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EFFECTS OF MOISTURE DEPENDENT CONSTITUENTS PROPERTIES ON THE HYGROSCOPIC STRESSES EXPERIENCED BY COMPOSITE STRUCTURES

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Abstract

This work investigates the effects related to the evolution, as a function of the moisture content, of the hygro-elastic properties of composite plies constituting a fiber-reinforced laminate, on the stress states predicted to take place, within the structure, during the transient part of a hygroscopic load. The proposed approach involves the coupling of the classical continuum mechanics formalism to Eshelby-Kröner self-consistent scale transition model. An inverse scale transition model provides the evolution of the local hygro-elastic properties experienced by the epoxy matrix as the moisture diffusion processes. Scale transition relations provide the local distribution of the stresses within the constituents (fiber and matrix) of each ply of the considered laminates, from the distribution of the macroscopic states of stresses. The numerical simulations show that accounting (or not) of the softening of the hygro-elastic properties experienced in practice by a composite structure submitted to a hygroscopic load yield significant discrepancies of the predicted multi-scale stress states.

1. Introduction

Carbon reinforced epoxy matrix composites constitute an answer to the needs of weight reduction and design flexibility for many industrial applications, such as, for instance, mechanical parts of airplanes. Composite structures are often submitted to various environmental conditions during their service life, including thermal and hygroscopic loading. Actually, carbon/epoxy composites can absorb significant amount of water and exhibit heterogeneous Coefficients of Moisture Expansion (CME) (i.e. the CME of the epoxy matrix are strongly different from the CME of the carbon fibers, as shown in: [1-3] moreover, the diffusion of moisture in such materials is a rather slow process, resulting in the occurrence of moisture concentration gradients within their depth, during at least the transient stage [4]. As a consequence, local stresses take place from hygroscopic loading of composite structures which closely depends on the experienced environmental conditions, on the local intrinsic properties of the constituents and on its microstructure (the morphology of the constituents, the lay-up configuration, ... fall in this last category of factors). Now, the knowledge of internal stresses is necessary to predict a possible damage occurrence in the material during its manufacturing process or service life. Thus, the study of the development of internal stresses due to hygro-elastic loads in composites is very important in regard to any engineering application. Moreover, it is reported in the literature that moisture diffusion in composite structures entails a significant softening of the elastic properties of the composite plies [5].
The present work is a part of a research project dedicated to the numerical determination of internal stresses in the constituents of carbon-fiber reinforced/epoxy composite structures submitted to hygroscopic loading, during the transient part of the moisture diffusion process. This communication is especially focused on investigating the effects related to the evolution of the elastic stiffness and coefficient of moisture expansion of the epoxy, as a function of its moisture content. The constituents properties dependence on the moisture content is determined from the evolution of the corresponding macroscopic properties, experienced in

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practice by the composite ply, during the transient part of the diffusion process. The required identification procedure involves an inverse self-consistent hygro-elastic scale transition model, which is described in the second section of this article. In the third section, a multi-scale analysis of the transient hygro-mechanical behaviour of various composite structures submitted to hygroscopic loads is achieved. The approach entails using continuum mechanics formalism in order to perform the determination of the macroscopic mechanical states as a function of time and space, during the transient phase of the moisture diffusion process. The mechanical states of stresses and strains experienced by the constituents of each ply of the structure are determined as a function of space and time, through analytical scale transition relations. In the fourth part of this work the mechanical states predicted by the model accounting of moisture dependent properties are compared to the reference values obtained assuming the materials properties independent from the moisture content. The last section is mainly dedicated to conclusions about the above listed sections.

2. Inverse scale transition modelling for the identification of the hygro-elastic properties of one constituent of a composite ply

2.1 Introduction

The precise knowledge of the local properties of each constituent of a composite structure is required in order to achieve the prediction of its behavior (and especially its mechanical states) through scale transition models. Nevertheless, the stiffness and coefficients of moisture expansion of the matrix and reinforcements are not always fully available in the already published literature. The practical determination of the hygro-mechanical properties of composite materials are most of the time achieved on uni-directionnaly reinforced composites whereas the properties of the unreinforced matrices are easily accessible though measurements, too [6-11]. In spite of the existence of several articles dedicated to the characterisation of the properties of the isolated reinforcements [12-14], the practical achieviement of this task remains difficult to handle, and the available published data for typical reinforcing particulates employed in composite design are still very limited. As a consequence, the properties of the single reinforcements exhibiting extreme morphologies (such as fibers), are not often known from direct experiment, but more usually they are deduced from the knowledge of the properties of the pure matrices and those of the composite ply (which both are easier to determine), through appropriate calculation procedures. In the present case, the literature provides the moisture dependent evolution of uni-directional fiber-reinforced plies elastic moduli [5], but not the corresponding properties for the constituents. Thus, a dedicated identification method is necessary before proceeding further. The question of determining the properties of some constituents of heterogeneous materials has been extensively addressed in the field of materials science, especially for studying complex polycrystalline metallic alloys (like titanium alloys, [15-17]) or metal matrix composites (typically Aluminum-Silicon Carbide composites [18-19] or iron oxides from the inner core of the Earth [20], for instance). The required calculation methods involved in order to achieve such a goal are either based on Finite Element Analysis [21] or on the inversion of scale transition homogenization procedures [15-19]: this solution will be extensively used in the following of the present work. Numerical inversion of Eshelby-Kröner hygro-elastic self-consistent model will be summarized and discussed in the following of this very section.

