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Behaviour and Optimization of Environmental Sensitive Layered Systems

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KEYWORDS*: Composite materials, environmental exposure, hygrothermal deformation, wood composites.*

SUMMARY*:*
The article discusses analytical methods for estimation of hygromechanical properties and the behaviour of composite materials under unilateral environmental exposure. An advanced graphite-epoxy composite plate, a densified wooden strand board and plywood with different configuration have been examined. It is determined that midplane strains, curvatures and warping at nonsymmetric moisture distribution depend on the moisture content profile, composite type, configuration, and stacking sequence of layers. The optimum configuration for hygrothermal response may not coincide with that for mechanical properties. Sensitivity of a certain configuration of laminate and moisture profiles is an effective means for evaluating the viscoelastic (viscoplastic) stress relaxation in a hygrothermal environment.

1. Introduction

Composite materials are constructed by bonding together several structural elements to form a common structure. The properties and orientation of the elements have to be chosen such that the composite is able to meet the design requirements of strength and stiffness. However, the behaviour of material under various environmental conditions has to be taken into account as well.

The use of advanced high-strength structural composites in aerospace systems and in other applications has expanded rapidly and significant quantities are in production. Due to industrialization of building process and production of inexpensive and effective building materials the utilization of wood and other raw materials is taking place. Accordingly suitable structural models are needed for predicting the hygrothermomechanical properties (Geimer, 1982; Vital et al., 1980) and for the optimum formation of composite materials by taking into account the properties of components and technological process (Rocens, 1983; Brauns and Rocens, 1994a).

In structural elements, composite panels can be affected by unilateral environmental exposure (Brauns and Rocens, 1994a,b; Pipes et al., 1976; Environmental effects…, 1981; Advanced composite materials…, 1978). In general case, the character of swelling and thermal deformation of a composite with moisture or temperature is nonlinear. This study is devoted to the estimation of the mechanical properties and behaviour of different layered systems under nonsymmetric environmental effect. The main purpose is to determine the effect of unilateral environment depending on composite configuration. The estimation is performed in linear region of environment-induced strains assuming on ideal bond between the layers. The numerical analysis was accomplished taking into account the changes in moisture content at the given level of temperature.

The hygrothermal deformation of a unidirectional element of composites in the transverse direction is much higher than in the longitudinal direction and distinctive oriented layers or fibers prohibit free deformation, nonsymmetric residual stresses develop in composite laminates. These environmental stresses can lead to the warping of a composite and initiation of micro cracks, especially under transient conditions, and further degrade the strength properties of composites. The temperature change and moisture absorption affect likewise the mechanical properties of the composite while the dimensional change can influence the performance of the structural element which can fail by buckling due to restrained expansion. Thus, hygrothermal behaviour affects not only the dimensional stability but also the safety of structures.

2. Heat conduction and moisture diffusion in composites

Considering a composite of thickness h as a system of elementary layers with parallel location of layers with respect to the midplane, a Cartesian coordinate system with axis $\{x_i\}$ is introduced (Fig. 1). The hygrothermomechanical properties of elementary layers are determined from the properties of the components by using analytical methods (Tsai and Hahn, 1980), or are found experimentally. The individual coordinate system $\{x_i'\}$ $(i = 1, 2, 3)$ is associated with the principal directions $\varphi^{(k)}$ of orthotropic elementary layers.

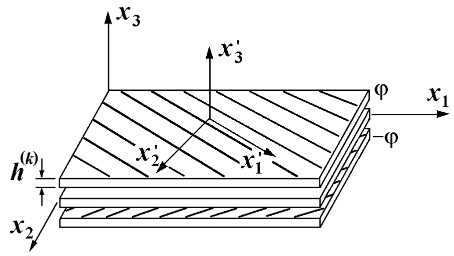

FIG. 1: Multilayer model of wooden composite.

