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Study and Localization by the Nonlinear Acoustic Technique of the Damage to the Fiber-Matrix Interface of a Bio-composite

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The objective of this paper is to study the effect of dissipated energy on the damage to the fiber-matrix interface of a Hemp/Pla bio-composite, localized by the non-linear acoustic technique. For this purpose, we used the model defining energy dissipation during a charge/discharge cycle in our numerical simulation based on the Weibull probabilistic model and Cox model. We found that the energy dissipated is directly related to the damage; and when the damage increases the dissipated energy increases rapidly in the first cycles (1, 2,3 and 4) and very quickly for the last charge/discharge cycles (5,6 and 7). We concluded that the energy dissipated showed the state of degradation of Bio-composite prior to its start-up, and that the non-linear acoustic technique also indicates and confirms the same results found.

Keywords: non-linear acoustic technique, bio-composite, damage, interface, Hemp, PLA.

1. Introduction

The performance of composite materials has many advantages for the design of mechanical structures [1]. Mention may in particular be made of a high resistance to weight ratio, absence of corrosion, vibration damping or impact resistance. The use of materials, the advantages of which are of particular interest in the advanced industrial sectors such as aeronautics, still clash with certain markets linked to the mechanisms of damage and breakage. These aspects lead to the introduction of severe safety coefficients and therefore higher costs than conventional materials (metallic in particular). In order to optimize the mechanical structures of composite materials, it is therefore necessary to control the processes of damage and to predict by the constituent models adapted to the consequences of these [1].
In practice, the composite materials can have a specific capacity of high energy absorption, provided that they adopt a progressive and effective mode of ruin. Energy is absorbed not by deformation but by the creation of multiple damage in the material, which is progressively fragmented [2].
Eco-composites have been the subject of a growing body of research in recent years [3, 4]. In addition to their ecological advantages (renewable natural resources, potential biodegradability, etc.), they also offer an excellent mass / stiffness / resistance ratio, a considerable asset for most transport, sports and leisure industries. Still with a view to increasing environmental performance, eco-composites with a thermoplastic matrix are developing gradually, offering an interesting recycling potential. [3-5] Some solutions are even fully biosourced. Most of these materials require shaping by thermo compression (under press or vacuum). Among the different natural reinforcements used, hemp fibers are appreciated for their mechanical performance and availability [6].
Due in part to a lack of knowledge of the behavior of bio-composites. For example, understanding and anticipating damage mechanisms is essential for any semi-structural or structural use. In this vision, we will study the effect of the dissipated energy on the damage of the fiber-matrix interface of a Bio-composite Hemp / PLA; This damage will be studied and localized by the non-linear acoustic technique.

2. Theory

2.1. *The analytical models*

When the stress is uniform, damage to the matrix is given by formula (1) de Weibull [7]:

$$D_m = 1 - \exp\left\{-V_m\left[\frac{\sigma + \sigma_m^T}{\sigma_{0m}}\right]^{m_m}\right\} \tag{1}$$

with:
σ – applied stress,
σ_m^T – thermal stress,
V_m – volume fraction of the matrix,
m_m, σ_{0m} – Weibull parameters.

$$D_f = 1 - \exp\left\{-A_f * L_{equi} * \left[\frac{\sigma_{\max}^f}{\sigma_{0f}}\right]^{m_f}\right\} \tag{2}$$