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2.2 Estimating constituents properties from Eshelby-Kröner self-consistent inverse scale transition model

2.2.1 Introduction

Scale transition models are based on a multi-scale representation of materials. In the case of composite materials, for instance, a two-scale model is sufficient:

- The properties and mechanical states of either the resin or the reinforcements are respectively indicated by the superscripts ^{m} and ^{r}. These constituents define the so-called "pseudo-macroscopic" scale of the material.
- Homogenisation operations performed over its aforementioned constituents are assumed to provide the effective behaviour of the composite ply, which defines the macroscopic scale of the model. It is denoted by the superscript ^{I}.

2.2.2 Estimating the effective properties of a composite ply through Eshelby-Kröner self-consistent model

Within scale transition modelling, the local properties of the i–superscripted constituents are usually considered to be known (i.e. the pseudo-macroscopic stiffnesses, $\mathbf{L^i}$ and coefficients of moisture expansion $\boldsymbol{\beta}^\mathbf{i}$), whereas the corresponding effective macroscopic properties of the composite structure (respectively, $\mathbf{L^I}$ and $\boldsymbol{\beta}^\mathbf{I}$) are a priori unknown and results from (often numerical) computations.
Among the numerous, available in the literature scale transition models, able to handle such a problem, most involve rough-and-ready theoretical frameworks: Voigt [22], Reuss [23], Neerfeld-Hill [24-25], Tsai-Hahn [26], and Mori-Tanaka [27-28] approximates fall in this category. This is not satisfying, since such a model does not properly depict the real physical conditions experienced in practice by the material. In the field of scale transition modelling, the best candidate remains Kröner-Eshelby self-consistent model [29-30], because only this model takes into account a rigorous treatment of the thermo-hygro-elastic interactions between the homogeneous macroscopic medium and its heterogeneous constituents, as well as this model enables handling the microstructure (i.e. the particular morphology of the constituents, especially that of the reinforcements). The method was initially introduced to treat the case of polycrystalline materials in pure elasticity. The model was thereafter extended to thermoelastic loads and gave satisfactory results on either single-phase or two-phases materials [18-19]. More recently, this classical model was improved in order to treat hygroscopic load related questions. Therefore, the formalism was extent so that homogenisation relations were established for estimating the macroscopic coefficients of moisture expansion [31]. The main equations involved in the determination of the effective hygro-elastic properties of heterogeneous materials through Kröner-Eshelby self-consistent approach reads:

$$\mathbf{L^I} = \left\langle \mathbf{L^i} : \left(\mathbf{I} + \mathbf{E^I} : \left[\mathbf{L^i} - \mathbf{L^I}\right]\right)^{-1} \right\rangle_{\mathrm{i=r,m}} \tag{1}$$

$$\boldsymbol{\beta}^\mathbf{I} = \frac{1}{\Delta C^I} \left\langle \left(\mathbf{L^i} + \mathbf{L^I} : \mathbf{R^I}\right)^{-1} : \mathbf{L^I} \right\rangle_{\mathrm{i=r,m}}^{-1} : \left\langle \left(\mathbf{L^i} + \mathbf{L^I} : \mathbf{R^I}\right)^{-1} : \mathbf{L^i} : \boldsymbol{\beta}^\mathbf{i} \Delta C^i \right\rangle_{\mathrm{i=r,m}} \tag{2}$$

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Where ΔC^i is the moisture content of the studied i element of the composite structure. The superscripts *r* and *m* are considered as replacement rule for the general superscript *i*, in the cases that the properties of the *reinforcements* or those of the *matrix* have to be considered, respectively. Actually, the pseudo-macroscopic moisture contents ΔC^r and ΔC^m can be expressed as a function of the macroscopic hygroscopic load ΔC^I [32].

In relations (1-2), the brackets < > stand for volume weighted averages. Hill [25] suggested arithmetic or geometric averages for achieving these operations. Both have been extensively used in the field of materials science. The interested reader can refer to [33-35] that take advantage of the geometric average for estimating the properties and mechanical states of polycrystals, whereas [19, 31, 36] show applications of arithmetic average. In a recent work, the geometric average was tested for estimating the effective properties of carbon-epoxy composites [37]. Nevertheless, the obtained results were not found as satisfactory than in the previously studied cases of metallic polycrystals or metal ceramic assemblies. Consequently, arithmetic average only will be used in the following of this manuscript. In the present case, where the macroscopic behaviour is described by two, separate, heterogeneous inclusions only (i.e. one for the matrix and one for the reinforcements), introducing v^r and v^m as the volume fractions of the ply constituents, and taking into account the classical relation on the summation over the volume fractions (i.e. $v^r + v^m=1$), the volume average of any tensor **A** writes:

$$\left\langle \mathbf{A}^{\mathbf{i}} \right\rangle_{i=r,m} = v^r\, \mathbf{A}^{\mathbf{r}} + v^m\, \mathbf{A}^{\mathbf{m}} \tag{3}$$