The hygrothermomechanical behaviour of layered media under environmental effects depends on the thermal conductivity and moisture diffusion properties of elementary layer. In the case of thermal exposure the heat conductivities λ_{ij}^T in an arbitrary coordinate system can be expressed in terms of those in the symmetry axes of the layer are given by

$$\lambda_{11}^T = l_1^2\lambda_{11}'^T + l_2^2\lambda_{22}'^T; \qquad \lambda_{12}^T = l_1 l_2\left(\lambda_{11}'^T - \lambda_{22}'^T\right); \qquad \lambda_{22}^T = l_2^2\lambda_{11}'^T + l_1^2\lambda_{22}'^T, \tag{1}$$

where $l_1 = \cos\varphi$ and $l_2 = \sin\varphi$. In the direction $x_3 \equiv x_3'$, the heat conductivity is $\lambda_{33}^T \equiv \lambda_{33}'^T$.

In the case of moisture diffusion, the relation between moisture flux q_i^W and moisture concentration gradient is expressed in terms of the moisture diffusion coefficient λ_{ij}^W so that

$$q_i^W = -\lambda_{ij}^W \frac{\partial W}{\partial x_j}. \tag{2}$$

Note that moisture content W represents the amount of moisture as a fraction of the dry mass of the composite.

In practice, very important is one-dimensional diffusion through the element thickness, i.e., in the x_3 direction. Maintaining the temperature and moisture concentration on both surfaces of the material at equilibrium values, as linear approximation for the temperature distribution across the thickness with time t the Fourier equation can be used:

$$\frac{\lambda_{33}^T}{\rho C}\frac{\partial^2 T}{\partial x_3^2} = \frac{\partial T}{\partial t}, \tag{3}$$

where ρ and C are the mass density of the composite and the specific heat, respectively. Similarly, the Fick equation is applicable to the moisture diffusion

$$\lambda_{33}^W \frac{\partial^2 W}{\partial x_3^2} = \frac{\partial W}{\partial t}. \tag{4}$$

The thermal diffusivity $\lambda^T/(\rho C)$ in Eq. (3) and the moisture diffusion coefficient λ^W in Eq. (4) are measures of the rate at which the temperature and moisture concentration change within the material. These parameters, in general, depend on the temperature and moisture concentration. However, over the range of temperature and moisture concentration prevailing in applications of composites, the thermal diffusivity is about 10^6 times higher than the moisture diffusion coefficient. As a result, the temperature will reach the given level long before the moisture concentration.

In many cases, the moisture absorption and desorbtion are prevented on one surface of the composite, while the other one is exposed to the environment. Since the moisture diffusion is through the thickness of the composite, in case of large structural elements it does not depend on the structure of layers. The moisture absorption through the thickness of material can be described by exact solution of Eq. (4) given in (Crank, 1956; Jost, 1960). Note, however, that nonsymmetric deformation (warpage) and buckling, due to restrained linear expansion, is sensitive to configuration of layered materials and to certain moisture profiles. Consequently, methods of predicting how various configuration parameters affect the dimensional stability of board are needed. Moreover, the dimensional change of the structural element can influence the performance of the material that results in degradation of the strength properties and decreases the safety of a structure.

Since, in the case of structural elements of finite width, the diffusivity considerably depends on the layer orientation for sufficiently large or short time periods, some approximations for the moisture distribution profile can be used. In the subsequent analysis, parabolic, hyperbolic, and linear moisture distribution has been chosen.

3. Stress-strain relationships including environmental effects

Composite materials deform when they absorb the moisture or when the temperature changes. To determine the resulting strain we assume that the material is elastic and the response of the material does not depend on the history of environmental conditions but only on its initial and final state. Since the order of application of various changes is immaterial, it is assumed that temperature is changed first, followed by moisture absorption.

