ANALYSIS OF THE CYCLIC FATIGUE BEHAVIOR OF ECO-COMPOSITE JUTE GREENPOXY56

Sid Ahmed BENMANSOUR[1, 2, *], Mohammed BENRAMDANE[3], Abdel Karim FEROUANI [1], Nadjib Sidi Mohamed SERDOUN [1], Abderrahim EL MAHI[4] , Abderrahim BENMOUSSAT[2]

[1] Ecole Supérieure en Sciences Appliquées de Tlemcen, ESSA -Tlemcen, Algeria.
[2] Material and corrosion researching Equip, LAEPO, research Laboratory University of Tlemcen, Algeria.
[3] ETAP Laboratory, Department of mechanical engineering, Faculty of technology, University of Tlemcen, Algeria.
[4] University of Maine Acoustics Laboratory (LAUM UMR CNRS 6613) Le Mans. France

* Corresponding Author Email : benman65@yahoo.fr

Abstract

This work focuses on the experimental analysis of the cyclic fatigue behavior of the eco-composite material jute Greenpoxy 56. The obtained results enabled us to accurately assess the lifespan of the laminated materials through tensile cyclic fatigue tests. The progression of damage was examined by tracking key indicators—including applied load, dissipated energy, and mean displacement—over the course of the cycling process. The results highlighted the properties of the jute fibers, the advantages of the effects of the eco-composite's orientation with a chain-direction stacking sequence on the mechanical fatigue behavior, and the damage mechanism leading to laminate failure.

Keywords: Eco-composites; Mechanical characterization; Jute fiber; Laminates; Fatigue behavior; GREENPOXY56.

1) Introduction

Since antiquity, humankind has been interested in using plant fibers in various practical fields, such as rope and textile manufacturing. Some traditional materials, like clay bricks or plaster, were the first to be used in composite materials reinforced with plant fibers. Following technological advancements, synthetic and natural fibers have expanded the applications of composites in numerous sectors (aerospace, automotive, housing, sports, defense, etc.).

Natural composites have a specific stiffness comparable to that of glass fiber composites [1,2], obtained by combining two elements: a reinforcement and a natural resin, resulting in an environmentally friendly material. This is the main reason for the interest shown by several research studies on their mechanical properties [3,4].

Fatigue damage and failure remain highly complex phenomena—whether in traditional materials or eco-composites—making them difficult to interpret and predict. As a result, they are most often analyzed through statistical distributions and probability-based approaches.

The elastic mechanical behavior of a laminated composite structure generally takes into account transverse shear, based on an evaluation of displacement fields that considers that a normal to the mean plane of a test piece remains a straight-line during deformation. However, this deformation does not remain normal to the deformation of the mean plane [5,6].

The influence of reinforcements and their architecture, as well as an increase in stiffness, have been highlighted in several studies conducted to characterize the fatigue behavior of eco-composites reinforced with jute, flax and hemp plant fibers [7]. Unidirectional and cross-laminated flax fiber composites and unidirectional composites dissipate more energy than cross-laminated flax fiber composites, which can be explained by the difference in temperature recorded during fatigue tests on the two material configurations. The temperature recorded for the unidirectional composite is twice as high as for the cross-laminated composite [8].

Several studies carried out on different eco-composite configurations and stacking sequences have shown that plant fiber composites offer clear advantages in terms of density and specific strength when compared with glass fiber composites [9,10]. Researchers have confirmed that the fatigue behavior of eco-composites depends heavily on the reinforcement architecture, with UD, laminated and woven configurations in particular showing very interesting fatigue resistance, comparable to synthetic fiber-reinforced composites, making it entirely feasible to consider using these materials for interesting industrial applications [11].

2) Materials and method

2-1) Eco-composite preparation

The experimental study was carried out by using composite material woven jute fibers (surfacic weight of 390 g m-2) and a green SR epoxy resin 56. The preparation of the composite is obtained by successive laminating warp direction oriented layers (O2)s for four plies. We have considered a plate of dimensions 400 mm x 400 mm and a nominal thickness of 4 mm, molded under vacuum (0.6 bar depression) for 8 hours between the mold and the counter-mold after the insertion of various molding tissues using the so called bag technique. However, it allows the production in large series of small pieces potentially complex [12].

The green epoxy resin SR 56 is an epoxy resin of which 56% of the molecular structure is of plant origin supplied by Sicomin. The polymerization rate at room temperature makes it easy to produce a large number of samples. The sample cutting test was performed with a diamond saw blade in the direction of the warp and weft fibers, from plates, according to ASTM D 3039 norm.

2-2) Mechanical tests

The four-layer jute/GreenPoxy 56 laminate—featuring two jute fiber orientations (warp and weft)—was subjected to cyclic fatigue testing. All experiments were carried out at a crosshead speed of 2 mm/min on composite specimens measuring 200 × 20 × 3.5 mm^3, using a testing machine equipped with a 100 kN load cell. Strain was recorded with a 25 mm gauge-length axial extensometer (5 mm stroke), under room-temperature and displacement-controlled conditions (Figure 1). The applied loading followed a sinusoidal waveform at a constant frequency of 5 Hz (Figure 2).