A broken fiber is discharged along its entire length [7]. That is, it can only break once. The rupture obeys a law similar to that described for the matrix. with:
$\sigma^{f}_{\max}$ – the maximum stress applied,
L_{equi} – is the length that the fibers would have for the same break under uniformly distributed.
For the interface their damage based on the model of Cox [8,9] that is defined by the following relation:

$$\tau = \frac{E_f a\varepsilon}{2}\beta\, th(\beta\, l/2) \qquad \beta^2 = \frac{2G_m}{E_f r_f^2 \ln(\frac{R}{r_f})} \tag{3}$$

with:
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.
The energy dissipation during a charge / discharge cycle is given by the following equation:

$$W = \frac{\alpha}{6}\frac{\tau^*}{\tau}\frac{S^2}{E_c} \tag{4}$$

with:
$\alpha = \frac{E_m V_m}{E_f V_F}$,
$E_c = E_m V_m + E_f V_f$,
S – level of peak stress less than the ultimate strength of the bio-composite (N/m^2), and:

$$\tau^* = \frac{\alpha r E_f S}{2dE_c} \tag{5}$$

τ^* – is the limiting shear rate.

2.2. *The non-linear acoustic technique*

Classical nonlinear acoustic behavior of materials is commonly described by the addition of a nonlinear term β in Hooke's law, which is written as:

$$\sigma = E\varepsilon(1 + \beta\varepsilon \tag{6}$$

In the last relation, σ and ε are the stress and strain respectively [10-14], E is the Young's modulus and β the parameter of non-linearity. If $\beta = 0$, we say that the material is homogeneous. E and β can be determined from acoustic measurements. [15, 16]. The Young's modulus E is obtained by determining the rates of longitudinal and transverse propagation. The harmonic generation method is based on the distortion of a sine wave of a high intensity through a given material or medium. When the material does not exhibit heterogeneity, different areas excited by the ultrasonic agitation vibrate at the same speed see figure, the ultrasonic wave is then subjected to any perturbation and its shape is the same that is to say sinusoidal. As against the presence of heterogeneity in the medium is traversed at a source of the local elevation of the module and density during compression and a local decrease of the density and modulus during expansion [15, 16]. This results in the change of the wave shape of the spectral content (FFT). As a result the received wave is not sinusoidal but contains harmonics.

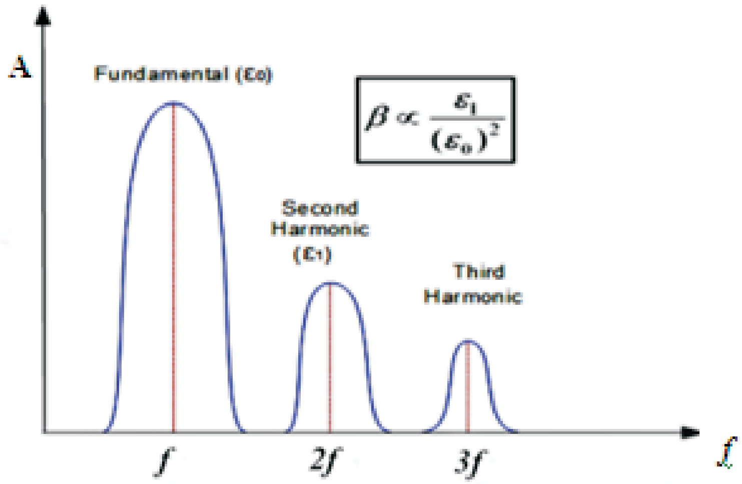

Figure 1 Fourier spectrum of the received signal for nonlinear parameter determination

3. The characteristics of the materials studied

3.1. *Polylactic acid (PLA)*

Polylactide or poly (lactic acid) is generally an aliphatic polyester is synthesized by condensation from an α–hydroxy acid (lactic acid) or by ring-opening polymerization from a cyclic monomer: the lactide (Fig. 2) [17–21].
Usually, commercial PLA is a poly–L–lactic (PLLA) and poly–DL lactic (PDLLA) acid copolymers [21–24].

3.2. *The Hemp fiber*

The characteristics of the hemp fibers are shown in Tab. 2. The length is 8 to 22 mm for a diameter of about 20-25 μm. The cellulose content is 67%, giving a stiffness exceeding 30 GPa for certain varieties of hemp. The tensile strength is very variable, showing the high dispersion of the mechanical properties of the hemp fibers.We presented in Tab. 1 and 2 the mechanical properties used in our study for the various constituents of the biocomposites materials.