According to equations (1-2), the effective properties expressed within Eshelby-Kröner self-consistent model involve a still undefined tensor, $\mathbf{R}^{\mathbf{I}}$. This term is the so-called “reaction tensor” [36]. It satisfies:

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

In the very preceding equation, **I** stands for the fourth order identity tensor. Hill’s tensor $\mathbf{E}^{\mathbf{I}}$, also known as Morris tensor [38], expresses the dependence of the reaction tensor on the morphology assumed for the matrix and its reinforcements [39]. It can be expressed as a function of Eshelby’s tensor $\mathbf{S}^{\mathbf{I}}_{\mathbf{esh}}$, through $\mathbf{E}^{\mathbf{I}} = \mathbf{S}^{\mathbf{I}}_{\mathbf{esh}} : {\mathbf{L}^{\mathbf{I}}}^{-1}$. It has to be underlined that both Hill’s and Eshelby’s tensor components are functions of the macroscopic stiffness $\mathbf{L}^{\mathbf{I}}$ (some examples are given in [36, 40].

2.2.3 Inverse Eshelby-Kröner self-consistent elastic model

The pseudomacroscopic stiffness tensor of the reinforcements can be deduced from the inversion of the Eshelby-Kröner main homogenization form over the constituents elastic properties (1) as follows:

$$\mathbf{L}^{\mathbf{r}} = \frac{1}{v^r}\mathbf{L}^{\mathbf{I}} : \left[\mathbf{E}^{\mathbf{I}} : \left(\mathbf{L}^{\mathbf{r}} - \mathbf{L}^{\mathbf{I}}\right) + \mathbf{I}\right] - \frac{v^m}{v^r}\mathbf{L}^{\mathbf{m}} : \left[\mathbf{E}^{\mathbf{I}} : \left(\mathbf{L}^{\mathbf{m}} - \mathbf{L}^{\mathbf{I}}\right) + \mathbf{I}\right]^{-1} : \left[\mathbf{E}^{\mathbf{I}} : \left(\mathbf{L}^{\mathbf{r}} - \mathbf{L}^{\mathbf{I}}\right) + \mathbf{I}\right] \tag{5}$$

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The application of this equation implies that both the macroscopic stiffness and the pseudomacroscopic mechanical behaviour of the matrix is perfectly determined. The elastic stiffness of the matrix constituting the composite ply will be assumed to be identical to the elastic stiffness of the pure single matrix, deduced in practice from measurements performed on bulk samples made up of pure matrix. It was demonstrated in [15] that this assumption was not leading to significant errors in the case that polycrystalline multi-phase samples were considered.
An expression, analogous to above-relation (5) can be found for the elastic stiffness of the matrix, through the following replacement rules over the superscripts/subscripts: $\mathrm{m} \to \mathrm{r}, \mathrm{r} \to \mathrm{m}$.
In the particular case, where impermeable reinforcements are present in the composite structure, $\Delta C^{r} = 0$. Accounting of this additional condition, the pseudo-macroscopic coefficients of moisture expansion of the matrix can be deduced from the inversion of the homogenization form (2) as follows (an extensive study of this very question was achieved in [31]):

$$\boldsymbol{\beta}^{\mathbf{m}} = \frac{\Delta C^{I}}{v^{m}\, \Delta C^{m}} \mathbf{L}^{\mathbf{m}-1} : \left(\mathbf{L}^{\mathbf{m}} + \mathbf{L}^{\mathbf{I}} : \mathbf{R}^{\mathbf{I}}\right) : \left\langle \left(\mathbf{L}^{\mathbf{i}} + \mathbf{L}^{\mathbf{I}} : \mathbf{R}^{\mathbf{I}}\right)^{-1} : \mathbf{L}^{\mathbf{I}} \right\rangle_{i=r,m} : \boldsymbol{\beta}^{\mathbf{I}} \qquad (6)$$

2.4 Application of inverse scale transition model to the determination of the moisture and temperature dependent pseudo-macroscopic elastic properties of carbon-epoxy composites

