) **ISSN:** 2812-9474

Article history: Received 08 June 2022; Accepted 25 June 2022

ABSTRACT

The subject of analysis in this paper are laminated composites as an always popular topic in the field of composite materials. The introductory part of the paper presents a brief overview of the current state of research in this area and points out further directions of research related to this very interesting topic. The classification of laminated composite plates from the aspect of different criteria are described in detail. As the subject of the paper is stress-strain analysis of laminated composite, the expression for the generalized Hooke's law of orthotropic class of material symmetry is given. The terms of the constitutive matrix are expressed through engineering constants. At the end, the bending analysis of the rigidly supported laminated plate under a sinusoidal load was performed. The mentioned analysis was conducted using software based on the finite element method. A comparative analysis of the plate with the different ply orientation (0°/90°/90°/0° and -45°/45°/45°/-45°) was done. The obtained results were analyzed and appropriate conclusions were made.

KEYWORDS

Laminated composite, Generalized Hooke's law, Finite element method, Bending analysis.

1. INTRODUCTION

Many elements of modern constructions require material characteristics that do not have conventional materials. Such requirements can only be met by composite materials (composites), which are a combination of two or more materials with different characteristics. The development of these materials stemmed primarily from the need to achieve the highest possible strength and rigidity in many structures while reducing weight. The advantage of composites over classic structural materials (metals) is that parts of the composite can be designed so that they can have different material properties in different cross-sections and different directions. Also, composite materials have high resistance to corrosion, material fatigue, good behavior in structural elements exposed to bending. Longer service life of composites reduces maintenance costs, on the one hand, and reduces exploitation costs due to the lower weight of structural elements, on the other hand. In addition to the above advantages, composite materials as well as other materials have their disadvantages. Due to the complexity of their structure (consist of two or more materials), it is often very difficult to diagnose damages at the internal structure of a composite material. Then, servicing and repairing structural elements made of composite materials can be much more difficult than constructions made of conventional materials, which ultimately increases maintenance costs. Delamination of laminated composites can occur due to the stress concentration at the contact of two layers with different material characteristics. This breaks the matrix and damages the laminate. Despite the mentioned disadvantages, having in mind all the above advantages, laminated composites are the current topic of research which is evidenced by a large number of review papers [1-4]. The static problems of bending and buckling of laminated plates for different cases of boundary conditions were analysed by the authors in the papers [5-7]. The influence of different ply orientation in square and rectangular laminated plates was studied for different cases of dynamic loading. In [8-10], free vibrations of laminated plates under different boundary conditions were studied. The propagation of elastic waves in laminated composite with special emphasis on Lamb waves was also analyzed [11-13]. In order to overcome delamination as the main disadvantage of laminated composites, in recent years the authors have been researching functionally graded materials [14-16].

2. CLASSIFICATION OF LAMINATED COMPOSITES

There are a large number of classification of composite plates with plies in the literature and there is no completely clear classification because they are such materials whose characteristics are under control of the designer. The type of composite plates with plies depends of the geometric parameters of the plate, the way that plies are combined, the material characteristics of the individual ply, etc.

Depending on the material of the constituents, the composite plates with plies can be:

1. **Sandwich composite plates or sandwich composites**
2. **Laminated composite plates or laminated composites**

Sandwich composites or laminates with core contains two outer plies and one middle ply that is usually made of cheaper and lighter material. In this way, the price is reduced but at the same time the bending stiffness of the laminate is improved.

Laminated composites, unlike sandwich laminates, do not have a core. Depending on whether they are plies consist of the same or different materials, their further classification is: homogeneous and hybrid laminated composites. Considering the way of defining sandwich laminates, it is completely clear that they can only be hybrid.