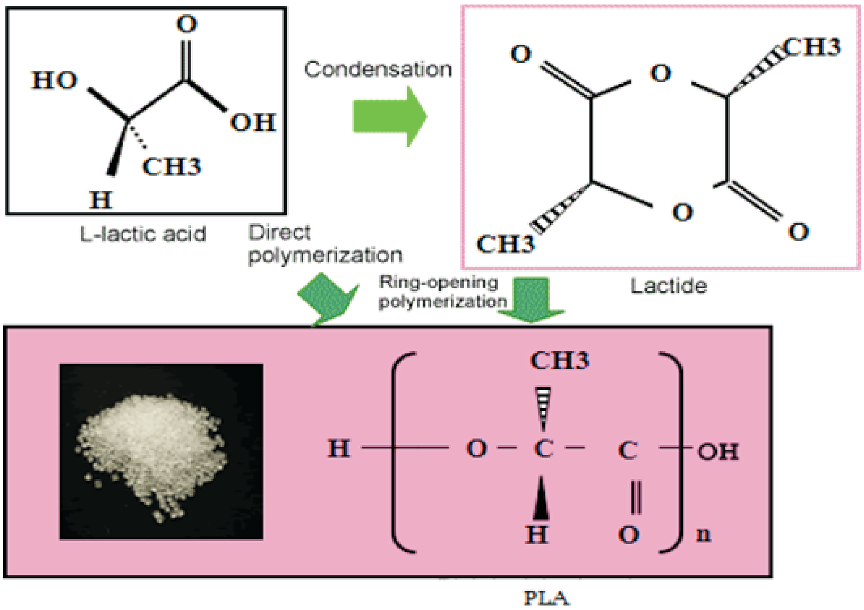

Figure 2 A block diagram of the numerical algorithm

Table 1 The characteristics of hemp fibers [25]

Design.	Organ used	Density (g/cm^3)	Length (mm)	Diameter (μm)	Cellulose (%)	Hemicellulose (%)	Lignin (%)
Hemp	Seed	1.48	22	25	67-75	16-18	2.9-3.3

Table 2 The mechanical properties of PLA

Design.	Density (g/cm^3)	Young's modulus Mpa	Radius (micron)	Poisson coefficient	Thermal expansion coefficient
PLA	1.25	3.5*103	40	0.36	7.85*10-5

4. Numerical simulation by a genetic algorithm and the non-linear acoustic technique

4.1. *Development*

The objective of this study is to show the effect of the dissipated energy on the resistance to the fiber-matrix interface of the bio-composite materials consisting of the hemp fiber and the PLA matrix. Our genetic simulation consists to use the values of each of the mechanical properties to calculate the damage level of the interface each time by using the Weibull equations (1, 2) and the Cox equation (3).

The damage to the interface is determined by the non-linear acoustic technique using the variable β in our genetic modeling (Equation 6). The evaluation of each generation is carried out by an objective function based on the Cox model which includes all the variables defined at the beginning of the algorithm (mechanical properties of each composite component, Young's modulus, ...), and finally the equation defining the dissipated energy. We have determined the damage to the fiber length of the interface for the two materials used (Hemp / Epoxy and Hemp / PLA). The numerical calculations are carried out using the software Matlab R2012b.