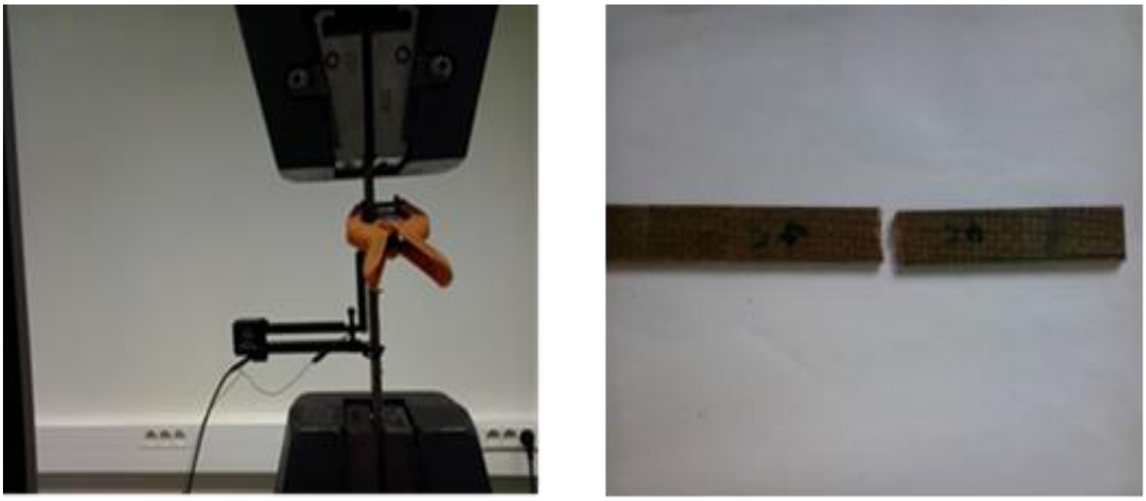

Figure 1: Mechanical properties obtained from static tests in the warp and weft fibers direction [12].

Table 1 :Mechanical properties obtained from static tests in the warp and weft fibers direction [12].

Fiber orientation	E (Young Modulus) GPa	σR (Ultimate stress) MPa
Warp fibers direction	7.437	73.984
Weft fibers direction	3.481	22.981

2-3) Characterization of laminates under cyclic loading

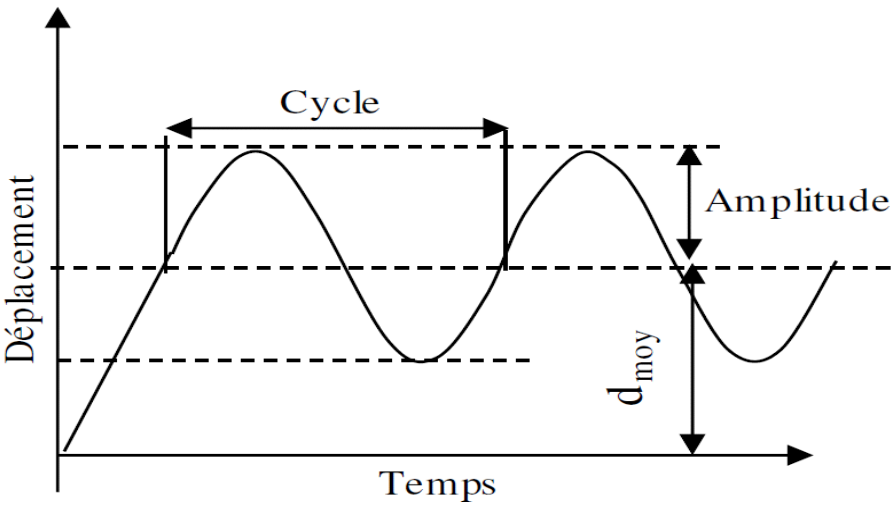

Figure 2: Example of a sinusoidal waveform for a fatigue test [13].

The matrix absorbs the dissipated energy, which is useful for estimating the fatigue behavior of laminates. In our study, the laminate test specimens are loaded in tension according to two fiber orientation configurations and then subjected to cyclic fatigue. When the load is sufficiently high, plastic deformation and damage are induced. The hysteresis loop formed is described by two phases: a loading phase, during which the load and displacement increase, and a second unloading phase. The maximum potential energy $E_{(p)}$ supplied to the system is represented by the total area under the loading curve (Figure 3).

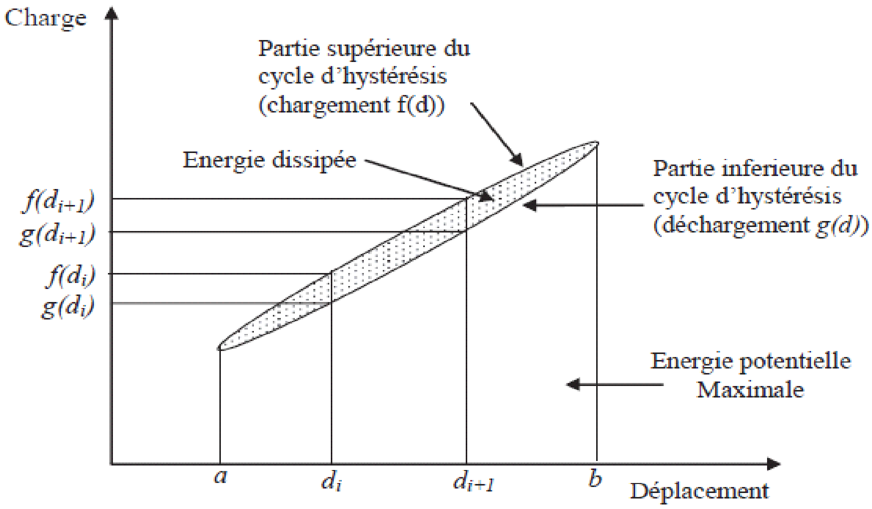

Figure 3: Hysteresis cycle representing potential energy and dissipated energy [14].

3) Analysis of mechanical behavior under cyclic fatigue

Two configurations of laminated eco-composite materials $[0_2]s$ and $[90_2]s$ were subjected to cyclic tensile fatigue. The tests were conducted by selecting a constant average displacement of 0.5 mm and varying the amplitude from 0.05 mm to 0.4 mm. During the tests, displacement and loading were recorded up to 10,000 cycles.

