Research Article

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Investigation of the effect of thermal stress on the interface damage of hybrid biocomposite materials

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Abstract: In this paper, we have studied the effect of thermal stress on the damage of fiber-matrix interface of a hybrid biocomposite composed of two natural fibers, Hemp, Sisal, and Starch matrix. Our genetic modeling used the nonlinear acoustic technique based on Cox's analytical model, Weibull's probabilistic model, and Lebrun's model describing the thermal stress by the two coefficients of expansion. The stress applied to our representative elementary volume is a uni-axial tensile stress.
The numerical simulation shows that the Hemp-Sisal/Starch hybrid biocomposite is most resistant to thermal stresses as compared with Hemp/Starch biocomposite. It also shows that hybrid biocomposite materials have a high resistance to applied stresses (mechanical and thermal) compared to traditional materials and biocomposite materials. The results obtained in our study coincide perfectly with the results of Antoine *et al.*, which showed through experimental tests that natural fibers perfectly improve the mechanical properties of biocomposite materials.

Keywords: Hemp, Sisal, Starch, damage, interface, genetic algorithm

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1 Introduction

Starch is a polysaccharide of plant origin composed of glucose units $C_6H_{10}O_5$. It is the main carbohydrate reserve substance of higher plants [1]. The most important sources of starch are cereals, tubers and legumes. Some fruits can be high in starch.

After cellulose, starch is the main carbohydrate substance synthesized by higher plants from solar energy. The native starch is found in the form of grains [2–4].

Starch is in the form of powder when it is extracted from plants from which it is derived. Starch does not have good mechanical properties at break and must first be plasticized or formulated with different additives. Starchy materials can then be implemented by casting or extrusion [5, 6]. For this reason, we thought of strengthening a Starch matrix by two natural fibers—Hemp and Sisal.

Sisal is a perennial plant consisting of a rosette of large leaves with triangular section up to 2 m long. It is a tropical plant and each plant can produce 180 to 240 leaves depending on the geographical situation, altitude, rainfall and variety considered. Sisal can be harvested in 2 years after planting and has a productive life of up to 12 years. It is mainly grown in South America and Africa; Sisal fiber is hard, coarse, long (1–1.5 m), very resistant and almost white, ivory or pale yellowish in color [7–9].

Hemp fibers are considered among the best reinforcements for composite materials due to the elimination of synthetic fibers affecting the environment [10]. Glass fibers have been used for reinforcing composite materials in wind turbine blades and boats, since glass fibers have a lower density than steel but a higher strength. The Hemp gives fiber properties similar to fiber glass E, which has very high mechanical properties [11].

Our work is based on the modeling by a genetic approach of the effect of thermal stress on the improvement of mechanical and physical properties of biocomposite material (Hemp-Sisal/Starch). The results of this modeling will be compared with the results of the nonlinear acoustic technique, which was used to locate the interface damage

Table 1: The characteristics of Hemp and Sisal fibers [12, 13].

Designation	Young's modulus GPa	Length (mm)	Diameter (µm)	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Hemp	30–60	22	25	67–75	16–18	2.9–3.3
Sisal	10–30	22	25	47–78	10–24	7–11

Table 2: The mechanical properties of starch [14–16]

Designation	Mechanical stress (MPa)	Young's modulus MPa	Radius (µm)	The half distance (R) (µm)
Starch	18	0.989	200	100

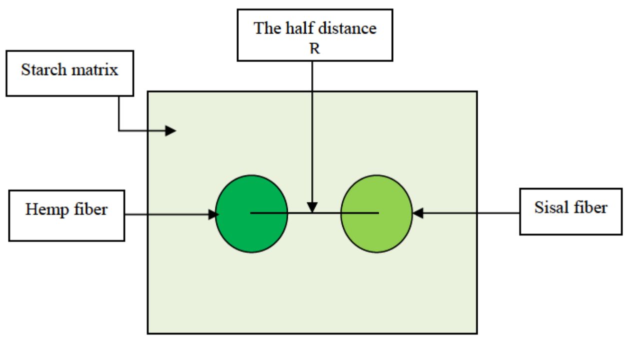

Figure 1: The representative elementary volume

of the materials studied according to our representative elementary volume (see Figure 1).

2 Study and numerical modeling

2.1 Materials studied

In Table 1 and Table 2, we have presented the physical and mechanical properties of the materials used in our genetic modeling.