The literature provides evolutions for the elastic properties of carbon-fiber reinforced epoxies, as a function of the moisture concentration and the temperature [5, 41]. Table 1 of the present work summarizes the previously published data for an unidirectional composite designed for aeronautic applications, containing a volume fraction v^{r}=0.60 of reinforcing fibers. These evolutions of the macroscopic mechanical properties are obviously directly related to the variation of the pseudo-macroscopic elastic properties experienced by the composite plies constituents, as a function of the environmental conditions. Nevertheless, it is usually assumed that carbon-fibers do not absorb water, thus, there is no reason for expecting to link the elastic properties of the reinforcements to the moisture content. Moreover, carbon fibers are a ceramic, and ceramics usually present thermo-mechanical properties being almost independent from temperature, contrary to metals or polymers [18-19]. Furthermore, according to Table 1, the macroscopic longitudinal Young modulus Y_1^{I} is independent from the environmental conditions, in the studied ranges of temperatures (T^{I} comprised between 300 K and 400 K), and macroscopic moisture content (C^{I} holds within 0 to 0.75 %), the longitudinal direction being parallel to the principal axis of the fibers. Now, it is well known that the macroscopic properties of such an unidirectional composite ply are governed by the pseudo-macroscopic properties of the reinforcements in the direction parallel to the fiber axis, whereas, on the contrary, they mainly depend on the pseudo-macroscopic properties of the constitutive matrix, along directions perpendicular to the fiber axis (see, for instance, [10, 26]). As a consequence, on the basis of the values presented in Table 1, it can be reasonably considered that the elastic properties of the carbon reinforcements are independent from the environmental conditions applied to the material. Thus, in first approximation, the properties of the reinforcements will be considered as fixed, and will be identified once and for all. However, the decreasing of Y_2^{I} (and G_{12}^{I}), observed for increased temperatures or moisture concentrations, according to Table 1 implies a softening of the pseudo-macroscopic elastic

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properties of the epoxy. Thus, the elastic moduli of the matrix should be identified for each available set of macroscopic data, in order to find their susceptibility to hygro-thermal conditions. As a consequence, due to the time-span of the moisture diffusion process, each ply of the composite structure and the constitutive epoxy matrix of them are expected to present different hygro-elastic properties from those of the neighbouring plies (and their constituting matrix), during the transient part of an hygroscopic load. The consequence of this physical phenomenon on the multi-scale stress distribution in composite structures will be studied in the next section.

3. Multi-scale stresses estimations in composite structures accounting of hygro-mechanical coupling for the elastic stiffness : T300/5208 composite pipe submitted to environmental conditions.

Thin laminated composite pipes, with thickness 4 mm, initially dry then exposed to an ambient fluid, made up of T300/5208 carbon-epoxy plies, with a fiber volume fraction v^r=0.6, were considered for the determination of both macroscopic stresses and moisture contents as a function of time and space.
The following hygroscopic external conditions was considered : a symmetric loading corresponding to 100 % relative moisture concentration on each boundary of the structure (so that the moisture content is equal to 1,5 %). The corresponding time-dependent moisture content profiles obtained assuming the moisture diffusion process following Fick's law are depicted on figure 1. The time-dependant evolution of the moisture content in each ply of the structure is associated to an evolution of the macroscopic and local hygro-elastic properties, according to the method proposed in section 2 of the present work. An example is given on figure 2, for the macroscopic transverse coefficient of moisture expansion of the composite plies constituting the cylinder.
The closed-form formalism used in order to determine the mechanical stresses and strains in each ply of the structure, induced by the distribution of moisture content, is described in [42]. The pseudo-macroscopic states of stresses and strains, experienced by the constituents of a given ply, are determined from their macroscopic counterparts (included the moisture content in the considered ply), trough the analytical scale transition relations established in [43] on the basis of the fundamental analytical achievements previously published in [44]. Figures 3 and 4 show the numerical results obtained for the time-dependent multi-scale distribution of transverse and shear stresses for ± 55° laminates and uni-directionnal composites, respectively (obviously for the uni-directionnaly reinforced structure, no shear stresses do occur, so that the corresponding pictures have not been provided). Figure 3 and 4 report the results obtained for two specific plies only: the external and the central plies of the hollow cylinder.

4. Discussion about the results

i) The results of figure 1 are typical of previously published works [31]: the transient part of the (slow) moisture diffusion process in composite materials induces strong moisture content gradients within the depth of the structure. The strongest gradients occur at the beginning of the diffusion process and weaken as the moisture content increases in the bulk of the structure : along the time, the saturation ensures that each ply of the structure experiences the same moisture content.
ii) Figure 2 provides original additional interesting results : The numerical simulation show that strong gradients occur for the macroscopic transverse coefficient of moisture expansion, especially at the vicinity of both the external and internal plies of the studied hollow cylinder, during the transient part of the moisture diffusion process (see figure 2). At the contrary, the

hygro-mechanical properties at any scale reach an uniform value when the permanent state is attained. Nevertheless, strong discrepancies between the macroscopic / local properties does still remain even at the saturation of the diffusion process, depending on the choice of the hypothesis concerning the dependence of the properties on the moisture content.

iii) According to figures 3 and 4, the fact of considering (or not) an evolution of the hygro-elastic properties of both the composite plies and its constitutive matrix do strongly affects the transverse stresses levels and their distributions in the plies and the constituents of them. According to figure 3, in the laminate, only the macroscopic stresses and those of the epoxy do significantly vary as a function of the hypothesis made on the materials properties: accounting of a softening of both the transverse Young's modulus of the matrix and the ply during the moisture diffusion obviously weakens the amount of transverse stresses induced by the hygroscopic load at macroscopic scale and at pseudo-macroscopic scale in the epoxy. The predicted stress states experienced by the plies and its constitutive matrix can be reduced by up to 30% in the case that the realistic evolution of the materials properties are taken into account, by comparison with the results of the simulation performed without taking into account of that additional physical phenomenon.

