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MODELING AND EXPERIMENTAL ANALYSIS OF MOISTURE DIFFUSION BEHAVIOR IN BIO-BASED BALSAMIC WOOD CORE COMPOSITE SANDWICH

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Abstract

This work investigates the moisture diffusion behavior of bio-based balsam wood and balsam core sandwich structures. All the special dog-bone balsam wood and sandwich specimens were immersed in water at room temperature to saturation, and the moisture absorption kinetics were identified analytically and numerically. It was found that the final saturated MC in the GFRP-balsam sandwich was only 18 % of that in the pure balsam wood. This suggests that the assembly of environmentally friendly balsam wood and conventional Glass-Fiber-Reinforced-Polymer (GFRP) skins may be a good alternative to the pure hydrophilic wood materials or high-carbon-footprint laminates. Interestingly, Fickian behavior was observed in the moisture diffusion process of pure balsam wood, while Non-Fickian behavior was discovered in the more complex sandwich. Accordingly, two different moisture diffusion models, the Fickian model and the Dual Fickian model, were considered to calculate the moisture diffusion coefficients and saturated moisture absorption capacity of the balsam wood and the sandwich, respectively. Moreover, the numerical model has demonstrated that the mesh size of the balsam wood core significantly impacts the accuracy of the prediction.

1. Introduction

In light of the mounting concerns about climate change on our planet, there has been a growing interest in bio-based composite materials, such as wood, flax and eco-foam core sandwich structures, in recent years. A common sandwich structure is composed of a light core and two thinner laminated skins [1,2], which are designed to ensure higher specific strength and stiffness. If the core is composed of bio-based natural plant fibers, the carbon footprint of a sandwich structure can be reduced throughout its entire life cycle. However, natural plant fibers often exhibit a high hydrophilic behavior [3], which could affect their mechanical performances. The moisture diffusion mechanism is highly dependent on the physical and chemical properties of the material, dimensions of the structure, and the ambient temperature, among other factors. For instance, the moisture diffusion coefficients and the saturated Moisture Content (MC) of balsam wood, which is a preferred core material, may vary with its density and thickness. When balsam serves as a core, owing to the protection from the stiffer skin, the moisture absorption behavior in the sandwich can significantly differ from that in pure balsam.

The objective of this study is to investigate and compare the moisture diffusion behavior of the bio-based balsa wood material and its sandwich structure with Glass-Fiber-Reinforced-Polymer (GFRP) skins [1,2]. To this end, water immersion tests were conducted on all dog-bone balsa wood and GFRP-balsa sandwich specimens. Analytical and numerical analysis were employed to predict the moisture diffusion coefficients and the saturated moisture absorption capacity of the balsa wood core and the sandwich, respectively, using the Fickian model [4] and Dual Fickian model [5].

2. Materials and methodology

2.1. Materials and dog-bone specimens

In order to prepare for the analysis of the behavior of the specimens under 4-point bending [1], specimens of pure balsa wood and GFRP-balsa sandwich material with a special triple dog-bone shape were fabricated, as seen in Figure 1. (a). The dimensions of the specimen are as follows: length 280 mm, maximum width 70 mm, minimum width 40 mm. The eco-friendly balsa wood core was supplied by BALTEK SB.100, with a density of 148 kg/m³. All GFRP skins were manufactured from 3-layer woven balanced fabric/epoxy laminates (Ref: Sicomin E glass fiber twill 3190 with 190 g/m², with 50% fiber volume fraction). The mean thickness of the balsa wood is 9 mm, while that of each GFRP skin is 0.5 mm.

