

A self-consistent approach for transient hygroscopic stresses and moisture expansion coefficients of fiber-reinforced composites

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ABSTRACT

Stress analyses are performed in unidirectional fiber-reinforced composites, exposed to ambient fluid, by extending a classical self-consistent model to hygro-elastic solicitations. Constitutive laws are given for the macroscopic elastic properties and Coefficients of Moisture Expansion (CME) by considering a jump in moisture content between the fiber and the matrix. The macroscopic (ply) and local (fiber and matrix) internal stress states are evaluated for various moisture content ratios between the matrix and the ply. The macroscopic stresses are calculated by using continuum mechanics formalisms and the local stresses are deduced from the scale transition model.

1. INTRODUCTION

The increasing deployment of composite laminates in engineering applications, because of their high strength-to-weight ratio as well as corrosion and fatigue resistance, has given greater attention to the long term behaviour of composite components in hygroscopic environments. Composite materials are more and more common alternative to traditional materials such as metals and polymers. Now, contrary to metallic materials or metal matrix composites, carbon/epoxy composites can absorb significant amount of water. Moreover, the moisture contents of the epoxy resin and the carbon fiber are strongly different, because carbon fibers are generally considered not to absorb water. In addition, carbon fibers and epoxy resin are characterized by heterogeneous Coefficients of Moisture Expansion (CME). As a consequence, internal stresses rise from hygroscopic loading of composites. Now, the knowledge of internal stresses is necessary to predict a possible damage occurrence in the material during its manufacturing process or service life.

Numerous papers available in the literature deal with this question, using Finite Elements Analysis or Continuum Mechanics based formalisms. These methods allow the calculation of the macroscopic stresses in each ply constituting the composites. But, they do not provide information on the local mechanical states in the fiber and matrix of a given ply. The present work is precisely focused on the study of the internal stresses in the constituents of the ply. In order to reach this goal, scale transition models are required. The classical elastic self-consistent scale transition model is extended in order to predict the multi-scale hygro-elastic behaviour of composite materials. The formalism described takes into account heterogeneities of moisture content between matrix and fiber. Constitutive laws are given for both the macroscopic elastic properties and the CME of the ply.

2. PREDICTION OF THE HOMOGENIZED HYGRO-ELASTIC PROPERTIES

2.1. Self-Consistent estimates for the hygro-elastic behaviour of composites

Self-Consistent models based on the mathematical formalism proposed by Kröner [1] constitute a reliable method to predict the micro-mechanical behaviour of heterogeneous materials. The model was extended by Hutchinson [2] to thermo-elastic cases. In the present paper, the classical model is improved in order to take into account stresses and strains due to moisture in carbon fiber-reinforced polymer matrix composites.

In the model, ellipsoidal inclusions are embedded in an infinite medium, called Homogeneous Effective Medium or HEM. HEM is assumed to behave as one particular ply: its hygro-elastic properties come from homogenization operations performed on the hygro-elastic constants of

the matrix and fibers constituting the considered ply. The material is investigated at two different scales for the needs of micro-mechanical modeling:

- the average behaviour of a ply, represented by the HEM, defines the macroscopic scale of the model. It is denoted by the superscript ^I.
- the properties and mechanical states of the matrix and fiber are respectively indicated by the superscripts ^m and ^f.

Within this approach, the hygroscopic dilatation generated by a moisture content increment ΔC^I is treated as a transformation strain. The macroscopic stresses σ^I are given by:

$$\sigma^I = \mathbf{L}^I : (\boldsymbol{\varepsilon}^I - \boldsymbol{\beta}^I \Delta C^I) \quad (1)$$

where \mathbf{L} is the elasticity tensor, $\boldsymbol{\varepsilon}$ the strains due to elastic and hygroscopic loads and $\boldsymbol{\beta}$ the coefficients of moisture expansion.

At microscopic scale, similar equations can be written:

$$\sigma^\alpha = \mathbf{L}^\alpha : (\boldsymbol{\varepsilon}^\alpha - \boldsymbol{\beta}^\alpha \Delta C^\alpha) \quad (2)$$

where α replaces the appropriate superscript (i.e. ^f or ^m) for the carbon fiber or polymer matrix. One should notice that, contrary to the thermo-elastic self-consistent model, where the temperature increment ΔT is generally considered homogeneous at every scale, the moisture content increment is often strongly different in the fiber and the matrix.