3-1) *Evolution of stiffness under cyclic fatigue*

For a given displacement and amplitude, the variations in the applied load were measured as a function of the number of cycles for the two fiber orientation configurations studied. Stiffness measurements obtained under cyclic loading are among the most widely used indicators for assessing material degradation during fatigue testing. Throughout the experiments, the evolution of the maximum load F_{max} is continuously monitored as a function of the number of cycles. The maximum load

$F_{(max)}$ is related to that obtained in the first cycle $F_{(omax)}$ .The evolution of the maximum load ($F_{(max)}/F_{(omax)}$) as a function of the number of cycles is shown in Figures 4 and 5 for different amplitudes and for the two configurations studied (warp direction and weft direction).

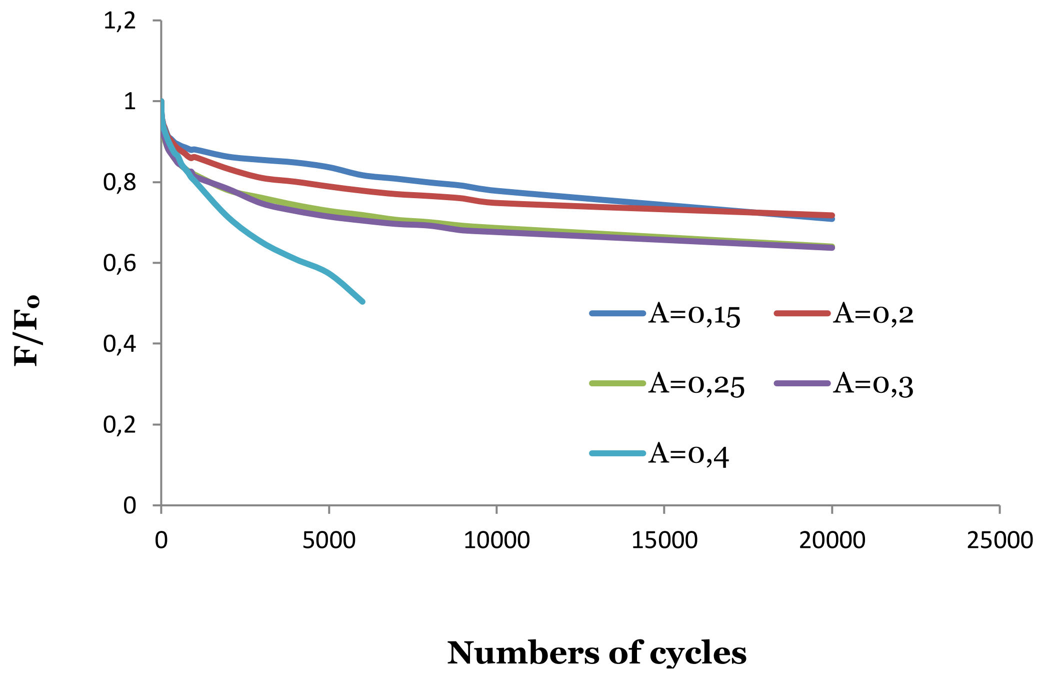

Figure4: Change in the F/Fo as a function of the number of cycles for different amplitudes for a warp fiber orientation

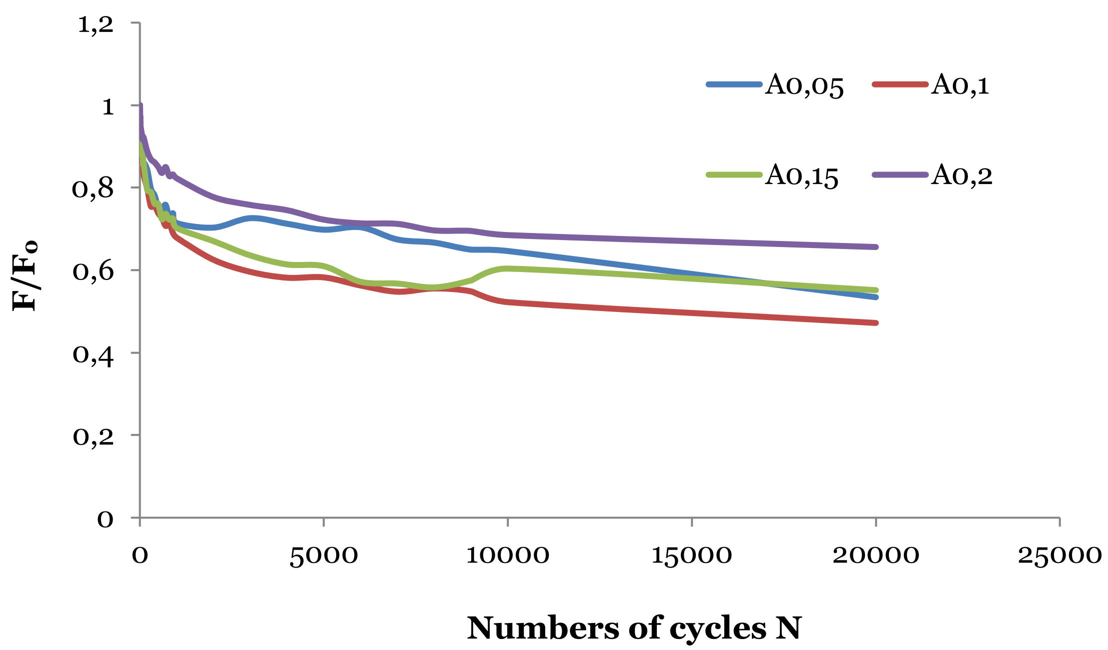

Figure 5: Change in the F/Fo as a function of the number of cycles for different amplitudes for a weft fiber orientation

The loss of stiffness, characterized by the decrease in maximum load, occurs in three distinct phases, as is the case for most composites. The first and second phases are characterized by a pronounced decrease in the F_{max}/F_{0max}ratio starting from the very first cycles. This reduction then continues progressively throughout the third phase, which extends over nearly the entire duration of the test, until the specimen ultimately fails. These two stages are attributed to the rapid onset of damage mechanisms during the first cycles and their propagation in the material following loading.