The other one classification of laminated composites is based on geometric parameters (angles of orientation of individual plies in relation to the adopted global coordinate system or in relation to the middle plane of the laminate, thickness of individual plies, mutual position of adjacent layers, etc.). The most general classification of laminated composites based on the geometric characteristics of the plies in relation to the middle plane is [17]:

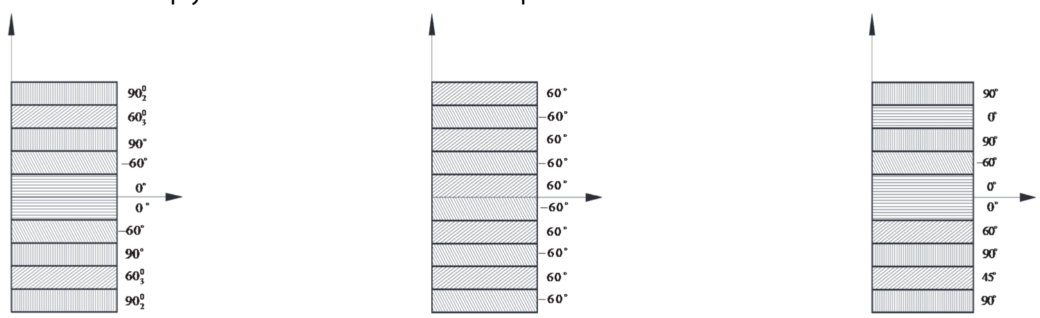
1. **Symmetrical laminates**
2. **Antisymmetrical laminates**
3. **Asymmetrical laminates ili non-symmetrical laminates**

Symmetrical laminates (Figure 1a) - The geometric characteristics are symmetrical in relation to the middle plane of the plate. It means that the angles of orientation of the plies, the thickness of the plies and the characteristics of the material above and below the middle plane are equal to each other:

$$\theta(z)=\theta(-z),\ C_{ij}^{k}(z)=C_{ij}^{k}(-z),\ h_k(z)=h_k(-z), \tag{1}$$

where are:

$z=0$ - equation of middle plane,
θ - the orientation angle of the fibers in relation to the global coordinate system,
C_{ij}^{k} - coefficients of elasticity of the ply "k" in relation to the middle plane,
h_k - the thickness of the ply "k" in relation to the middle plane.



a) symmetrical laminates b) antisymmetrical laminates c) asymmetrical laminates

Figure 1: Laminated composite constituted of single-directional plies with different orientation

Antisymmetrical laminates (Figure 1b) - the plies thicknesses and material characteristics of the plies above and below the middle plane are equal to each other, while the angles of orientation of the fibers relative to the global coordinate system, above and below the middle plane, are opposite signs:

$$\theta(z)=-\theta(-z),\ C_{ij}^{k}(z)=C_{ij}^{k}(-z),\ h_k(z)=h_k(-z), \tag{2}$$

Asymmetrical laminates (Figure 1c) - there is a complete independence of the geometric characteristics of the plies above and below the middle plane, so a mathematical relationship cannot be established between the orientation angles, material characteristics and ply thickness above and below the middle plane.

Further, based on geometric characteristics, ie. based on the orientation of plies, laminates can be classificated as:

1. **Angle ply laminates**
2. **Cross ply laminates**
3. **Angle ply and cross ply laminates**
4. **Quasi-isotropic laminates**
5. **General laminates**

Angle ply and cross ply laminates have two orthogonal planes of symmetry which do not necessarily coincide with the planes of the adopted coordinate system. The directions of the plane of symmetry in relation to the adopted coordinate system are bisector directions, while the angle between of the bisector line and one of the axes of the coordinate system is the bisector angle⊠⊠. The fibers of individual plies are shifted relative to the bisector direction by laminate angles ±⊠. The main difference between angle ply and cross ply laminates is: angle ply laminates can have arbitrary values of angles ⊠⊠and ±⊠, while cross ply laminates have fixed value of the bisector and laminate angle (⊠=45° and⊠⊠=±45°). For the value of the bisector angle ⊠=0°, the directions of material symmetry and coordinate axes coincide.

Quasi-isotropic laminates are a type of laminate in which the plies are laid in such a way that the laminate acts as an isotropic ply under plane load.

Generalized laminates are laminates in which the plies can have completely different fiber orientations and analysis such laminates is difficult in terms of macromechanical properties.