4.2. *The Organigram of our simulation*

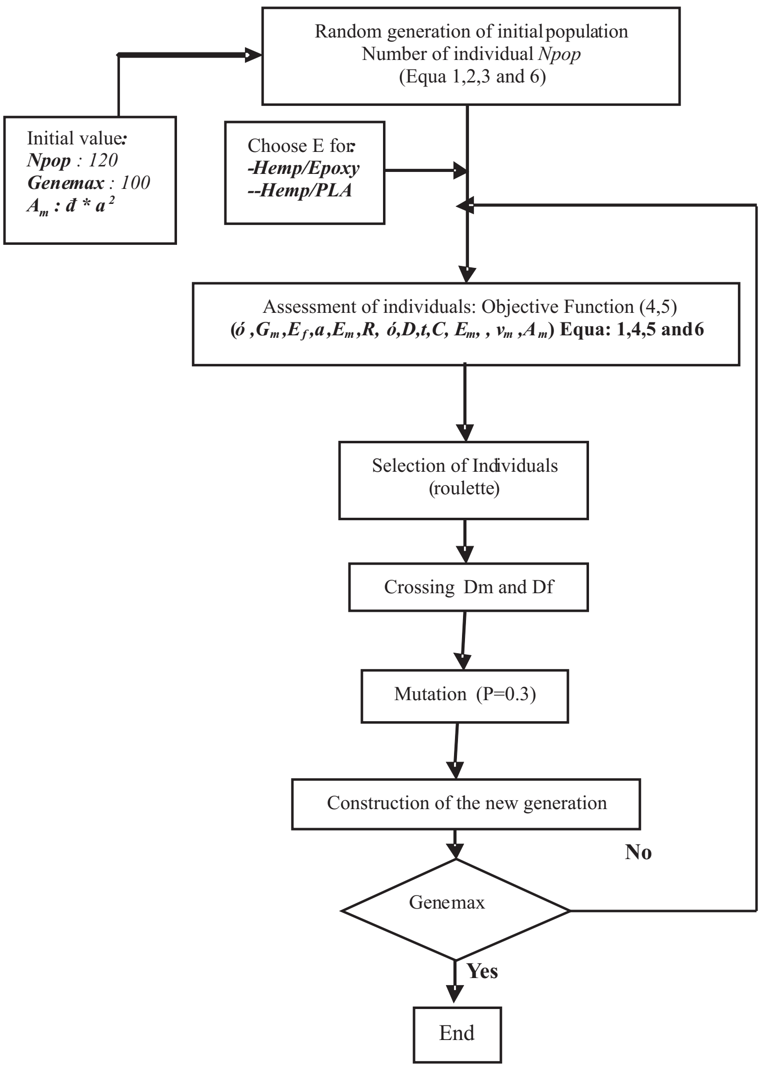

Figure 3 A block diagram of the numerical algorithm

5. Results and discussions

To assert our approach based on the nonlinear acoustic technique, a calculation was carried out on two types of composite materials Hemp/PLA and Hemp/Epoxy. Based on simulation results by a genetic algorithm, we have examined the strength of our material by applying different stresses ((95 N/m^2), (115 N/m^2), (135 N/m^2), which allowed us to calculate the damage to the interface fiber-matrix. Figures 4, 5, 6 and 7, 8, 9 show the level of damage to the interface of Hemp/PLA and Hemp/Epoxy.

Figures 10 and 11 also show that the energy dissipated has a strong influence on the damage of the interface for the two materials studied and when the energy increases the damage increases rapidly in the first cycles (1, 2, 3 and 4) and very quickly for the last charge / discharge cycles (5, 6 and 7).

