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Research Article

Modeling of Moisture Diffusion in Carbon Braided Composites

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In this study, we develop a methodology based on finite element analysis to predict the weight gain of carbon braided composite materials exposed to moisture. The analysis was based on the analogy between thermal conduction and diffusion processes, which allowed for a commercial code for finite element analysis to be used. A detailed finite element model using a repetitive unit cell (RUC) was developed both for bundle and carbon braided composites. Conditioning tests were performed to estimate the diffusivity of both the resin and composite. When comparing numerical and experimental results, it was observed that the procedure introduces an average error of 20% and a maximum error of 31% if the RUC is assumed to be isotropic. On the other hand, the average error does not exceed 10% and the maximum error is less than 20% when the material is considered as orthotropic. The procedure is independent of the particular fiber architecture and can be extended to other composites.

1. INTRODUCTION

Moisture absorption is a critical factor in the design of polymer composite materials applied to aerospace structure, as it affects the dimensional stability of the pieces in long and short times.

Even small quantities of moisture absorbed from the environment can modify significantly the mechanical and physical properties of composite materials [1–4]. Moisture produces swelling, reduces the glass transition temperature of the matrix, and affects matrix-dominated properties such as interlaminar shear strength, toughness to fracture, impact resistance, and possibly debonding [1]. Other properties related to the life cycle of the structure, such as resistance to fatigue, are affected as well: the fatigue behavior of any composite is influenced by the toughness of the resin and its resistance to microcracking.

The degradation of mechanical properties of composites is strictly correlated with the weight change due to moisture absorption. Previous studies show that the weight change and the amount of moisture at equilibrium depend on the environmental conditions and the fiber architecture. Bao and Yee investigated temperature effects on the moisture absorption process for a BMI resin and its composites [4]. Experimental results verified that an increment of temperature corresponds to an acceleration of the diffusion process and to a decrease of the maximum amount of moisture at equilibrium. The authors determined the diffusivity by measuring the weight variation as a function of time at different temperatures, and found that the activation energy for the reaction depends on the resin, whereas the initial diffusivity depends strongly on the presence of the fibers. Some authors highlight a previously neglected problem, which is the dependence of the diffusivity on the humidity concentration in the material [5]. Experimental results show that the rate of absorption is faster during the initial transition and then it tends to slow down as it approaches equilibrium. This behavior is justified by the authors with the presence of voids and fractures created during the curing process. During the final stage, the increase of the humidity content in the composite induces swelling which causes the closure of such spaces and therefore a decrease in diffusivity.

Zhou and Lucas [6] conditioned a unidirectional graphite/epoxy composite by immersing it in distilled water at various temperatures. They found that the difference between theoretical and experimental results increases with the temperature of conditioning. The authors individuated the limit temperatures, and concluded that if $T/T_g \leq 0.25$, the absorption process follows Fick's law; if $T/T_g \geq 0.5$, the anomalies are present in the mechanisms of diffusion. Similar results were obtained from Wan et al. for a three-axial braided composite [7]. The complex fiber architecture and the presence of voids inside the composite justify the divergence between Fick's law and the experimental data. The authors also investigated the effects of external loads on absorption and diffusion processes. The preloaded material showed an acceleration of the initial diffusion process with respect to unloaded material and a subsequent reduction of the mechanical performances. On the other hand, an external load applied to the material reduces the absorption process and improves the mechanical performance. Initially, the external load produces an increment of microcracks with an enhancement of diffusivity; then the load induces plasticity that blocks the microcracks reducing the rate of absorption.

Conditioning testing has been a useful way to understand the mechanism of moisture diffusion and the effects on composite behavior and it is still the popular technique for designing composites. However, testing can require months of experiments with obvious costs. Prediction models for composite moisture diffusion and long term behavior would be powerful tools for the designer. In the past, some efforts have been made to develop numerical and analytical methods to predict degradation properties and moisture absorption. These studies give an acceptable prediction of the final moisture content and the swelling coefficient for unidirectional fiber composites [3]. However, it is difficult to build effective methods for complex fiber architecture, due to the intrinsic nature of dual-scale phenomenon. Kondo and Taki and Lundgren and Gudmundson focus their attention on the analogy and the importance of the fiber distribution in the composite [8, 9]. Tang et al. investigated the effects of the tow microstructure on the moisture diffusion for woven composites and determined the cross-sectional diffusivity of a single bundle adopting a 3D unidirectional composite model with random fiber distribution [10].

Vaddadi et al. developed a methodology based on inverse analysis techniques in order to estimate the parameters of moisture diffusion processes for unidirectional carbon reinforcements [11, 12]. Both diffusion coefficient and humidity content at equilibrium were determined using few and simple measurements of weight gain. This method used a cyclic prediction process based on the Kalman filter theory, which is particularly effective in determining variables under nonlinear conditions. The authors adopted the repetitive unit cell model for determining composite properties in equilibrium conditions, but this analysis cannot be extended to the transitory period because the material cannot be analyzed uniformly.

Here, we propose a numerical method based on finite element analysis to predict the weight gain as a function of the exposure time to moisture for composites with complex fiber architecture such as a carbon braid. The analogy between Fourier's and Fick's laws has been adopted to use an available commercial code, Femap 8-Maya TMG, which implements the finite element analysis. To account for the moisture absorption in a composite as a dual-scale phenomenon, bundle- and carbon-braided RUCs were used for the finite element analysis. Conditioning tests were performed to validate the numerical model. Future work will determine stress and strain produced in the composite by the moisture concentration field assessed using this model.

2. THEORY

For most composites, such as carbon-glass/epoxy-polyester, it is assumed that the fibers are impermeable and that moisture diffuses only in the matrix. This hypothesis is not valid for composites with aramid fibers, which can absorb significant amount of moisture.