Figure 4 reports the classical results expected in the case that a uni-directional composite is submitted to a transient hygroscopic load: the macroscopic stresses raise at the beginning of the moisture diffusion, but decrease thereafter, so that the plies are not anymore submitted to any stress when the permanent state is reached. However, the absolute value of the corresponding pseudo-macroscopic transverse stresses increase almost continuously during the moisture diffusion process, so that the strongest stress level occur when the saturation state is attained. It should be underlined that in this specific case, the pseudo-macroscopic transverse stress calculated for the carbon-fiber vary significantly depending on the choice of the hypothesis concerning the dependence of the properties on the moisture content.

iv) Macroscopic and local shear stresses are negative for the external ply, whereas they are positive for the central ply of the considered structure. According to figure 3, accounting of an evolution of the materials properties as a function of the moisture content experienced by the composite ply do have an effect on the concentration of the shear stresses within the reinforcements, contrary to the case previously studied of the transverse stresses. From the three calculated shear stresses (i.e., those of the ply, the epoxy, or the reinforcements), the hypothesis of a possible evolution of the materials properties with the moisture content has its strongest effect on the reinforcements shears stress states, in spite of the fact that the carbon fibers properties are actually constant during the moisture diffusion process. The weaker local shear stresses experienced by the carbon fibers come from the localization of a weaker macroscopic counterpart, which itself is explained by the softening of the plies hygro-elastic properties as a function of the moisture content.

v) According to the comments i) to iv) listed above, accounting of an evolution of the multi-scale hygro-elastic properties of composite plies has two main consequences which can be considered as responsible for the reduced amount of estimated stresses compared to the reference values (corresponding to the estimations achieved in the case that the properties of the dry material are considered to be still valid at any time during the moisture diffusion process). Firstly, strong deviation occur between the effective properties of the humid material, and their counterparts for the dry material (see figure 2). This effect increases along the time, as the mass of water having penetrated the structure increases, and reaches its maximum when the permanent stage of the diffusion process occur. Since the predicted stresses are obviously intimately linked to the hygro-elastic properties exhibited by the material, this effect partially explains the discrepancies displayed on figures 3 and 4, between the two sets of curves (depending on the assumption considered for defining the materials properties). Secondly, moisture contents gradients occur during the transient stage of the diffusion of moisture within the structure, since it is a rather slow process (see figure 1). The distribution of the hygroscopic load within depth of the structure directly induces a distribution of the hygro-elastic properties, in the case that their dependence on the moisture content is taken into account for achieving the calculations. Heterogeneous distributions of the hygro-mechanical properties explain therefore the discrepancies occurring at the beginning of the moisture diffusion process between the internal stresses predicted depending on whether the practical evolution of the materials properties as a function of the moisture content are taken into account or not. Thus, the effects on the raising of internal stresses, related to the softening of the material induced by the diffusion of water can be expected to occur even at the beginning of the hygroscopic loading of a composite structure.

5. Conclusions and perspectives

In this work, for the first time, the evolution, as reported in the literature, of the macroscopic hygro-elastic properties of a composite ply, as a function of its moisture content, is taken into account in a scale-transition based approach dedicated to the prediction of the multi-scale states of stresses experienced by the plies and the constituents of them, during the transient part of the hygroscopic loading of a composite structure. The scale-transition approach involves the inversion of the classical homogenisation procedure in order to estimate the evolution of the stiffness tensor of the epoxy matrix, as a function of its moisture content.
The mechanical states predicted with the model accounting of moisture dependent properties were compared to the reference values obtained assuming the materials properties independent from the moisture content. The numerical computations show that, as expected, the longitudinal mechanical states (expressed in the reference frame of the ply) are unaffected by the fact of taking into account an evolution of the hygro-elastic materials properties as a function of the moisture content. This result is understandable, because the hygro-mechanical behaviour of carbon-fiber reinforced composite plies, is controlled by the reinforcements, in the longitudinal direction. Since the carbon fibers do not absorb water, their properties remain constant at any state of the moisture diffusion process. Thus the longitudinal properties and mechanical states are independent from interactions between the moisture content and the hygro-elastic properties, in a fiber-reinforced composite structure. At the opposite, the estimated transverse and shear stress components, which strongly depend on the hygro-mechanical behaviour of the composite plies constituting matrix, the properties of which do vary as a function of the moisture content, can deviate from the reference values by up to 30%.
As a conclusion, since the sizing of composite structures is strongly related to the amount of internal states of stresses predicted for the typical loads expected to occur during the service life, the present study demonstrates that the multi-scale evolution of the materials properties as a function of the moisture content cannot be neglected, at least for composite structures designed for performing in humid environments.
The next step concerning this axis of research will still deal with some additional physical factors in order to improve the realism and the reliability of the predictions obtained through the scale-transition models. For instance, the moisture diffusion process was assumed, in the present work, to follow the linear, classical, established for a long time, Fickian model. Nevertheless, some valuable experimental results, already reported in [45], have shown that certain anomalies in the moisture sorption process, (i.e. discrepancies from the expected Fickian behaviour) could be explained from basic principles of irreversible thermodynamics, by a strong coupling between the moisture transport in polymers and the local stress state [46-47]. Thus, hygro-mechanical coupling will be investigated in further works.