2.2 The analytical simulation models

2.2.1 Thermal stresses

The field of thermal stresses resulted from the differential expansion of the fibers and matrix during cooling, after the preparation of the composite at high temperature. It is given by the following equations [17]:

$$\sigma_f^T = E_f \frac{a}{1+a}(M_2 - M_0) \tag{1}$$

With:

$$M_0(T) = \int_{T_0}^{T_e} (\alpha_m - \alpha_f)\, dT$$

$$M_2(T) = \int_{T_e}^{T} (\alpha_m - \alpha_f)\, dT$$

where T_0 is room temperature, T_e is temperature of development, T is test temperature, and finally, α_f and α_m are expansion coefficients of fiber and matrix [17, 18].

2.2.2 The analytical model of Cox

For the interface, their damage is based on the model of Cox [19], that is defined by the following relation:

$$\tau = \frac{E_f a \varepsilon}{2} \beta th(\beta 1/2) \tag{2}$$

$$\beta^2 = \frac{2G_m}{E_f {r_f}^2 \ln(\frac{R}{r_f})}$$

where:
(G_m) – Shear modulus of the matrix
(E_f) – Young's modulus of fiber
(ε) – the deformation
(a) – radius of the fiber
(R) – the half distance
(τ) – the shear stress of the interface

2.2.3 The probabilistic models of Weibull

When stress is uniform, damage to the matrix is given by formula (3) [20]:

$$D_m = 1 - \exp\left\{-\frac{V_{eff}}{V_0}\left[\frac{\sigma_m^T}{\sigma_0}\right]^m\right\} \tag{3}$$

where:
(σ) – the applied stress
$\left(\sigma_m^T\right)$ – the thermal stress
$\left(V_{eff}\right)$ – the volume of the matrix
(m and σ_0) – Weibull parameters

A broken fiber is discharged along its entire length [19], that is, it can only break once. The rupture obeys a law similar to that described for the matrix.

$$D_f = 1 - \exp\left\{-A_f * L_{equi} * \left[\frac{\sigma_{\max}^f}{\sigma_{0f}}\right]^{m_f}\right\} \tag{4}$$

where:

- ($\sigma_{\max}^f$) – the maximum stress applied
- (L_{equi}) – it is the length that the fibers would have for the same break if uniformly distributed

2.2.4 The non-linear acoustic technique

To describe the classical non-linear acoustic behavior of materials, they have often added a non-linear term β in Hooke's law, which is written as:

$$\sigma = E\epsilon\,(1 + \beta\epsilon) \tag{5}$$

In equation (5), σ represents the applied mechanical stress and ϵ represents the strain, E is the Young's modulus and β the non-linearity parameter [21–25]. If $\beta = 0$, we say that the material is homogeneous. E and β can be determined from acoustic measurements [26, 27]. The Young's modulus E is obtained by determining the longitudinal and transverse propagation velocities. The harmonic generation method is based on the distortion of a high intensity sine wave through a given material or medium. When the material does not exhibit heterogeneity, the different zones excited by the ultrasonic agitation vibrate at the same speed, as shown in the figure. The ultrasonic wave is then subjected to any disturbance and its shape is the same, that is to say sinusoidal. On the other hand, the presence of heterogeneity in the medium is traversed at a source of the local elevation of the modulus and the density during the compression and a local decrease of the density and of the modulus during the expansion [26, 27]. This results in the change of the spectral content waveform (FFT). As a result, the received wave is not sinusoidal but contains harmonics.

3 Modeling and numerical simulation

3.1 Genetic algorithm

The modeling of the effect of the thermal stress on the damage of the interface by using analytical models is difficult to realize, since the interface has a random behavior and each time one does not know the origin of its damage. For this purpose, probabilistic modeling is the most appropriate for simulating the effect of thermal stress on the damage of the fiber-matrix interface of the hybrid Hemp-Sisal/Starch biocomposite by a genetic algorithm using an analytical model based on Weibull's probabilistic approach and Lebrun's equation. The principle of this algorithm is based on the use of genetic operators (selection, crossover, mutation) to predict a population of one hundred (280) randomly generated individuals with a maximum output of 140 as a stopping criterion. The chromosome genes represent the following variables defined by the analytical shear model of the Cox interface: the mechanical stress, which is between 0 and 125 N; Young's modulus of the fiber; modulus of shear of the matrix; radii of the fibers; and the distance between fiber. The damage of the interface is produced by the crossing of two damages of the two constituents – fiber and matrix, using a mutation probability between 0.4 and 0.5. The found individuals are ranked and positioned to get the best of them; these individuals are inserted in the first row, and building a new generation, the process is repeated until convergence, this damage will be located by the nonlinear acoustic technique (equation 5). The numerical calculations are performed using Matlab R2012a software.