Based on the thickness of the plies, it is possible to classificated the laminate as:

1. **Balanced laminates**
2. **Unbalanced laminates**

Balanced laminates - all plies must have the same thickness.

Unbalanced laminates - the thicknesses of the plies may be partially or completely different.

It should be emphasized that there are no clear boundaries between the previously listed tupes of laminates, so for example one laminate can be at same time symmetrical, quasi-isotropic and unbalanced. Therefore, in the literature often when describing macromechanical characteristics can be found, for example, symmetric quasi-isotropic laminates or non- symmetric cross ply laminates, etc.

3. GENERALIZED HOOK'S LAW

3.1. Coefficients of the constitutive matrix

The coefficients of constitutive matrix can be expressed by using:

1. Engineering constants
2. Elastic constants defined in Spencer's papers

Expressing the coefficients of the constitutive matrix by using engineering constants is a much more common, especially in engineering practice. Also, this way of expression is more suitable for application in numerical methods such as the finite element method. The second principle of expressing the coefficients of the constitutive matrix is useful due to its invariance in relation to the rotation of the coordinate system, so it is not necessary to use transformations of the constitutive matrix. Depending on the class of symmetry of the constituents, composite materials require the definition of a greater number of material constants then to conventional materials. Experimental static and dynamic methods are used to determine the material constants. Laminated composite are a type of composite material that consists of several individual fiber-reinforced plies of the same or different orientation. Plies can be composed of materials with different types of symmetry from isotropic to completely anisotropic and can have different structures, thicknesses and mechanical properties. The most common constituents of laminated composite are plies with the following classes of symmetry:

1. Isotropic
2. Transversely isotropic
3. Orthotropic
4. Anisotropic with monoclinic type of symmetry
5. Anisotropic with triclinic type of symmetry

When the laminate is constituted of fiber-reinforced materials, then the constituents of the laminate are most often orthotropic classes of symmetry. Coordinate system rotations can cause the ply symmetry class relative to the global coordinate system to correspond to anisotropic material with monoclinic symmetry type. Orthotropic single-directional composite layer are obtained as a combination of single-directional plies which have one privileged direction that coincides with one of the axes of the global coordinate system. Planes normal in that direction have isotropic characteristics. They represent the simplest structure of orthotropic materials and consist of single-directional layers whose material coordinates 1, 2 and 3 coincide with the coordinates of the layers x, z, y. Figure 2 shows layer with orthotropic type of material symmetry.

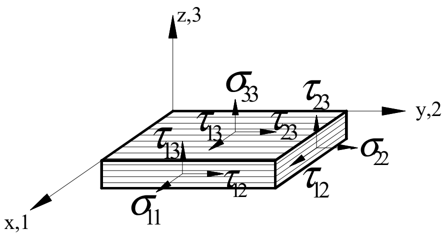


Figure 2: Layer with orthotropic type of material symmetry

Hook's generalized law for orthotropic type of material symmetry is:

$$\begin{Bmatrix}\sigma_{11}\\ \sigma_{22}\\ \sigma_{33}\\ \tau_{23}\\ \tau_{13}\\ \tau_{12}\end{Bmatrix}=\begin{bmatrix}\frac{1-\nu_{23}\nu_{32}}{E_2E_3\Delta} & \frac{\nu_{21}+\nu_{23}\nu_{31}}{E_2E_3\Delta} & \frac{\nu_{31}+\nu_{21}\nu_{32}}{E_2E_3\Delta} & 0 & 0 & 0\\ \frac{\nu_{21}+\nu_{23}\nu_{31}}{E_2E_3\Delta} & \frac{1-\nu_{13}\nu_{31}}{E_1E_3\Delta} & \frac{\nu_{32}+\nu_{12}\nu_{31}}{E_1E_3\Delta} & 0 & 0 & 0\\ \frac{\nu_{31}+\nu_{21}\nu_{32}}{E_2E_3\Delta} & \frac{\nu_{32}+\nu_{12}\nu_{31}}{E_1E_3\Delta} & \frac{1-\nu_{12}\nu_{21}}{E_1E_2\Delta} & 0 & 0 & 0\\ 0 & 0 & 0 & G_{23} & 0 & 0\\ 0 & 0 & 0 & 0 & G_{13} & 0\\ 0 & 0 & 0 & 0 & 0 & G_{12}\end{bmatrix}\begin{Bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \varepsilon_{33}\\ \gamma_{23}\\ \gamma_{13}\\ \gamma_{12}\end{Bmatrix} \tag{3}$$