In a fundamental work [3], Eshelby demonstrated that when the elementary inclusions (here the matrix and the fiber) were assumed to have ellipsoidal shapes, stresses and strains were related by the following scale transition relation:

$$\sigma^\alpha - \sigma^I = -\mathbf{L}^I : \mathbf{R}^I : (\boldsymbol{\varepsilon}^\alpha - \boldsymbol{\varepsilon}^I) \quad (3)$$

\mathbf{R}^I is the reaction tensor. It satisfies:

$$\mathbf{R}^I = (\mathbf{I} - \mathbf{S}_{\text{esh}}^I) : \mathbf{S}_{\text{esh}}^{I^{-1}} = (\mathbf{L}^{I^{-1}} - \mathbf{E}^I) : \mathbf{E}^{I^{-1}} \quad (4)$$

In (4), \mathbf{I} stands for the fourth order identity tensor. Hill's tensor \mathbf{E}^I expresses the dependence of reaction tensor on the morphology assumed for the matrix and its reinforcements [4]. It can be expressed as a function of Eshelby tensor, through $\mathbf{E}^I = (\mathbf{L}^I)^{-1} : \mathbf{S}_{\text{esh}}^I$.

In another main paper, Hill demonstrated the following useful volume average equations [5]:

$$\begin{aligned} \langle \sigma^\alpha \rangle_{\alpha=f,m} &= \sigma^I \\ \langle \boldsymbol{\varepsilon}^\alpha \rangle_{\alpha=f,m} &= \boldsymbol{\varepsilon}^I \end{aligned} \quad (5)$$

Using (1-5), we easily obtain a linear relation between microscopic and macroscopic fields:

$$\boldsymbol{\varepsilon}^I = \left\langle (\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I)^{-1} : (\mathbf{L}^I + \mathbf{L}^I : \mathbf{R}^I) \right\rangle_{\alpha=f,m} : \boldsymbol{\varepsilon}^I + \left\langle (\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I)^{-1} : [\mathbf{L}^\alpha : \boldsymbol{\beta}^\alpha \Delta C^\alpha - \mathbf{L}^I : \boldsymbol{\beta}^I \Delta C^I] \right\rangle_{\alpha=f,m} \quad (6)$$

Since this relation must be satisfied for any hygro-mechanical state $\{\boldsymbol{\varepsilon}^I, \Delta C^I, \Delta C^f, \Delta C^m\}$, the first term of the right member of (6) must be equal to \mathbf{I} , while the second term must be null.

Then, we obtain the very classical self-consistent estimate for the macroscopic elastic stiffness (7) and the homogenized CME for the composite (8):

$$\mathbf{L}^I = \left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} : \left(\mathbf{L}^I + \mathbf{L}^I : \mathbf{R}^I \right) : \mathbf{L}^\alpha \right\rangle_{\alpha=f,m} \quad (7)$$

$$\left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} : \mathbf{L}^\alpha : \boldsymbol{\beta}^\alpha \Delta C^\alpha \right\rangle_{\alpha=f,m} = \left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} : \mathbf{L}^I : \boldsymbol{\beta}^I \Delta C^I \right\rangle_{\alpha=f,m} \quad (8)$$

\mathbf{L}^I , $\boldsymbol{\beta}^I$ and ΔC^I being constant over the microscopic elements, we may extract them from the summation:

$$\left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} \right\rangle_{\alpha=f,m}^{-1} : \left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} : \mathbf{L}^\alpha : \boldsymbol{\beta}^\alpha \Delta C^\alpha \right\rangle_{\alpha=f,m} = \mathbf{L}^I : \boldsymbol{\beta}^I \Delta C^I \quad (9)$$

Finally, we obtain an explicit form for the macroscopic CME:

$$\boldsymbol{\beta}^I = \frac{1}{\Delta C^I} \mathbf{L}^{I^{-1}} \left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} \right\rangle_{\alpha=f,m}^{-1} : \left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} : \mathbf{L}^\alpha : \boldsymbol{\beta}^\alpha \Delta C^\alpha \right\rangle_{\alpha=f,m} \quad (10)$$

Since the increment of moisture concentration in fiber is usually null, the introduction of this additional assumption (i.e. $\Delta C^f = 0$) involves the following simplifications:

$$\boldsymbol{\beta}^I = v^m \frac{\Delta C^m}{\Delta C^I} \mathbf{L}^{I^{-1}} \left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} \right\rangle_{\alpha=f,m}^{-1} : \left(\mathbf{L}^m + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} : \mathbf{L}^m : \boldsymbol{\beta}^m \quad (11)$$

where v^m stands for the volume fraction of matrix in the considered ply ($v^m + v^f = 1$).