Considering that the matrix is homogeneous and isotropic, the moisture mass diffusion through the composite material can be described using Fick's law (equation (1)). The adoption of Fick's law implies that the composite does not have any defects, as voids and microcracks.

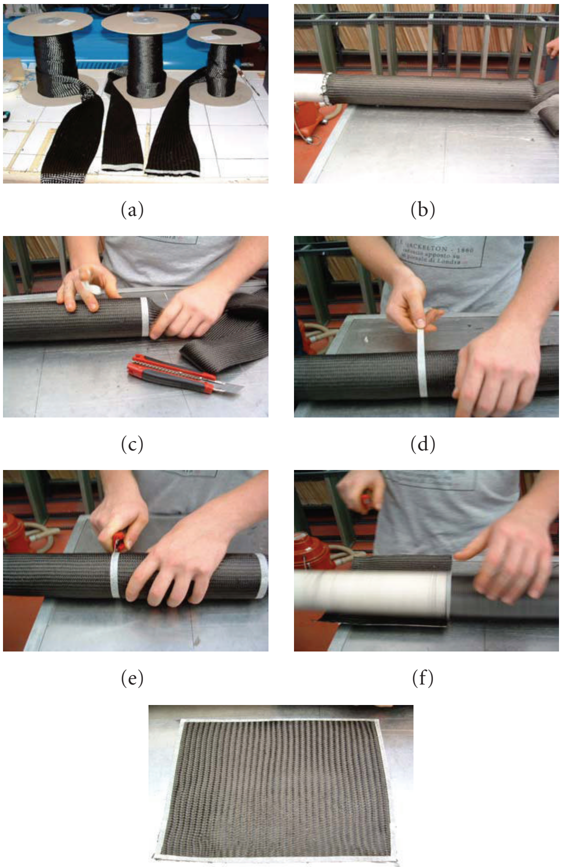
Fick's law (equation (1)) [2, 3, 13] is the equivalent of Fourier's law (equation (2)) [13] for thermal diffusion, so it is possible to use this analogy to study the diffusion of moisture through a material

$$\frac{\partial C}{\partial t} = \overline{D}\cdot\left(\frac{\partial^2 C}{\partial x^2}+\frac{\partial^2 C}{\partial y^2}+\frac{\partial^2 C}{\partial z^2}\right), \quad (1)$$

$$\frac{\partial T}{\partial t} = \frac{\overline{k}}{\rho\cdot c}\cdot\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right). \quad (2)$$

The concentration C in (1) is equivalent to the temperature T in (2), whereas the diffusivity D is equivalent to the thermal diffusivity $\alpha = k/\rho\cdot c$. However, the correspondence between the boundary conditions is not so straightforward. The major problem is the discontinuity at the interface between fiber and matrix. In fact, while the contact temperature between two materials can be assumed to be the same, this is not the case for moisture diffusion. Kondo and Taki and Lundgren and Gudmundson [8, 9] proposed to introduce the relative concentration r, which represents the ratio between moisture amount at the instant t and the moisture amount at equilibrium. This parameter can be considered approximately continuous through the interface and can be used to set the boundary condition. The other boundary condition can be obtained from the flux, which is constant through the interface for both thermal and diffusion processes. The moisture diffusion inside the material is slower than the heat flow by many orders of magnitude.

The analogy above is used to describe two different levels of moisture flow: inside the tow and through the tow, that is, in the microscale and in the mesoscale. Indeed, the textile structure is made of fiber tows that are braided together to define the macrostructure of the composite. The fiber tows are formed by bundles of well-aligned fibers, yet significant empty volume is present in a tow. The arrangement within the bundles represents the microstructure of the material. We assumed that the empty space is completely replaced by the matrix, and that the adhesion between fiber and matrix is perfect. Therefore, moisture diffuses through the macrostructure and through the space among the fiber tows.



(a) (b) (c) (d) (e) (f) (g)

Figure 1: Procedure for cutting a preform to a given braided angle using a PVC mandrel.

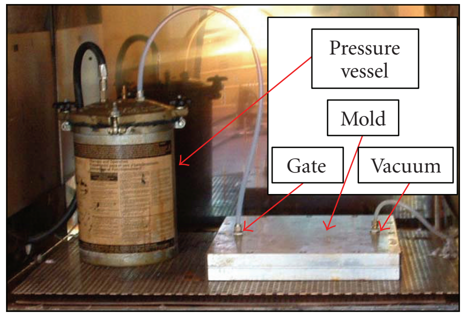


Figure 2: Experimental apparatus for RTM process.

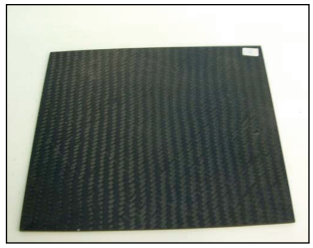


Figure 3: 12 K carbon-braided/polyester laminate.

3. MATERIALS AND METHODS

3.1. Materials

T300 biaxial carbon-braided 12 K was produced in a tabular shape with braided angle of $\pm 45^\circ$. This material is identified with the trade name 144/11 by Eurocarbon and it is shown in Figure 1. The material is characterized by an average density of 1.76 g/cm^3, a weight per unit area of 6.6 g/cm^2 and a fiber diameter of about 7 μm. The resin was polyester from Aropol with an average density of 1.2 g/cm^3, T_g of 69°C, and cure cycle of 24 hours at room temperature. The resin was degassed for 12 hours to eliminate entrapped air bubbles before use. The laminates have a uniform thickness of 3 mm, with fiber volume fraction v_F of 0.5. The fiber volume fraction was set to have an even number of layers; this choice simplifies the finite element model of the RUC-braided composite.