The final axial strains ε_i' in the unidirectional element are the sum of three types of strain induced by the temperature change, moisture absorption and applied stresses σ_j, respectively

$$\varepsilon_i'(T,W,\sigma_j) = \varepsilon_i'^{T}(T,\sigma_j) + \varepsilon_i'^{W}(T,\sigma_j) + S_{ij}'(T,W)\sigma_j', \tag{5}$$

where S_{ij}' are the compliances of the unidirectional element. Thermal and moisture deformation are the nonlinear functions of T and W, respectively (Environmental effects…, 1981; Advanced composite materials…, 1978). To calculate strains $\varepsilon_i'^{T}$ and $\varepsilon_i'^{W}$, specific thermal strain $\alpha_i'(T)$ and specific swelling $k_i'(W)$ of the element can be used:

$$\varepsilon_i'^{T}(T) = \alpha_i'(T)(T-T_0); \qquad \varepsilon_i'^{W}(W) = k_i'(W)(W-W_0), \tag{6}$$

where T_0 and W_0 are initial temperature and moisture content, respectively. The specific strains denote free expansion of the element when the temperature or moisture content changes per one unit.

Within the composite, the deformation of one layer is constrained by the other with different orientation, and hence environmental stresses arise in each layer. In the general case, the stresses in the elementary layers are different and the stress state of a composite is inhomogeneous. The static equivalent system of average force stresses σ_j and couple stresses μ_j acting on a unit volume of material has been used (Koiter, 1964; Mindlin, 1964). By applying matrix notations, the following constitutive relations for the midplane strains ε_i^0 and the curvatures κ_i are given by

$$\left[\frac{\boldsymbol{\varepsilon}^0(T,W,t)}{\boldsymbol{\kappa}(T,W,t)}\right] = \left[\frac{\boldsymbol{\alpha}(T,W,t)\ \mid \boldsymbol{\beta}(T,W,t)}{\boldsymbol{\beta}^{\mathrm{T}}(T,W,t) \mid \boldsymbol{\delta}(T,W,t)}\right] \cdot \left[\frac{\boldsymbol{\sigma}(T,W,t)}{\boldsymbol{\mu}(T,W,t)}\right]. \tag{7}$$

In Eq (7), the tensor indices are omitted and T denotes transposition. The compliance components α_{ij}, β_{ij}, δ_{ij} $(i,j=1,...,6)$ depend on the temperature and moisture content. The force and couple stresses in the unit volume of the composite are calculated by averaging:

$$\sigma_j(T,W,t) = \int_{-h/2}^{h/2} \tilde{\sigma}_j^{(k)}(T,W,t)dx_m \; ; \tag{8}$$

$$\mu_j(T,W,t) = \int_{-h/2}^{h/2} x_m \tilde{\sigma}_j^{(k)}(T,W,t)dx_m \; , \tag{9}$$

where m = 1 or 2 or 3; $m \neq j$.

The stresses $\tilde{\sigma}_j^{(k)}$ in kth elementary layer in the coordinate system $\{x_i\}$ can be determined by using the variation in temperature of the material or moisture content of the material starting from their initial values and the specific environmental stresses $\tilde{r}_j(W)$ or $\tilde{r}_j(T)$. For some type of composites produced by compression, for example, wooden composites, the stiffness properties also depend on the initial partial density $\hat{\rho}_*$. The analysis is performed at fixed temperature. In this particular case, when $T = \text{const}$ and $W \neq \text{const}$ at a fixed time moment, the stresses in the layers can be found as

$$\left\{ \tilde{\sigma}_j(W)_{|\hat{\rho}_*} \right\}^{(k)} = \left\{ \tilde{r}_j(W)_{|\hat{\rho}_*} \right\}^{(k)} (W - W_0) \, . \tag{10}$$