5.1. *Hemp/Epoxy*

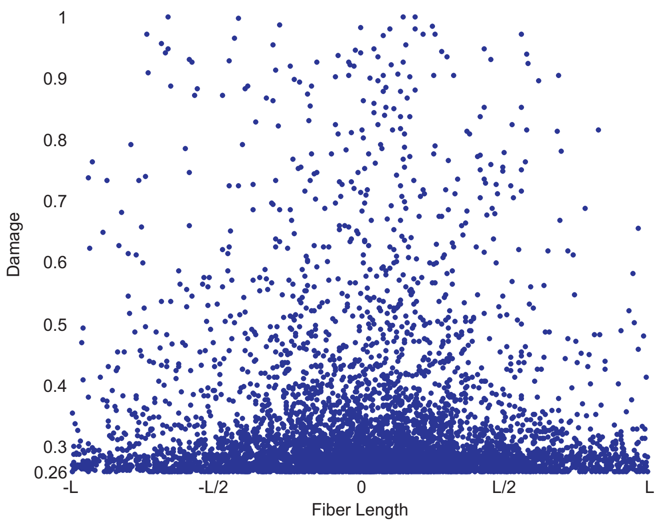

Figure 4 The influence of the stress (95 N/m^2) on the damage of the interface

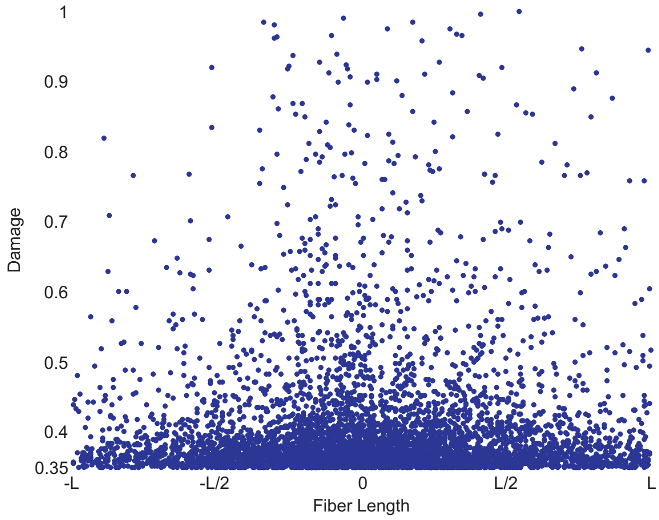

Figure 5 The influence of the stress (115 N/m^2) on the damage of the interface

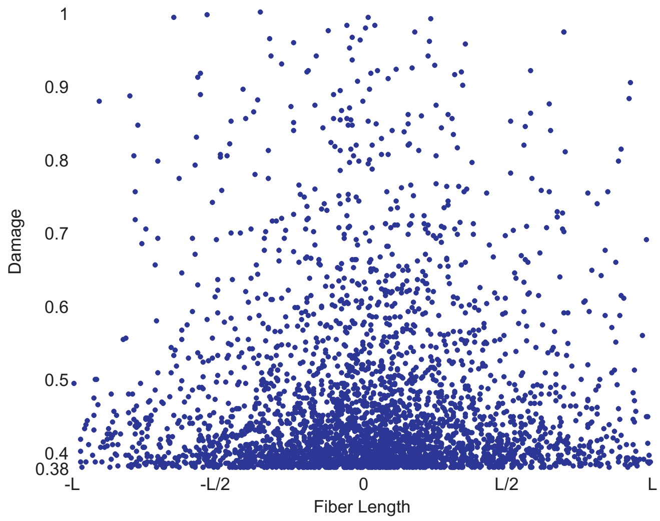

Figure 6 The influence of the stress (135 N/m^2) on the damage of the interface

Figures 4, 5 and 6 show that the "D" interface damage begins at 0.25 (95 N/m^2), then increases to a maximum value of 0.46 (135 N/m^2) , One notices the presence of a symmetry of the damage to the interface, dense in the middle and weak at the ends. It can be said that the increase in level of damage meant the concentration of stresses which gives a strong degradation of the interface in the medium by bringing in the ends.noindent

