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PROCESS RELATED LOADINGS VARIATIONS OF UNIDIRECTIONAL FIBERS-REINFORCED COMPOSITES

Horatiu Teodorescu-Draghicescu[1], Sorin Vlase[2]
[1] Transilvania University of Brasov, Brasov, ROMANIA, e-mail: draghicescu.teodorescu@unitbv.ro
[2] Transilvania University of Brasov, Brasov, ROMANIA, e-mail: svlase@unitbv.ro

Abstract: *Some simulations regarding thermo-mechanical behavior of four unidirectional fibers-reinforced laminae subjected to temperature and humidity variations have been presented. Following composite laminae have been considered: [-45] and [45] glass/epoxy, [30] glass/epoxy and [55] carbon/epoxy. Process related loadings variations from curing to environment temperature as well as some percentage humidity variation of these composites have been taken into account to compute the coefficients of thermal and humidity expansions. Distributions of these coefficients as well as respective strains have been computed versus fibers volume fraction variation of each composite.*
Keywords: *CLTEs, Fibers-reinforced composites, Temperature variation, Humidity variation, Fibers volume fraction*

1. INTRODUCTION

Both fibers and matrix material, present extreme different deformations at temperature and humidity variations. These variations can cause internal stresses in a laminate structure, both at micro and macro mechanical level. This paper takes only the macro mechanical internal stresses into account, stresses that appear, for example, at cooling from the curing temperature to the environment temperature of a laminate structure. These internal stresses, due to temperature variations, are very dangerous and can lead to the damage of the structure even in the absence of an external mechanical loading [1]. This fact is more striking in case of carbon fibers-reinforced composite structures, fibers that present extreme different coefficients of linear thermal expansion along and perpendicular to their direction. Exposing a composite laminate structure to humidity, inside of it appears an internal stress state caused by the matrix volume increase, due to its swelling. Glass and carbon fibers do not absorb humidity but aramid fibers are strongly influenced by it. Extended researches regarding the mechanical behavior of polymer matrix glass fibers-reinforced composite structures subjected to various loadings have been presented in references [2], [3], [4], [5], [6], [7], [8], [10] and [11]. Behavior of carbon fibers-reinforced composite structures under tensile loadings are presented in papers [9] and [12].

2. THEORETICAL APPROACH

According to Schneider, the coefficients of linear thermal expansion along and perpendicular to fibers direction of a unidirectional fibers-reinforced lamina, are [13]:

$$\alpha_{II} = \alpha_{FII} + \frac{\alpha_M - \alpha_{FII}}{\frac{\varphi}{1-\varphi} \cdot \frac{E_{FII}}{E_M} + 1}, \tag{1}$$

$$\alpha_{\perp} = \alpha_M - \left(\alpha_M - \alpha_{F\perp}\right)\left[\frac{2\left(\upsilon_M^3 + \upsilon_M^2 - \upsilon_M - 1\right)\cdot 1{,}1\varphi}{1{,}1\varphi\cdot\left(2\upsilon_M^2 + \upsilon_M - 1\right) - \left(1 + \upsilon_M\right)} - \frac{\upsilon_M \cdot \frac{E_{F\perp}}{E_M}}{\frac{E_{F\perp}}{E_M} + \frac{\left(1 - 1{,}1\varphi\right)}{1{,}1\varphi}}\right], \tag{2}$$

where: $\alpha_{F\parallel}$ is the coefficient of linear thermal expansion for the fiber in the longitudinal direction; $\alpha_{F\perp}$ is the coefficient of linear thermal expansion for the fiber in the radial direction; α_M represents the coefficient of linear thermal expansion for the matrix; $E_{F\parallel}$ is the fiber longitudinal modulus; $E_{F\perp}$ represents the fiber radial modulus; E_M is the matrix modulus; υ_M represents the matrix Poisson's ratio and φ is the fibers volume fraction.
Equations (1), (2) show that these coefficients of linear thermal expansion can be calculated as a function of the properties of composite material components and fibers volume fraction. If the fibers are disposed at an angle θ with the x-axis direction, the coefficients of thermal expansion in the x and y directions can be determined using $\alpha_\parallel$ and $\alpha_\perp$ [14]:

$$\alpha_{xx} = \alpha_{II} \cos^2\theta + \alpha_\perp \sin^2\theta, \tag{3}$$

$$\alpha_{yy} = \alpha_{II} \sin^2\theta + \alpha_\perp \cos^2\theta, \tag{4}$$

$$\alpha_{xy} = (2\sin\theta\cos\theta)(\alpha_{II} - \alpha_\perp), \tag{5}$$

where α_{xx} and α_{yy} are coefficients of linear thermal expansion and α_{xy} is the coefficient of shear thermal expansion. According to Tsai and Hahn, in case of a unidirectional fibers-reinforced lamina, the coefficients of expansion due to the humidity can be computed from the following equations [15]:

$$\beta_{II} = \frac{\beta_M \cdot E_M}{\varphi \cdot E_{FII} + (1-\varphi)\cdot E_M} \cdot \frac{\rho_{composite}}{\rho_M}, \tag{6}$$

$$\beta_\perp = \frac{(1-\upsilon_M)\cdot \beta_M \cdot \rho_{composite}}{\rho_M} - \left[\varphi \cdot \upsilon_F + (1-\varphi)\cdot \upsilon_M\right]\cdot \beta_{II}, \tag{7}$$

where: $\beta_\parallel$ is the coefficient of expansion due to the humidity, in the longitudinal (0°) direction; $\beta_\perp$ represents the coefficient of expansion due to the humidity, in the transverse (90°) direction; β_M is the coefficient of expansion due to the humidity, for the matrix and $\rho_{composite}$ represents the density of the composite material.

3. THEORETICAL CONTRIBUTIONS

Similar to equations (3) – (5), the coefficients of expansion in x and y directions, due to humidity, if the fibers are disposed at an angle θ with the x-axis direction, are:

$$\beta_{xx} = \beta_{II} \cos^2\theta + \beta_\perp \sin^2\theta, \tag{8}$$

$$\beta_{yy} = \beta_{II} \sin^2\theta + \beta_\perp \cos^2\theta, \tag{9}$$

$$\beta_{xy} = (2\sin\theta\cos\theta)(\beta_{II} - \beta_\perp), \tag{10}$$

where β_{xx} and β_{yy} are coefficients of linear expansion and β_{xy} is the coefficient of shear expansion due to humidity. The strains of a fibers-reinforced composite lamina $\varepsilon_{xx\ t\text{-}h}$, $\varepsilon_{yy\ t\text{-}h}$ and $\gamma_{xy\ t\text{-}h}$ due to a ΔT temperature and ΔH humidity variation, without a mechanical loading, can be computed in the following manner:

$$\varepsilon_{xx\ t-h} = \alpha_{xx} \cdot \Delta T + \beta_{xx} \cdot \Delta H, \tag{11}$$

$$\varepsilon_{yy\ t-h} = \alpha_{yy} \cdot \Delta T + \beta_{yy} \cdot \Delta H, \tag{12}$$

$$\gamma_{xy\ t-h} = \alpha_{xy} \cdot \Delta T + \beta_{xy} \cdot \Delta H, \tag{13}$$

where: $\varepsilon_{xx\ t\text{-}h}$ is the strain of lamina in x-axis direction, due to a combined loading of ΔT temperature and ΔH humidity variation; $\varepsilon_{yy\ t\text{-}h}$ represents the strain of lamina in y-axis direction due to a combined loading of ΔT temperature and ΔH humidity variation; $\gamma_{xy\ t\text{-}h}$ is the shear strain of lamina due to a combined loading of ΔT temperature and ΔH humidity variation. The index *t-h* denotes the combined action of a temperature variation ΔT and a humidity variation ΔH. Some applications are presented in following sections.

3.1. Coefficients of thermal expansion in case of [30] glass/epoxy lamina

A unidirectional glass fibers-reinforced lamina with 30° fibers disposal angle in an epoxy matrix is considered. The fibers volume fraction is 60%. The coefficients of thermal expansions in x and y-axis directions have been computed. The distribution of these coefficients versus fibers volume fraction variation is presented in Fig. 1. Following input data regarding the fibers, matrix and composite material have been considered: E_M = 3000 MPa; υ_M = 0.35; $\alpha_M = 65 \cdot 10^{-6}\ K^{-1}$; θ = 30°; $E_{F\parallel} = E_{F\perp}$ = 73000 MPa; $\alpha_{F\parallel} = \alpha_{F\perp} = 4.8 \cdot 10^{-6}\ K^{-1}$.

