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Research Article

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3D Finite Element and Micromechanical Modeling of the Tensile Behavior of Bamboo Fiber Composites

Mouad Chakkour[1*], Mohamed Ould Moussa[1], Ismail Khay[1], Mohamed Balli[1], Najma Laaroussi[2] and Tarak Ben Zineb[3]

[1]Laboratory of Renewable Energies and Advanced Materials (LERMA), College of Engineering and Architecture, International University of Rabat, Morocco

[2]Materials Energy and Acoustics Team (MEAT), EST Sale, Mohammed V University in Rabat, Morocco

[3]Université de Lorraine, CNRS, Arts et Métiers ParisTech, LEM3, F-54000, Nancy, France

[*]Correspondence to:
Mouad Chakkour
Laboratory of Renewable Energies and Advanced Materials (LERMA),
College of Engineering and Architecture,
International University of Rabat, Morocco.
E-mail: Moouad.chakkour@uir.ac.ma

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Abstract

Recently, research activities are oriented towards natural fibers that seem to be the best candidate to replace synthetic fibers (i.e., carbon, glass, and Kevlar). Particularly, bamboo fiber is a promising candidate in several industries due to its low cost and important specific mechanical properties. However, a limited attention is devoted to its contribution to the mechanical properties of polymer composites. Herein, the current paper reports on the finite element and micromechanical modeling of the tensile behavior of continuous bamboo fiber composites. More importantly, the experimental tensile test is performed for validation purposes. First, bamboo fibers are isolated from stems using combined mechanical and manual techniques. Composite specimens are manufactured using hand layup and compression techniques. Interestingly, the findings show that the addition of 30 wt.% of bamboo fibers drastically improves the tensile strength of the composite. SEM (Scanning electron microscope) observations of the fractured surface reveal adequate fiber-matrix interfaces indicating the good stress distribution between matrix and fibers. More, the rule of mixture model validates the experimental data due to the low void content of the considered composites. Attractively, the anisotropic finite element model correctly predicts the tensile strength of composites.

Keywords

Biocomposite, Mechanical properties, Finite element modeling, Micromechanics

Introduction

Environmental consciousness has increased these recent years, and therefore the new environmental regulations are somehow one of the factors that lead to think about the use of ecofriendly materials that combine the lightness and strength [1-5]. In particular, cellulosic fibers attract the attention of researchers and seem to be the best candidate to replace synthetic fibers (i.e., carbon and glass fibers) in several industrial applications [1, 5-8]. Indeed, they are currently used as reinforcement for composites in several applications such as automotive, aeronautic, construction, military and sporting equipment's thanks to their attractive mechanical properties, low cost, lightness, renewability and biodegradability [1, 7]. Automotive industry is leader in the use of bio composites especially in internal applications [9, 10]. In addition, hemp fibers are widely used to manufacture thermoplastic composites to reinforce external retro visors of various vehicles [1, 11]. In fact, this great attention devoted to the integration of these fibers in the automotive sector aims to decrease the annual CO_2 (Carbon dioxide) emissions. Chakkour et al. [1] reported that a decrease of 25% of the cars' weight may reduce the annual CO_2 emissions of about 100 billion kilograms. Additionally, cellulosic fibers are also used to replace asbestos fibers in cement composites for building applications due to their interesting thermal and acoustic insulation [7, 9].