3.2. Methods

To manufacture the laminate, the flat layers of the stack sequence were obtained from the tubular braid. Particular attention was used to cut the braided sleeves while maintaining the braided angle. Changes in the braided angle can generate stretching or compression along the fiber, resulting in fiber deformation. To avoid such defects, the tubular braid was put on a PVC cylindrical mandrel, of a certain diameter, and fixed with tape along the edges. The preparation sequence is reported in Figure 1. The layers were then positioned inside the metallic mould for RTM process.

Composite laminates were manufactured using resin transfer molding (RTM) process to obtain finished surfaces and to minimize the formation of internal microvoids. The apparatus for the fabrication process is shown in Figure 2: a pressure vessel pumps the resin inside the mold via the injection gates; the resin forces the air out from the vent, while saturating the preform. After the mould is filled, gate and vent were clamped to permit the cure of the laminate. When the polymerization of the resin is complete, the mould was open to remove the final piece.

After curing, the absence of dry spots, porosity, resin pocket, and other defects, classified in the standard ASTMD 2562, was verified by the visual inspection. The void content was calculated according to the standard ASTM D 2734. The highest percentage of void content was 0.1%. The fiber volume fraction was confirmed to be 0.5 ± 0.01 using the method resin burn-off according to the ASTM D 2584. Figure 3 shows a carbon-braided/polyester laminate used to obtain the specimens for the conditioning test. Samples were cut from the composite laminate in agreement with the ASTM D 6856-03 and ASTM D 5229/D 5229M-92 standards. According to these standards, the specimen dimensions must be at least twice the thickness of the unit cell in the direction of the moisture flow, and the test must be performed with a relative humidity RH of 85% and a conditioning temperature lower than T_g of -25°C. The used polyester has a T_g of 69°C, and conditioning tests were performed at the

Figure 4: Running conditioning test with a particular of internal chamber.

maximum allowable temperature of 35°C to accelerate the slow dynamic of the moisture diffusion process. As visible in Figure 4, the lateral surfaces of the samples were insulated in order to avoid the direct exposure to the moisture. This precaution was adopted in order to simplify the boundary condition in the FEM analysis.

A CHALLENGE-CH 250 climatic chamber was used, and the weight changes of the samples were documented with a precision balance (±0.1 mg). Each sample was weighted every 24 hours. Figure 4 shows the climatic chamber used to perform the conditioning tests; also shown is the internal chamber during test, with resin and composite specimens. Neat resin specimens were obtained injecting the uncured resin into the RTM mold, which allowed to have a controlled thickness. The conditioning test of neat resin was used to calculate the resin diffusivity D_M and the relative weight gain at equilibrium w_{eM}. D_M and w_{eM} were calculated from (3) [3] implementing an iterative procedure in MATLAB based on the minimization of the error between calculated weight gain and the relative weight gain $w_S(t)$ after exposure to moisture

$$w_C(t) = (w_{eM} - w_i) \cdot \left\{ 1 - \exp\left[-7.3 \cdot (D_M \cdot t/h^2)^{0.75} \right] \right\} + w_i, \tag{3}$$

$$C = \frac{W_e - W_0}{W_0} \cdot \rho \cdot 100. \tag{4}$$

Once the relative weight gain at equilibrium is determined, the moisture concentration C_M can be calculated using (4), where W_0 is the initial weight.

4. EXPERIMENTAL RESULTS

The experimental results of the conditioning test for matrix and braided composite are shown in Figure 5. The graphs represent the trend of the percentage weight gain as a function of the square root of time. The regression analysis shows that the weight gain is well fitted with cubic interpolation, as confirmed by the coefficient of determination R^2. The constants a_1, a_2, and a_3 used in the regression analysis are, respectively, 0.0236, 0.0077, and −0.0009.

Moreover, the trend relative to the transient period is closely linear (Figure 5). The slope of the linear curve is related to the moisture diffusion, which increases with the slope. Since the moisture absorbed approaches the moisture

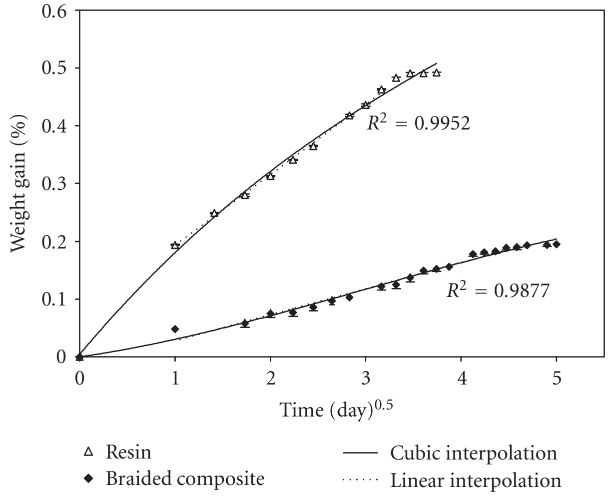


Figure 5: Weight gain as a function of the time of exposure to moisture for resin and composite.

equilibrium content, the local slope decreases until approximately zero at the saturation point, where no significant weight variation is recorded. The saturation point is reached after 600 hours and the percentage weight gain at this time is 0.195%. Moisture diffuses more easily in the specimens of neat resin than in composite ones; therefore, the amount of moisture at equilibrium is reached earlier in the resin with respect to the composite. The different response is due to the presence of fiber reinforcements. As described above, the matrix parameters used in the numerical model were calculated from experimental data: $D_M = 5.182\ 10^{-9}\ \mathrm{cm^2 s^{-1}}$, $w_{eM} = 0.782\%$, $C_{eM} = 9.386\ 10^{-3}\ \mathrm{g/cm^3}$.