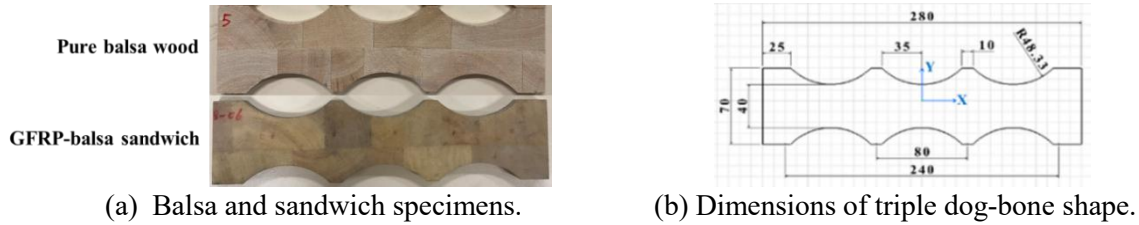


Figure 1. Triple dog-bone balsa wood and sandwich specimens.

2.2. Moisture absorption tests

As explained in our previous study [1], the hygroscopic sorption properties of the bio-based balsa wood and GFRP-balsa sandwich specimens were evaluated in accordance with ISO 12571. A total of at least five specimens of balsa wood and five GFRP-balsa sandwiches were initially dried in an oven at 40 °C and then immersed in distilled water at room temperature until equilibrium was reached. Saturation point was reached when the mass change between three consecutive measurements varied by less than 0.1 % of the total mass. The mass change was quantified at 24 h (86,400 s) intervals. Finally, the Moisture Content (MC) of each specimen, which is the ratio of the mass of the absorbed moisture to the initial dried mass, can be defined by Eq. (1):

$$MC(\%) = C(t) = \frac{M_w - M_d}{M_d} \times 100\%. \quad (1)$$

Where M_d is the initial dried mass, M_w is the wet mass that varies as a function of immersion time t .

2.3. Fickian and Dual Fickian model in composites

Very often moisture absorption in composite structures follows a typical Fickian diffusion trend [4, 6], as shown in Eq. (2):

$$C(t) = \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-D_1 \left(\frac{2n+1}{e}\right)^2 \pi^2 t\right) \right] \times C_s \quad (2)$$

Where, $C(t)$ is the MC (%) at time t ; D_1 and C_s represent the moisture diffusion coefficient and saturated MC. e corresponds to the dimension in the diffusion direction, generally representing the

thickness, length, and width in three directions for a 3D model. In particular, for specimens whose thickness is much smaller than the other dimensions, diffusion in the thickness direction is predominant. Herein, in this work, moisture diffusion along the thickness is preferentially considered.

However, when significant mass loss due to chemical decomposition occurs during the moisture diffusion process, Fickian theory is not satisfactory to describe the actual moisture diffusion behavior. In such cases, the parallel Dual Fickian model [5] is sometimes used to elucidate the two-stage moisture diffusion process (see Figure 2), and Eq. (3) provides a detailed explanation of the curve:

$$\begin{aligned}
 C(t) &= C_I(t) + C_{II}(t) \\
 &= \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-D_I \left(\frac{2n+1}{e}\right)^2 \pi^2 t\right) \right] \times C_{SI} + \\
 &\quad \left[1 - \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-D_{II} \left(\frac{2n+1}{e}\right)^2 \pi^2 t\right) \right] \times C_{SII}
 \end{aligned} \tag{3}$$

Where, $C(t)$ is the MC (%) at time t ; $C_I(t)$ is the MC (%) at time t in stage I where D_I and C_{SI} represent the moisture diffusion coefficient and saturated MC, respectively in this stage; $C_{II}(t)$ is the MC (%) at time t in stage II where D_{II} and C_{SII} represent the moisture diffusion coefficient and saturated MC, respectively in this stage; e is the same as that in Eq. (2).

Consequently, the five parameters, including D_I , C_{SI} , D_{II} , C_{SII} and e , mainly determine the moisture diffusion rate and saturation capacity in the Dual Fickian model.