For all tests, a variation in the F_{max}/F_{omax} as a function of the number of cycles can be observed before failure. Thus, the F_{max}/F_{omax} corresponding to the same amplitude level for both fiber orientations (warp and weft) was compared. The results are shown in Figure 6.

It should be noted that the characteristics of the fatigue phenomenon (loss of stiffness) can be seen in three phases, as follows:

- Two phases, the first of which corresponds to a rapid decrease in loss of stiffness (F_{max}/F_{omax}) during the first 100 cycles. It is 4% for laminates with a fiber orientation in the warp direction $[0_2]$s and 7% for laminates in the weft direction $[90_2]$s. This phase corresponds to the elastic deformation of the fiber cell walls and the initiation and the appearance of micro-cracks in the resin and fibers, mainly due to manufacturing defects such as porosity and micro-defects , followed by a second phase representing a slight decrease in the loss of stiffness, which stabilizes at 2,000 cycles with a 15% loss of stiffness for the $[0_{(2)}]$s laminate configuration and at 3,000 cycles with a 22% loss of stiffness for the $[90_2]$s, corresponding to the propagation of microcracks in the material.
- The third phase represents the loss of stiffness, revealing a sudden increase in damage up to 25,000 cycles, leading to a loss of stiffness of 20% for the test pieces with a fiber orientation of $[0_2]$s and 25% for the test pieces with a fiber orientation of $[90_2]$s.

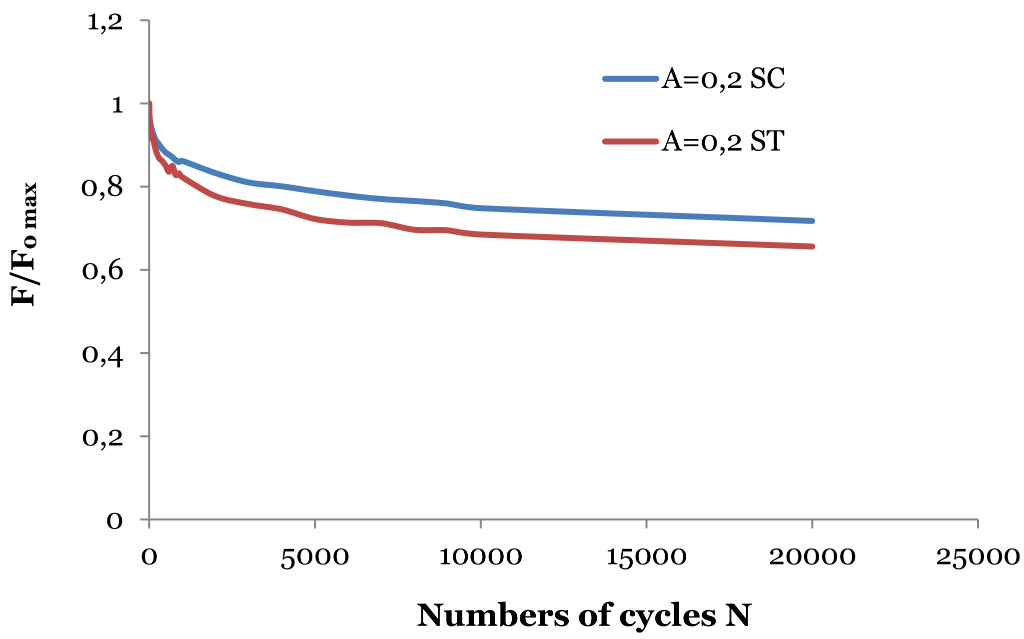

Figure 6: Comparison of the evolution of the F/Fo ratio as a function of the number of cycles for the same amplitude for a warp and weft fiber orientation

3-2) *Evolution of hysteresis cycles for the laminate*

The hysteresis loops have a quasi-elliptical topology and are obtained for at least 200 experimental points recorded for each cycle during cyclic fatigue tests applied to jute specimens, based on experimental data on load and displacement as a function of time. An example corresponding to laminates tested in tension for a warp and weft fiber orientation is shown in Figures 7 and 8.

These two figures show the evolution of the hysteresis loops obtained for different numbers of cycles (1, 10, 100, 1000 and 10,000) of the laminates. Each laminate configuration shows different load peaks on the hysteresis curves, but the behavior remains similar for both fiber orientations. The results show that as the number of cycles increases, the maximum load—represented by the peak of the load–displacement curve—decreases, while the inner area of the hysteresis loop increases. This reduction in maximum load, combined with the enlargement of the hysteresis area, reflects the progressive development of micro-damage within the material. As cycling continues, the laminated eco-composite begins to behave locally like a continuous, non-porous medium. Consequently, intensified friction mechanisms lead to a greater amount of energy being dissipated, primarily through the Joule effect.