3.2 The flowchart of the genetic algorithm

4 Results and discussions

Our calculation was carried out on two types of hybrid biocomposite and biocomposite materials—Hemp/Starch and Hemp-Sisal/Starch. From the results of simulation by a genetic algorithm localized by the nonlinear acoustic technique, we have examined the strength of our material by the application of different constraints ((105), (115), (125 N/m^2)), which allowed us to calculate the interface damage in the function of thermal stress. Figures 3–5 and 6–8 show the level of damage to the interface for the two materials as a function of thermal stress.

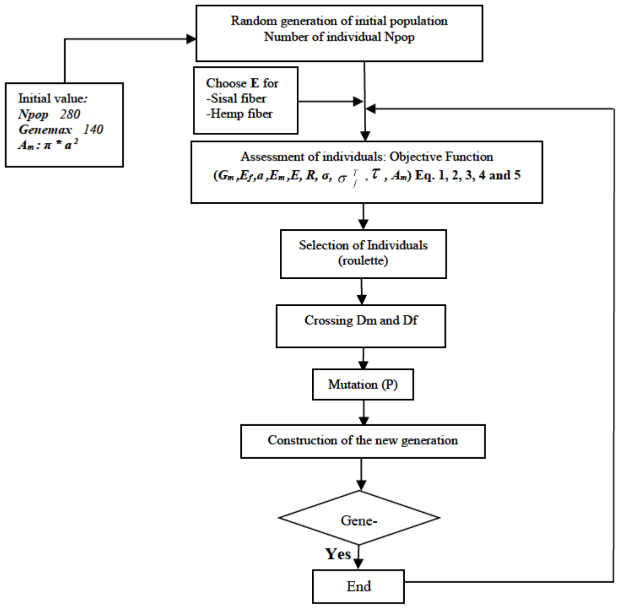

Figure 2: The flowchart of the genetic algorithm

4.1 Hemp/Starch

Figures 3, 4 and 5 show that the damage "D" of the interface starts at the level of 0.3 (105 N/m^2), then increases to a maximum value of 0.45 (125 N/m^2) and when the thermal stress increases, the damage increases and reaches its maximum of 0.7 for a value of the thermal stress of 100. It can also be said that the increase in the level of the damage signifies the concentration of the stresses, which gives a strong degradation to the interface.

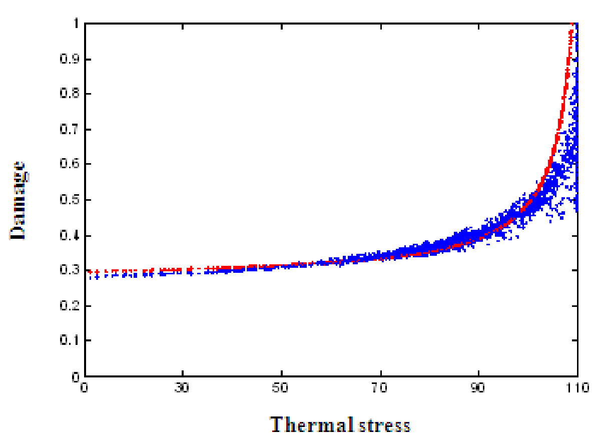

Figure 3: The influence of the thermal stress on the interface damage (σ = 105 N/m^2)

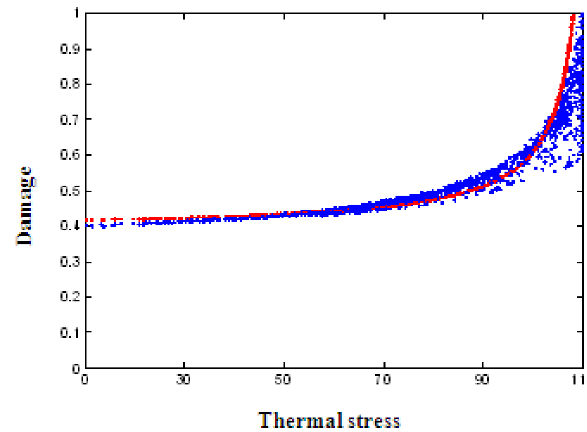

Figure 4: The influence of thermal stress on the interface damage (σ = 115 N/m^2)