5.2. *Hemp/PLA*

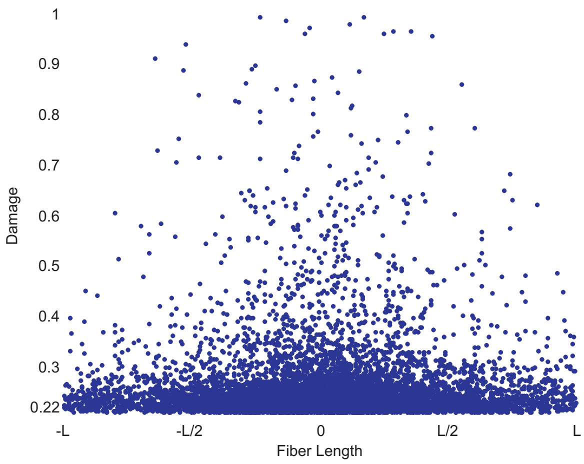

Figure 7 The influence of the stress (9 N/m^2) on the damage of the interface

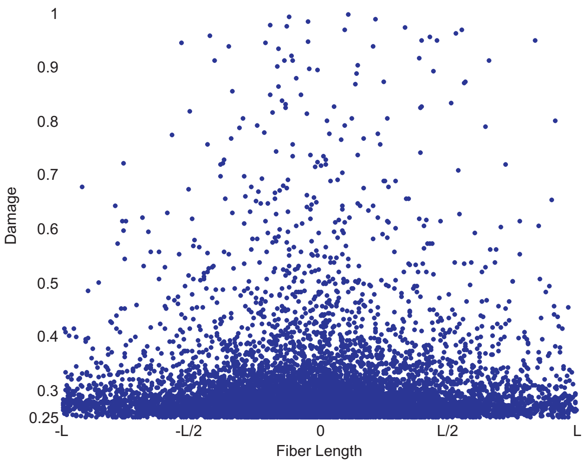

Figure 8 The influence of the stress (115 N/m^2) on the damage of the interface

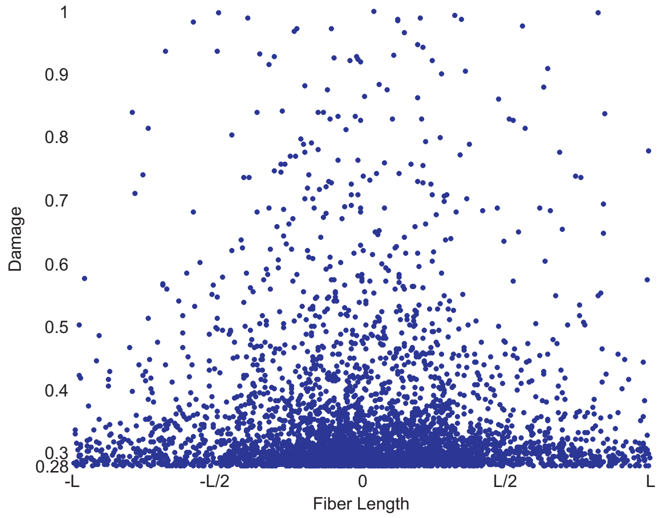

Figure 9 The influence of the stress (135 N/m^2) on the damage of the interface

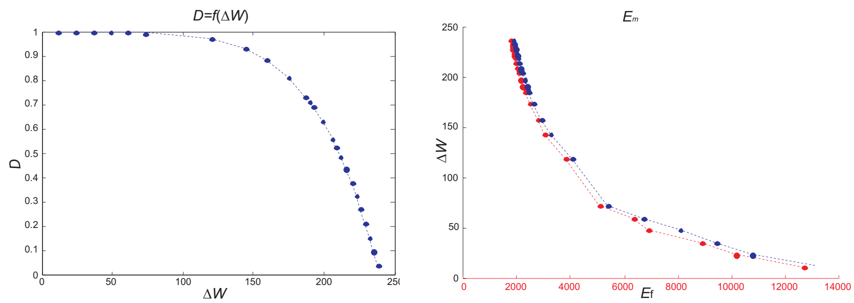

Figure 10 The relationship between energy dissipation and damage to the interface of Hemp/PLA

Figrs. 7, 8 and 9 show that the "D" interface damage begins at 0.21 (95 N/m^2), then increases to a maximum value of 0.37 (135 N/m^2). We find the presence of a symmetry of the damage to the interface, which dense at the middle and weak at the ends. It can also be said that the increase in level of damage meant the concentration of stresses which gives a strong degradation of the interface in the medium by bringing in the ends, values lower than those found for Hemp/Epoxy.

