CHARACTERIZATION OF UNIDIRECTIONAL DISCONTINUOUS BAMBOO FIBRE/EPOXY COMPOSITES

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Abstract
Bamboo culms consist of a nodal structure in which the fibres are as long as the internode length (between 15 and 30 cm), limiting the length of the reinforcing fibres. The implementation of these fibres to reinforce polymers in large-scale applications, leads to the production of discontinuous composites in unidirectional configuration. The influence of the average overlapping length between adjacent fibre layers (bundles) on the mechanical characteristics of aligned (5 cm length) fibre bamboo-epoxy composites is investigated using a tensile testing procedure. The results showed that the experimental values for longitudinal tensile stiffness and strength for continuous fibres, reached 92% and 79% respectively of the theoretical values. Furthermore, tensile testing results have indicated that the overlapping patterns have a significant influence on the tensile strength of the composite samples and low impact on the stiffness of the composite.

1. Introduction

Bamboo fibres are part of the natural fibres family and have one of the most favourable combinations of low density (1.4 g/cm³) and good mechanical properties which can compete with glass fibres in terms of specific properties [1]. Furthermore, bamboo fibres are renewable resource with high growth and CO_2 fixation rate making it a good alternative to reduce of the environment impact of high performance composite structures by replacing less environment-friendly fibres such as glass fibres [2]. One of the bottlenecks that hindered the introduction of bamboo fibres as composite reinforcing materials has been the extraction of undamaged long fibres [3-7]. Recently, a new environmental friendly mechanical process, which produces high quality long bamboo fibres suitable to be used as a reinforcement in polymeric matrices, was developed by Osorio et al. [1]. Another obstacle towards the large-scale industrial application of bamboo fibre composites is the discontinuous structure of the bamboo fibre culm. Bamboo culms consist of a nodal structure where in the nodes, the reinforcing fibres come across and contribute to the buckling strength of the culm [8, 9]. This structural morphology, inherent to the bamboo plants, limits the extracted technical fibres to the internode length which is set to be between 25 and 35 cm for the species *Guadua angustifolia* [10] as seen in Figure 1.

The fibre diameter for the current extracted bamboo technical fibres range between 90 and 250 µm, that in combination with its high modulus gives a high bending stiffness of the fibres impeding the production of endless bamboo yarns. Therefore, an innovative approach towards the use of these fibres to reinforce polymers in large-scale applications leads to the development of unidirectional discontinuous preforms. This type of fibre configurations would allow the use of existing technology to produce high performance composite parts and to overcome the actual restriction of having discontinuous fibres.

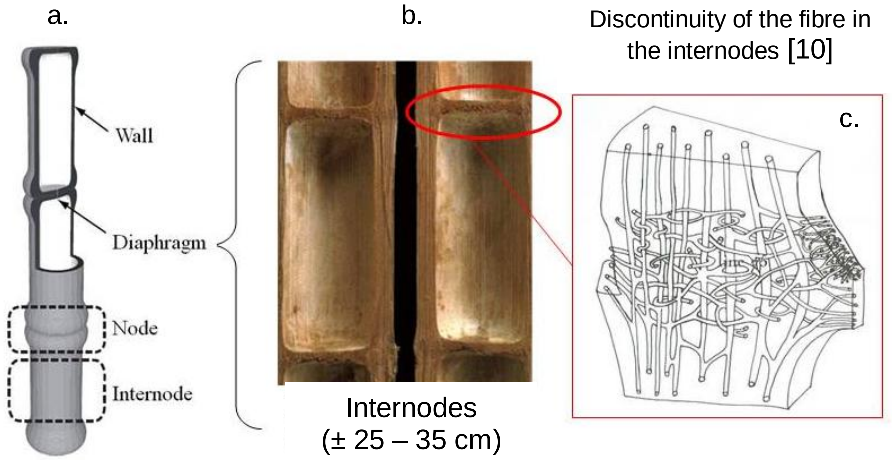

Figure 1: Fibre bundle discontinuity into the bamboo culm. a) bamboo culm, b) internodes and c) schematics for the discontinuity in the node [11].