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Tables

macroscopic hygro-thermal load		Macroscopic elastic moduli				
moisture content ΔC^{I} [%]	Temperature T^{I} [K]	Y_1^{I} [GPa]	Y_2^{I} [GPa]	ν_{12}^{I} [1]	G_{12}^{I} [GPa]	G_{23}^{I} [GPa]
0	300	130	9.5	0.3	6.0	3.0
0.25	300	130	9.25	0.3	6.0	3.0
0.75	300	130	8.75	0.3	6.0	3.0
0	325	130	8.5	0.3	6.0	3.0
0	400	130	7.0	0.3	4.75	2.39

Table 1: Experimental macroscopic elastic moduli at elevated moisture content and temperatures, according to [41].

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Elastic moduli	Y_1^m [GPa]	Y_2^m [GPa]	ν_{12}^m [1]	G_{12}^m [GPa]	G_{23}^m [GPa]
	5.35	5.35	0.350	1.98	1.98
Stiffness tensor components	L_{11}^m [GPa]	L_{22}^m [GPa]	L_{12}^m [GPa]	L_{44}^m [GPa]	L_{55}^m [GPa]
	8.62	8.62	4.66	1.98	1.98

Table 2: Pseudo-macroscopic elastic moduli and stiffness tensor components assumed for the epoxy matrix of the composite plies at $\Delta C^I = 0$ % and T^I = 300 K, according to [10].

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Elastic moduli	Y_1^r [GPa]	Y_2^r [GPa]	ν_{12}^r [1]	G_{23}^r [GPa]	G_{12}^r [GPa]
Eshelby-Kröner inverse model	213.2	13.3	0.27	4.0	12.1
Typical expected properties	232	15	0.279	5.0	15
Stiffness tensor components	L_{11}^r [GPa]	L_{22}^r [GPa]	L_{12}^r [GPa]	L_{44}^r [GPa]	L_{55}^r [GPa]
Eshelby-Kröner inverse model	219.2	23.9	10.8	4.0	12.1
Typical expected properties	236.7	20.1	8.4	5.0	15

Table 3: Pseudo-macroscopic elastic moduli and stiffness tensor components identified for the carbon fiber reinforcing the composite plies at $\Delta C^I = 0$ % and T^I = 300 K, according to Eshelby-Kröner inverse self-consistent model. Comparison with the corresponding properties exhibited in practice by typical high-strength carbon fibers, according to [10].

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macroscopic hygro-thermal load		Elastic moduli			Stiffness tensor components		
moisture content ΔC^I [%]	Temperature T^I [K]	Y^m [GPa]	ν^m [1]	G^m [GPa]	L^m_{11} [GPa]	L^m_{12} [GPa]	L^m_{44} [GPa]
0	300	5.35	0.35	1.98	8.62	4.67	1.98
0.25	300	5.22	0.33	1.98	7.68	3.75	1.98
0.75	300	4.95	0.28	1.98	6.29	2.41	1.98
0	325	4.81	0.25	1.98	5.76	1.91	1.98
0	400	4.17	0.27	1.04	5.20	1.92	1.04

Table 4: Moisture and temperature dependent pseudo-macroscopic elastic moduli and stiffness tensor components identified for the epoxy matrix constituting the composite plies, according to Eshelby-Kröner inverse self-consistent model.