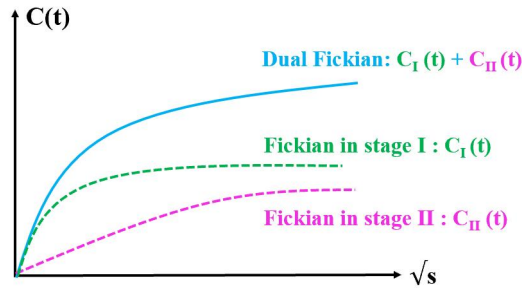
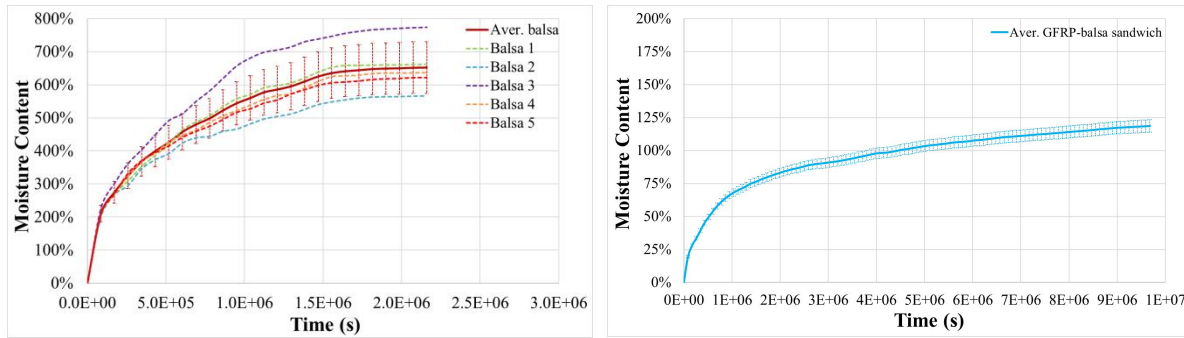


Figure 2. Dual Fickian model in composites: $C(t) = C_I(t) + C_{II}(t)$ [5].

3. Results and discussions

3.1. Experimental results on pure balsa and sandwich specimens

Figure 3 presents the Moisture Content (MC) absorption curves of the pure balsa wood and GFRP-balsa sandwich specimens. For sandwich specimens, the repeatability is satisfactory, and thus, only the average value is shown here [1]. However, the pure balsa wood specimens exhibit greater dispersion due to the typical anisotropic material property. The pure balsa wood specimens required 22 days to reach a final stable value: 652 % MC (± 76.71 %), while it took almost 115 days for the GFRP-balsa sandwich specimens to reach a final stable value: 120 % MC (± 3.68 %). It is interesting to note that the moisture diffuses much faster in pure balsa wood than in GFRP-balsa sandwich. This indicates that the outer GFRP skins have become effective protective layers, preventing moisture from diffusing into the balsa core, especially in the direction of the wood fibers along the thickness. This demonstrates that the assembly of eco-friendly lightweight balsa wood and conventional stiffer GFRP laminates can be a viable alternative to pure hygroscopic wood materials and high-carbon-emission laminates.



(a) Pure balsa.

(b) GFRP-balsa sandwich [1].

Figure 3. Moisture absorption curves of pure balsa and balsa core sandwich specimens.

3.2. Fickian Model in moisture diffusion process of pure balsa

Figure 4 compares the moisture diffusion process predicted by the analytical models in Mathematica and numerical modeling in Abaqus, as well as the average experimental curve of pure balsa specimens. Firstly, in Mathematica, the Fickian model enables the identification of the moisture diffusion coefficient in the thickness direction and the saturated MC by fitting the experimental curve: $D_{33} = 1.44 \times 10^{-5} \text{ mm}^2\text{s}^{-1}$, $MC_{\infty} = 674 \%$. Additionally, moisture diffusion coefficients along the length and width directions were calculated according to [2]: $D_{11} = D_{22} = 1.34 \times 10^{-6} \text{ mm}^2\text{s}^{-1}$. So, D_{33} in the longitudinal direction of balsa wood is more influential than the coefficients in the other two directions.