5. FINITE ELEMENT ANALYSIS

The finite element numerical analysis was performed using the commercial FEMAP TMG software, adopting the analogy between the heat conduction and the moisture diffusion processes. The software solves the thermal conduction problem using a FEM/control volume approach, determining the temperature at the calculation points. The calculation points are the gravity center, where boundary conditions are applied, and the boundaries of an element. The position of the boundary elements depends on the type of element. For 3D elements, the boundary elements are positioned in the middle of volume surfaces, whereas for 2D elements, the boundaries are in the middle of the surfaces edge. Once the temperature matrix is solved at these points, temperatures are interpolated to the mesh nodes. The temperature field inside the elements is assumed to be linear.

The numerical model shows some complexities due to the different length scales of the diffusion process inside the composite. To take into account this aspect, two different models have been developed. We assumed that fiber and matrix are perfectly bonded and that the carbon fibers are impermeable to the moisture, so their diffusivity is zero. With this hypothesis, moisture flows only through the resin. Assuming the bundle as a unidirectional composite, the diffusivity parallel to the bundle direction is equivalent to the matrix diffusivity, while the diffusivity normal to the bundle direction is coincident with the diffusivity into the bundle, that is, the matrix diffusivity in microscale. This parameter was determined performing the thermal analysis of the RUC bundle model and then setting the material properties of the carbon-braided RUC. Simulations were run after defining the RUC models, the material properties, and the numerical convergence.

In order to reduce the computational cost due to the large number of elements of carbon-braided RUC, we considered the tow as an isotropic material with diffusivity equal to the diffusivity normal to the tow directions D_{Fn}. This assumption was supported considering that the moisture flow is directed along the thickness of the material, the z-axis. In fact, the angle between the z-axis and the fibers direction varies from 90° to 81°.

The postprocessing was carried out using two programs: the first one imports the mass of the elements in two matrices, for tow and resin, respectively, and calculates the total mass. The second program receives in input the vector of the temperature of the elements and the matrices determined from the first program. The mass variation is calculated by multiplying the temperature of every element for W_e and the corresponding mass. Then, the relative mass gain is determined by dividing such variation for the starting mass. These two programs have been implemented in MATLAB.

5.1. Model of the RUC bundle

The particular geometry of the bundle permits to consider only the cross section, reducing the analysis to a two-dimensional problem. The first step to build the model is to determine the area that represents the RUC. In order to do that, the fibers distribution, the number of fiber filament, and the correspondent fiber volume fraction have to be defined. Previous works on unidirectional fibers have shown that a random distribution gives closer agreement with the experimental data than a regular one. This can be explained considering that in a random distribution there are zones with high fiber density that creates a barrier for moisture diffusion. On the other hand, a regular fiber distribution is characterized by a uniform distance among the fibers, which generates paths for the moisture flux.

Previous works determined that the minimum number of fiber filaments necessary to describe the behavior of the bundle is eight [9], and that the fiber volume fraction for bundle of 12 K carbon braided at $\pm 45^\circ$ is in the range of 0.7 to 0.78 [10, 11]. Assuming that the values for v_{fF} is 0.747 and that the fiber diameter is 7 μm, the section areas of the fiber filaments and the total area of the RUC A_{RUC} can be easily calculated. The moisture absorption process relative to the bundle can be simulated using a quadratic two-dimensional model having edge l = 20.3 μm, with eight randomly distributed fibers. The fibers are modeled as voids because the diffusivity and the moisture content at equilibrium are approximately zero, so these regions can be considered as invisible to the diffusion process. The model was meshed with plate elements as shown in Figure 6; the total number of elements was 4839 and the total number of nodes was 5381. The material properties of the matrix used for the analogy are reported in Table 1.

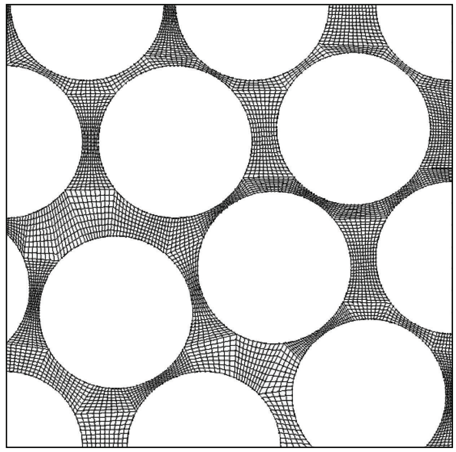


Figure 6: Two-dimensional model of the bundle with eight fibers randomly distributed.

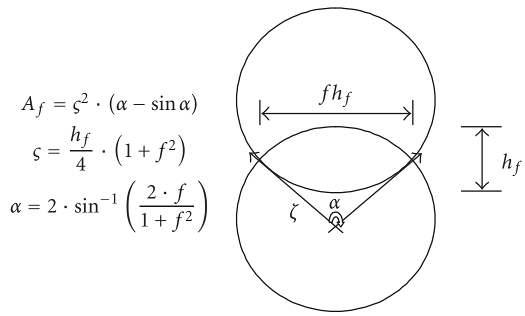


Figure 7: Construction and geometrical parameters of the tow section.

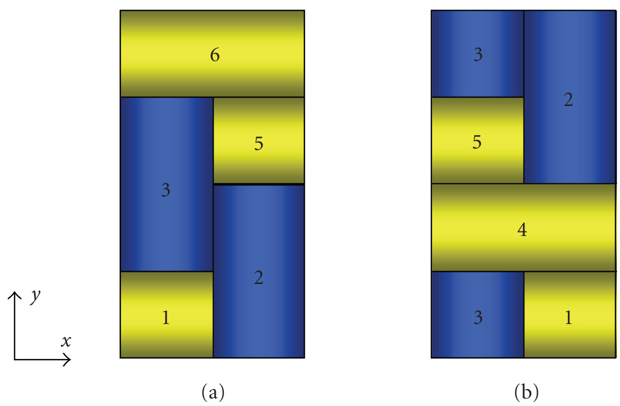


Figure 8: Top and bottom view of the RUC with tows in the y-direction (blue) and in the x-direction (yellow). Numbers indicate the tows.