The aim of this study is to perform a systematic study of the effect of different unidirectional (UD) fibre patterns, ranging from a fix overlapping length of adjacent fibre bundles, to a full randomized fibre bundles into the composite. This characterization, benchmarked with the mechanical behaviour of a fully continuous unidirectional bamboo fibre-epoxy composite (UDC), will show the feasibility to use UD discontinuous bamboo technical fibres in endless preforms to be used in high-end composites applications.

2. Materials and methods

In this study, mechanically extracted bamboo fibres were used. A thermoset epoxy resin, Epikote 828 LVEL epoxy resin and a DYTEK® DCH-99 Amine hardener at a 15.2phr proportion were used to manufacture the composite. After the composite production, the resin cures at 70°C for an hour and completed with an additional post-curing step at 150°C for 1 hour. The impregnated bundles were manufactured with epoxy Araldite® LY564 and amine Aradur® 3486 as a hardener, mixed in a ratio 100/34 and following the same procedure for preparation and curing described above. The mechanical properties of the used matrices are presented in Table 1.

Epoxy resin	Tensile strength (MPa)	Tensile modulus (GPa)	Elongation at fracture (%)	Density (g/cm^3)	Sample manufacturing
Epikote 828	70	2,7	4,1	1,1	UDC* and DCO**
Araldite LY564	70 -74	2,8 – 3,0	4,0 – 4,2	1,2	Impregnated fibre bundle test

*UDC: unidirectional continuous bamboo fibre-epoxy composites. **DCO: unidirectional discontinuous bamboo fibre-epoxy composites.

Table 1. Properties of the epoxy resins used as a matrix in this study.

2.1 Composites production

In this study several unidirectional discontinuous patterns (preforms) for bamboo technical fibres with a fibre length (L_s) of 50 mm were produced to manufacture different types of discontinuous composites (DCO's). The first one consisted in fibre bundles (clusters) with an overlapping distance (L_v) of 50% of the length of the technical fibres and half of the total width (*w*) of the sample, see Figure 2. The second one contains bundles of fibres of 1/5 of *w* and a randomly distributed L_v. The results will be compared with the mechanical behaviour of UDC samples and the impregnated bundle test containing continuous fibre preforms, see Figure 3. A schematic view of the configuration of the DCO samples is shown in Figure 2. In all the cases the fibres were weighed after being conditioned for at least 72 hours, carefully aligned and evenly spread by hand in order to have a homogeneous thin layer of fibres. The fibre volume fraction was recalculated through weight measurements and normalized at 40%.

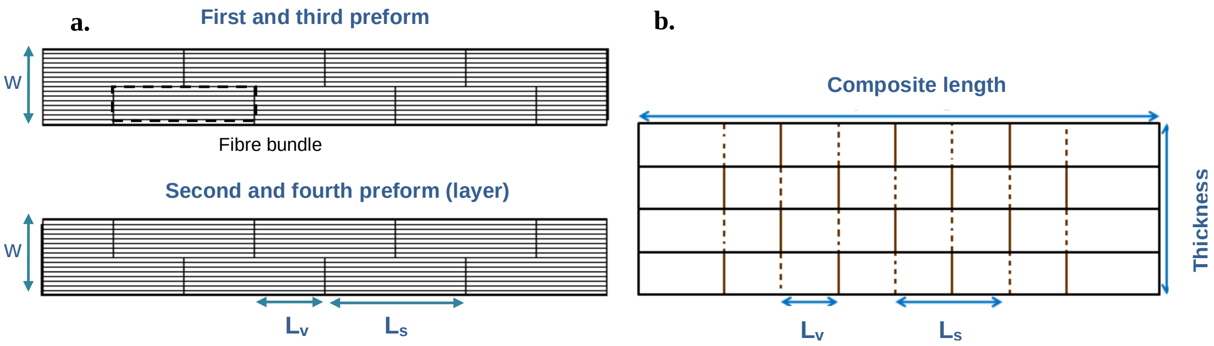

Figure 2. Schematic pattern for DCO samples with fix fibre bundle overlapping length. a) the upper view showing the inversion symmetry that exists between adjacent layer of fibres and b), the lateral view presenting a "brick wall" pattern assembly.

Figure 3. Unidirectional bamboo fibre preforms ready be used for composite production.