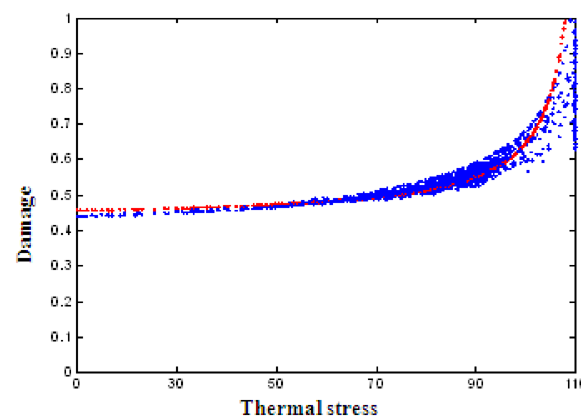

Figure 5: The influence of the thermal stress on the interface damage (σ = 125 N/m^2)

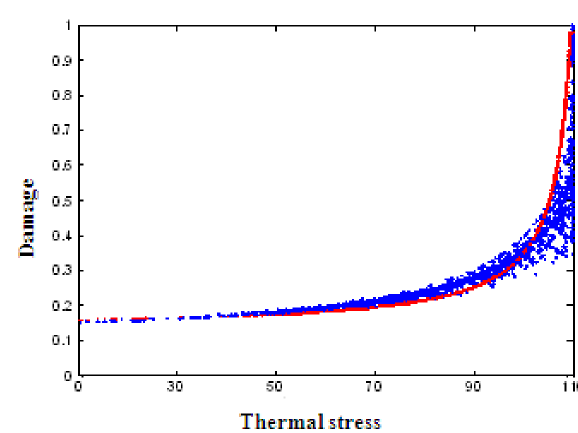

Figure 6: The influence of thermal stress on the interface damage (σ = 105 N/m^2)

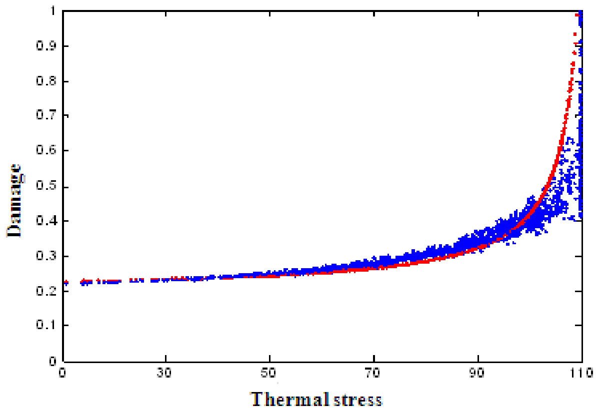

Figure 7: The influence of thermal stress on the interface damage (σ = 115 N/m^2)

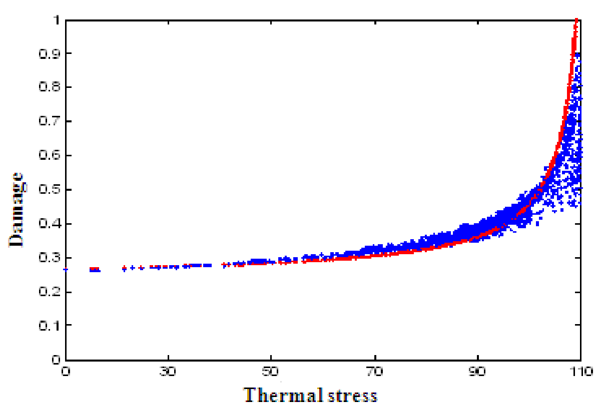

Figure 8: The influence of thermal stress on the interface damage (σ = 125 N/m^2)

4.2 Hemp-Sisal/Starch

Figures 6, 7 and 8 show that the damage "D" of the interface starts at the level of 0.15 (105 N/m^2), then increases to a maximum value of 0.28 (125 N/m^2), and when the thermal stress increases, the damage increases and reaches its maximum of 0.6. One can also say that the increase in the level of damage signifies the concentration of the stresses which gives a strong degradation to the interface.

5 Conclusion

The genetic approach allowed us to model the damage of the fiber-matrix interface and to give us the possibilities of analysis and interpretation of our different results, and this was done in the absence of the analytical models, which describe the damage to the interface. The results show that the level of damage is related to the material resistance for both hybrid biocomposite and biocomposite materials that have been studied for Hemp/Starch and Hemp-Sisal/Starch and in the middle where exposed. The results also show a good match between the numerical simulation and the real behavior of the two materials. The numerical simulation shows that the Hemp-Sisal/Starch hybrid biocomposite is most resistant to thermal stresses as compared to Hemp/Starch biocomposite. Additionally, the results show that hybrid biocomposite materials have a resistance to applied stresses (mechanical and thermal) when compared with traditional materials and ordinary biocomposite materials. The results obtained in our study coincide perfectly with the results of Antoine *et al.* [28], which showed by experimental tests that natural fibers perfectly improve the mechanical properties of biocomposite materials.

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