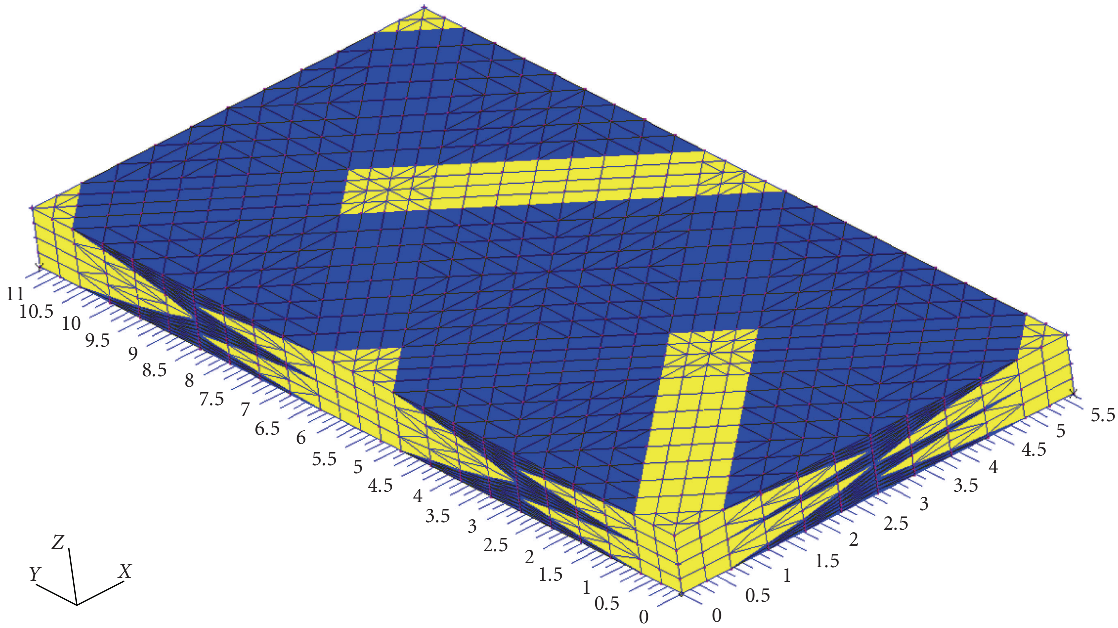


Figure 9: View of the carbon-braided RUC with matrix elements (blue) and fiber tow (yellow).

Table 1: Material properties associated with the bundle RUC used for the analogy.

Thermal conductivity	$k_M = D_M \cdot C_{eR} = 4.864 \cdot 10^{-15}$
Specific heat	$c_M = \dfrac{C_{eM}}{\rho_M} = 7.822 \cdot 10^{-3}$
Matrix density	$\rho_M = 1.2 \cdot 10^{-12}$

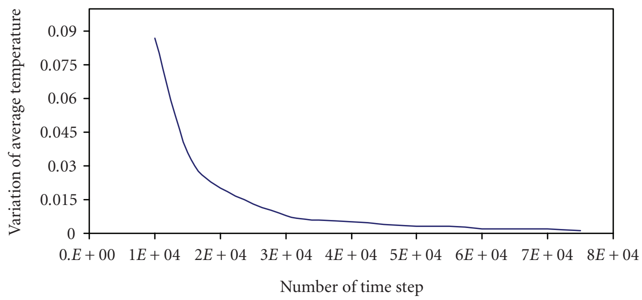


Figure 10: Temporal convergence analysis for the bundle RUC.

5.2. *Model of the RUC-braided composite*

The RUC-braided model is three-dimensional and presents some geometric complexities due to the braided architecture. In order to create a true representation of the material, bundles are considered having lenticular sections. Each section is built by the intersection of two circumferences. Figure 7 shows the geometrical construction and the relative parameters used in the model; when the thickness and the length of the tows are known, the tow geometry can be completely defined.

The thickness can be determined by observing that the real composite is a 3 mm thick laminate with 4 layers. Each layer has an average thickness of 0.75 mm and two tows overlap for every layer. Therefore, the thickness of the lenticular section h_f is 0.375 mm.

The determination of the bundle length is more complex and is based on the repetitive unit cell shown in Figure 8. Here, we show the top and bottom surfaces of a braided RUC schematization, which for simplicity is rotated of 45° with respect to the material axes; the tows in the y-direction are in blue, whereas the tows in the x-direction are in yellow. The tows were numbered to define their respective position on the top and bottom surface. Indicating with l the tow width, the RUC volume V_{RUC}, and the tows total volume $V_{f\mathrm{TOT}}$ can be expressed as a function of this; l is then calculated by setting the fiber volume fraction of the composite $v_F = 0.5$, as illustrated in the equation

$$v_F = \frac{V_{f\mathrm{TOT}}}{V_{\mathrm{CRU}}} = \frac{V_{F\mathrm{TOT}} \cdot v_{fF}}{V_{\mathrm{CRU}}} = 0.5. \quad (5)$$

Equation(5) was numerically solved using an iterative procedure implemented in MATLAB, after expressing V_{RUC} and $V_{f\mathrm{TOT}}$ as function of the geometric factor f (Figure 7) and considering that the tow total volume in the carbon-braided RUC can be obtained by multiplying the total length of the tows $d_{f\mathrm{TOT}}$ (equation (6)) with the cross-section area:

$$d_{f\mathrm{TOT}} = \sum_{i=l}^{6} d_i = 8 \cdot \left(l + \sqrt{l^2 + 0.375^2} \right). \quad (6)$$

The results are $h_f = 10.759$ mm and $l = 4$ mm, which are in agreement with the experimental observations.