where is:

$$\Delta=\frac{\left(1-\nu_{12}\nu_{21}-\nu_{23}\nu_{32}-\nu_{13}\nu_{31}-2\nu_{21}\nu_{32}\nu_{13}\right)}{E_1E_2E_3}. \tag{4}$$

In the case of small thickness orthotropic ply as a constituent of laminate, assuming plane type of stress state as well as that the displacement normal to plane of plate is constant, it can be neglect the third type and third column of the constitutive matrix, so equation (3) reduces to:

$$\begin{Bmatrix}\sigma_{11}\\ \sigma_{22}\\ \tau_{23}\\ \tau_{13}\\ \tau_{12}\end{Bmatrix}=\begin{bmatrix}\frac{1}{E_2\Delta} & \frac{\nu_{21}}{E_2\Delta} & 0 & 0 & 0\\ \frac{\nu_{21}}{E_2\Delta} & \frac{1}{E_1\Delta} & 0 & 0 & 0\\ 0 & 0 & G_{23} & 0 & 0\\ 0 & 0 & 0 & G_{13} & 0\\ 0 & 0 & 0 & 0 & G_{12}\end{bmatrix}\begin{Bmatrix}\varepsilon_{11}\\ \varepsilon_{22}\\ \gamma_{23}\\ \gamma_{13}\\ \gamma_{12}\end{Bmatrix} \tag{5}$$

where is:

$$\Delta = \frac{(1-\nu_{12}\nu_{21})}{E_1 E_2}. \tag{6}$$

4. FINITE ELEMENT MODELLING OF LAMINATED COMPOSITE

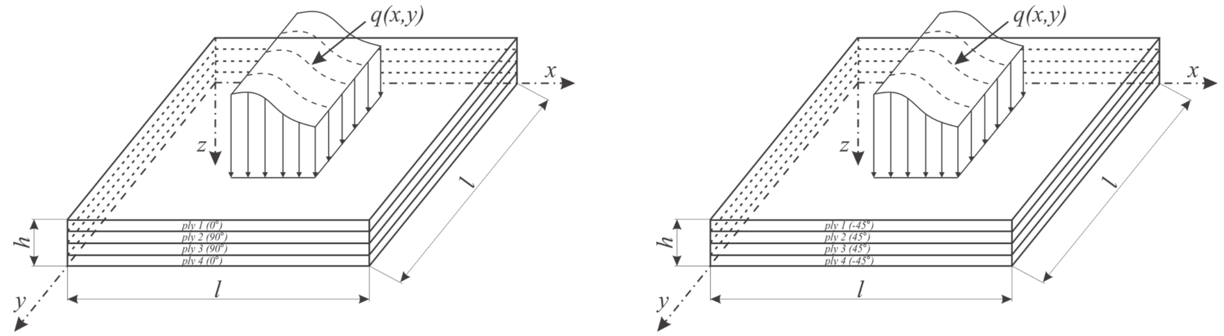
In most cases when the analyzed structural element has a complex geometry, complex load and different materials, it is not possible to find a solution in analytical form. Analytical solution involves obtaining analytical expressions for calculating the required quantities at different points (stress, deformation, temperature, etc.). To obtain such data, it is necessary to solve differential [18] or partial differential equations, which can only be done for very simple problems. Therefore, numerical methods are used. One of the most commonly used numerical method is finite element method (FEM). The development of computer technology has led to the expansion of the use of numerical methods, so that today numerical analysis is often a mandatory part of project documentation. The use of numerical methods can achieve significant savings in economic terms, especially in structures where it is not necessary to perform experiments.