Subsequently, the aforementioned parameters were input into the Abaqus model [4, 6] in order to simulate the moisture diffusion process. The average MC of the entire model was calculated in Figure 4 in order to facilitate comparison with other methods. It was observed that the average MC reached the saturated value of 674 % after 22 days, which is in accordance with the experimental observations.

In particular, the dependence of the calculation accuracy on the mesh size was investigated through numerical modeling with different cell sizes of 2 mm, 1.5 mm, 1.2 mm and 1 mm, as illustrated in Figure 4. It is noteworthy that the accuracy of prediction can be significantly enhanced when the mesh size is continuously reduced to 1.2 mm. In order to achieve an optimal balance between the computational efficiency and accuracy, the 1.2 mm mesh element (curve in green) was finally chosen for the modeling of moisture diffusion process in the pure balsa wood. It means that there are 8 elements in the thickness direction of the model (see Figure 5).

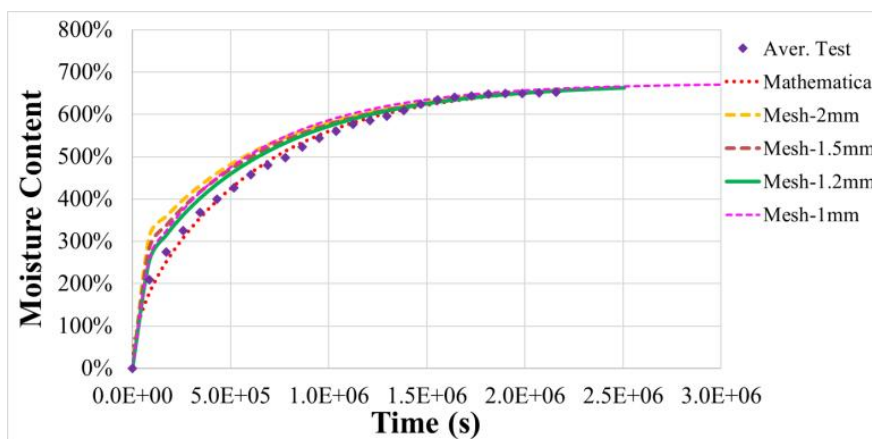
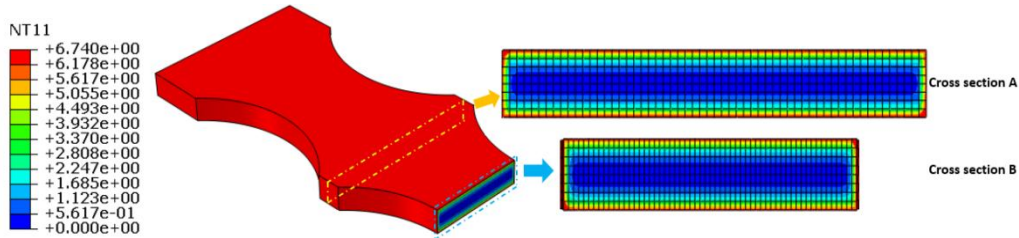
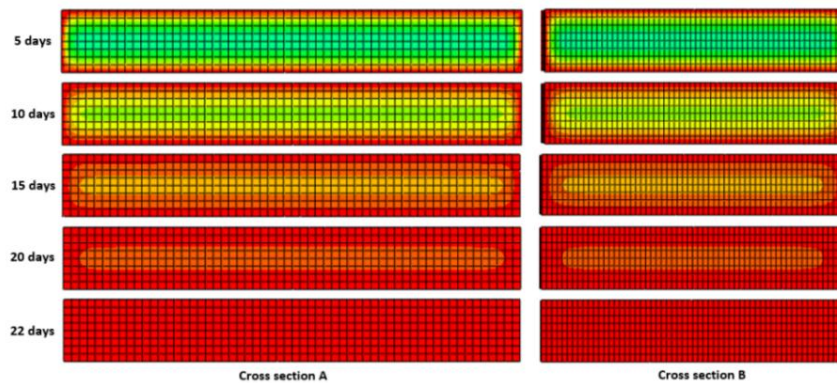


Figure 4. Analytical and numerical modeling of moisture diffusion process in the pure balsa.