Cellulosic fibers provide outstanding mechanical properties when used to reinforced polymer composites [6]. Sanjeevi et al. [12] studied the effect of the incorporation of areca fine and *Calotropis gigantea* fibers on the tensile and flexural properties of phenol formaldehyde reinforced hybrid composites at different fiber fractions. The obtained results show a significant improvement in the tensile and flexural properties of the composites when compared to the neat matrix. The findings reveal that the tensile and flexural strengths of the composites increase with respect to the fiber fraction until a critical threshold of 35 wt.%. At this fiber content, the tensile and flexural strengths reach 58 MPa and 72 MPa, respectively. This high mechanical performance is attributed to the good interfacial bonding between the reinforcement and matrix. Upon this fraction, the tensile and flexural strengths decreased to 48 MPa and 63 MPa, respectively. This was explained by the agglomeration of fibers that reduce the stress transfer from the fibers to the matrix leading to crack nucleation growth in the matrix. Similarly, Chin et al. [13] investigated the contribution of bamboo fibers at different fiber fractions on the mechanical properties (i.e., tensile and bending) of bamboo fiber epoxy composites. The obtained results reveal that the addition of bamboo fibers significantly enhances the tensile and flexural strengths of composites. In a similar vein, they found that the mechanical strengths increase as the fiber content increases until reaching about 40 vol.%. Herein, the tensile and flexural strengths reach 119 MPa and 161 MPa which is attributed to the strengthening effect of the fibers, respectively.

Among all natural fibers, bamboo fibers are more attractive than others due to their low density (Between 0.6 - 1.1 g/cm^3), the rapid growth rate of their plant (Between 11 and 21 cm per day), their high world production (30 million tons) as well as their low cost (Between 300 - 500 Dollars/ton) [1, 6, 7]. It belongs to the most available trees especially in Asia (China) and that mainly grows in dense and equatorial forests [1]. Bamboo fibers are known as natural glass fibers due to their high specific strength and the alignment of the cellulosic microfibrils in the longitudinal direction [6]. Indeed, the specific strength of bamboo can reach 1250 MPa/cm^3 for fibers extracted by chemical and compression combined methods compared to about 480 - 600 MPa = cm^3 for E-glass fibers, as reported by Zakikhani et al. [6].

To the best of our knowledge, a limited attention is devoted to the evaluation of the contribution of these fibers on the mechanical properties of polymer composites. Herein, this paper shed light on the experimental evaluation of the mechanical properties of bamboo fiber polymer composites as well as finite element and micromechanical modeling of their behavior. Bamboo fibers are extracted from stems using combined mechanical and manual techniques and used to manufacture epoxy composites at 30 wt.% fiber content using hand layup and cold compression methods. Herein, the tensile and morphological properties of the considered bio composites are deeply analyzed. In addition, 3D finite element and micromechanical models of the tensile behavior of the involved composite are addressed using Abaqus software and analytical model, respectively.

Materials and Method

Experimental set up

Extraction of fibers

Bamboo fibers were extracted using a combination of water retting and compression processes. Firstly, bamboo plants aged between five and six years were harvested in Rabat, Morocco. Afterwards, they were immersed in distilled water at room temperature for three days in order to be molten, then, pressed using a manual press with a pressure of about 10 tons, as reported by [14]. This process is repeated between 9 and 11 times until the separation of fibers which were subsequently washed with distilled water and air-dried using an air-oven at 105 ˚C for 48 h in order to remove any adsorbed moisture. The produced fibers have a total length ranging from 100 mm to 150 mm. All used materials are nanoscale materials.

Composites manufacturing

Composite specimens were elaborated using the well-known hand layup at room temperature and relative humidity of about 80 RH% [15-17], according to ISO 6892-1 standard. Epoxy *Poliep 507* resin and its corresponding hardener were manually mixed for 20 min following weight fractions 2:1, respectively. The resulting mixture was added to the continuous fibers which were placed in a metal mold with dimensions 75 x 16 x 4 mm^3 and manually impregnated by the final mixture using a silicon spatula. Finally, a pressure of 5 kPa was applied on the top of the counter-mold for 20 h for surface uniformity of the specimens. After demolding, the specimens were subjected to post-curing at room temperature of 25 ˚C and relative humidity of 80 RH% for 20 days, before performing mechanical tests. Figure 1 illustrates the elaborated bamboo fiber composites. The proposed fiber fraction in the current study is about 30 wt.%, which is found to be the optimal content for maximum mechanical properties of bamboo fiber epoxy composites, as reported in our earlier study [14].

Tensile test

Tensile test was performed on three flat composite specimens with dimensions 75 x 16 x 1.5 mm^3 according to ISO 6892-1 standard. The test was conducted under a relative humidity of 80 RH% and a displacement rate of 2 mm/min at room temperature, using a 50 kN capacity Tinius Olsen universal testing machine, as shown in figure 2.