The matrix of the specific environmental stresses $\{\tilde{r}_j\}^{(k)}$ of the layers in the coordinate system $\{x_i\}$ can be represented as

$$\left\{ \tilde{r}_j(W)_{|\hat{\rho}_*} \right\}^{(k)} = [g_{ij}] \left\{ r_i'(W)_{|\hat{\rho}_*} \right\}^{(k)} , \tag{11}$$

where $[g_{ij}]$ is the stress transformation matrix (Tsai and Hahn, 1980). The specific constraining stresses $[r_j']$ in (11) and specific moisture strains $[k_i']$ are associated with the layer stiffness A_{ij}', and for the plane stress state are given by

$$\left\{ r_j'(W)_{|\hat{\rho}_*} \right\} = [A_{ij}'(W)_{|\hat{\rho}_*}] \left\{ k_i'(W)_{|\hat{\rho}_*} \right\}. \tag{12}$$

For the general case, the compliance matrices in (7) can be represented in terms of the general stiffness of the composite:

$$\boldsymbol{\alpha}(W)_{|\hat{\rho}_*} = \mathbf{S}(W)_{|\hat{\rho}_*} + \mathbf{S}(W)_{|\hat{\rho}_*} \mathbf{B}(W)_{|\hat{\rho}_*} \mathbf{C}(W)_{|\hat{\rho}_*} \mathbf{B}(W)_{|\hat{\rho}_*} \mathbf{S}(W)_{|\hat{\rho}_*} \; ; \tag{13}$$

$$\boldsymbol{\beta}(W)_{|\hat{\rho}_*} = -\mathbf{S}(W)_{|\hat{\rho}_*} \mathbf{B}(W)_{|\hat{\rho}_*} \mathbf{C}(W)_{|\hat{\rho}_*} \, , \tag{14}$$

where

$$\mathbf{C}(W)_{|\hat{\rho}_*} = \left[\mathbf{D}(W)_{|\hat{\rho}_*} - \mathbf{B}(W)_{|\hat{\rho}_*} \mathbf{S}(W)_{|\hat{\rho}_*} \mathbf{B}(W)_{|\hat{\rho}_*} \right]^{-1} . \tag{15}$$

The components of the stiffness of the laminate are evaluated by integration:

$$\left[A_{ij}(W)_{|\hat{\rho}_*} , B_{ij}(W)_{|\hat{\rho}_*} , D_{ij}(W)_{|\hat{\rho}_*} \right] = \int_{-h/2}^{h/2} \tilde{A}_{ij}^{(k)}(W)_{|\hat{\rho}_*} \left[1, x_3, x_3^2 \right] dx_3 \, . \tag{16}$$

In Eq. (16), the stiffness matrix $\left[\tilde{A}_{ij}\right]^{(k)}$ of the elementary layer in the coordinate system $\{x_i\}$ can be determined by using the transformation formula. The compliance matrix in Eqs (13) – (15) is $[S_{ij}] = [A_{ij}]^{-1}$. The multilayer model based on the laminate analogy (Halpin et al., 1971) is used to determine the stiffness in Eq. (16) for the high filled wooden strand board (WSB) with short-fiber volume fraction of about 90...95% and more.

4. Numerical results and discussion

In the discussion of hygrothermoelastic behaviour of layered composites, the temperature and the moisture concentration are assumed to be nonuniform over the thickness of material. Since the order of application of various changes is immaterial, conceptually it is imagined that the temperature is changed first and is fixed, while the moisture changes with time and with the coordinate x_3 in the thickness direction. To determine the environmental midplane strains and curvatures, the Eqs (7) – (9) are used. Two types of composites are examined: an advanced graphite-epoxy composite (AS/E) plate and a densified aspen WSB.