When the equilibrium state is reached, the maximum moisture content of the neat resin may be estimated from the maximum moisture content of the composite. By assuming that the fibers do not absorb any moisture, ΔC^I and ΔC^m are related by the expression given by Loos and Springer [6]:

$$\Delta C^I = \Delta C^m W^m = \Delta C^m \frac{v^m \rho^m}{\rho^I} \quad (12)$$

where W^m is the weight fraction (percent) of the resin in the composite, ρ^I and ρ^m are respectively the composite and resin densities.

Actually, the theoretical relation (12) of Loos and Springer can be affected by a factor γ ($\gamma \geq 1$). γ stands for the ratio between mass water in the composite and the matrix. An imperfect adhesion in fiber-reinforced composites or a porosity of the matrix plays an important role in the diffusion process. Taking into account this particularity leads to the following modifications for the relation (12):

$$\Delta C^I = \gamma \Delta C^m W^m = \gamma \Delta C^m \frac{v^m \rho^m}{\rho^I} \quad (13)$$

Introducing (13) in (11), the macroscopic CME are then expressed:

$$\boldsymbol{\beta}^I = \frac{\rho^I}{\gamma \rho^m} \mathbf{L}^{I-1} \left\langle \left(\mathbf{L}^\alpha + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} \right\rangle_{\alpha=f,m}^{-1} : \left(\mathbf{L}^m + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} : \mathbf{L}^m : \boldsymbol{\beta}^m \quad (14)$$

2.2. Tsai-Hahn model for the estimation of the macroscopic CME

Usually, identical models are used for the coefficients of thermal expansion and coefficients of moisture expansion. Thus, these models do not take into account a jump in moisture content between the constituents. On the opposite, the Tsai-Hahn model [7], which introduces different moisture contents in the fiber and the matrix, constitutes an interesting assessment of the validity of SC estimates for CME.

Introducing the ratio between mass water in the composite and the matrix and assuming that the fibers do not absorb any moisture, the Tsai-Hahn estimation of macroscopic CME is:

$$\begin{cases} \beta_{11}^I = \frac{E^m \beta^m}{(v^f E^f + v^m E^m)} \frac{\rho^I}{\gamma \rho^m} \\ \beta_{22}^I = (1 + v^m) \beta^m \frac{\rho^I}{\gamma \rho^m} - (v^f v^f + v^m v^m) \beta_{11}^I \end{cases} \quad (15)$$

3. MACROSCOPIC ANALYSIS

3.1 Moisture concentration

Consider an initially dry, uni-directionally reinforced composite pipe, whose inner and outer radii are a and b respectively, and let the laminate be exposed to an ambient fluid with boundary concentration c_0 . The macroscopic moisture concentration, $c^I(r, t)$, is solution of the following system with Fick's equation (16), where D^I is the transverse diffusion coefficient of the composite. Boundary and initial conditions are described in (17):

$$\frac{\partial c^I}{\partial t} = D^I \left[\frac{\partial^2 c^I}{\partial r^2} + \frac{1}{r} \frac{\partial c^I}{\partial r} \right], \quad a < r < b \quad (16)$$

$$\begin{cases} c^I(a, t) = c_0 \text{ and } c^I(b, t) = c_0 \\ c^I(r, 0) = 0 \end{cases} \quad (17)$$

Applying the Laplace transform to the latter system and using the residue theory to express the solution in time space [8], we finally obtain the macroscopic moisture concentration:

$$c^I(\bar{r}, \tau) = c_0 + \sum_{m=1}^{\infty} \frac{2 \exp(-\omega_m^2 \tau)}{\omega_m \Delta'_u(\omega_m)} \{ A_m J_0(\omega_m \bar{r}) + B_m Y_0(\omega_m \bar{r}) \} \quad (18)$$

where J_0 and Y_0 are Bessel's functions of order zero, Δ_u is the determinant of 2*2 matrix $[a]$. A_m and B_m are determinants of matrices deduced from $[a]$ by substituting respectively column 1 and 2 by the constant vector $\{g\}$. $\Delta'_u(\omega_m)$ is the derivative of Δ_u with respect to ω calculated for ω_m the m^{th} positive root of Δ_u . \bar{r} and τ are defined by the relations $\bar{r} = r/b$ and $\tau = (D^I t)/b^2$.