Figure 5 provides a clear illustration of the moisture diffusion process within the half inner structure of the dog-bone balsa wood. The figure also depicts the distribution of moisture in two cross sections A and B over a period of 22 days of absorption. It can be seen that moisture diffusion in the thickness direction is the most significant factor. This therefore verifies that the diffusion coefficient in the longitudinal direction of the balsa wood fiber [2] along the thickness of the material is the primary factor determining the rate of moisture absorption of the entire structure.



(1) After 1 day (half model).



(2) Until saturation after 22 days.

Figure 5. Moisture diffusion process in the pure balsa wood in Fickian model.

3.3. Dual Fickian Model in moisture diffusion process of GFRP-balsa sandwich

Based on the experimental observations, it can be found that the parallel Dual-Fickian model better fits the average moisture absorption curve of GFRP-balsa sandwich. Similarly, the analytical fitting was finished in Mathematica to calculate the four predominant coefficients (see Table 1) in the thickness direction in the two stages I and II of Dual Fickian model : $D_I = 1.44 \times 10^{-5} \text{ mm}^2\text{s}^{-1}$, $C_{SI} = 53 \%$; $D_{II} = 1.34 \times 10^{-6} \text{ mm}^2\text{s}^{-1}$, $C_{SII} = 82 \%$. These four coefficients primarily determine the overall moisture diffusion rate in a sandwich structure, and it is interesting to find that D_I is the same as D_{33} found in Fickian model in the longitudinal direction of pure balsa wood. It highlights that it is the balsa core that mainly determines moisture absorption rate of the sandwich in the earlier period of diffusion. Additionally, coefficients of GFRP skin in the thickness direction in all stages can be regarded as the same as D_{II} [2]. Next, the coefficients were included into the Abaqus model to predict the MC distribution in each element of the sandwich structure. The 1.2 mm mesh element was also used for balsa core. However, for the GFRP skin, only one 0.5 mm element was employed due to the much smaller thickness.

In reference [2], it has been demonstrated that the moisture diffusion coefficients in the epoxy resin in the three directions can be considered to be identical with a value of approximately $1 - 2.5 \times 10^{-6} \text{ mm}^2\text{s}^{-1}$. So, in this work, based on the real physical meaning than liquid resin was infused into the skin and core simultaneously during the co-curing manufacturing process of the sandwich structure

[1], moisture diffusion coefficients in the other two directions (length and width) of the skin and core are considered to be the same as that of the resin (see Table 1). Consequently, it means that the moisture diffusion coefficient in the longitudinal balsa wood fiber direction along the thickness would mainly determine the initial absorption rate in stage I, while the moisture absorption rate in the resin exerts a significant influence on the overall diffusion process in stage II.

Table 1. Moisture diffusion coefficients and saturated MC in GFRP-balsa sandwich.

Stage	C	Constituents	D_{11} (mm^2s^{-1})	D_{22} (mm^2s^{-1})	D_{33} (mm^2s^{-1})
I	53 %	Balsa core	1.34×10^{-6}	1.34×10^{-6}	1.44×10^{-5}
		GFRP skin	1.34×10^{-6}	1.34×10^{-6}	1.34×10^{-6}
II	82 %	Balsa core	1.34×10^{-6}	1.34×10^{-6}	1.34×10^{-6}
		GFRP skin	1.34×10^{-6}	1.34×10^{-6}	1.34×10^{-6}

Figure 6 presents the average moisture absorption curves of the entire Abaqus model obtained from the first stage I ($C_I(t)$) until C_{SI} and the second stage II ($C_{II}(t)$) until C_{SII} in Eq. (3), respectively. Based on the definition of Dual-Fickian model in Figure 2, the theoretical sum ($C(t)$) of the MC absorbed in the first stage I ($C_I(t)$) and that in the second stage II ($C_{II}(t)$) is shown by the blue curve. This numerical curve demonstrates a satisfactory fit to the experimental and analytical results, with an average relative error of 5.16 %. Figures 7 and 8 highlight the moisture diffusion process within the half structure during the two absorption stages, employing the parallel Dual-Fickian model.