By using the properties of unidirectional layer with infinite fibers or short-length flakes, the displacement vector in Eq (7) of the structural behaviour is determined. One way to assess warpage is to fix the laminate at one corner and determine the lateral displacement at the diagonally opposite corner (Fig. 2). This structural behaviour can be predicted by the following equation for a rectangular flat laminate

$$w = 1/2(a^2\kappa_1 + b^2\kappa_2 + 2ab\kappa_6), \tag{17}$$

where w is the corner displacement, a and b are the side dimensions, and κ_i is the curvature determined from Eq. (7). The ratio w/a obtained for the square laminate $a = b = 25$ cm for four laminate configurations from an AS/E composite in the case of three different moisture profiles at moisture content difference $\Delta W = 0.6\%$ are summarized in Fig. 3. Note that the linear (L), parabolic (P) and hyperbolic (H) moisture profiles induce approximately the same warpage for configurations $[(\pm\varphi)_2]_S$ but the differences can be substantial for configurations $[\varphi/0/-\varphi]_S$. The variation of the corner displacement as a function of ply angle is shown in Fig. 4 for the laminates with parabolic moisture profiles. Note that the warpage for configuration $[(\pm\varphi)_2]_S$ is greater and varies regularly with orientation compared with the configuration $[\varphi/0/-\varphi]_S$.

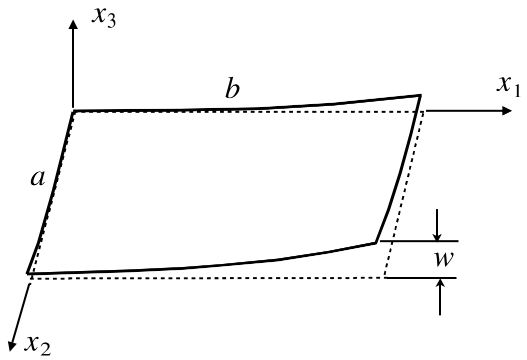

FIG. 2: Corner displacement of a composite plate induced by nonsymmetric moisture distribution.

Due to warpage induced by nonuniform moisture distribution, the corner displacement can be substantial. In numerical analysis, the moisture concentration difference was 0,6%, which corresponds to the linear region of the moisture-induced strain. The displacement depends on the moisture distribution type and composite configuration. Note that the corner displacements exceeding 2,5 cm is probably beyond the limits of linear structural analysis. The hygrostresses in the plies of laminates in the transverse direction and interlaminar shear reach magnitudes, which are comparable to ply strengths. In the elastic analysis, the warpage of the AS/E laminate is large. Sensivity to a certain configuration of the laminate and moisture profiles is an effective means for evaluating the stress relaxation in hygrothermal environment. Note that the corner displacement ratio depends on the composite configuration and increases with the number of the ±45° layers while the mechanical load is the dominant source of the shear stress in the ±45° plies responsible for the shear stiffness.

Analysis of the AS/E composite with the above-mentioned nonsymmetric moisture distribution is performed by using the following experimental characteristics of a unidirectional dry ply at room temperature: $E_1' = 138$, $E_2' = 9.65$, $G_{12}' = 4.21$ GPa; $\nu_{21}' = 0.30$; $k_1' = 0.01$, $k_2' = 0.45$ %. Note that the hygromechanical properties of the AS/E composite change with the moisture content, including specific swelling deformation k_2'. In order to take into account the moisture-caused changes, the reduction factors were used in the calculation.

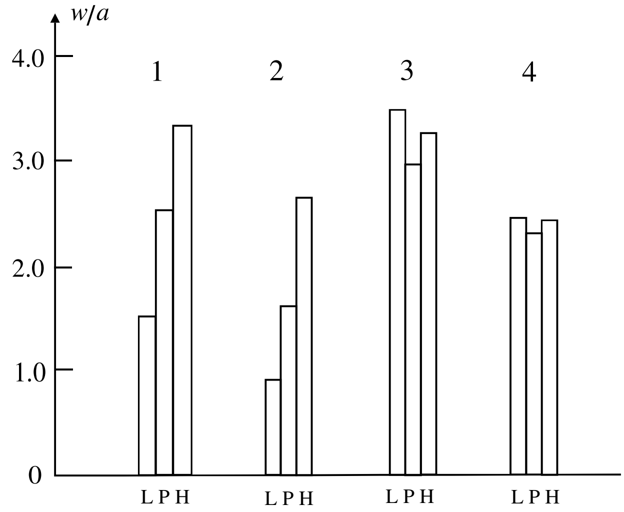

FIG. 3: Predicted warpage induced by nonsymmetric moisture content in AS/E laminates: 1 – $[30/0/–30/0]_S$; 2 – $[45/0/–45/0]_S$; 3 – $[(\pm30)_2]_S$; 4 – $[(\pm45)_2]_S$.