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Figures

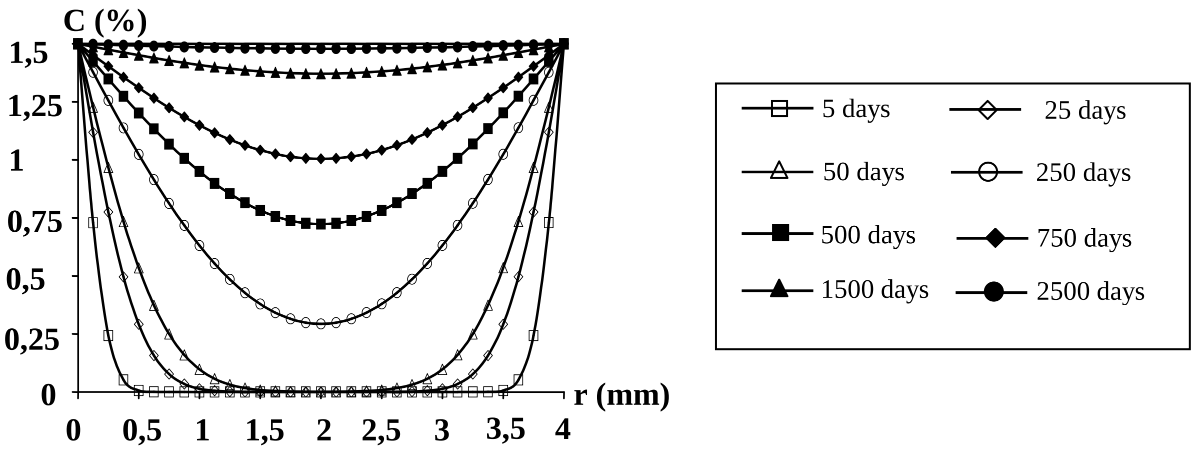

Figure 1 : time and space dependent moisture content profiles in the composite structure.

Youssef, G., **Fréour, S.,** Jacquemin, F. (2009). Effects of moisture dependent constituents properties on the hygroscopic stresses experienced by composite structures, *Mechanics of Composite Materials*, **45**(4), 369-380.

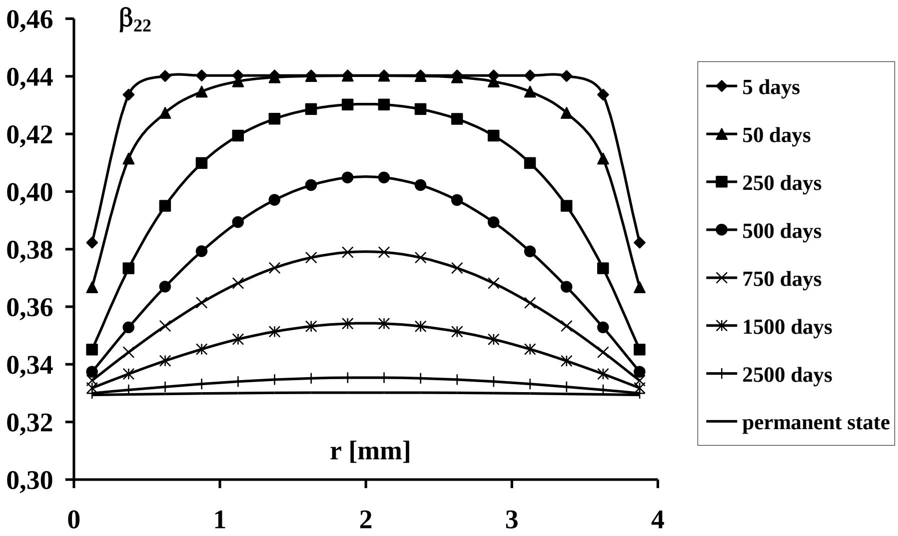

Figure 2: Time-dependent profile of the macroscopic transverse coefficient of moisture expansion.