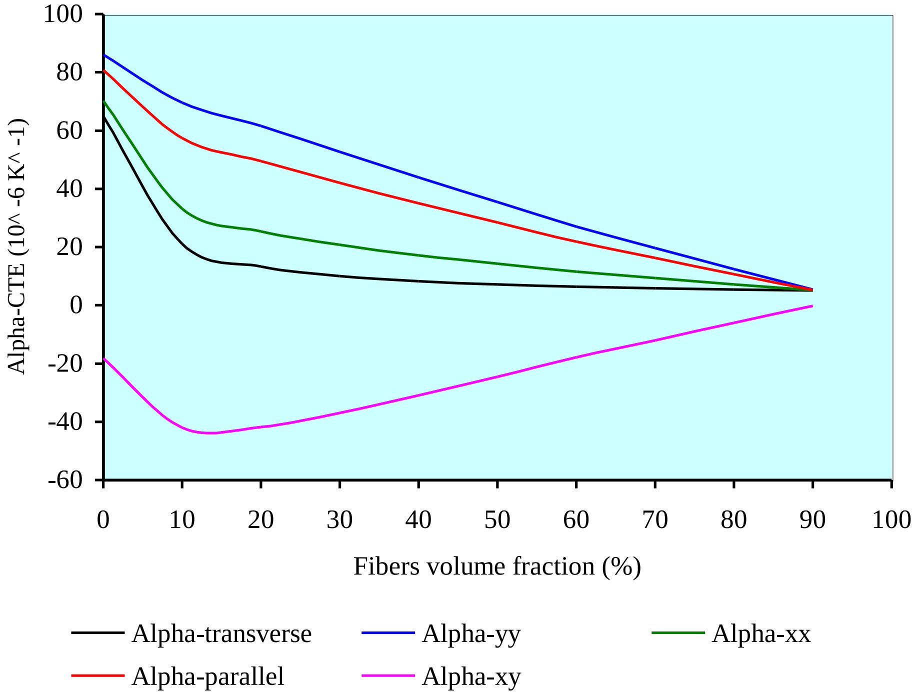

Figure 1: Coefficients of thermal expansion in case of a unidirectional [30] glass/epoxy lamina

3.2. Coefficients of humidity expansion in case of [30] glass/epoxy lamina

A unidirectional glass fibers-reinforced lamina with 30° fibers disposal angle in an epoxy matrix is considered. The fibers volume fraction is 60%. The coefficients of humidity expansions in x and y-axis directions have been computed. The distribution of these coefficients versus fibers volume fraction variation is presented in Fig. 2. Following input data regarding the fibers, matrix and composite material have been considered: $\rho_{composite} = 1950$ kg/m^3; $\rho_M = 1200$ kg/m^3; $E_M = 3000$ MPa; $\upsilon_M = 0.35$; $\beta_M = 0.18$; $\upsilon_F = 0.25$; $E_{F\parallel} = 73000$ MPa; $\theta = 30°$.