Composition boards, such as flake boards and plywood, change in dimension as the moisture content varies. Since the dimensional stability of the composition boards is critical in most applications, the maximum allowable dimensional change in such products is limited by standards. Consequently, methods of predicting how various processing parameters affect the dimensional stability of the board are needed.

The elementary layers of the composite with short-length components consist of previously calculated elements with the properties determined with regard to pressing during the fabrication of the material and considering the statistical length distribution of flakes as well as incomplete bonding. The technical characteristics of a densified orthotropic layer with unidirectionally oriented short-length aspen flakes at W_0 = 6% and $\hat{\rho}_*$ = 750 kg/m^3 are as follows: E_1' = 4.8, E_2' = 0.53, G_{12}' = 0,77 GPa, ν_{21}' = 0,22. Nonlinear dependences of the mechanical properties on moisture were taken into account. The specific moisture strains at the given initial conditions are k_1' = 0,01 and k_2' = 0,25 %, while the dependencies of these strains on the moisture are based on experimental data.

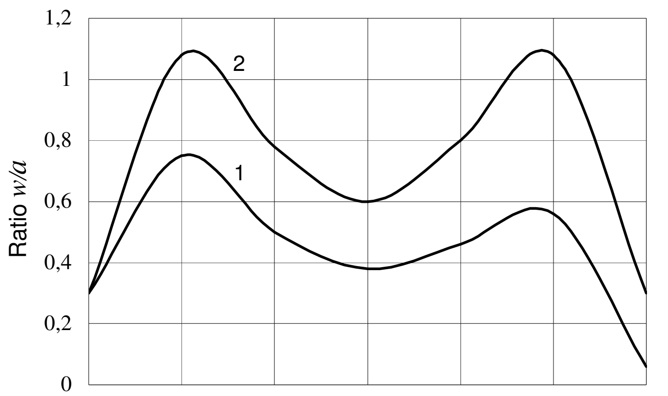

FIG. 4: Predicted warpage induced by 0,6% *nonsymmetric moisture distribution in AS/E laminates* (*parabolic profile*): 1 – $[\varphi,0,-\varphi,0]_S$; 2 – $[(\varphi,-\varphi)_2]_S$.

In the production process of wooden composites, the variation of the properties of wood by means of increasing the volume fraction of cell wall is realized by compressing the wood perpendicular to the grain, i.e., flattening its cavities. For the wood with a decreased void volume resulting from compression, compliance of wood in the direction of pressing (axis x_3) appears to be higher in comparison with natural wood. Accordingly, unless complete flattening of the vessels is reached, a decrease of the cell-wall material resisting the action of the stresses σ_3 is taking place. The fraction of the cell-wall material of the layer resisting the action of the stresses σ_1' and σ_2' increases, decreasing the compliance in the directions x_1' and x_2'. Plastic, or unrecoverable, deformation is the major part of deformation of the wood that occurs during the hot pressing. When moistening, plastic deformation becomes recoverable and there is a large difference between swelling of the densified wood in the direction of pressing and in the transversal x_2' direction. According to reconstituted wood structure, the specific moisture strain of the densified wood in comparison with the customary wood increases nonlinearly when moisture content grows in the direction of pressing, but decreases in the transversal direction.