The dimensions of a basic RUC are 5.657 mm × 11.318 mm × 0.375 mm. The RUC is not unique, but to minimize computational costs, we considered the RUC having

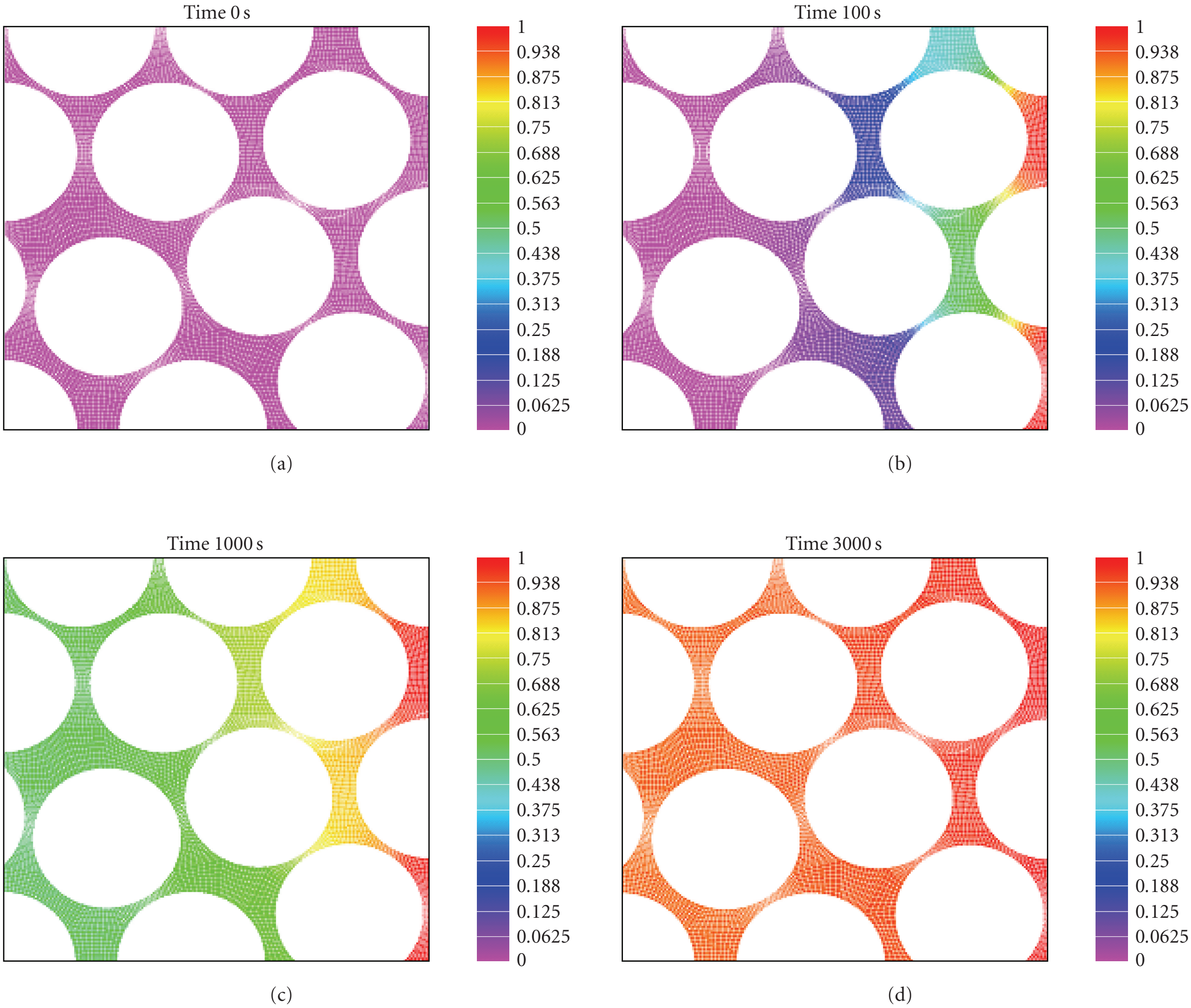


Figure 11: Simulation of the diffusion process of a bundle RUC. The image shows the simulation at four different time steps: 0 second, 100 seconds, 1000 seconds, and 3000 seconds. It is assumed that the transitory regime ends at 3000 seconds. The different colors represent the different moisture concentration normalized with respect to the moisture concentration at equilibrium.

Table 2: Material properties associated with the diffusion process for carbon-braided RUC.

	Diffusivity [mm^2 /h]	Weight gain % to the equilibrium	Concentration to the equilibrium [g/mm^3]	Density [g/mm^3]
Matrix	$1.866 \cdot 10^{-3}$	0.782	$9.386 \cdot 10^{-6}$	$1.200 \cdot 10^{-3}$
Fiber bundle	$D_{fn} = 1.307 \cdot 10^{-4}$ $D_{fp} = 1.866 \cdot 10^{-3}$	0.147	$2.375 \cdot 10^{-6}$	$1.618 \cdot 10^{-3}$

Table 3: Material properties of carbon-braided RUC from the heat-diffusion analogy.

	Thermal conductivity	Specific heat	Density [g/mm^3]
Matrix	$K = D \cdot C_e = 1.751 \cdot 10^{-8}$	$c = C_e/\rho = 7.822 \cdot 10^{-3}$	$1.200 \cdot 10^{-3}$
Fiber bundle	$k_{Fn} = 3.104 \cdot 10^{-10}$ $k_{Fp} = 1.751 \cdot 10^{-8}$	$1.468 \cdot 10^{-3}$	$1.618 \cdot 10^{-3}$

the smallest dimensions. In any case, a single RUC is sufficient to investigate the moisture diffusion process in stationary conditions, yet not during the transitory regime. In fact, moisture already diffuses in the adjacent RUC before reaching the equilibrium: in this case, the absorption occurs through the thickness. Considering that the composite is manufactured with four layers, a model based on four overlapping RUCs should be adopted. The symmetry of the laminate and the boundary conditions of the medium plane reduce the number of RUCs to two overlapping unitary cells. The model was meshed using 22480 elements and 6233 nodes, using the three-dimensional solid elements CHEXA and CTETRA. Figure 9 shows the carbon-braided RUC model used for the analysis: the matrix zones are in blue, while the yellow indicates the fiber zones.

