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RESEARCH

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The Equivalent Macro-Mechanical Characteristics of Composite Laminate

Growing demands of the industry for applications of fibre-reinforced composites requires efficient analysis of their mechanical characteristics. Application of composite materials in industry gives wide range of possibilities in design of macro-mechanical characteristics. In this paper we analyzed variation of macro-mechanical properties of typical composite laminates due to laminate parameters. The aim of this paper is to develop efficient modeling of laminate parameters to obtain necessary data for optimal design of the composite structures.

Keywords: *composite*, *mechanical characteristics*

1. ANALYZE OF MACRO-MECHANICAL CHARACTERISTICS OF THE COMPOSITE LAMINATES

Equivalent macro-mechanical characteristics of the laminates are influenced by number of parameters. Those factors are distinguished as materials and geometrical ones. With materials parameters one can consider choice of materials that participate in the laminate configuration, type of the laminate configuration, etc. On the other hand, geometrical parameters are type of sequence of laminate configuration, direction of layer reinforcement, volume ratio of layer sequences to the total thickness of the laminate, etc.

Appropriate choice of materials and geometrical properties of the laminate configuration is essential for laminate structure design. Depends on type of mechanical load that composite construction is exposed, one can dictate equivalent in-plane, bending and coupling components of elasticity tensor. Coupling effect is characteristic of the unsymmetrical laminates that is not case for the configurations with geometrical and material mid-plane symmetry.

Based on known material characteristics of layers reinforced by one family of straight fibers, equivalent laminate macro-mechanical characteristics can be calculated as:

$$A_{ij} = \int_{-h/2}^{h/2} Q_{ij}\, dz \tag{2.1}$$

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$$B_{ij} = \int_{-h/2}^{h/2} Q_{ij}\; z\, dz \tag{2.2}$$

$$D_{ij} = \int_{-h/2}^{h/2} Q_{ij}\; z^2\, dz \tag{2.3}$$

where:

A_{ij}, B_{ij}, D_{ij} are tensor components of in-plane, bending and coupling modules of layer,

Q_{ij} - modules of unidirectional layer,

h - laminate thickness.

Relations (2.1-2.3) are valid in linear-elastic area and can be written in function of ply directions and stiffness tensor invariants as follows:

$$\begin{aligned}
&[A_{11}, B_{11}, C_{11}] = U_1 [h, 0, h^3/12] + U_2 [V_{1A}, V_{1B}, V_{1D}] + U_3 [V_{2A}, V_{2B}, V_{2D}] \\
&[A_{22}, B_{22}, C_{22}] = U_1 [h, 0, h^3/12] - U_2 [V_{1A}, V_{1B}, V_{1D}] + U_3 [V_{2A}, V_{2B}, V_{2D}] \\
&[A_{12}, B_{12}, C_{12}] = U_4 [h, 0, h^3/12] - U_3 [V_{2A}, V_{2B}, V_{2D}] \\
&[A_{66}, B_{66}, C_{66}] = U_5 [h, 0, h^3/12] - U_3 [V_{2A}, V_{2B}, V_{2D}] \\
&[A_{16}, B_{16}, C_{16}] = 0.5 \cdot U_2 [V_{3A}, V_{3B}, V_{3D}] + U_3 [V_{4A}, V_{4B}, V_{4D}] \\
&[A_{26}, B_{26}, C_{26}] = 0.5 \cdot U_2 [V_{3A}, V_{3B}, V_{3D}] - U_4 [V_{4A}, V_{4B}, V_{4D}]
\end{aligned} \tag{2.4}$$

In above equations, functions of plays direction are given with next integral relations:

$$V_{1\begin{Bmatrix} A \\ B \\ D \end{Bmatrix}} = \int_{-h/2}^{h/2} \cos(2\theta) \begin{Bmatrix} 1 \\ z \\ z^2 \end{Bmatrix} dz$$

$$V_{2\begin{Bmatrix}A\\B\\D\end{Bmatrix}} = \int_{-h/2}^{h/2} \cos(4\theta) \begin{Bmatrix}1\\z\\z^2\end{Bmatrix} dz$$

$$V_{3\begin{Bmatrix}A\\B\\D\end{Bmatrix}} = \int_{-h/2}^{h/2} \sin(2\theta) \begin{Bmatrix}1\\z\\z^2\end{Bmatrix} dz$$

$$V_{4\begin{Bmatrix}A\\B\\D\end{Bmatrix}} = \int_{-h/2}^{h/2} \sin(4\theta) \begin{Bmatrix}1\\z\\z^2\end{Bmatrix} dz \qquad (2.5)$$