By using a multilayer model for the composite with short-length wooden flakes, the total binder volume is distributed in separate layers proportionally to the volume of flakes. To illustrate the effect of flake alignment on moisture deformation, we consider laminates with different orientation of the principal axes of the elementary layers with respect to, e.g., machine direction (x_1). For any laminate, the average orientation angle of fibers (disregarding its sign) relative to the x_1 axis is labeled $\overline{\varphi}$ and the relative alignment ξ is defined as

$$\xi = \left[(45^\circ - \overline{\varphi})/45^\circ\right] \cdot 100\% . \qquad (18)$$

The model of the board used consists of 12 elementary layers, which form a symmetric or nonsymmetric structure. Effect of a nonsymmetric nonlinear distribution of the moisture content of nonsymmetric and antisymmetric structure on warpage was studied. The warpage of the board with antisymmetric structure is essentially higher.

In the case of plywood, the technical characteristics of densified birch veneer used in the analysis are: modulii of elasticity E_1 = 16.5 and E_2 = 0.7 GPa; shear modulii G_{12} = 0.9, G_{13} = 1.5 and G_{23} = 0.3 GPa; Poisson's coefficients ν_{21} = 0.45, ν_{31} = 0.34 and ν_{32} = 0.30. The corrections for moisture change of the elasticity and shear modulii, respectively, are: α_1 = 250, α_2 = 25, α_{12} = 25, α_{13} = 30, and α_{23} = 20 MPa. The specific moisture strains at given initial conditions are: β_1 = 0.00003, β_2 = 0.002, β_3 = 0.003 $(\%)^{-1}$. The partial density of plywood is 660 kg/m^3.

The relationship between expansion (ε_i), thickness swelling (ε_3) and alignment for an increase of moisture content of 12% is shown in Fig. 4. The preferable boards are with relative flake alignment ξ = 0 – 40%. Fig. 4 also shows relationships between alignment and specific reaction F^* in bending and critical stress σ_1^{cr} in compression of a hinged square board.

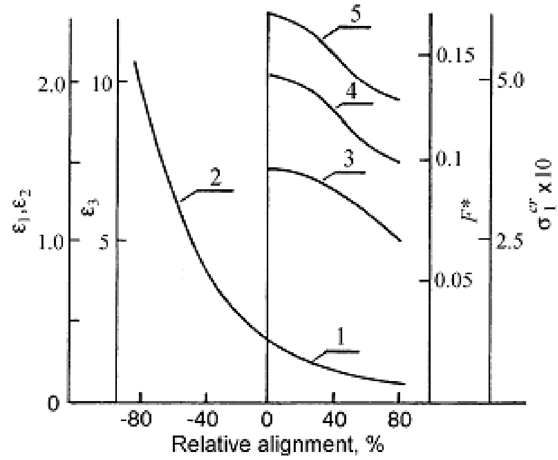

FIG. 4: Effect of flake alignment on swelling and mechanical properties of flakeboard: 1 – ε_1; 2 – ε_2; 3 – ε_3; 4 – F^* (kN); 5 – σ_1^{cr} (MPa).

Conclusions

The following main conclusions can be drawn from the present study:

1. The midplane strains, curvatures and warping of an advanced graphite-epoxy composite plate and a wooden strand board of different configurations densified in technological pressing with nonsymmetric moisture distribution (linear, parabolic and hyperbolic) taking into account the nonlinear swelling properties are determined.
2. Hygrostrains depend on the moisture content and profile, laminate configuration, composite type as well as the ply stiffness, and should be calculated basing on the precise stacking sequence, while thermal deformation in angle-ply laminates, except wooden composites with densified orthotropic layers, can be predicted by using the equivalence principle between the hygro and thermal expansions.
3. The optimum configuration for the hygrothermal behaviour may not coincide with that for the mechanical properties and, for every type of loading, composite materials with an appropriate structure should be used. Sensitivity of a certain configuration of laminate and moisture profiles is an effective means for evaluating the viscoelastic (viscoplastic) stress relaxation in a hygrothermal environment.

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