Furthermore, the elements of $[a]$ and $\{g\}$ are:

$$a_{11} = J_0(\omega\bar{a}), \quad a_{12} = Y_0(\omega\bar{a}), \quad a_{21} = J_0(\omega), \quad a_{22} = Y_0(\omega),$$

$$g_1 = c_0, \quad g_2 = c_0.$$

3.2 Macroscopic stresses

At the initial time, let us assume that the pipe is stress free. The hygroelastic stresses for every ply at any time are calculated by using the classical equations of solid mechanics: constitutive laws of hygroelastic orthotropic materials, strain-displacement relationship, compatibility and equilibrium equations and boundary conditions [9].

Introducing a characteristic modulus L_0 , we introduce the following dimensionless variables:

$$\bar{\sigma}^I = \sigma^I / L_0, \quad \bar{L}^I = L^I / L_0, \quad (\bar{u}^I, \bar{v}^I, \bar{w}^I) = (u^I, v^I, w^I) / b.$$

The axial and circumferential components of the displacement field of the i^{th} ply, respectively $\bar{u}^I(\bar{x}, \bar{r})$ and $\bar{v}^I(\bar{x}, \bar{r})$, are then expressed:

$$\begin{cases} \bar{u}^I(\bar{x}, \bar{r}) = R_1 \bar{x} \\ \bar{v}^I(\bar{x}, \bar{r}) = R_2 \bar{x} \bar{r} \\ R_1, R_2 \text{ are constants.} \end{cases} \quad (19)$$

The radial component of the displacement field \bar{w}^I satisfies the following equation:

$$\bar{r}^2 \frac{\partial^2 \bar{w}^I}{\partial \bar{r}^2} + \bar{r} \frac{\partial \bar{w}^I}{\partial \bar{r}} - \bar{w}^I = \frac{K_1 \bar{r}^2}{\bar{L}_{22}^I} \frac{\partial \Delta C^I}{\partial \bar{r}} \quad (20)$$

$$\text{with, } K_1 = \bar{L}_{12}^I \beta_{11}^I + \bar{L}_{23}^I \beta_{22}^I + \bar{L}_{22}^I \beta_{22}^I, \quad \Delta C^I = \frac{c^I}{\rho^I}.$$

It is shown that the general solution of equation (20) writes as the sum of a solution of the homogeneous equation and of a particular solution [9].

$$\begin{aligned} \bar{w}^I(\bar{r}) = & R_3 \bar{r} + \frac{R_4}{\bar{r}} - \\ & \sum_{m=1}^{\infty} \frac{2 \exp(-\omega_m^2 \tau)}{\omega_m \Delta'_u(\omega_m)} \frac{K_1}{\bar{L}_{22}^I} \left[A_i \sum_{k=0}^{\infty} \frac{(-1)^k \left(\frac{1}{2}\right)^{2k+1} (\omega_m)^{2k+2}}{k!(k+1)!} \frac{\bar{r}^{2k+3}}{((2k+3)^2 - 1)} + \frac{B_i}{\pi} \left\{ \right. \\ & \sum_{k=0}^{\infty} \frac{(-1)^k \left(\frac{1}{2}\right)^{2k+1} (\omega_m)^{2k+2}}{k!(k+1)!} \left[2 \ln\left(\frac{1}{2}\omega_m\right) - \psi(k+1) - \psi(k+2) \right] \frac{\bar{r}^{(2k+3)}}{((2k+3)^2 - 1)} + \\ & \left. 2 \sum_{k=0}^{\infty} \frac{(-1)^k \left(\frac{1}{2}\right)^{2k+1} (\omega_m)^{2k+2}}{k!(k+1)!} \left[\frac{\ln(\bar{r}) \bar{r}^{2k+3}}{((2k+3)^2 - 1)} - \frac{2(2k+3) \bar{r}^{2k+3}}{((2k+3)^2 - 1)^2} \right] - \bar{r} \ln(\bar{r}) \right\} \right] \end{aligned}$$

Finally, the displacement field depends on four constants to be determined : R_i for $i=1..4$. These four constants result from the following conditions: global force balance of the cylinder; nullity of the normal stress on the two lateral surfaces.

4. EXAMPLE

4.1. Evaluation of the overall CME of a ply in a T300/5208 composite using Self-Consistent model

The predictive integral form (14) demonstrated for the homogeneous equivalent CME of a ply, according to the self-consistent scale transition formalism developed in the present work, was checked in the case of a T300/5208 lamina.

Table 1 presents typical data for the properties of the T300 carbon fibers and N5208 epoxy matrix and the mechanical properties of the T300/5208 composite, deduced from SC computations. CME for the constituents are given in Table 2.