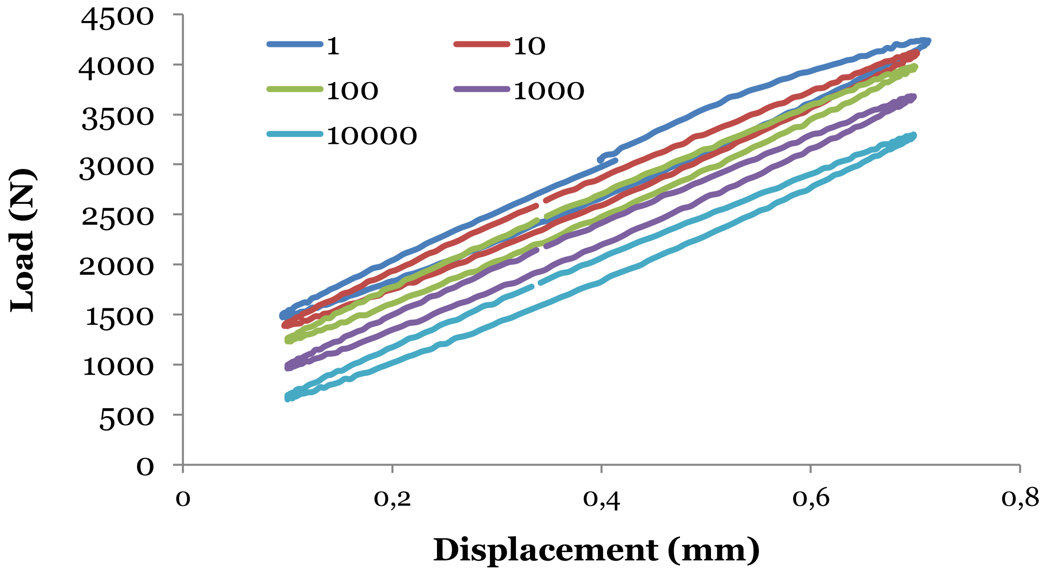

Figure 7: Hysteresis loops for different numbers of cycles for a test piece with warp-oriented fibers.

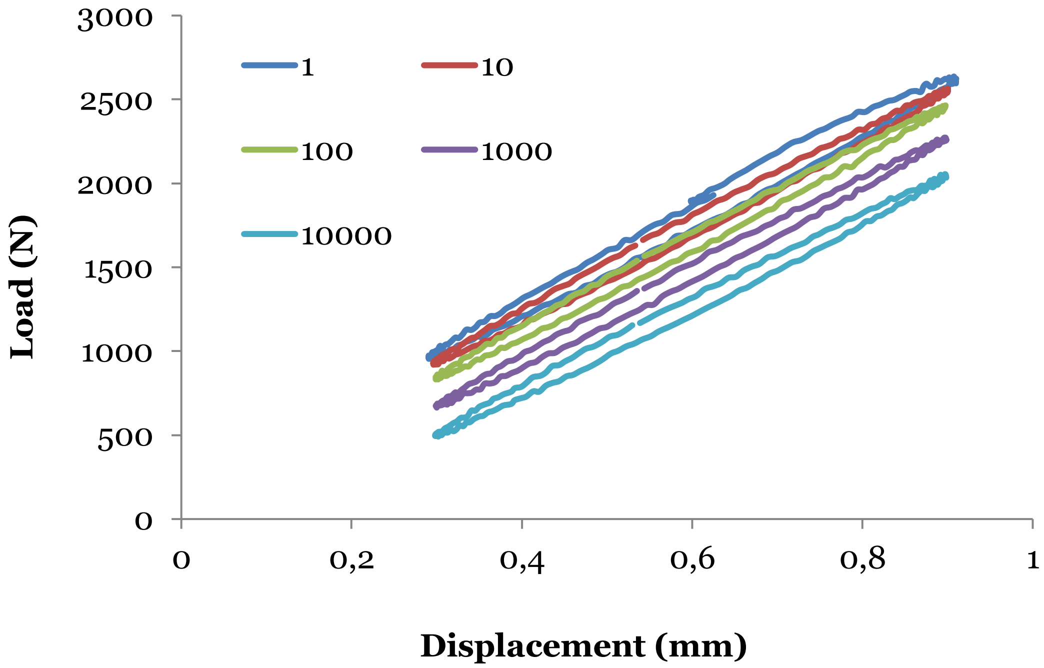

Figure 8: Hysteresis loops for different numbers of cycles for a test piece with weft-oriented fibers.

3-3) *Energy dissipated for the laminate*

The dissipated energy is the quantity used to estimate the fatigue behavior of laminates. The test specimens are loaded in tension and then subjected to cyclic fatigue. When the load is sufficiently high, plastic deformation and damage occur. The load-displacement curve is loop-shaped due to hysteresis.

The trapezoidal method is used for the numerical calculation of dissipated energy, considering that the cycle consists of 2n measurement points, $f(d_i)$ the image of the displacement point di on the loading phase, and $g(d_i)$ its image on the unloading phase, then The interior area generated by the loading-unloading curves as a function of the number of cycles represents the energy dissipated during a cycle E_d is given by [58], while the area under the upper part of the load/displacement loop of a cycle represents the maximum deformation energy E_p and the restored energy E_r represents the area under the discharge curve .

For a given number of cycles (N), the maximum potential energy E_p, the restored energy E_r and the dissipated energy E_d are given by the following relationships:

$$E_P = \frac{1}{2}\sum_{i=1}^{n}(d_{i+1} - d_i)(f(d_{i+1}) + f(d_i)) \quad (1)$$

$$E_r = \frac{1}{2}\sum_{i=1}^{n}(d_{i+1} - d_i)(g(d_{i+1}) + g(d_i)) \quad (2)$$

$$E_d = \frac{1}{2}\sum_{i=1}^{n}(d_{i+1} - d_i)\big((f(d_{i+1}) + f(d_i)) - (g(d_{i+1}) + g(d_i))\big) \quad (3)$$

3-4) *Analysis of the effects of fiber orientation and load amplitude on dissipated energy*

Figures 9 and 10 show similar behavior of dissipated energy as a function of the number of cycles of the eco-composite laminate for both fiber orientations (warp and weft).