Morphological analysis

A SEM "FEI FEG 450" is used to analyze the fractured surface of bamboo fiber composites. The working voltage and the corresponding distance are 10 kV and 10 mm in high vacuum mode, respectively.

Finite element modeling

To model the 3D mechanical behavior of continuous bamboo fiber composites, the mechanical equilibrium balance is given in equation 1.

Figure 1: Continuous bamboo fiber composites elaborated using the hand layup technique.

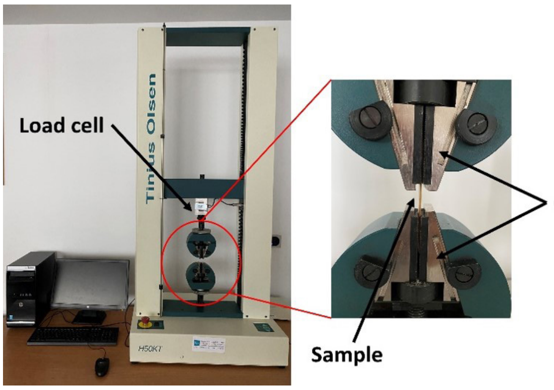

Figure 2: Tinius Olsen machine used for tensile testing.

$$div(\sigma)=0 \quad \forall(x,t)\in \Omega \times [0,T] \tag{1}$$

The stress-strain relationship for the elastic response of the composite is expressed in equation 2.

$$\sigma = H:\varepsilon^{el} \quad \forall(x,t)\in \Omega \times [0,T] \tag{2}$$

Where H, σ, and ε correspond to the elasticity, stress and strain tensors, respectively.

Equations listed in table 1 are solved using Abaqus software by means of HP Zbook i7-8650U-CPU 2.11 GHz - 64 bits computer. After performing the mesh sensitivity analysis, the involved 3D anisotropic model is finally meshed using 7100 wedge elements C3D6T, as shown in figure 3. The structure is clamped from one side $\partial\Omega_u^s$ and loaded at the opposite one $\partial\Omega_L$. The subdomain $\partial\Omega_L$ corresponds to the free surfaces.

Table 1: Equilibrium equation, constitutive law, and boundary conditions of the 3D anisotropic mechanical model.

Mechanical equilibrium	$div(\sigma)=0$	$\forall(x,t)\in\Omega \times [0,T]$
Anisotropic elastic behavior	$\sigma = H:\varepsilon^{el}$	$\forall(x,t)\in\Omega \times [0,T]$
Boundary conditions	$u.n=0$ $u.n=u_{max}$ $\sigma.n=0$	$\forall(x,t)\in\partial\Omega_u^s \times [0,T]$ $\forall(x,t)\in\partial\Omega_L \times [0,T]$ $\forall(x,t)\in\partial\Omega_L \times [0,T]$

A transverse isotropy assumption is assumed to model the anisotropic mechanical behavior which allows to reduce the elastic constants of the stiffness tensor to five independent parameters. These parameters were estimated based on Ekvall formulas. Herein, the Young's modulus of the Epoxy matrix and bamboo fibers are obtained from experimental data as 1 GPa [18] and 10 GPa [19], respectively.

Moreover, the failure in bamboo fiber composites is simulated using the uncoupled traction separation law based cohesive model. A surface-to-surface contact is considered at the middle of the meshed structure since the failure occurs at the middle of specimens as observed in experiments. The failure criterion or the opening of the cohesive zone is considered using the maximum separation criterion MAXS, as given in equation 3.

$$\max\left\{\frac{\delta_n}{\delta_n^0},\frac{\delta_s}{\delta_s^0},\frac{\delta_t}{\delta_t^0}\right\}=1 \tag{3}$$

Where δ_i^0 correspond to the shear and normal displacement at damage initiation. Subscripts n, s and t refer to the first, second orthogonal and normal components, respectively. The damage separation δ_i (I = s, t, and n) is given in equation 4.

$$\delta_i^0=\frac{\sigma_i^0}{K_i} \tag{4}$$

Micromechanical modeling

Different micromechanical models are frequently used to predict the elastic properties of natural fiber polymer composites such as: Rule of mixture (ROM), inverse rule of mixture (IROM), Halpin Tsai, Madsen and Chamis models. IROM and Halpin-Tsai models are rather used to predict the mechanical properties of transverse fiber and aligned short fiber filled composites, respectively, while the ROM is the most widely used for continuous filler composites.