“Table 1. Mechanical properties.”

	E_1 [GPa]	E_2, E_3 [GPa]	ν_{12}, ν_{13}	G_{23} [GPa]	G_{12} [GPa]
T300 fibers [10]	230	15	0.2	7	15
N 5208 epoxy matrix [11]	4.5	4.5	0.4	1.6	1.6
T300/5208 (SC)	139.6	9.8	0.28	3.5	6.4

“Table 2. CME for the components of T300/5208 composite.”

	β_{11}	β_{22}, β_{33}
T300 fibers [10]	0	0
N 5208 epoxy matrix [11]	0.6	0.6

Calculations have been performed for several moisture content ratios varying from 1 to the maximum moisture content ratio. In the studied case, the ratio between composite and resin densities being 1.33, the maximum moisture content ratio given by (12) is about 3.33. Ply CME estimated through SC model were compared to the corresponding values predicted by Tsai-Hahn forms (15). Results obtained for longitudinal (β_{11}) and transverse (β_{22}) macroscopic CME have been drawn on Fig. 1.

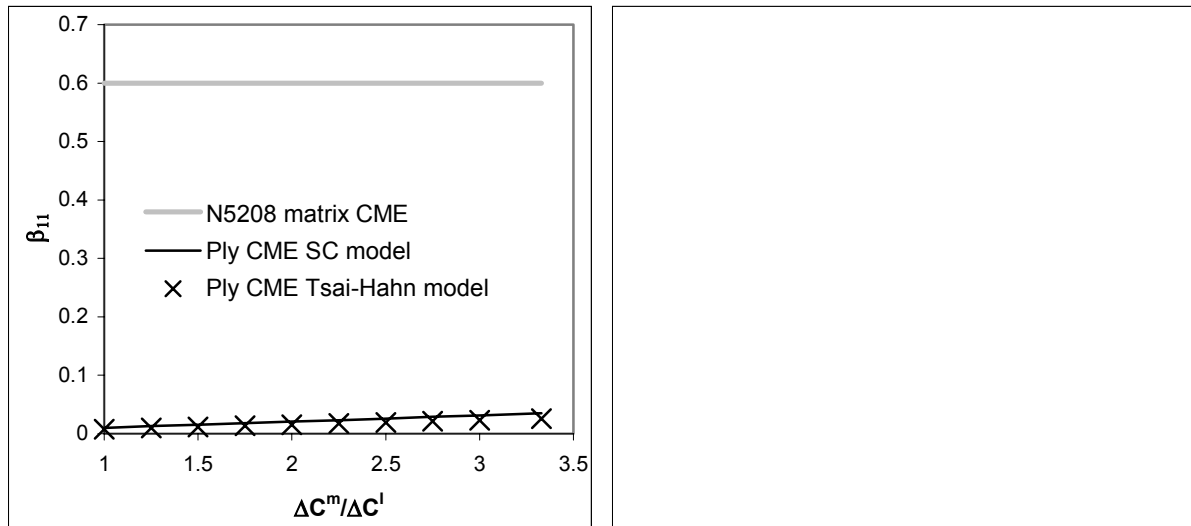


Fig. 1. Longitudinal and transverse CME estimated for T300/5208 composite. Comparison between SC and Tsai-Hahn models

SC model yields satisfactory numerical values in comparison with Tsai-Hahn reference CME. Computations show that SC formalism achieves to reproduce a strongly anisotropic hygroscopic behaviour at macroscopic scale: the longitudinal CME of the ply remains times

weaker than the one of epoxy matrix, whatever the assumed moisture content ratio. On the opposite, transverse macroscopic CME can be either higher or weaker than resin CME. As predicted by Tsai-Hahn forms, the CME calculated owing to SC model can be stronger in the ply than in the epoxy matrix, especially for high values of $\Delta C^m/\Delta C^l$. This corresponds to quasi-perfect materials, i.e. non porous matrix and no adhesion defects at its interface with the fiber. Transverse macroscopic CME significantly increases with moisture content ratio. In the studied case, T300/5208 CME reaches the values observed in the resin for $\Delta C^m/\Delta C^l \cong 2$.

4.2 Local and macroscopic stress states

4.2.1 Macroscopic stress state

A thin uni-directionally reinforced composite pipe, with thickness 4 mm, initially dry then exposed to an ambient fluid, made up of T300/5208 carbon-epoxy plies, is considered. The hygroscopic properties are presented in Table 3.

“Table 3. Hygroscopic properties for T300/5208 composite [6].”

