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Fatigue in sisal fiber reinforced polyester composites: hysteresis and energy dissipation

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Abstract

Natural fibre reinforced polymer biocomposites (NFPBCs) constitute an important branch in the field of green composite materials. The work describes the fatigue behaviour of polyester biocomposites reinforced with natural sisal fibres and stacked as cross laminates with $[0/90]_s$ sequence Three-point bending static and cyclic tests have been used to investigate the fatigue behaviour of these particular bio-reinforced composites. The cyclic tests have been carried out at 1.5 Hz of frequency using a sinusoidal waveform and loading levels varying between $r_d = 0.55$ to 0.95 and the curves of stiffness degradation (F/F_0) has been plotted. Failure is reached after the first few cycles for high loading levels, whereas for low values of r_d (0.55) fracture is only partial, even after reaching one million of cycles.

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*Keywords:*sisal fibre, polyester, biocomposite, 3-point bending, fatigue

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1. Introduction

In the recent years researchers have developed new classes of sustainable material, and natural fibre "green" composites have shown significant interest within the community because of their recyclability and biodegradation characteristics useful in applications to replace currently status-of-the-art synthetic fibres (e.g. glass fibres) **[1]**. The need to preserve agricultural natural resources has pushed composite industries to consider natural fibres produced with eco-friendly methods, which can be obtained at a low price using locally available manual labour and green material **[2]**. Natural fibre biocomposite are in general low cost, low density and feature high specific strength and modulus. These biocomposites are intrinsically recyclable and easy to source locally because they are already

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present in fibrous form **[3]**. Vegetable bio-fibres that have been extensively evaluated are flax **[4],** sisal **[5] [6]**, cactus **[7]** and hemp **[8]**, all exhibiting high specific mechanical properties compared to glass fibres ones.

Regarding the fatigue behaviour of single sisal fibres, more recently Belaadi *et al* **[6]** have observed the quasi-static tensile and fatigue behaviour of single sisal fibre at gauge length GL=20 mm. Tensile cyclic fatigue loading at eight loading levels (from 0.6 to 0.95) has been carried out. The experimental results lead to significant dependence of the hysteresis loops, energy dissipation of the sisal fibres versus the cycle and loading ratio levels. The values for $r_d = 0.60$, dissipated energy (E_d) is almost constant at value around 1.2 mJ. However, for higher level at $r_d = 0.95$ of dissipated energy are observed around to 3.2 mJ during the first cycle.

The present paper describes the flexural fatigue behaviour under displacement-control loading of a cross ply laminate $[0/90]_s$ sisal/polyester biocomposite. A series of fatigue test measurements was performed on samples at different values of loading levels r_d, defined as the ratio of dynamic loading level with respect to the static failure load. The use of those cyclic loading characteristics leads to a different and more pronounced hysteresis loops, with a strong dependency over the number of cycles and the loading ratios used.

2. Manufacturing and testing

The details of sisal fibres used in this work have been reported by the authors in a previous work **[6]**. The mechanical properties of the sisal fibres considered are a tensile strength of 462 ± 71 MPa, ultimate strain of 7.83 ± 1.25 % and tensile modulus of 7.47 ± 1.37 GPa, all obtained at a gauge length GL=20 mm **[6]**. The chosen polyester resin has a 32 MPa in tensile strength, 2.7 % in elongation, 1.12 GPa in tensile modulus, and a density of 1410 kg/m^3. The composite plates have been produced using a moulding technique at low pressure, with impregnation at room temperature (21°C). The plates were allowed to cure for 24 hours at room temperature before removing the mould. To get a complete polymerization of the resin, the plates are kept at room temperature in the open air for 15 days before being cut into specimens using a diamond saw according to ASTM D 790. The weight fraction for the composites prepared was 25%.