In Figure 7, in the first stage I, MC reaches the saturated 53 % in all GFRP skin and balsa core elements after 73 days. In contrast, the MC in the GFRP skin reaches saturation value of 82 % after only 20 days in the second stage II in Figure 8, while the MC in the balsa core increases very slowly without final saturation. This indicates that the moisture diffusion coefficient of the resin present in the balsa wood core plays a more significant role following the attainment of saturation in the first stage I. However, the moisture diffusion coefficient in the longitudinal direction of the balsa wood fiber is of greater importance during the first stage I. This is consistent with the experimental observation [1] that the degradation of bending stiffness of the balsa wood core sandwich is faster in the initial quicker hygroscopic period, while the bending strength shows a more significant decrease, particularly during the latter, slower moisture absorption phase. Since bending stiffness of the sandwich is mainly affected by the stiffness of the skin and the ratio of the core-to-skin thickness, while the bending strength is determined by the strength of the glass fiber and epoxy resin.

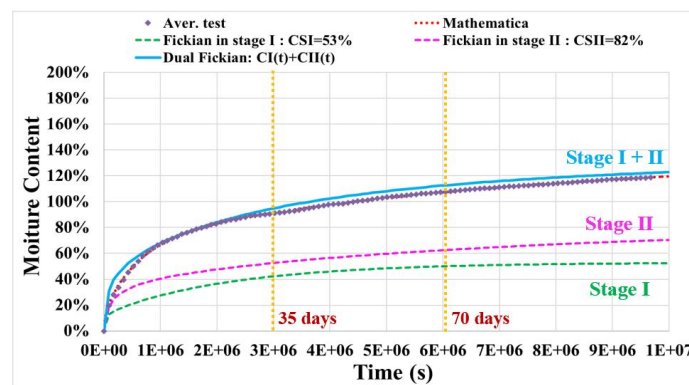
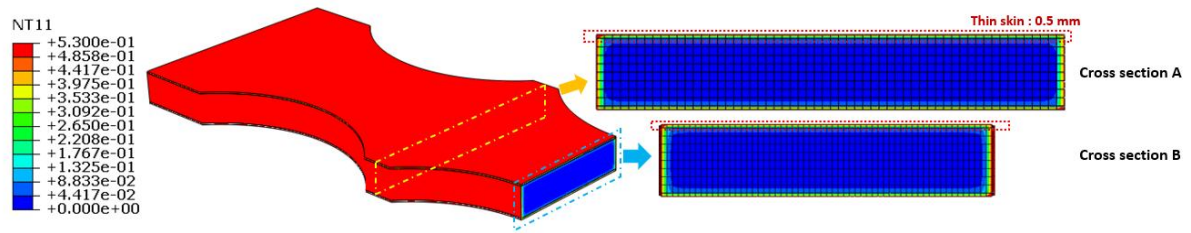
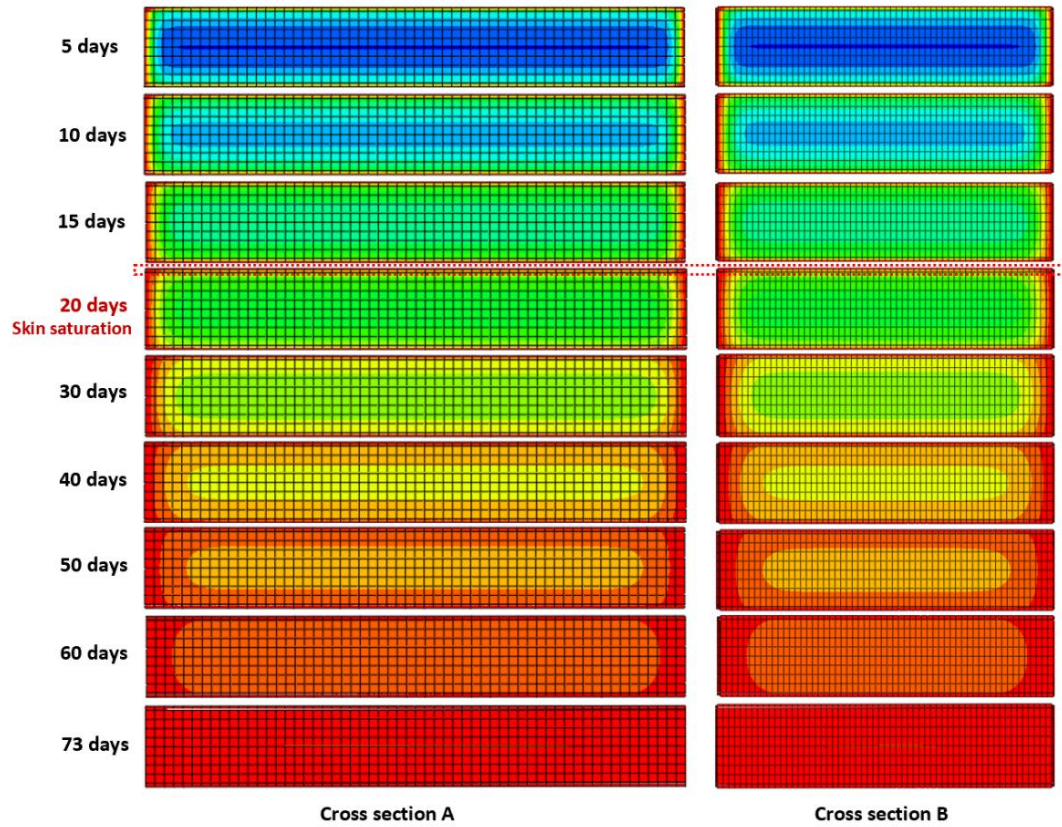