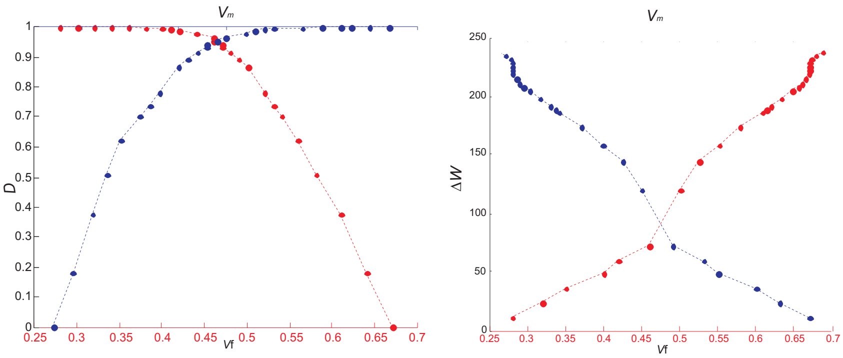

Figure 11 The influence of the volume fraction (fiber and matrix) on the dissipated energy and the damage to the interface of the Hemp/PLA

6. Conclusion

The results found by a genetic calculation, based on the use of the nonlinear acoustic technique, show that the level of damage is related to the material resistance for the two composites that were studied Hemp/PLA and Hemp/Epoxy, and also show good agreement between the numerical simulation and the actual behavior of the two materials. Numerical simulation shows that Hemp/PLA is more resistant than Hemp/Epoxy. The results obtained in our study are in good agreement with the experimental results which showed that Bio-composites have better mechanical properties and are more resistant than composite materials. The results found that our material is resistant, and that gives us more environmental advantage.

References

[1] **Goidescu, C.**: Caractérisation et modélisation de l'endommagement par microfissuration des composites stratifiés - Apports des mesures de champs et de l'homogénéisation, PhD Thesis, **2011**.

[2] **Guillon, D.**: Étude des mécanismes d'absorption d'énergie lors de l'écrasement progressif de structures composites à base de fibre de carbone, PhD Thesis, Université de Toulouse, **2008**.

[3] **Monti, A., el Mahi, A., Guillaumat, L. and Jendli, L. Z.**: Analyse de l'endommagement d'un composite à matrice thermoplastique renforcée de fibres de lin par émission acoustique, *22ème Congrès Français de Mécanique*, **2015**.

[4] **Faruk, O., Bledzki, A. K., Fink, H.-P. and Sain, M.**: Biocomposites reinforced with naturel fibers: 2000-2010, *Progress in Polymer Science*, 37, 1552–1596, **2012**.

[5] **Yan, L., Chouw, N. and Jayaraman, K.**: Flax fibre and its composites - A review, *Composites: Part B*, 56, 296–317, **2014**.

[6] **Charlet, K., Baley, C., Morvan, C., Jernot, J. and Bréard, J.**: Characteristic of Hermés flax fibres as a function of their location in the stem and properties of the derived unidirectional composites, *Composites: Part A*, 38, 1312–1921, **2007**.

[7] **Weibull, W.**: Theory of the strength of materials, *Royal Swedish Academy of Eng. Sci. Proc.*, 151, 1–45, **1939**.

[8] **Cox, H. L.**: The elasticity and strength of paper and other fibrous materials, *British Journal of Applied Physics*, 12, 72–79, **1952**.

[9] **Mokaddem, A., Alami, M., Doumi, B. and Boutaous, A.**: Prediction by a genetic algorithm of the fiber matrix interface damage for composite material. Part1: study of shear damage to two composites T300/914 and Peek/APC2, *Strength Materials*, 46, 4, 543–547, **2014**.