After defining the model, it is necessary to determine the thermal properties of the materials using the analogy between absorption and heat conduction; these properties are reported in Tables 2 and 3.

6. NUMERICAL RESULTS

6.1. Fem analysis of moisture diffusion in bundle RUC

The simulation of the diffusion process of the bundle model allows calculating the diffusivity normal to the bundle direction. Figure 10 shows the convergence analysis performed to estimate the accuracy of the numerical results. The numerical convergence was considered as reached when the variation of the average temperature as a function of the time step was less or equal to 10^{-3}. This variation corresponds to 75000 time steps. Figure 11 shows the simulation at four different time steps from the initial time to the start of stationary process. The transitory stage of the diffusion process is considered as finished at 3000 seconds, when the temperature, which is equivalent to the relative concentration for the heat-mass analogy, reached a constant value. Subsequently, the material can be assumed as saturated and the equilibrium parameters can be determined. The different colors represent the different values of the thermal field, which represents the distribution of the moisture concentration normalized with respect to the moisture concentration at equilibrium.

Results of postprocess performed to estimate the weight gain as a function of the square root of the time are shown in Figure 12.

The tow diffusivity normal to the tow direction, which is equal to the bundle diffusivity normal to the bundle direction, was calculated by MATLAB

$$D_{\mathrm{Fn}} = 3.63\cdot 10^{-2}\,\frac{\mu\mathrm{m}^2}{\mathrm{s}}. \tag{7}$$

6.2. Fem analysis of moisture diffusion in carbon-braided RUC

As in the previous analysis, a convergence study was also made. Convergence was reached when the variation of the average temperature was smaller or equal to 10^{-3}, which corresponds to time step 2000 (Figure 13). The numerical results show that assuming the tow as isotropic material gives

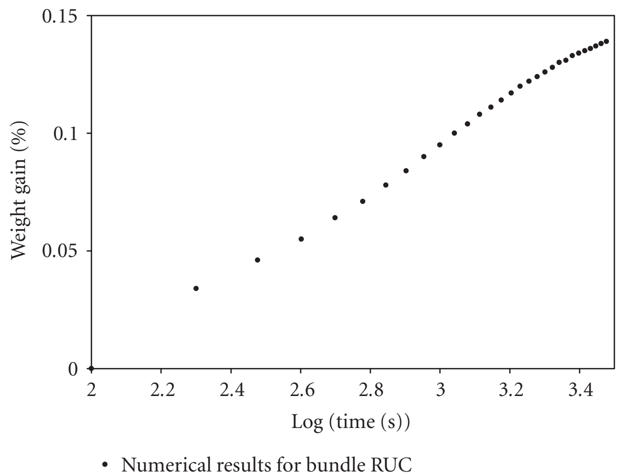


Figure 12: Weight gain as a function of the time for bundle RUC by postprocessing of numerical results from the FEM analysis.

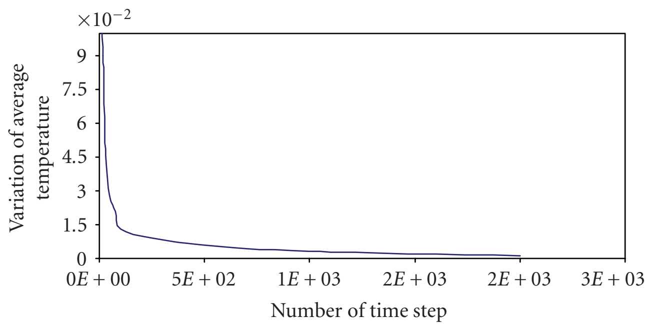


Figure 13: Temporal convergence analysis for the carbon-braided RUC as orthotropic material.

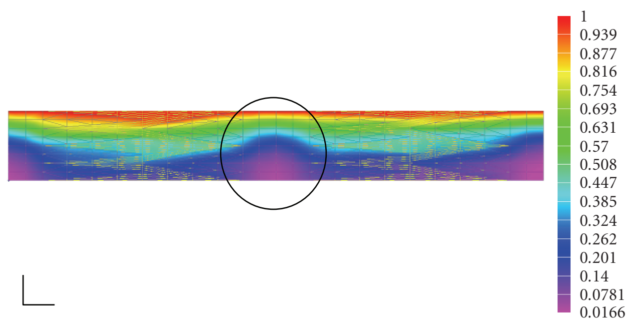


Figure 14: Section of carbon-braided RUC. The circle highlights the gradient of concentration through the thickness of the braided RUC considering the tows as isotropic material.

a large gradient of concentration in x-z plane (Figure 14). A large gradient with a large value of $D_{Fx\text{-}y}$ indicates that the approximation of isotropic bundles is not valid. The diffusion coefficient $D_{Fx\text{-}y}$ is a linear combination between D_{Fn} and D_{Fp}.