Figure 6. Analytical and numerical modeling of moisture diffusion in the GFRP-balsa sandwich.

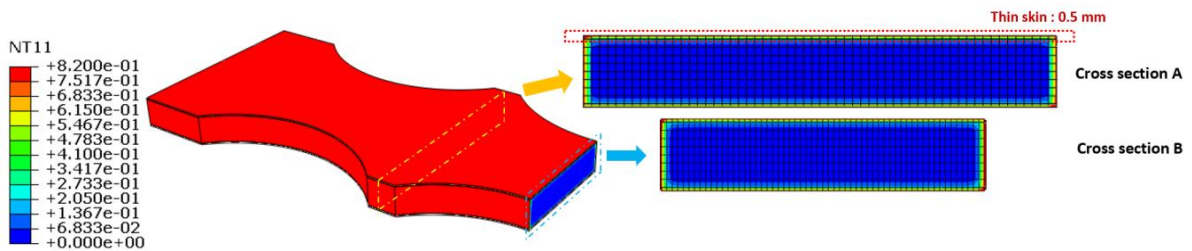


(1) After 1 day (half model).

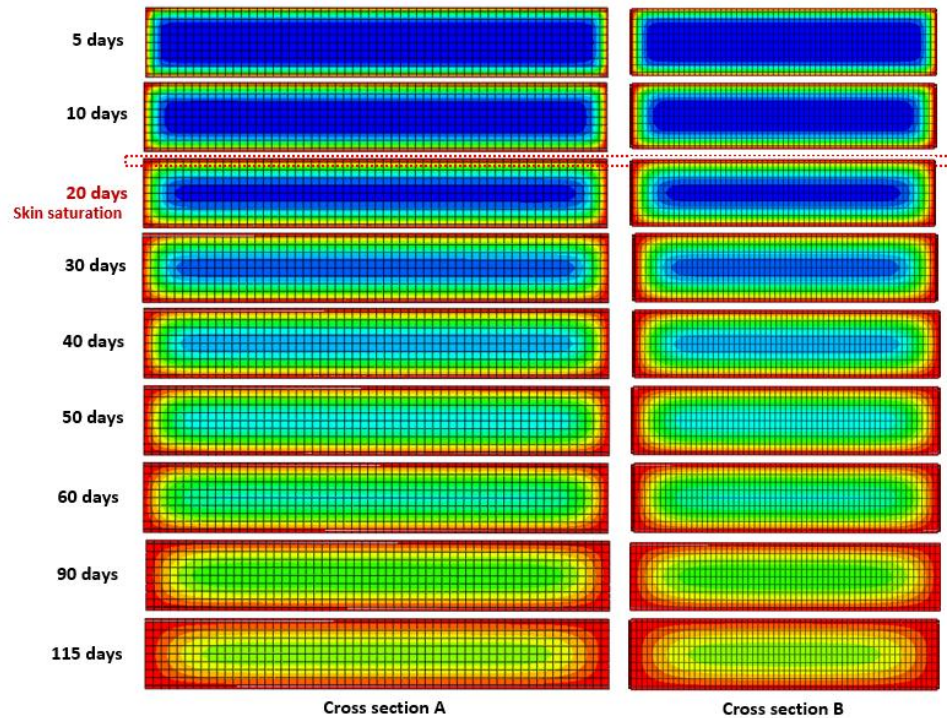


(2) Until saturation of 53 % after 73 days.

Figure 7. Moisture diffusion in stage I of GFRP-balsa sandwich in Dual Fickian model.



(1) After 1 day (half model).



(2) Non-saturation until 115 days.

Figure 8. Moisture diffusion in stage II of GFRP-balsa sandwich in Dual Fickian model.

4. Conclusions

This work presents an experimental, analytical, and numerical investigation on the moisture absorption kinetics in pure balsa wood and GFRP-balsa sandwich specimens. The Fickian model was found to provide an accurate representation of the moisture diffusion mechanism in the pure balsa, while the Dual Fickian model was identified as a more suitable approach for the complex sandwich case. Finally, the moisture diffusion coefficients and saturated moisture absorption capacity were calculated to accurately predict the moisture diffusion behavior of the balsa wood and the sandwich. Nevertheless, further studies are required on sandwich structures with different thicknesses to validate the consistency of the numerical Dual Fickian model proposed in Abaqus.