The energy dissipated decreases as the number of cycles increases. This decrease is much more pronounced in the first cycles and becomes practically constant and flat for a high number of cycles. In fact, the energy dissipated is twice as high in the laminate with a warp fiber orientation than in the laminate with a weft fiber orientation.

At the beginning of the cyclic fatigue tests, the deformations of the specimens are reversible. As micro-cracks appear in the resin, the folds start to deteriorate, eventually allowing fiber–matrix delamination to occur. After several hundred cycles, the matrix begins to separate from the fibers, and the fabric fibers start to tear, ultimately resulting in complete failure.

The energy dissipated also depends on the amplitude applied during the cyclic fatigue test. For a given number of cycles, the energy dissipated by the laminate with a high amplitude is greater than that of the laminate with a lower amplitude.

The decrease in energy dissipated at the start of the cyclic test is much more noticeable for an amplitude of 0.1 mm. After a few dozen cycles, the energy dissipated has become virtually constant, whereas it continues to decrease in the other case. Microcracks propagate more easily in laminates with fibers oriented in the weft direction and with lower amplitudes.

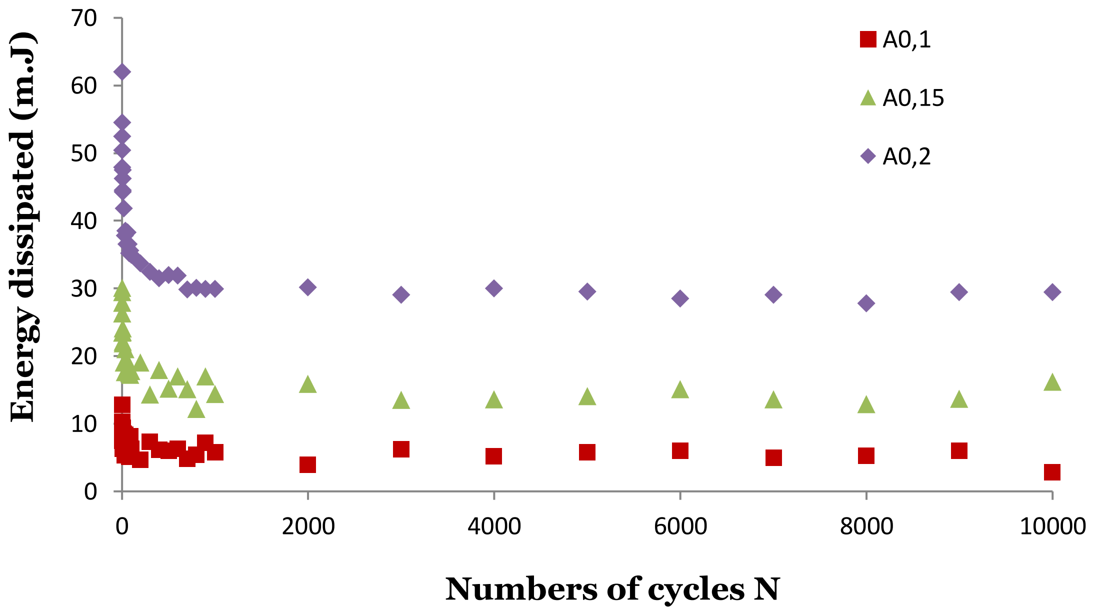

Figure 9: Energy dissipated as a function of the number of cycles for a warp-oriented fiber orientation

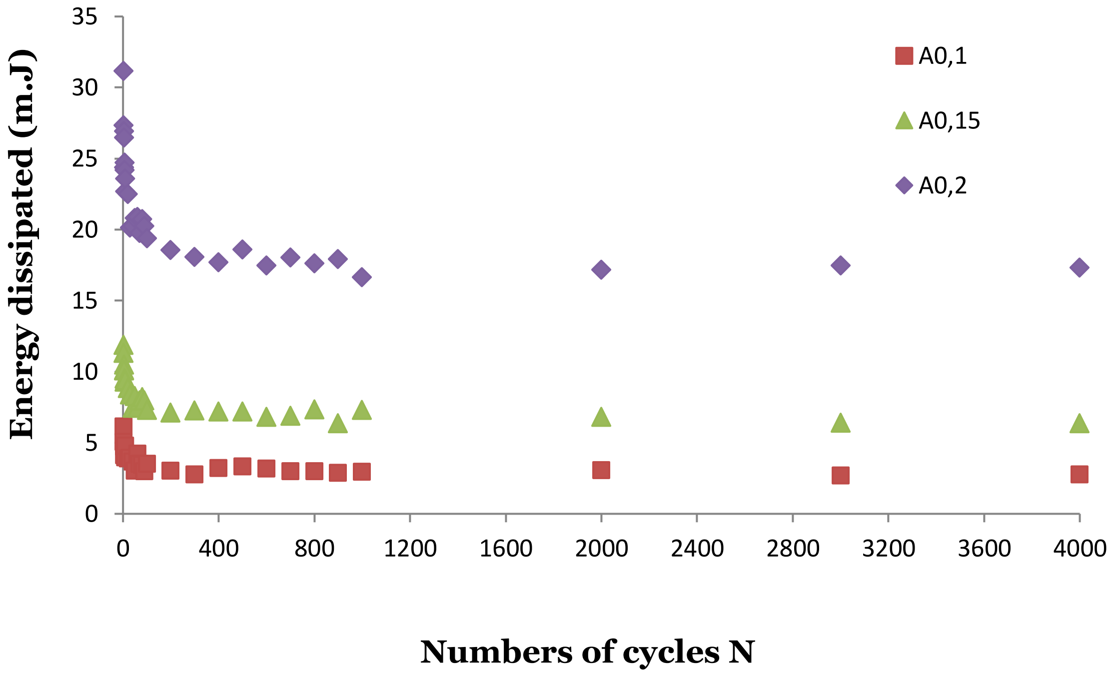

Figure 10: Energy dissipated as a function of the number of cycles for a weft-oriented fiber orientation.