Diffusion coefficient	$1.5 \times 10^{-7} \text{ mm}^2/\text{s}$
Boundary concentration	$c_0=1.5 \%$

Fig. 2 shows the time-dependent concentration profiles, resulting from the application of a boundary concentration c_0 , as a function of the normalized radial distance from the inner radius r_{dim} .

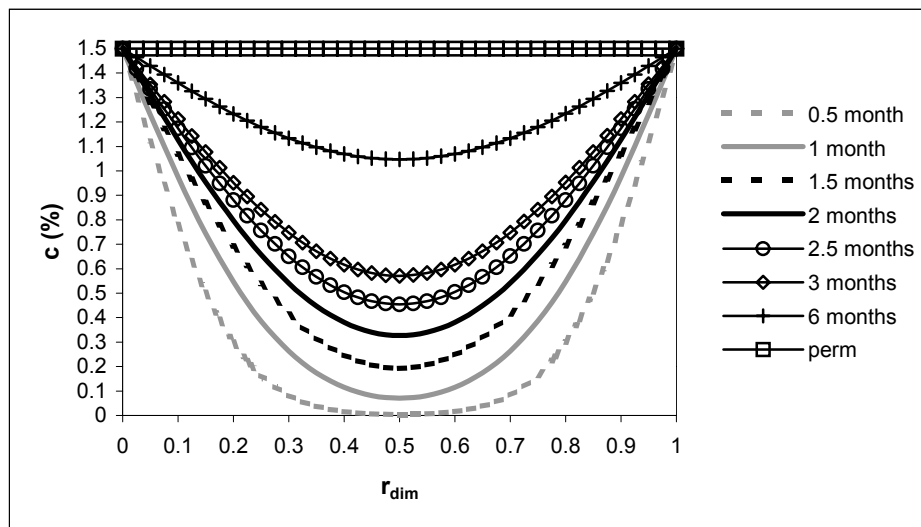


Fig. 2. T300/5208 concentration profiles

At the beginning of the diffusion process, important concentration gradients occur near the external surfaces. As time advances, the concentration increases and finally reaches its uniform equilibrium level (noticed *perm* in the caption).

Fig. 3 shows the transverse macroscopic stresses for different moisture content ratios. As time advances, the transverse stress in the central ply increases, attaining its maximum value after a short time interval, then decreasing gradually as the concentration distribution (Fig. 2) approaches its uniform equilibrium level. The maximum transverse stress, reached in the central ply, is growing function of the moisture content ratio. The transverse stresses for a moisture content ratio of 2 (Fig. 3a) reach positive values which are about 70 % of the transverse tensile strength Y (Table 4). For the maximum moisture content ratio, the transverse stress exceeds the macroscopic tensile strength in the transverse direction. The transient analysis emphasizes the existence of maximum stresses in the first times. In the

inner ply, the macroscopic transverse stress is not constant. Fig. 3b shows the average transverse macroscopic stresses in the inner ply. The average transverse stresses remain negative whatever the moisture content ratio. For the maximum moisture content ratio, the average transverse stresses do not reach the compressive strength in the transverse direction Y' . Finally, a macroscopic tensile failure occurs in the central ply.