4.1. Description of model

A laminated composite plate fixed along all four edges and loaded with a sinusoidally distributed load was analyzed (Figure 3):

$$q(x,y) = q_0 \sin\left(\frac{\pi x}{a}\right)\cos\left(\frac{\pi y}{b}\right). \tag{7}$$

The geometric and material characteristics of the composite plate are given (8). Static analysis was performed for two cases of ply orientation of symmetrical cross ply laminate (0°/90°/90°/0° и -45°/+45°/+45°/-45°) by using the finite element method. The FE model is discretized with 1024 finite elements and 1089 nodes.



a) symmetrical cross ply laminate 0°/90°/90°/0° b) symmetrical cross ply laminate -45°/+45°/+45°/-45°

Figure 3: Laminated composite plates under sinusoidally distributed load

Geometric and material characteristics of laminated composite plate are:

$$\begin{aligned} & h = 0.24\,cm; \qquad l = 12\,cm; \\ & E_1 = 174.6 \cdot 10^5 \frac{N}{cm^2}; \qquad E_2 = 7 \cdot 10^5 \frac{N}{cm^2} \\ & G_{12} = 3.5 \cdot 10^5 \frac{N}{cm^2}; \qquad G_{1z} = 3.5 \cdot 10^5 \frac{N}{cm^2}; \qquad G_{2z} = 1.4 \cdot 10^5 \frac{N}{cm^2} \\ & \nu_{12} = 0.25 \end{aligned} \tag{8}$$

4.2. Numerical results

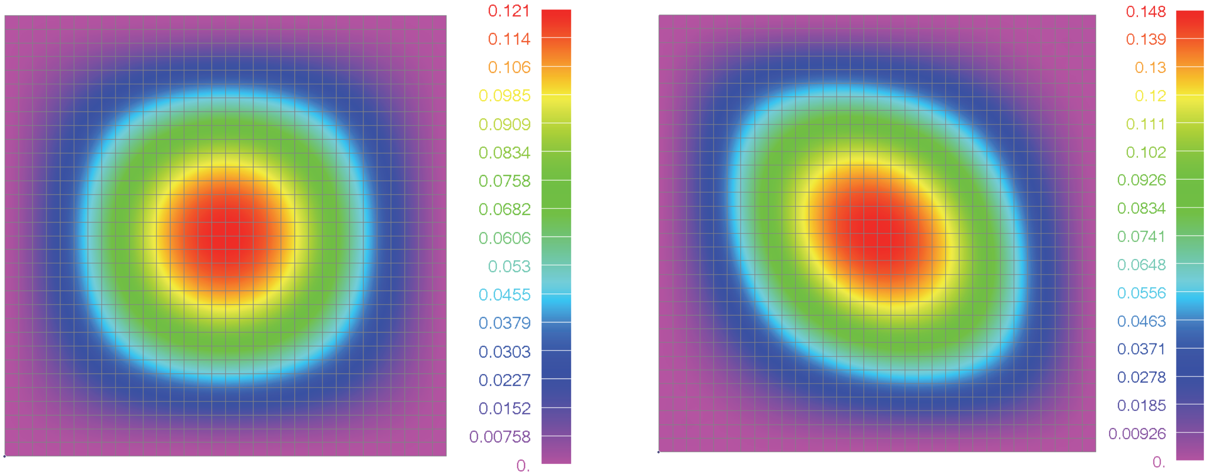
Bending analysis of plate for two different cases of ply orientation was performed. In order to perform a comparative analysis of the obtained values of displacement and stress, the mentioned values are normalized according to:

$$\bar{w} = \frac{100 E_2 h^3}{q_0 l^4} w\left(\frac{l}{2},\frac{l}{2}\right); \quad \bar{\sigma}_{xx}(z) = \frac{h^2}{q_0 l^2}\sigma_{xx}\left(\frac{l}{2},\frac{l}{2},z\right); \quad \bar{\sigma}_{yy}(z) = \frac{h^2}{q_0 l^2}\sigma_{yy}\left(\frac{l}{2},\frac{l}{2},z\right); \quad \bar{\tau}_{xy}(z) = \frac{h^2}{q_0 l^2}\tau_{xy}(z). \tag{9}$$

Table 1 shows the comparative results of normalized values of vertical displacement $\bar{w}$, normal stresses $\bar{\sigma}_{xx}$, $\bar{\sigma}_{yy}$ and shear stress $\bar{\tau}_{xy}$ for symmetrical cross ply laminate with two different combinations of ply orientation.