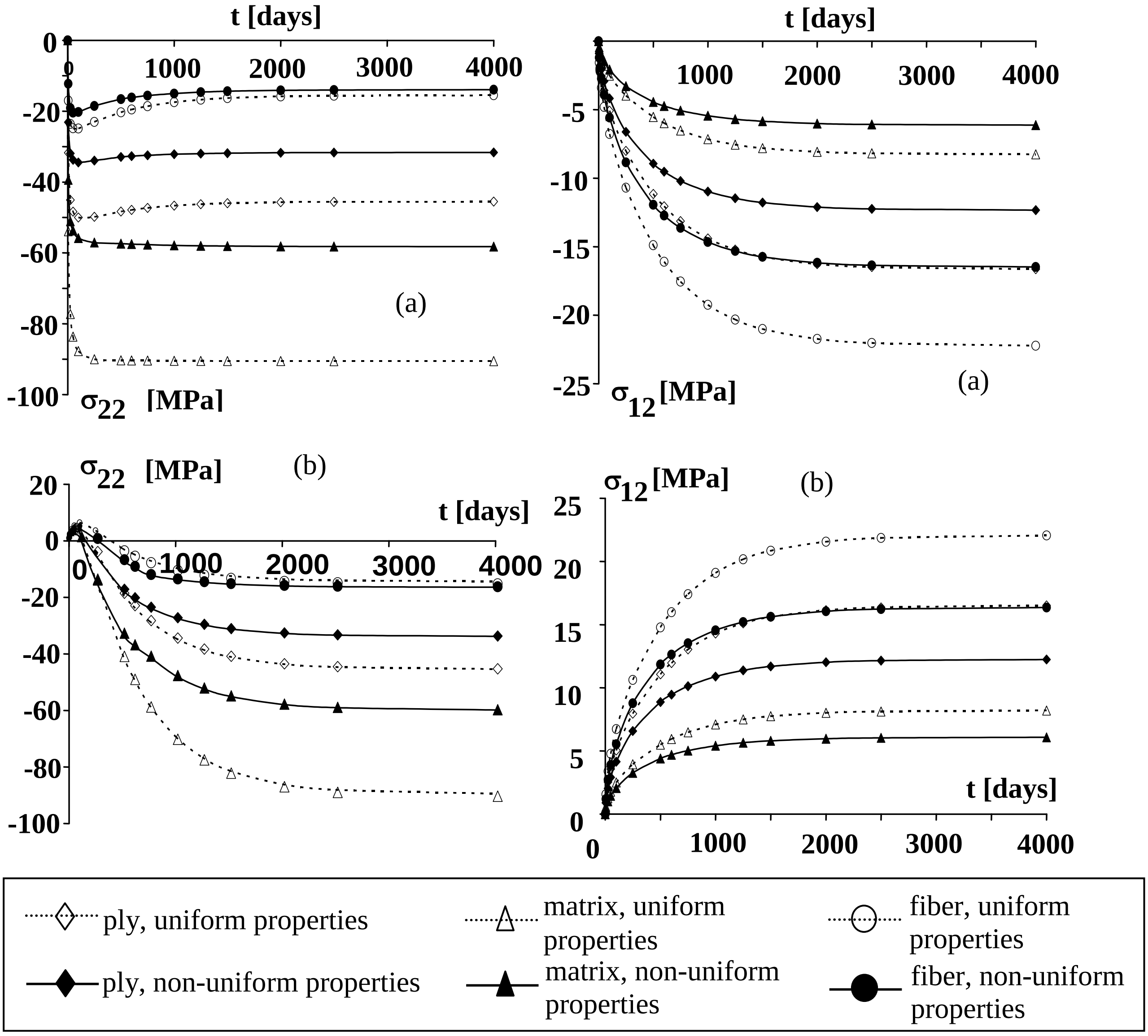

Figure 3: Multi-scale stress states in (a) the external ply / (b) the central ply of a ± 55° composite during the transient part of the moisture diffusion process.

Youssef, G., **Fréour, S.,** Jacquemin, F. (2009). Effects of moisture dependent constituents properties on the hygroscopic stresses experienced by composite structures, *Mechanics of Composite Materials*, **45**(4), 369-380.

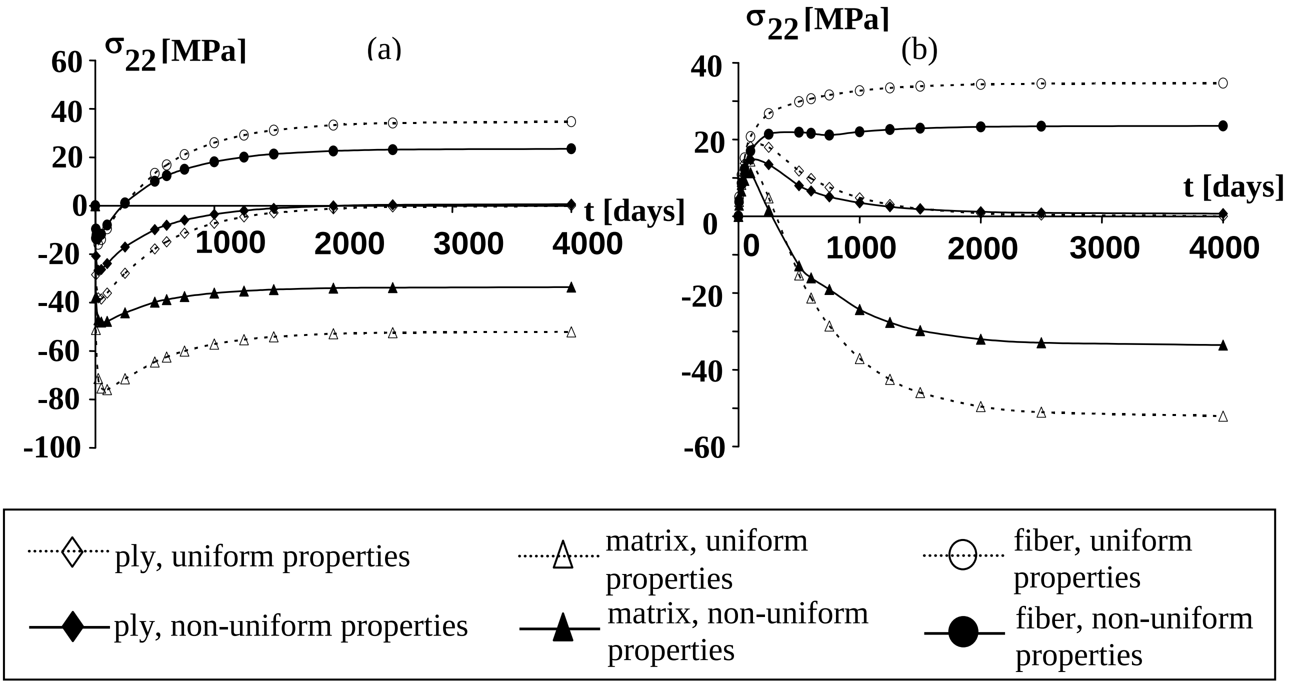

Figure 4: Multi-scale stress states in (a) the external ply / (b) the central ply of a uni-directional composite during the transient part of the moisture diffusion process.