A finite element analysis was performed considering orthotropic bundles with parameters of absorption as reported

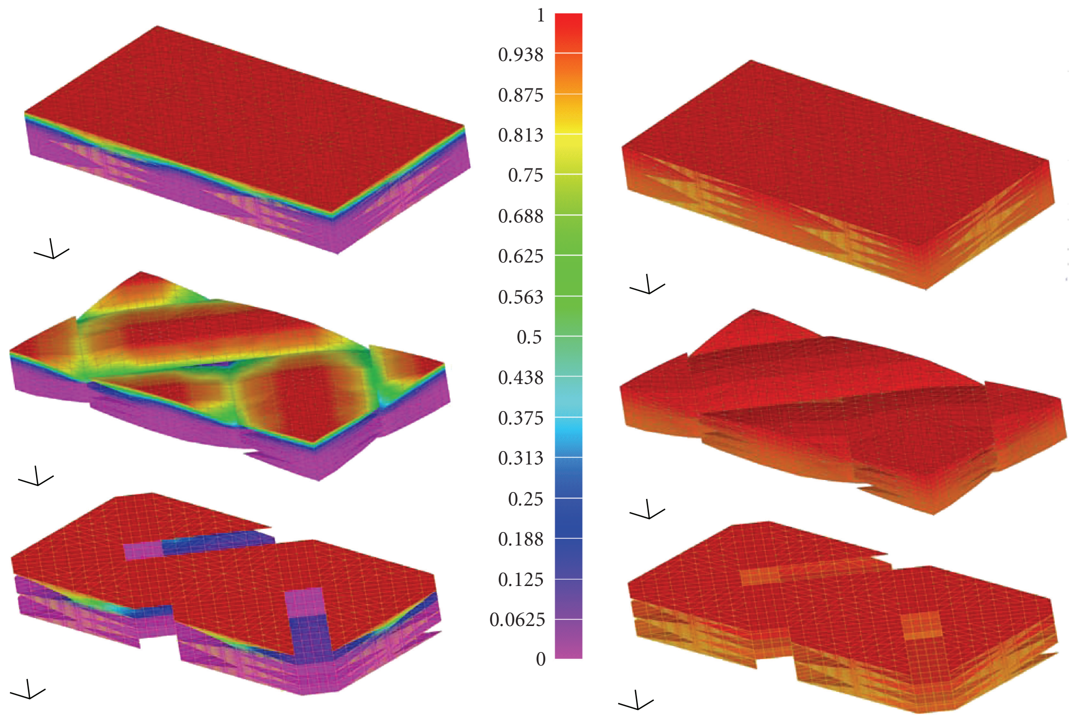


FIGURE 15: Simulation of the diffusion process in the RUC of a carbon-braided composite. The image shows the simulation at two different time steps: at 1 day (left) and at 90 days (right). It is assumed that the transitory regime ends after 90 days.

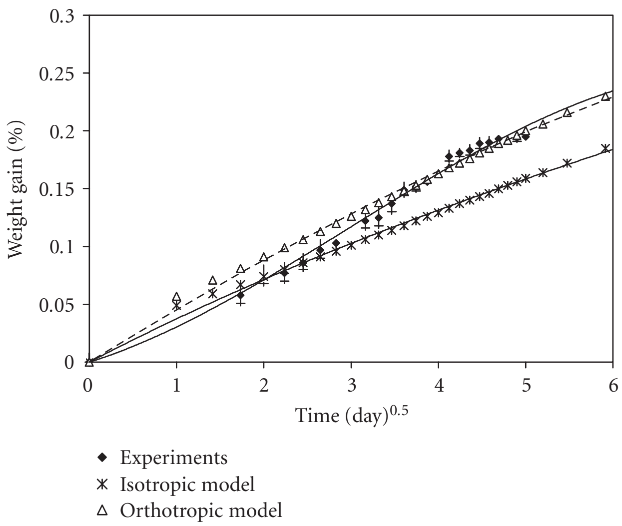


FIGURE 16: Numerical and experimental results of relative weight gain as a function of time.

in Tables 2 and 3. This analysis shows that the moisture reaches equilibrium in 90 days (Figure 15).

7. DISCUSSION

The finite element numerical analysis was performed to simulate the moisture diffusion process in a carbon-braided structure. Figure 16 shows experimental and numerical results for the relative weight gain in percentage as a function of the exposure time. There is good agreement between the experimental trend and the numerical evaluation. Moreover, we observed that the initial content of moisture affects the result considerably. Considering w_i equal to zero (equation (3)), the value of D_M is 54% larger than the experimental result.

The first step of the analysis was to determine the diffusion coefficients and the moisture content of the fiber bundle. The presence and the arrangement of the fibers were taken into account in the moisture absorption study. After the determination of the diffusion parameters, these were introduced in the repetitive unit cell of the carbon-braided composite. The analysis of the moisture diffusion in the RUC of carbon-braided composite was approached in two different ways. In the first one, the composite material was considered isotropic with diffusivity D_{Fn}. In this case, the moisture flow is orthogonal to the direction of the fibers. However, the analysis highlighted that the concentration gradient in the x-y plane, due to the nonhomogeneity of the material, could not be neglected. Therefore, the composite was modeled as an orthotropic material. The second analysis confirmed such hypothesis. Figure 16 shows that there is a large difference between the trends obtained assuming the tow as isotropic or orthotropic and the experimental results. The isotropic hypothesis introduces an average error of 20% and a maximum error of 31%. On the other hand, the average error does not exceed 10% and the maximum error is less than 20% when considering the material as orthotropic.

The percentage weight gain is higher in the orthotropic model than in the isotropic model, due to the concentration gradients in the x-y plane. For concentration gradient, the diffusivity is a linear combination of the diffusivities in the x-y plane. Therefore, in isotropic materials, the diffusivity is constant in all directions, whereas in orthotropic materials, the diffusivity is one order magnitude higher than the other direction. The approximation introduced with the assumption of isotropic material reduces the accuracy considerably. However, the orthotropic model improves the accuracy of the results, but it increases the computational time cost of approximately four times with respect to the isotropic case.

8. CONCLUSIONS

The methodology developed in this study allows simulating the process of moisture diffusion in a composite braided material with sufficient approximation starting from a limited set of experimental data. We developed an analysis that reduces drastically the number of experimental tests necessary to understand the behavior of a composite material in moisture environment. At the same time, the analysis decreases considerably the design costs and times. A commercial code for FEM analysis was used to estimate in few hours and with good approximation the weight gain as a function of time, which normally requires several months of experiments.

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