[10] **Doumi, B., Mokaddem, A., Benrekaa, N., Alami, A. Beldjoudi, N. and Boutaous, A.**: Simulation by a Genetic Algorithm and Location by the NonlinearAcoustic Technique of the Shear Damage to the Fiber-Matrix Interface of a Hybrid Composite Material Alfa-Carbon/Epoxy, *Journal of Hybrid Materials*, De Gruyter, 2015;2:10-16. DOI 10.1515/hyma-2015-0002, **2015**.

[11] **Johnson, P. A. and McCall, K. R**. Observation and Implications of Nonlinear Elastic Wave Response in Rock, *Geophysical Research Letters*, 21, 165, **1994**.

[12] **Moussatov, A, Castagnède, B. and Gusev, V.**: Observation of nonlinear interaction of acoustic waves in granular materials : demodulation process, *Phys. Lett. A.*, 283, 21, **2001**.

[13] **Nagy, P. B.**: Fatigue damage assesment by nonlinear ultrasonic material chracterization, *Ultrasonics*, 36, 375, **1998**.

[14] **El Guerjouma, R., Faiz, A., Godin, N., Bentahar, M and, Baboux, J. C.**: Linear and non linear ultrasonics for material damage evaluation and health monitoring, *Matériaux et Techniques*, 48, **2002**.

[15] **Van Den Abeele, K. E. and Johnson, P. A.**: Elastic Pulsed Wave Propagation in media with second or higher-order nonlinearity. Part II. Simulation of Experimental Measurement on Berea Sandstone., *J. Acoust. Soc.*, 99, 6, **1996**.

[16] **Van Den Abeele, K. E.**: Elastic Pulsed Wave Propagation in media with second or higher-order nonlinearity. Part I. Theoretical framework, *J. Acoust. Soc.*, 99, 6, **1996**.

[17] **Caillol, S.**: Synthese et caracterisation de nouveaux copolymeres potentiellement autoassociatifs, *Material chemistry*, Universite Sciences et Technologies - Bordeaux I, in French, **2002**.

[18] **Maghchiche, A.**: Characterisation of Esparto Grass Fibers Reinforced Biodegradable Polymer Composites, *Biosciences Biotechnology Research*, 10, 2, 665–673, **2013**.

[19] **Pras, O.**: Utilisation de cellulose pour l' elaboration de mat eriaux photoluminescents ou conducteurs, *Universite de Grenoble*, in French, **2011**.

[20] **Wertz, J-L.**: Les biocompositess et composites polym'ere-chanvre en particulier, Unite de Chimie biologique industrielle, *Universite de Li'ege – Gembloux Agro-Bio Tech.*, **2014**.

[21] **Tadjedit, s., Mokaddem, A., Temimi, L., Doumi, B., Boutaous, A. and Beldjoudi, N.**: Comparative study by a genet rials reinforced with natural fiber, *Journal of Mechanics and Mechanical Engineering*, 20, 3, **2016**.

[22] **Maghchiche, A., Haouam, B. and Immirzi, A.**: Extraction and characterization of algerian alfa grashort fibers (stipa tenacissima), *Chemistry and Chemical Technology*, 7, 3, **2013**.

[23] **Pras, O.**: Utilisation de cellulose pour l' elaboration de matériaux photoluminescents ou conducteurs, *Universite de Grenoble*, in French, **2011**.

[24] **Wertz, J-L.**: Les biocompositess et composites polym'ere-chanvre en particulier, Unité de Chimie biologique industrielle, *Université de Liège – Gembloux Agro-BioTech.*, **2014**.

[25] **Ilczyszyn, F., Cherouat, A. and Montay, G.**: Mechanical behaviour and properties characterization of hemp fibres, *Matériaux & Techniques*, 100, 5, https://doi.org/10.1051/mattech/2012015, **2012**.