Figure 3: Refined meshing of the involved model using 7100 wedge elements.

In this study, the rule of mixture model is used to predict the tensile strength of continuous bamboo fiber composites and compared to experimental data performed at room temperature and relative humidity of 80 RH%. Herein, the tensile strength of Epoxy matrix is experimentally identified while the fiber one is considered [6].

ROM is the simplest model to predict the mechanical properties (i.e., tensile strength and Young's modulus) of unidirectional and continuous fiber reinforced composites, according to Voigt's assumption. In this model, perfect contact or bonding between fibers and matrix is assumed. The longitudinal tensile strength can be expressed following equation 5.

$$\sigma_c = \sigma_m.V_m + \sigma_f.\left(1 - V_f\right) \quad (5)$$

Where σ and V correspond to the tensile strength and volume fraction, respectively. Subscripts c, m and f are related to the composite, matrix and fibers, respectively.

Results and Discussion

Figure 4a shows a comparison between experimental, finite element and micromechanical models of the ultimate tensile strength of continuous bamboo fiber composites at room temperature and relative humidity of 80 RH%. The incorporation of continuous fibers was found to increase the tensile strength from 10 MPa for neat Epoxy to about 149 MPa for polymer composites due to the strengthening effect of bamboo fibers.

In general, the matrix protects the reinforcement from the environment and transfers the load to the fibers through shear stresses [14]. Herein, the involved fibers withstand the applied load due to the alignment of the cellulosic microfibrils in the load direction. Indeed, Wenting et al. [20] have reported that bamboo fibers exhibit relatively a small microfibrillar angle MFA of about 10° which represents the low orientation of the cellulosic fibrils with respect to the fiber axis, resulting in important mechanical properties in the longitudinal direction. Figure 4b shows SEM image of the fractured surface of bamboo fiber composites. It reveals an adequate fiber-matrix interface, fiber breakage as well as delamination crack indicating good load distribution.

Similar results were reported by Sanjeevi et al. [12] who have investigated the effect of 35 wt.% of areca fine and *C. gigantea* fibers on the tensile strength of phenol formaldehyde composites. The findings reveal that the tensile strength increases from 28 MPa to 58 MPa for neat phenol formaldehyde and hybrid fibers composites which is explained by the strengthening effect of the fibers, respectively. Chin et al. [13] have studied the influence of 30 wt.% of bamboo fibers on the tensile strength of epoxy composites. The obtained results show that the ultimate strength increases from 18 MPa to 103 MPa for neat epoxy and composites due to the appropriate bonding between fibers and matrix, respectively.

Regarding the analytical model, the simple ROM shows a good prediction of the ultimate strength of bamboo fiber composites at 30 wt.% fibers fraction which could be related to the low void content in the composites as this model assumes a perfect fiber-matrix interface [14]. Indeed, it may refer to the low pores and void content generated during the hand lay-up manufacturing method. Most importantly, the fibers are well impregnated by the resin resulting in an adequate fibers-matrix interface, as shown in figure 4b. However, other models such as Halpin-Tsai, IROM are not adequate for predicting the properties of longitudinal fiber composites. They are rather used to assess the mechanical properties of aligned short and transversal fiber composites, respectively.