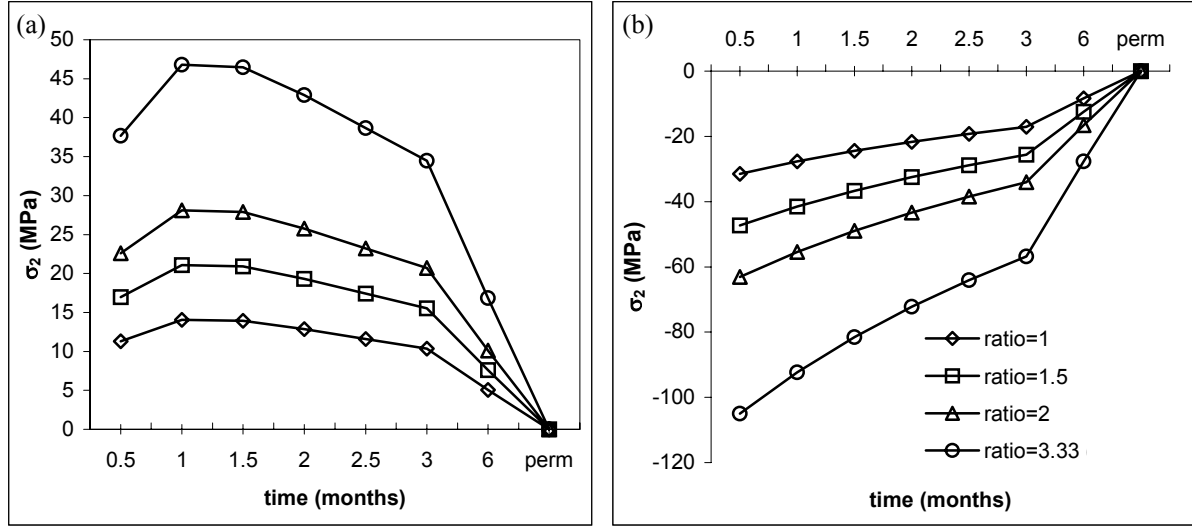


Fig. 3. T300/5208 Transverse macroscopic stresses: a) central ply, b) inner ply

“**Table 4.** Macroscopic failure stresses in the longitudinal, transverse and normal directions [11].”

Strengths [MPa]	X, X'	Y, Z	Y', Z'	S
T300/5208	1500	40	246	68

4.2.2 Local stress states

By assuming that the fibers do not absorb any moisture, the local stresses-strains relation in reinforcements (2) becomes:

$$\boldsymbol{\sigma}^f = \mathbf{L}^f : \boldsymbol{\varepsilon}^f \quad (21)$$

Using (21) in (1,3) we obtain the following scale transition expression for the strains in fibers:

$$\boldsymbol{\varepsilon}^f = \left(\mathbf{L}^f + \mathbf{L}^I : \mathbf{R}^I \right)^{-1} : \left(\boldsymbol{\sigma}^I + \mathbf{L}^I : \mathbf{R}^I : \boldsymbol{\varepsilon}^I \right) \quad (22)$$

The use of (22) implies the knowledge of the macroscopic stresses and strains in the ply. This especially requires the measurement or calculation of the CME of the composite material. If these conditions are satisfied, the local mechanical states in the epoxy matrix are provided by Hill's strains and stresses average laws (5):

$$\begin{cases} \boldsymbol{\sigma}^m = \frac{1}{v^m} \boldsymbol{\sigma}^I - \frac{v^f}{v^m} \boldsymbol{\sigma}^f \\ \boldsymbol{\varepsilon}^m = \frac{1}{v^m} \boldsymbol{\varepsilon}^I - \frac{v^f}{v^m} \boldsymbol{\varepsilon}^f \end{cases} \quad (23)$$

Forms (21-23) depend on neither the local CME of the matrix nor its moisture content.

The transverse stresses in the matrix and fiber, corresponding to the macroscopic stresses in the central ply, for the different moisture content ratios are respectively plotted in Figs. 4a and 4b.

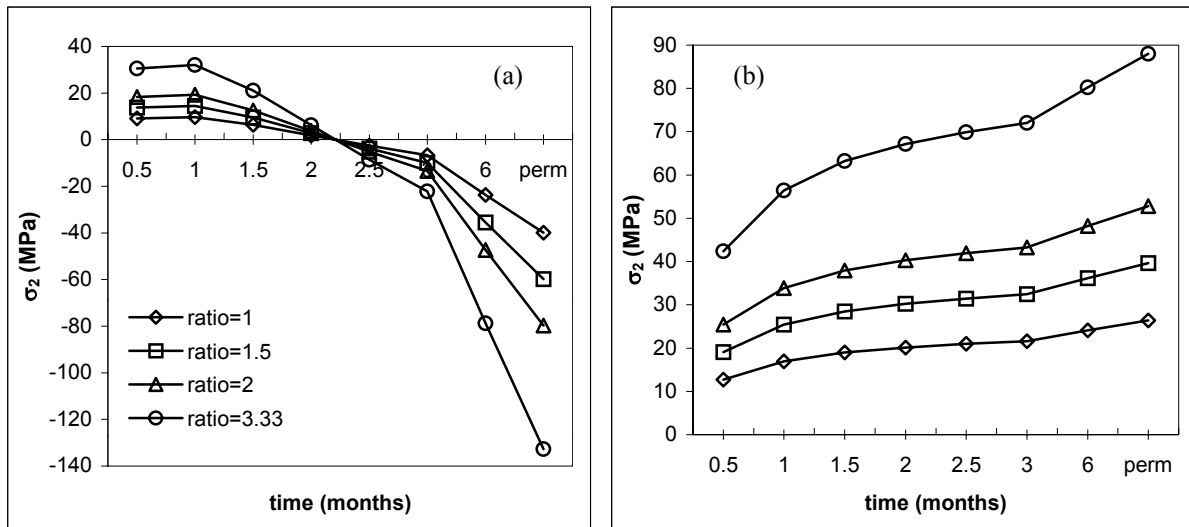


Fig. 4. a) Transverse stresses in N5208 matrix (central ply), b) Transverse stresses in T300 fiber (central ply)

The transverse stresses in the matrix and fiber are growing functions of the moisture content ratio. For the maximum moisture content ratio, the transverse stress in the matrix (Fig. 4a) varies with time from tensile values superior to 30 MPa (first stages) to compressive values around 130 MPa (corresponding to the permanent state).