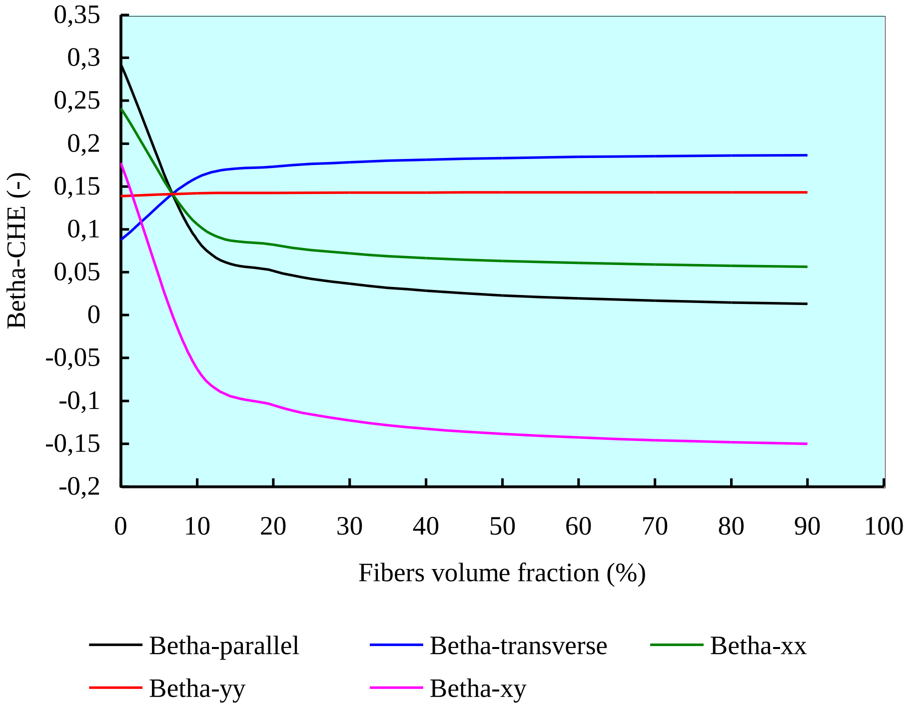

Figure 2: Coefficients of humidity expansion in case of a unidirectional [30] glass/epoxy lamina

3.3. Application in case of [-45] glass/epoxy lamina subjected to ΔT = - 100 K temperature variation

A unidirectional glass fibers-reinforced lamina with - 45° fibers disposal angle in an epoxy matrix is considered. The fibers volume fraction is 60%. In case in which the lamina is subjected only to ΔT = - 100 K temperature variation due to its cooling from cure to environment temperature, the $\varepsilon_{xx\ t}$, $\varepsilon_{yy\ t}$ and $\gamma_{xy\ t}$ strains in x and y-axis directions have been computed. Following input data regarding the fibers and matrix material have been considered: $E_M = 3500\ MPa;\ \upsilon_M = 0.35;\ \alpha_M = 65 \cdot 10^{-6}\ K^{-1};\ \theta = -45°;\ E_{F\parallel} = E_{F\perp} = 73000\ MPa;$ $\alpha_{F\parallel} = \alpha_{F\perp} = 4.8 \cdot 10^{-6}\ K^{-1}$. In Fig. 3, a schematic representation of these strains acting on [-45] glass/epoxy lamina is shown.

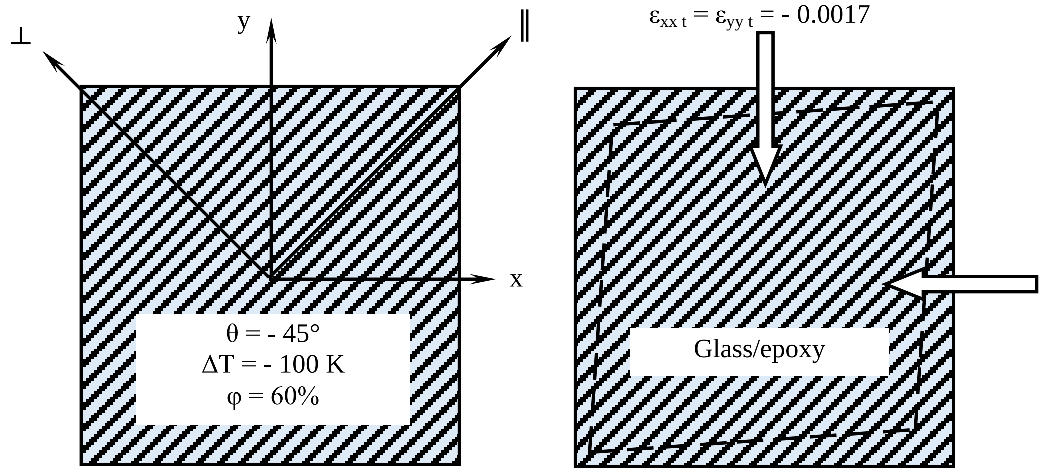

Figure 3: Specific shrinkages of [-45] glass/epoxy lamina from curing to environment temperature