Stiffness tensor invariants related to fiber play directions, in global coordinate system, are written as U_i. Detailed evaluations of those invariants are given in [1,2,5]. Integration of relations (2.5) is performed by summing of plies stiffness modules multiplied by appropriated weighting factors. Ply weighting factor defines influence of single ply module on equivalent laminate elasticity (stiffness) module. Low of weighting factors distributions depends on shape of sub integral function in relations (2.5). In definitions of equivalent plane elasticity modules we assumed that weighting factor of all plies are equal. Hence, value of these modules does not depend on stacking sequence of plies in chosen directions. On the other hand, stacking sequence of plies in chosen directions has high influence on equivalent bending and coupling characteristics. It is due the fact that in definition of coupling characteristics weighting factors with quadratic distribution, till in definition of bending material properties these factors reach cubic distributions. From this cause weighting factors are very important in procedure of establish equivalent bending and coupling modules of layer.

2. CHOICE OF PARAMETERS FOR ANALYSIS

Having in mind relations (2.4) and (2.5), one can concludes that equivavalent mechanical properties are influenced by numbers of factors. In order to reach better and more efficient control of material and geometrical parameters, the original software was developed. Although, relations (2.4) and (2.5) are relatively simple, but variation of just one parameter requires significant CPU extra time for obtaining equivalent laminate properties. Developed software provides variation of material and geometrical parameters and tracking down of laminate parameters in function of:

- Number of ply,
- Plies directions,
- Volume ratio of plies in laminate,
- Geometrical properties related to mid-plane.

With ply we imply sequence of succession layer with the same direction. Further, software provides variation of angles φ and γ in case of angle-ply (AP) laminate, fig. 1.a., angle γ for cross-ply (CP) or angles φ and γ for (AP\CP) laminate.

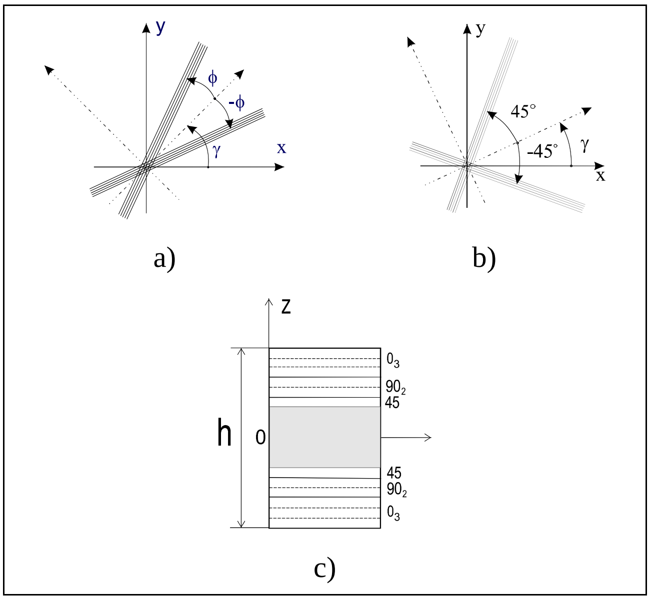


Figure 1. Setup of laminate; a) Angle-ply laminate, b) AP\CP laminate, c) Sandwich laminate

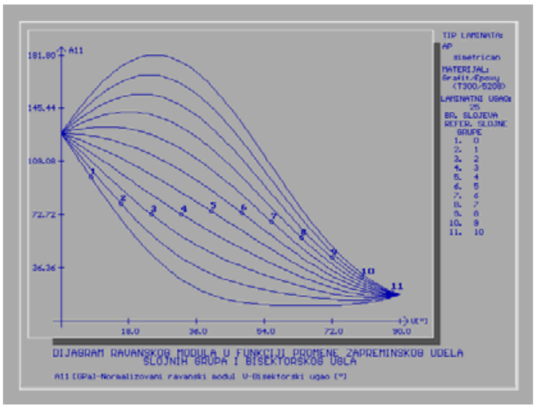
General scheme of angle-ply and sandwich laminates is shown on Fig. 1. Sandwich laminates are commonly embedding in parts subjected to higher bending loading. Bending stiffness increases with shifting unidirectional layers away from mid-plane. It can be obtain by inserting of lighter and cheaper material in central part of the plate. It shall be notice that values of plane stiffness will not increase by using comb core.

3. RESULTS OF ANALYZE

In this paper we analyzed influence of geometrical parameters on equivalent properties of two-directional AP and AP-sandwich laminates. AP-laminates are characterized by bisector angle (γ), laminate angle (φ) and ply volume ratios (γ_1, γ_2, $\gamma_1=\gamma_2=1$). Bisector angle defines direction of axis of laminate material symmetry in global coordinate system. Laminate angle defines fibers orientation related to bisector direction. Ply volume ratio is amount of ply volume in total laminate volume.