The static and fatigue tests performed in 3-point bending have been carried out with a testing machine type Zwick-Roelle Z005 type, with a 5 kN load cell. The quasi-static flexural loading has been applied following ASTM D 790, with a constant velocity of 2 mm/min, while tensile fatigue tests, were conducted under displacement control, with a sinusoidal waveform at 1.5 Hz frequency. The fatigue tests were carried out at a mean displacement level corresponding to 50 % ultimate flexural displacement corresponding to static failure. The loading level r_d ($r_d = d_{max}/d_{fail}$) imposed on the specimens have been used (0.55-0.95). The fatigue test has been repeated at least three times. The tests were carried out at a room temperature of around 21 °C.

3. Results and discussions

3.1. Static tests

The static tests were performed on cross ply laminates sisal/polyester at room temperature and the typical curve of the mechanical stress-displacement behavior is shown in **Figure 1**. It is noted that the stress-displacement curve of the cross-laminate $[0/90]_s$ is characterized by three regions. The first one corresponds to a quasi-linear behavior (displacement from 0 to 4.8 mm), while second region staircase behavior has registered (up to a deflection of about 5 and 6.5 mm), corresponding to the initiation of cracks in matrix. Increasing the load causes the development of these cracks to the sudden rupture of the specimen at 8 mm in displacement. The average value of the mechanical properties of the biocomposite such as ultimate flexural load, ultimate flexural strength and Young modulus, respectively are 234 N, 102 MPa and 6090 MPa.

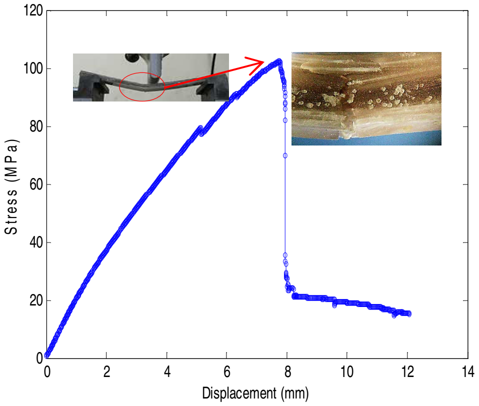

Fig.1. Stress–displacement curves for the 3-point bending of cross ply laminates sisal/polyester biocomposite.

3.2. Fatigue tests

Fig. 2 (a, b) shows the hysteresis loops behaviour of the biocomposites specimens for $r_d = 0.65$ at specific cycle and comparison between the composites hysteresis loops at $N = 1$ and for different loading levels. During the first cycle of loading level $r_d = 0.65$, the maximum forces tend to decrease significantly with increasing fatigue cycle numbers their speed depends on the loading level (from 142 N at $N = 1$ to 85 N at $N = 10^6$). It is also important to note that with the increase of the number of cycles, the hysteresis loops tend to close and this is valid for all loading levels. After a number of cycles at low loading levels, some hysteresis loops are substantially closed (having a very small areas) where the dissipated energy is very small. The pseudo- ellipses hysteresis loops tend to follow an exponential behavior, with low numbers of exhibitors for the highest cycles N, this particular behavior is more evident at lower loading levels r_d ($r_d = 0.65$). This phenomenon was also observed in the case of a fatigue cyclic behavior for a single sisal fiber subjected to tension-tension loading [6]. However, the decrease of the peak strength of the hysteresis loops as a function of the number N of cycles can be attributed to a decrease in fatigue life, in other words it represents the stiffness degradation as a function of the number of cycle of the biocomposite.