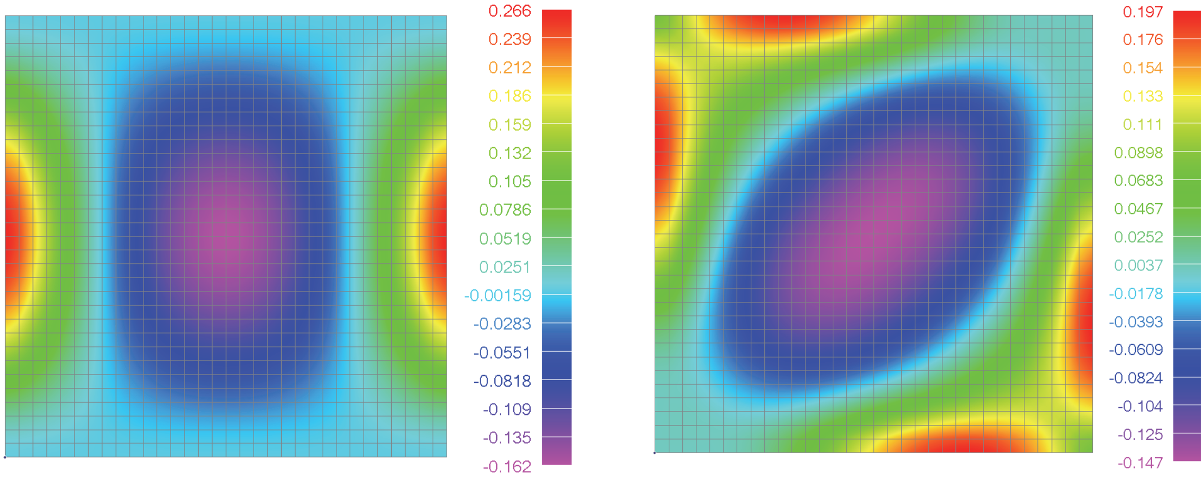
Table 1: Normalized values of vertical displacement $\bar{w}$, normal stresses $\bar{\sigma}_{xx}$, $\bar{\sigma}_{yy}$ and shear stress $\bar{\tau}_{xy}$

Ply orientation	w	σ_{xx}				σ_{yy}				τ_{xy}			
		ply 1	ply 2	ply 3	ply 4	ply 1	ply 2	ply 3	ply 4	ply 1	ply 2	ply 3	ply 4
0°/90°/90°/0°	0.1213	-0.1620	-0.0552	0.0552	0.1620	-0.0082	-0.0027	0.0027	0.0082	0.0038	-0.0013	0.0013	-0.0038
-45°/45°/45°/-45°	0.1484	-0.1470	-0.0835	0.0835	0.1470	-0.0114	-0.0028	0.0028	0.0114	-0.0092	0.0031	-0.0031	0.0092