Figure 5 shows a cross section of the spatial distribution of the axial component of stress $\sigma_{33} = S_{33}$ at the middle of the model (Length/2) where the strength is evaluated. The anisotropic predicted and cohesive models were found to estimate correctly the experimental tensile strength due to the mesh refinement. In fact, the finite element simulation depends on the constitutive model and failure criterion. Herein, the use of the anisotropic elastic constitutive model is justified by the brittle failure in bamboo fiber composites as observed in experiments and reported by Hassan et al. [21]. Most importantly, the maximum separation damage initiation criterion is found to be accurate for predicting the tensile strength of bamboo fiber composites.

Conclusion

Research activities are currently oriented towards the development of cellulosic fibers for lightweight applications. The important specific tensile properties, low cost and large availability offered by bamboo fibers make them a potential can-

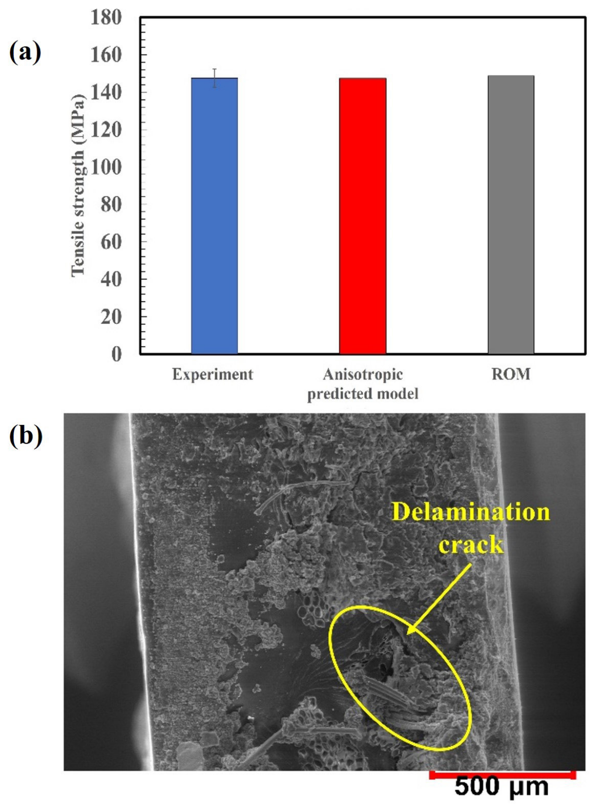

Figure 4: (a) Comparison between experimental, finite element and micromechanical models of the tensile strength of bamboo fiber composites and **(b)** SEM image of the fractured surface of bamboo fiber composites.

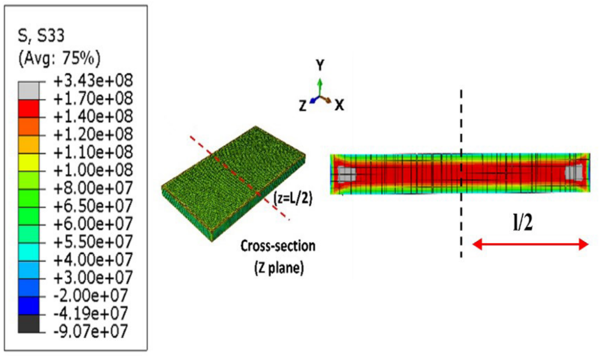

Figure 5: Cross section of the spatial distribution of the axial component of stress $\sigma_{33} = S_{33}$ at the middle of the considered model (Length/2).

didate in several industries. For this reason, the current study focuses on the finite element and micromechanical modeling of the tensile behaviour of continuous bamboo fiber composites. More importantly, the experimental tensile test is performed to validate the analytical results. First, bamboo fibers were extracted from stems using water retting and compression techniques. The isolated fibers were used to manufacture composite specimens using the hand layup technique. Interestingly, the findings show that the addition of 30 wt.% of bamboo fibers enhances the tensile strength of the considered composites. SEM analysis of the fractured surface reveals adequate fiber-matrix interfaces leading to an outstanding tensile strength. In addition, the ROM shows a good prediction of the tensile strength. This was explained by the low void content generated during the hand layup technique as well as the good fiber-matrix bonding. Moreover, the stress predicted using the 3D anisotropic model is found to be in agreement with experimental data.

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Conflict of Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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