3.4. Application in case of [45] glass/epoxy lamina subjected to ΔU = 1% humidity variation

A unidirectional glass fibers-reinforced lamina with 45° fibers disposal angle in an epoxy matrix is considered. The fibers volume fraction is 40%. In case in which the lamina is subjected only to ΔU = 1% humidity variation, the $\varepsilon_{xx\ h}$, $\varepsilon_{yy\ h}$ and $\gamma_{xy\ h}$ strains in x and y-axis directions have been computed. Following input data regarding the fibers, matrix and composite material have been considered: $\rho_{composite} = 1900\ kg/m^3;\ \rho_M = 1100\ kg/m^3;$ $E_M = 3450\ MPa;\ \upsilon_M = 0.35;\ \beta_M = 0.18;\ \upsilon_F = 0.25;\ E_{F\parallel} = 73000\ MPa;\ \theta = 45°$. In Fig. 4, a schematic representation of these strains acting on [45] glass/epoxy lamina subjected to ΔU = 1% humidity variation can be visualized.

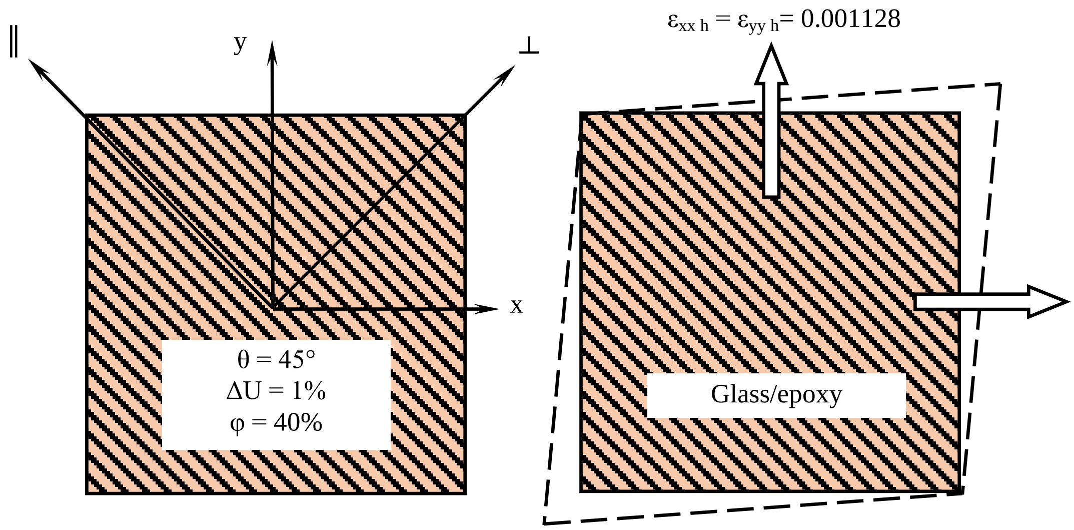

Figure 4: Strains of [45] glass/epoxy lamina subjected to ΔU = 1% humidity variation

3.5. Application in case of [55] carbon/epoxy lamina subjected to ΔT = - 40 K temperature and ΔU = 1.5% humidity variation

A unidirectional carbon fibers-reinforced lamina with 55° fibers disposal angle in an epoxy matrix is considered. The fibers volume fraction is 60%. In case in which the lamina is subjected to a combined loading of ΔT = - 40 K temperature variation due to its cooling from cure to environment temperature and ΔU = 1.5% humidity variation, the $\varepsilon_{xx\ t\text{-}h}$, $\varepsilon_{yy\ t\text{-}h}$ and $\gamma_{xy\ t\text{-}h}$ strains in x and y-axis directions have been computed. Following input data regarding the fibers, matrix and composite material have been considered: $E_M = 3.9\ GPa$; $\upsilon_M = 0.35$; $\alpha_M = 65 \cdot 10^{-6}\ K^{-1}$; $\theta = 55°$; $\varphi = 60\%$; $E_{F\parallel} = 540\ GPa$; $E_{F\perp} = 27\ GPa$; $\alpha_{F\parallel} = -0.5 \cdot 10^{-6}\ K^{-1}$; $\upsilon_F = 0.2$; $\alpha_{F\perp} = 30 \cdot 10^{-6}\ K^{-1}$; $\rho_{composite} = 2100\ kg/m^3$; $\rho_M = 1250\ kg/m^3$; $\beta_M = 0.18$. In Fig. 5, a schematic representation of these strains acting on [55] carbon/epoxy lamina subjected to a combined loading of ΔT = - 40 K temperature and ΔU = 1.5% humidity variation is presented.