References

- [1] Y. Wu, M. L. Pastor, M. Perrin, P. Casari, X. Gong. A new methodology to predict moisture effects on mechanical behaviors of GFRP-balsa sandwich by acoustic emission and infrared thermography. *Composite Structures*, 287:115342, 2022.
- [2] V. Legrand, L. TranVan, F. Jacquemin, P. Casari. Moisture-uptake induced internal stresses in balsa core sandwich composite plate: Modeling and experimental. *Composite Structures*, 119: 355-364, 2015.
- [3] A. Céline, S. Fréour, F. Jacquemin, P. Casari. The hygroscopic behavior of plant fibers: a review. *Frontiers in chemistry*, 1: 43, 2014.
- [4] J. J. Machado, E. A. S. Marques, A. Q. Barbosa, L F. M. da Silva. Effect of hygrothermal aging on the quasi-static behaviour of CFRP joints varying the overlap length. *Composite Structures*, 214: 451-462, 2019.
- [5] A. Mubashar, I. A. Ashcroft, G. W. Critchlow, A.D. Crocombe. Modelling cyclic moisture uptake in an epoxy adhesive. *The Journal of Adhesion*, 85(10): 711-735, 2009.
- [6] J. Wang, Y. Li, T. Yu, Q. Li, Z. Li. Anisotropic behaviors of moisture absorption and hygroscopic swelling of unidirectional flax fiber reinforced composites. *Composite Structures*, 297: 115941, 2022.