The transverse stresses in the matrix and fiber, corresponding to the average macroscopic stress on the inner ply, for the different moisture content ratios are respectively plotted in Figs. 5a and 5b.

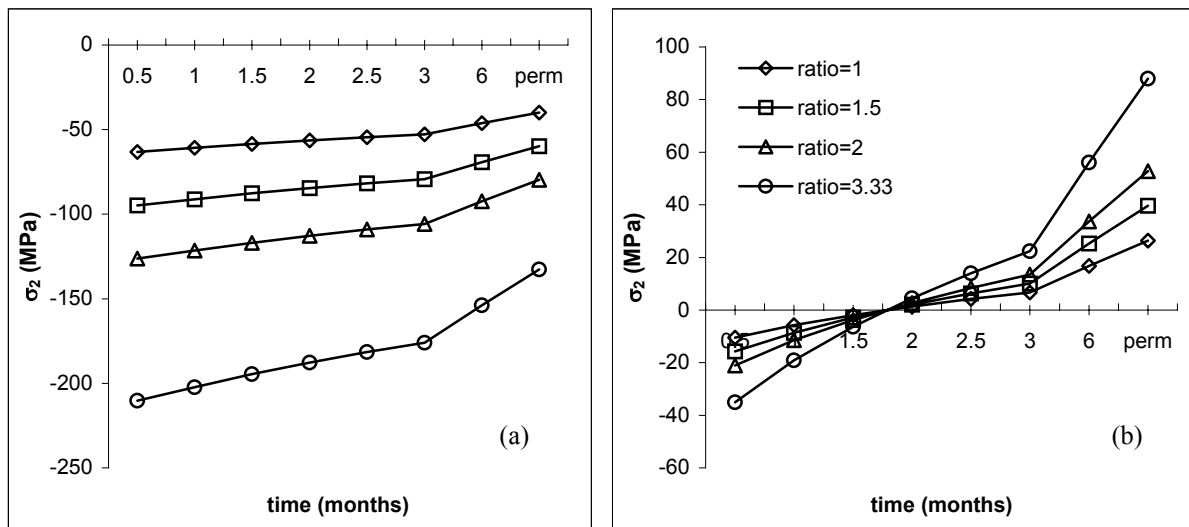


Fig. 5. a) Transverse stresses in N5208 matrix (inner ply), b) Transverse stresses in T300 fiber (inner ply)

The transverse stress in the matrix remains negative whatever the moisture content ratio. The maximum transverse compressive stress is reached at the first time and for a ratio of 3.33; the stress values could reach the compressive strength of the matrix while macroscopically a transverse tensile failure occurs in the central ply. The stress in the fiber is initially compressive and becomes tensile as time advances.

5. CONCLUSIONS

A hygro-elastic self-consistent model for unidirectional fiber-reinforced composites subjected to transient moisture concentration has been investigated in this paper. The moisture contents in the matrix and fiber are strongly different. Accordingly the classical self-consistent approach is extended in order to predict the macroscopic elastic properties and the Coefficients of Moisture Expansion (CME). CME predicted have been compared to Tsai-Hahn estimates. An imperfect adhesion in fiber-reinforced composites and a porous matrix induce various ratio between the moisture content of the neat resin and the moisture content of the composite. The macroscopic (ply) and local (fiber and matrix) internal stress states are evaluated for various moisture content ratios between the matrix and the ply. The macroscopic stresses are calculated by using continuum mechanics formalisms and the local stresses derived from the scale transition model. It is shown, for maximum moisture content ratio, corresponding to a perfect adhesion between the fiber and matrix and a non porous matrix, that a macroscopic tensile failure occurs in the central ply of the composite pipe considered. On the contrary, scale transition model enlightens a possible damage due to compressive stresses in the matrix for the inner ply. This demonstrates the complementarities between continuum mechanics and scale transition modeling for the study of heterogeneous materials such as composites.

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