In this analyze we choose symmetrical laminate in order to eliminate coupling modules. Figure 2, shows distributions planes and bending stiffness modules with variations angle γ and volume ratio ν_1. Angle γ is varied in interval (0 - 90°) while angle φ has been frozen, i.e., φ=25°. Lines 1-11, at Fig. 2, relate to constant values of ν_1, i.e., 0%, 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%. Lines 1 and 11 (Fig.2) relate to unidirectional composites with orientation $\theta = \gamma - \varphi$ and $\theta = \gamma + \varphi$. Line 6 relate to balanced AP-laminate. In this configuration, total laminate thickness is constant i.e., h=2.5mm. Thickness of all Graphite/Epoxy (T300/5208) plies is 0.125mm.

From Fig.2, it is clear that extreme values of modules are obtained with unidirectional composite (lines 1 and 11). For plane modules (A_{ij}) and γ =*const.*, it appears constant increment among curves 1-11. On the other hand, for γ =*const.*, D_{ij} curves are clearly bunched with variation of ν from 0% to 40%, that is effect of cubic weighting factors distribution in definition of bending modules.



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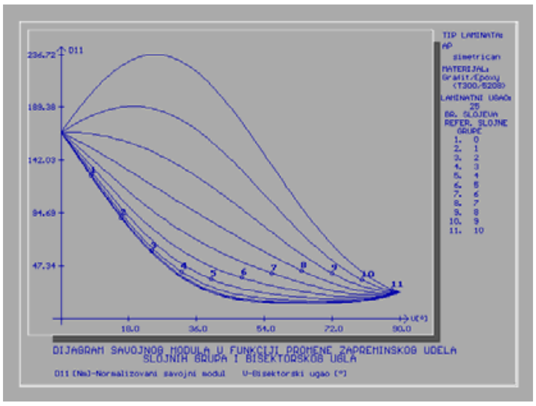

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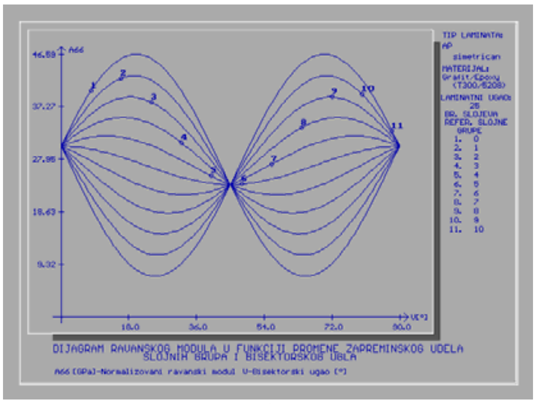

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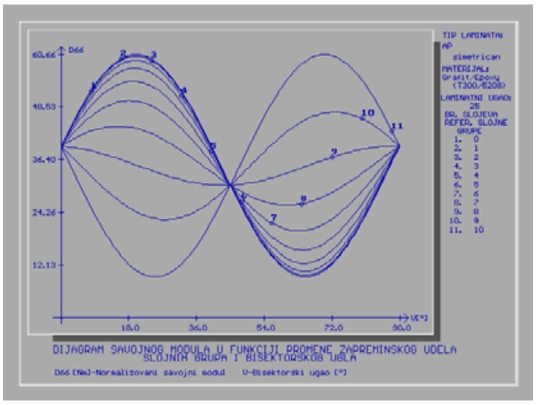

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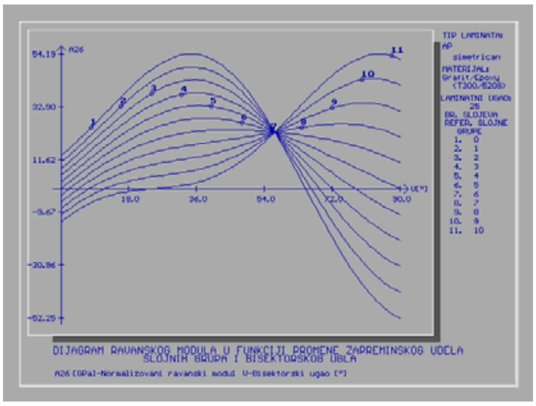