Vacuum resin infusion (VARI) technique was used to manufacture the UD bamboo fibre – epoxy composites and the impregnated UD fibre bundles. This technique allowed good alignment of the fibres and also a good surface quality in both sides of the composite. The fibre preforms, described in the previous sections (according to the case), were placed into a multi-cavity mould with their corresponding upper moulds to produce the samples.

2.2 Testing

An Instron 4467 machine with a load cell of 30 kN was used for the test. The span length was kept in 150 mm and the crosshead speed in 2 mm/min. The samples are mechanically clamped with sand paper inserted between the clamps and the samples to prevent slippage. An extensometer with a gauge length of 25 mm is used to accurately measure the elongation of the composite. Before testing all specimens were kept at room conditions (20 °C, 50 % RH) for at least 72 hours. Tensile test samples are prepared according to ASTM D3039. For the impregnated fibre bundle the ISO-10618 standard was followed. In order to carry out the test, the same set-up described above for the UDC and DCO samples was used, except for the crosshead speed that was set at 1 mm/min and an extensometer of 50 mm gauge length. The fibre volume fraction was 38 ± 4 % after recalculation based in weight and sample's dimensions. For all type of tensile samples the Young's modulus was calculated at the initial part of the curve stress-strain, between 0.1 and 0.3% of deformation. Micrographs of fibres and composites were made by scanning electron microscopy (SEM30 XL FEG). The samples were sputter coated with gold for further observations using secondary electrons and with a beam voltage between 10 and 15 kV.

3. Results and discussion

3.1 Tensile properties evaluation

The results presented in Table 2 reveals that the experimental values for longitudinal tensile stiffness and strength for UDC respectively reach 92% and 79% of theoretical values. This points out that a strong fibre-matrix interface is present between fibres and matrix and that the resin impregnates the fibres very well. A visual inspection of the samples after failure indicates in general, a brittle fracture with a crack mostly propagating in one plane as shown in Figure 4. The fracture failure examined with SEM shows good resin impregnation and clear fracture of the sample, with relatively low presence (~25 – 30 %) of fibre pull out. This estimation is based on the number of pulled out fibres relative to the total number of bamboo fibres in the micrographs. It is possible to observe a good dispersion of the fibres where the layer wise initial configuration of the composite is not visible in the final material.

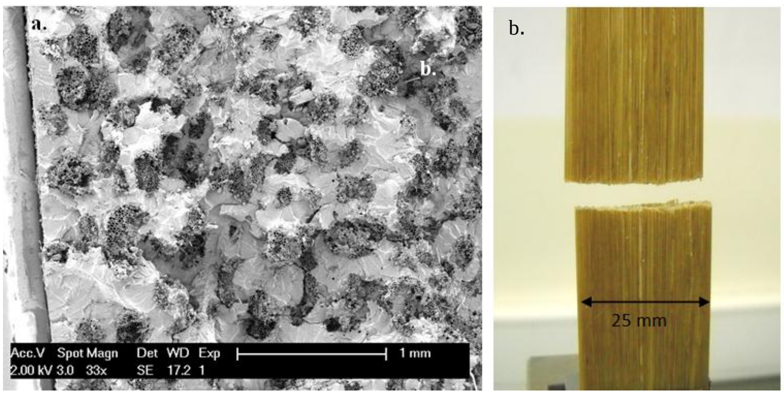

Figure 4. a) SEM observations of the fracture plane of the UD continuous fibre composites after tensile testing and b) composite fracture after testing.

For (UDC) impregnated bundles, the values for longitudinal tensile stiffness and strength are 94% and 90% respectively. The stiffness value (~19 GPa), is improved around 10% in comparison with the standard UDC samples. This improvement can be attributed due to the fact of having less amount of reinforcing material, where the alignment of the fibre is in practice is much easier to control and positively affects the stiffness of the composite material. Based on the results, a back calculation from the rule of mixture, the Young' modulus for the single fibre, considering an efficiency factor of 94% (as it was estimated in Table 2), a value of around 41 GPa is found. This value is in close agreement with the one reported previously reported by Osorio et al. [1] after applying a theoretical correction for the machine compliance. The tensile strength for this type of specimens was around 11% higher than the "standard" UDC samples. This result can be expected if the volume of the sample is considered due to the smaller transversal area, meaning less probability of presence of defects and having a positive effect in the strength properties