3-5) Material Lifespan

Under fatigue at lower load levels, in traction with imposed displacement, a clean break of the test specimens is not often observed. For the construction of the Wöhler curves, two end-of-life criteria were defined, denoted N20 and N25, corresponding respectively to a 20% and 25% reduction in the initial load. Figures 11 and 12 show the results obtained for the service life for the two fiber orientations and for the different imposed load levels, with the number of cycles required to reach the criteria defined above. Due to the considerable data scatter, trend lines were applied and plotted to interpolate the results. The analysis shows that laminates with weft-oriented fibers exhibit a shorter service life compared to those with fibers oriented in the warp direction.

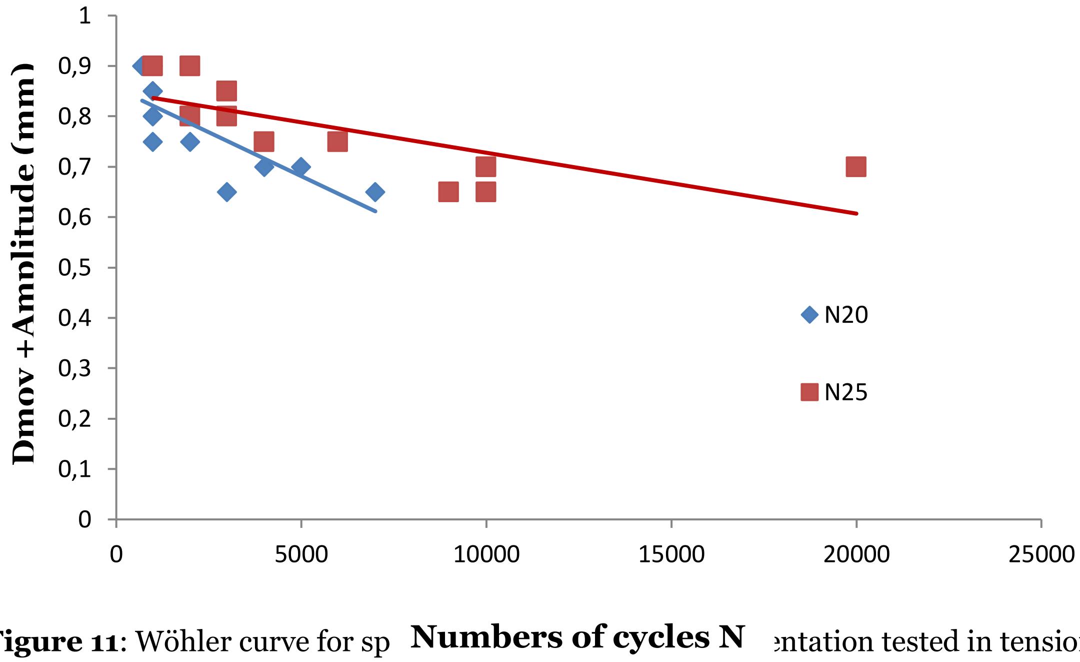

Figure 11: Wöhler curve for sp entation tested in tension for different amplitudes.

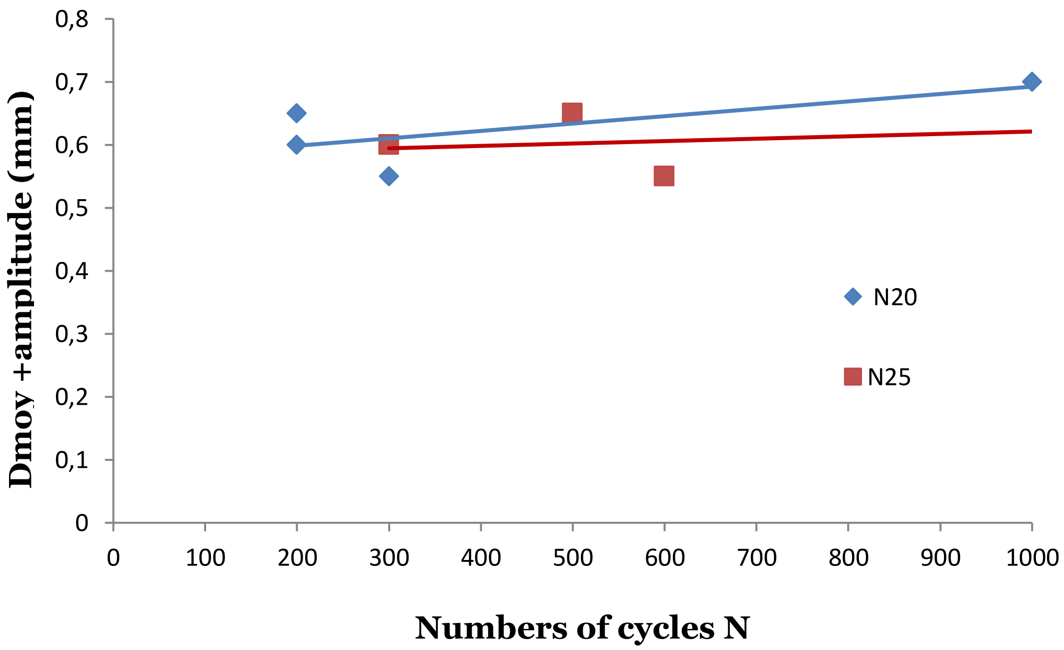

Figure 12: Wöhler curve for specimens with weft-oriented fibres tested in tension for different amplitudes.