Fig. 3 shows the quantity E_d versus the number of cycles for different loading levels for the biocomposite $[0/90]_s$ cross ply laminates (sisal/polyester). The energy dissipated E_d (mJ/cm^3) can be defined as **[6, 7]** : $E_d = \int_{-\varepsilon_{min}}^{\varepsilon_{max}} \sigma \, d\varepsilon$, where ε_{max} and ε_{min} are the maximum and minimum strain respectively. The variation of the dissipated energy per unit volume versus the number of cycles N occurs in two stages. The first stage (i) corresponds to a sharp decrease until about the firsts cycles ($N = 10$) for $r_d = 0.55$ to 0.70 and at few hundred cycles (about $N = 500$) for $r_d > 0.70$, while second stage (ii) is related to a very slow decrease and flat behaviour is unregistered, due to stable crack propagation with no significant energy dissipation involved. It is interesting to note that the fatigue behaviour exhibits significant changes during the initial part of the fatigue life due to energy dissipation in bio-composite material. Similar two-stages trends in energy dissipated have been also observed in other type of vegetable fibre reinforced biocomposite such as cactus/polyester subjected in 3-points banding behaviour under cyclic fatigue loading **[7]** and tensile fatigue cyclic behaviour of single sisal fibre at GL = 20 mm **[6]**. It's clearly visible that the energy dissipated per unit volume versus the number of cycles is strongly dependent on the loading level applied (**Fig. 3**). For $r_d = 0.55$, the damping capacity maintains an almost constant value around 0.9 mJ/cm^3 (at $N = 1$). For $r_d = 0.65$, the energy dissipated drops to an average value of 4.6 mJ/cm^3 at $N = 1$, 2.4 mJ/cm^3 at ($N = 1000{,}000$). However, higher levels of the maximum value of the dissipated energy are observed at $r_d = 0.95$, with 30 mJ/cm^3 at $N = 1$, decreasing to 5.2 mJ/cm^3 before the failure of the sample ($N = 100$).

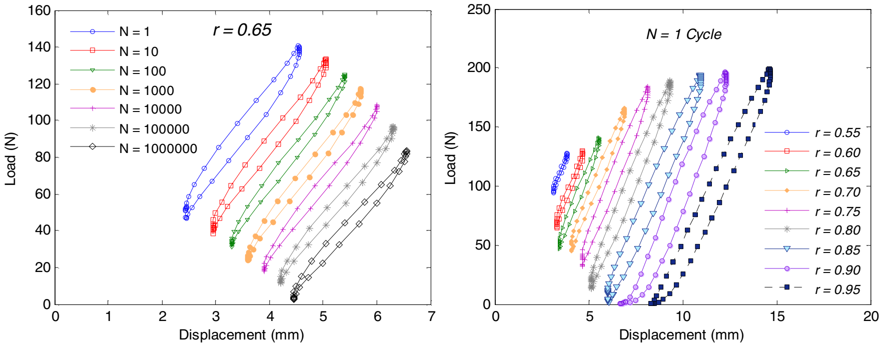

Fig.2. Hysteresis loops for (a) $r_d = 0.65$ at specific cycles N, (b) $N=1$.

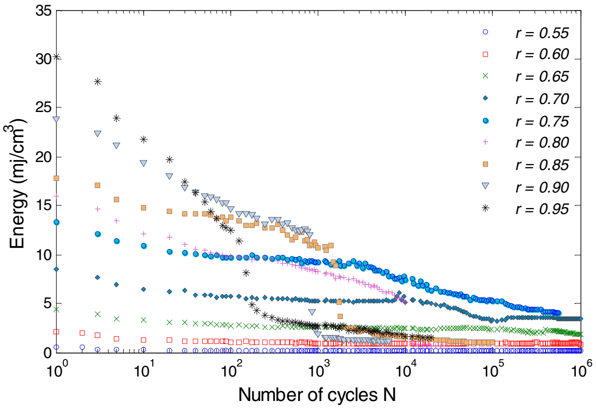

Fig. 3. Energy dissipated versus the number N of cycles.

4. Conclusions

The investigation of the sisal/polyester biocomposites subjected to 3-point bending under static loading shows that the stress-displacement curve of the cross-laminate $[0/90]_s$ is characterized by tree regions, first one a quasi-linear, followed by staircase behaviour on the second region and finally the brutal rupture of the specimens. In cyclic loading one has to note that the hysteresis loop and the dissipated energy per unit volume as a function of cycle number is highly dependent on the loading levels applied to the scpecimens.

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