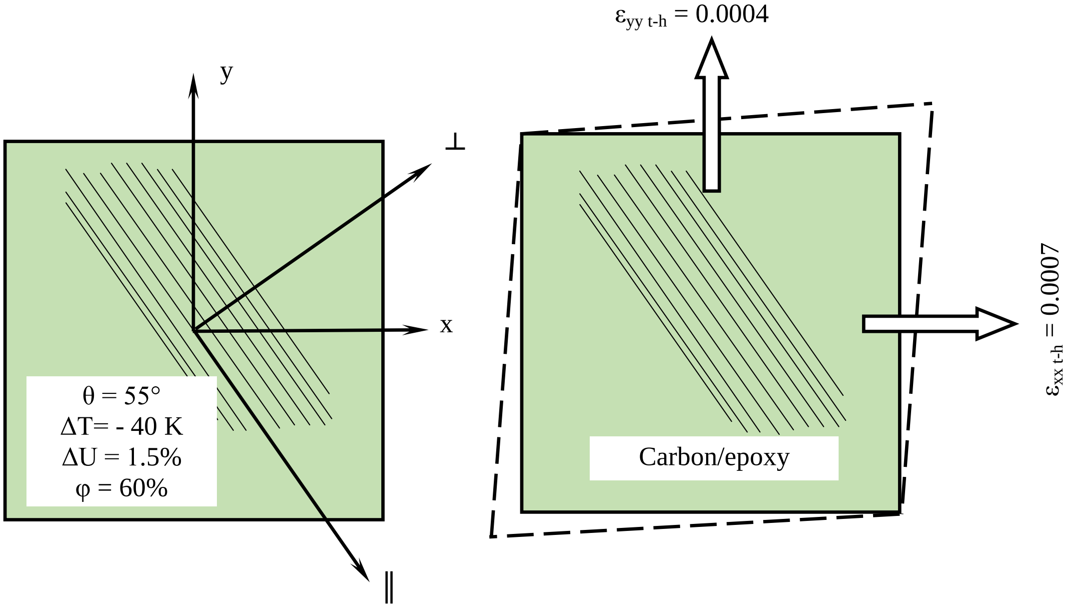

Figure 5: Strains of [55] carbon/epoxy lamina subjected to a combined loading of ΔT = - 40 K temperature and ΔU = 1.5% humidity variation

4. CONCLUSIONS

At 10% fibers volume fraction, the coefficients of thermal expansion in x and y-axis directions in case of a unidirectional [30] glass/epoxy lamina present the widest range of values. With the increase of fibers volume fraction, these coefficients present closer values (Fig. 1). In case of a unidirectional glass fibers-reinforced lamina with 30° fibers disposal angle in an epoxy matrix, the distributions of coefficients of humidity expansion in x and y-axis directions present very small variations at fibers volume fractions greater than 20% (Fig. 2). This phenomenon is due to the outstanding stability at humidity variations of glass fibers.
Subjecting a [-45] glass/epoxy lamina (60% fibers volume fraction) only to a ΔT = - 100 K temperature variation due to its cooling process from cure to environment temperature, the specific shrinkages exhibit the same values in x and y-axis directions (Fig. 3). The unidirectional glass fibers-reinforced lamina with 45° fibers disposal angle in an epoxy matrix subjected only to a ΔU = 1% humidity variation shows equal strains in lamina's x and y-axis directions (Fig. 4). Both strains presented in Figs. 3 and 4 present equal values in x and y-axis directions due to the fact that both the trigonometric functions at 45° and - 45°, given in equations (3) – (5) and (8) – (10), present equal values. In case of a [55] carbon/epoxy lamina subjected to a combined loading of ΔT = - 40 K temperature variation due to its cooling process from cure to environment temperature and ΔU = 1.5% humidity variation, the strains exhibit different values mainly due to the strong anisotropy of the carbon fibers that present extreme different coefficients of linear thermal expansion along and transverse to their direction (Fig. 5). The different values of trigonometric functions at 55° fibers disposal angle play also a significant role.

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