The convergence towards unity clearly shows that, for a load level close to 100%, failure occurs after the first few cycles. Once again, we see a dispersion of results characteristic of the fatigue phenomenon. However, this dispersion is greater for tests on specimens with a $(90°_2)s$ configuration.

4) Conclusion

Dynamic fatigue tests were carried out on jute/GreenPoxy 56 laminated eco-composites to investigate their mechanical behavior under tension, taking fiber orientation into account. The experiments were conducted using displacement-controlled loading, with a sinusoidal waveform applied at a frequency of 5 Hz.

The maximum load, amplitude and dissipated energy were monitored as a function of the number of cycles. The results of the evolution of mechanical properties as a function of the number of cycles for each type of fiber configuration were presented. The results obtained highlighted the influence of jute on the cyclic fatigue behavior of laminates and the effects of reinforcement fiber orientation combined with a partially biodegradable resin on the energy dissipated. The stiffness and evolution of the hysteresis loops were analyzed.

The results showed a compromise between bio-based content and service life management. This led to the development of an eco-composite structure with a thermosetting matrix reinforced with jute fibers. This is one of the first thermosetting bio-based matrices suitable for previously well-defined processes, which opens up new prospects for the production of parts of different sizes using the lamination process for the implementation of composite structures.

Moreover, literature studies have emphasized the advantageous properties of jute fibers, which notably display non-linear behavior under tension, a characteristic arising from the inherent microstructure of these natural fibers. This behavior can be found in jute fiber-reinforced composites. Consequently, these fibers are an attractive choice for the production of eco-composite materials that meet the criteria of rigidity and durability.

Furthermore, the three phases of the loading curves or the amplitude as a function of the number of cycles according to the different configurations can be explained by the initiation of resin cracking in the first phase, followed by its stable propagation leading to fiber/matrix delamination in the second phase, and finally fiber breakage leading to material failure in the last phase. The first stage accounts for only 25% of the service life, while corresponding to 75% of the damage rate.

The results have shown the advantages of the effects of eco-composite orientation with a chain-direction stacking sequence on the mechanical fatigue behavior and on the damage mechanism leading to laminate failure.

5) Acknowledgements:

The authors are very grateful to LAUM Acoustics Laboratory, LeMans University, France, for their great help to make a part of this work to be done. They appreciate to thank Professor Abderrahim EL MAHI for his experimental contribution.

REFERENCES

[1] K. Oksman, “High quality flax fiber composites manufactured by the resin transfer moulding process”, Journal of Reinforced Plastics and Composites, 20 (2001), pp : 621–627.

[2] J. Baets, D. Plastria, J. Ivens, I. Verpoest, “Determination of the optimal flax fibre preparation for use in unidirectional flax/epoxy composites”, Journal of Reinforced Plastics and Composites, 33 (5) (2014), pp: 493–502.

[3] D. Scida, M. Assarar, C. Poilâne, “Influence of hygrothermal ageing on the damage mechanisms of flax/fiber reinforced epoxy composite”, Composites Part B, 48 (2013) pp:51–58.

[4] F. Z. Arrakhiz, M. Elachaby, R. Bouhfid, et al., “Mechanical and thermal properties of polypropylene reinforced with Alfa fiber under different chemical treatment”, Materials and Design, 35 (2012), pp: 318–322.

[5] J. M. Berthelot, “Comportement mécanique et analyse des structures”, Matériaux Composites, Éditions TEC & DOC, 4ème édition, (2006).

[6] J. M. Berthelot, “Mechanical Behaviour and Structural Analysis», Composite Materials, New York Springer, U. S. A., (1999).

[7] Darshil U. Shah, Peter J. Schubel, Mike J. Clifford, and Peter Licence. Fatigue life evaluation of aligned plant fibre composites through S-N curves and constant-life diagrams”. Composite Science and Technology, 74 (2013), pp: 139–149.

[8] M. Haggui, A. El Mahi, Z. Jendli, A. Akrout and M. Haddar, “Static and fatiguecharacterization of flax fiber reinforced thermoplastic composites by acoustic emission”, Applied Acoustics,147 (2019), pp:100-110.

[9] S. Liang, P. B. Gning, and L. Guillaumat, “A comparative study of fatigue behavior of flax epoxy and glass epoxy composites”. Composites Science and Technology, 72 (2012), pp : 535–543.

[10] S. Liang, P. B. Gning, and L. Guillaumat, “Properties evolution of flax epoxy composites under fatigue loading”, International Journal of Fatigue,63 (2014), 36–45.

[11] F. Bensadoun, K.A.M. Vallons, L. B. Lessard, I. Verpoest and A.W. Van Vuure “Fatigue behaviour assessment of flax epoxy composites” Composites Part A, 82 (2016), pp: 253–266.

[12] S.A. Benmansour, A. Benmoussat, A. El Mahi, A. Bourdim, “Static And Dynamic Characterization Of A Woven Eco-Composite Young‟s Modulus And acoustic Emission Analysis”, U.P.B. Sc. Bull., Series D, 82(2020),pp:19-30

[13] H. Daoud, “Contribution à l’étude du comportement mécanique et vibratoire des composites biosourcés incorporant des matériaux fonctionnels”, Thèse de Doctorat, Université de Sfax, Tunisie, (2018).

[14] M. Idriss, “Analyse expérimentale et par élément finis du comportement statique et vibratoire des matériaux, Thèse de doctorat, Université du Maine, Le Mans, France, (2013).