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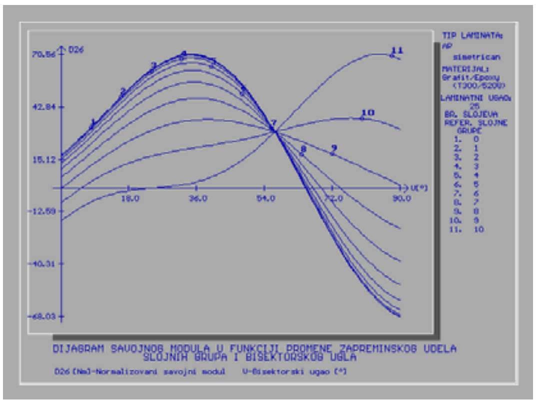
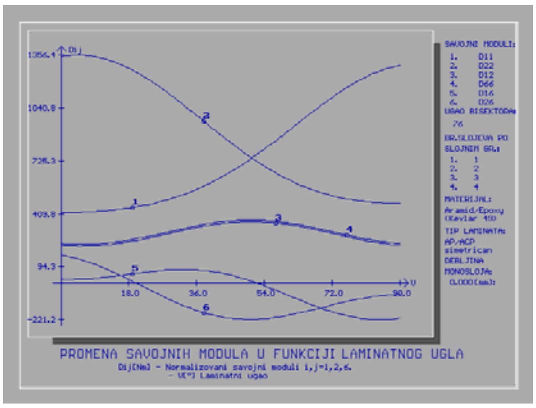


f)

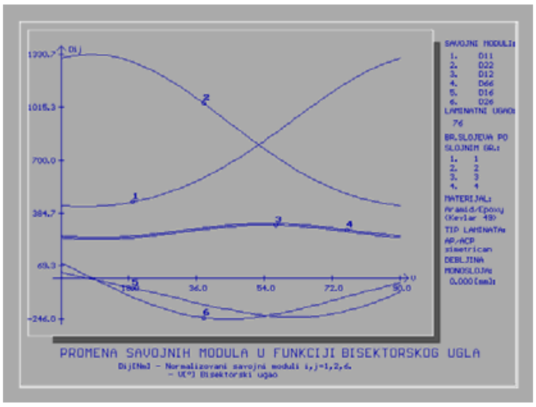
Figure 2.Distribution of the in-pane and bending AP-laminate stiffness modules

It may be note that for γ=0° and γ=90°, coefficient ν doesn't respond on yield of modules A_{11}, D_{11} (A_{22}, D_{22}) as well as for γ=0°, 45° and 90°, modules A_{66}, D_{66} (A_{12}, D_{12}) are independent on ν. Signification dispersion of modules A_{26}, D_{26} (A_{16}, D_{16}) is evidenced for γ=0° and γ=90° while selected value of ν for γ=60° doesn't influence on modules A_{26}, D_{26} (A_{16}, D_{16}). Modules A_{26} (A_{16}) could be eliminated if balanced laminate configuration for γ=0° and γ=90° is adopted, i.e., laminate $\left[-25^{\circ}_{5}/25^{0}_{5}\right]_S$ but $\left[65^{\circ}_{5}/115^{0}_{5}\right]_S$ (Fig. 2.e). Modules D_{26} (D_{16}) vanish with using bisector angle γ=0° and γ=90°, i.e., laminates $\left[-25^{\circ}_{9}/25^{0}_{1}\right]_S$ but $\left[65^{\circ}_{9}/115^{0}_{1}\right]_S$ (Fig. 2.f). It is obvious that for complex loading, coupling effect can't be simultaneously eliminated by using one configuration. From that reason, for complex loading, it is necessary to make compromise and eliminate parameters A_{16}, A_{26} or D_{16}, D_{26}, by using properly configuration.

On Figure 3., it is shown distribution of bending stiffness modules of AP\CP laminates, with variation of laminate angle φ (Fig. 3.a) as well as with variation of bisector angle γ (Gig. 3.b). In both cases, layers material is Aramid/Epoxy composite [9]. Laminate core is comb with thickness h_j=5*mm* while total laminate thickness is 7.62 *mm*. In the first case φ=76° till φ is varied from 0^0 to 90^0. In the other case, φ=76° with variation of γ in interval (0-90°). Lines that represent distribution of D_{12} and D_{66}, are very close in both cases. Also, parameter D_{12} characterized by increasing till parameter D_{22} characterized by decreasing trend. For φ=*const*. and γ=9° (Fig 3.b.), modules D_{16} and D_{26} practically vanish, while for proposed γ=const. (Fig. 3.a.) both parameters can't be eliminated simultaneously.



a)



b)

Figure 3. Distribution of bending stiffness module (D_{ij}) in case of AP\CP sandwich laminate; a) φ, γ=const., b) γ, φ=const.

4. CONCLUDING REMARKS

Advantage of composite laminates compare to conventional materials is in possibility to model and control their equivalent mechanical properties. Efficient algorithm for selection laminate parameters is very important due to fact that equivalent mechanical properties of laminate represent input in numerical analyses of stress-strain state and stability of construction.

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