	DCO with fixed fibre bundle overlapping length (L_v = 50%, L_s = 50 mm)		**DCO with random fibre bundle overlapping length (L_v = random, L_s = 50 mm))**		**UDC (impregnated fibre bundle, L_s = continuous)**		**UDC (L_s = continuous)**	
Property	**Eff. factor (%)**	**Average value***	**Eff. factor (%)**	**Average value***	**Eff. factor (%)**	**Average value***	**Eff. factor (%)**	**Average value***
Tensile stiffness (GPa)	91 ± 5	16.6 ± 2	89 ± 5	16.8 ± 1	94 ± 4	19.4 ± 1	92 ± 6	17.6 ± 1
Tensile strength (MPa)	29 ± 5	81 ± 13	35 ± 6	100 ± 18	90 ± 3	254 ± 18	79 ± 5	222 ± 13
Strain at breakage (%)	-	0.5 ± 0.09	-	0.7 ± 0.1	-	1.3 ± 0.1	-	1.4 ± 0.2

Table 2. Tensile test results for unidirectional continuous (UDC) and discontinuous (DCO) patterns for bamboo fibre-epoxy composites. *The results are normalized at a fibre volume fraction of 40%.

The results of the tensile tests, performed on DCO with fixed fibre bundle overlapping length samples in which the overlapping fibre bundle length is fixed (L_v= 50%), is presented also in Table 2. It is shown that introduction discontinuities significantly reduces the strength of the composites samples. This property reduces around one third with the insertion of these weak points and the efficiency factor drops to approximately 30%. The strain reduces from approximately 1.3% to only 0.5%. This suggests that these discontinuities result in the presence of a matrix enriched area in the composite, as visible in Figure 5. The application of a tensile load produces intensive stress concentrations around these resin rich zones and finally trigger the crack initiation. The stress singularities at the tip of this critical crack could be initially reduced due to plastic yielding of the matrix. However, the limited ductility of the epoxy resin facilitates crack propagation. The Young's modulus remains in ~17 GPa for all the DCO (L_v= 50%) configurations what represents a 6% of reduction in comparison with the full UD composite (UDC).

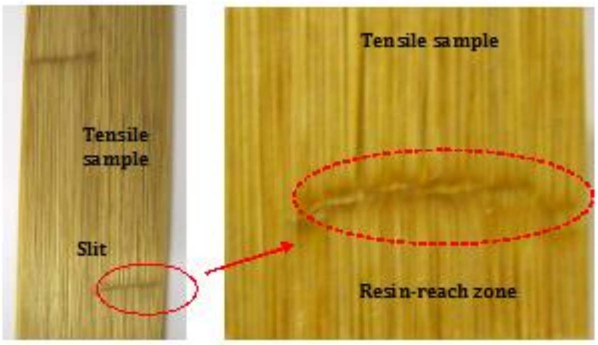

Figure 5. DCO sample with L_v=50%, where the introduction of the discontinuities give as a result the presence of resin-rich zones.

The results of the tensile tests, performed on DCO with random L_v and 1/5 of the *w* are given in Table 2. As compared to the composites with fixed overlapping length, the reduction of the slit width and their overlap randomization allow an increase in efficiency factor by ~5% for the longitudinal tensile strength. SEM observations showed, in some cases, a similar fracture phenomenon presented in the DCO samples with fixed overlapping length

4. Conclusions

Unidirectional continuous (UDC) and discontinuous (DCO) bamboo fibre-epoxy composites have been manufactured with the aim to evaluate several unidirectional fibre patterns on their tensile mechanical properties. For the manufacturing these composites, not only a UD fibre alignment procedure was developed allowing the production of high quality bamboo fibre-epoxy samples, but also, a discontinuous UD fibre randomization technique has been proposed for lab scale. High strength is found for the unidirectional continuous samples (UDC) tested in tension and in flexural test and they were close to what could be expected based on single fibre properties in terms of the efficiency factors. One of the main reasons for this good behaviour is the high quality bamboo fibre after mechanical extraction process that conserves their intrinsic good characteristics and their high fibre surface roughness that promotes a good mechanical interlock with the epoxy matrix. Furthermore, tensile testing results have indicated that the overlapping patterns have a significant influence on the tensile strength of the composite samples and low impact on the stiffness of the composite

Acknowledgements

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