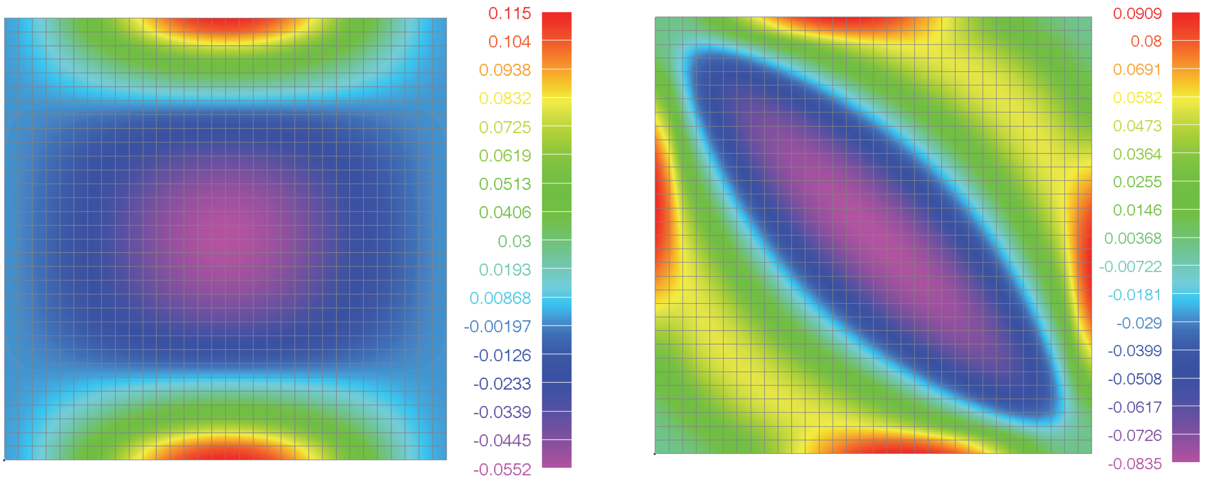
a) symmetrical cross ply laminate 0°/90°/90°/0° b) symmetrical cross ply laminate -45°/+45°/+45°/-45°

Figure 4: Normalized values of vertical displacement field $\bar{w}$



a) symmetrical cross ply laminate 0°/90°/90°/0° b) symmetrical cross ply laminate -45°/+45°/+45°/-45°

Figure 5: Normalized values of normal stress field $\bar{\sigma}_{xx}$ - ply 1



a) symmetrical cross ply laminate 0°/90°/90°/0° b) symmetrical cross ply laminate -45°/+45°/+45°/-45°

Figure 6: Normalized values of normal stress field $\bar{\sigma}_{xx}$ - ply 2

By analyzing the obtained results, it can be concluded that a higher value of vertical displacement was obtained for the laminated plate with the ply orientation -45°/45°/45°/-45° compared to laminated plate with the ply orientation is 0°/90°/90°/0°. The value of the maximum displacement of the center point on the plate is about 20% higher in the second case compared to the first case of ply orientation. When we analyze the stresses, different values of normal and shear stresses in different layers are obtained. For example, the normal stresses and shear stress are about 3 times higher in ply 1 compared to ply 2 for plate with 0°/90°/90°/0° ply orientation. The same relation is in ply 4 compared to ply 3. Precisely different values of certain stresses in different plies can serve as a starting point in the design phase of laminated structural elements. By a different combination of the orientation of the plies, the desired strength and rigidity of the designed structural element can be achieved. The influence of the different ply orientation of the laminated plate to the values of displacement and stresses can best be seen in Figures 4-6. Figure 4 shows the normalized values of vertical displacement field $\bar{w}$ of the laminated plate while normalized values of normal stress field $\bar{\sigma}_{xx}$ in ply 1 and 2 are presented in Figure 5 and Figure 6.

5. CONCLUSIONS

This paper points out the importance of research and use of composite materials with special emphasis on laminated composite materials. A brief overview of the current state of research related to mentioned area is given. Particular accent is placed on the basic advantages and disadvantages of composite materials compared to conventional materials. The classification of laminated composites from the aspect of different criteria is presented. The relations between stress and strain in the field of linear elasticity is given by the generalized Hooke's law. The constitutive matrix for the orthotropic class of material symmetry are expressed by engineering constants. Finally, a comparative bending analysis of two laminated composite plates with different ply orientations was performed by using finite element methods. Comparative results of vertical displacement and stresses for the cases of symmetrical cross ply laminate 0°/90°/90°/0° and symmetrical cross ply laminate -45°/45°/45°/-45° are shown. By analyzing the results, it was noticed that higher vertical displacement of central point at plate is obtained in the case of the ply orientation -45°/45°/45°/-45° compared to the laminated plate with the ply orientation 0°/90°/90°/0°.

ACKNOWLEDGEMENTS

Research presented in this paper was supported by Ministry of Education, Science and Technological Development of Republic of Serbia, Grant TR33015, TR32036 and multidisciplinary project III 44007.

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