

Test method

Mechanical behaviour analysis of the interface in single hemp yarn composites: DIC measurements and FEM calculations



Amélie Perrier*, Fabienne Touchard, Laurence Chocinski-Arnault, David Mellier

Institut Pprime, CNRS-ISAE-ENSMA-Université de Poitiers UPR 3346, Département Physique et Mécanique des Matériaux, ENSMA 1 av Clément Ader, 86961 Futuroscope, Chasseneuil, France

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ABSTRACT

The present work aims to investigate the local deformation mechanisms around a yarn in an eco-composite. Different hemp yarn orientations and two types of epoxy resin were tested. Full-field measurements were realised with the digital image correlation technique on specific single yarn composites, either on the face of the specimens, or on the edge. The tensile tests were performed under an optical microscope to give sufficient precision, and a numerical model was developed. The experimental results showed high heterogeneities in strain fields which increase with the applied stress level. The comparison with the underlying microstructure and the numerical model enabled us to study the influence of the yarn on the mechanical behaviour. The local constitutive behaviour of the different constituents of the specimens could be approached by these analyses. These results constitute a complete and original database on hemp/epoxy interface mechanical behaviour.

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1. Introduction

Plant fibres are good candidates for the replacement of some synthetic fibres in semi-structural applications, thanks to their good specific properties comparable to those of glass fibres [1–4]. However, one of the main issues of using these fibres is the incompatibility between the hydrophilic fibres and the hydrophobic matrix. Indeed, this induces a decrease in interfacial characteristics compared to glass/polymer composites [5]. The highest strength level of a composite material is achieved when the ability to transfer stress across the fibre-matrix interface is high, i.e. when adhesion is the best. Thus, a fine characterisation of the interface between plant fibre and polymer matrix is required.

Many techniques exist to quantify the strength of a fibre/matrix interface in eco-composites, such as fragmentation test [6,7], pull-out test [5,8] or its variant, the microdroplet test [9,10]. These techniques allow measuring the interfacial shear strength (IFSS) but, in order to improve the understanding of the deformation mechanisms involved at the interface, the whole strain fields also have to be investigated. In the present work, deformation mechanisms around a hemp yarn in epoxy resin are studied thanks to a

full-field strain measurement method.

The digital image correlation (DIC) method is a non-contact full-field displacement measurement technique. First developed by Sutton et al. [11], this technique has been widely used for several applications, including determination of stress-strain behaviour [12], residual stress measurement [13] or observation of crack growth [14]. It has also been successfully used at the ply scale to measure local strain fields in composites made with epoxy matrix reinforced with woven synthetic [15–17] or natural fibres [18]. In these studies, strain distribution at the surface of composites could be compared with the underlying microstructure, showing the influence of the fabric architecture.

In woven or braided composites, yarns are close and interfere with each other. To avoid such influence, single yarn composites are considered in this paper. Their mechanical properties are studied and longitudinal, transverse and shear strain fields are measured by digital image correlation under an optical microscope, which, as far as we know, has never been published in literature. The single hemp yarn composites used in this study enable the determination of local strains at the yarn scale, with comparison with the underlying microstructure. Furthermore, composites made with two types of epoxy resins are compared, one being partially bio-based.

A finite element model is also developed, with the aim of using the numerical stress values at some specific points in the composite together with experimental strains to determine local behaviour of

* Corresponding author.

E-mail address: amelie.perrier@ensma.fr (A. Perrier).

the different composite components.

2. Materials and methods

2.1. Materials

The composite materials studied were made of a single hemp yarn embedded in an epoxy matrix. Hemp yarns, which were not treated, were made of hemp fibres with an average diameter of $13 \pm 5 \mu\text{m}$ [19]. Those yarns were produced with twist level of 324 tpm (yarn surface twist angle of 11°) and a linear density of 83 tex. Besides the irregular cross-section, the hemp yarns had an apparent diameter of about $300 \mu\text{m}$ [7]. Two epoxy resins were used: a fully synthetic epoxy resin, Epolam 2020 (Axson technologies), with a density of 1.10 g/cm^3 after curing [19], and a partially bio-based resin, Greenpoxy 56 (from Sicomin, France), containing 56% of bio-based carbon atoms, with a density of 1.18 g/cm^3 . Composite plates were manufactured at Pprime Institute by contact moulding in a specific mould [20]. The plates made with Epolam 2020 were cured with the following cycle: 24 h at ambient temperature, 3 h at 40°C , 2 h at 60°C , 2 h at 80°C and 4 h at 100°C . The plates with Greenpoxy 56 were cured 24 h at 40°C , 16 h at 60°C , 8 h at 80°C and 30 min at 95°C . The curing cycles were chosen in order to reach a maximum degree of crosslinking for each resin. Glass transition temperatures, measured by differential scanning calorimetry, were found to be equal to $89 \pm 1^\circ\text{C}$ for fully synthetic resin and $83 \pm 1^\circ\text{C}$ for partially bio-based resin. Dumbbell samples 53 mm long were cut from these 2 mm thick plates in two different directions, in such a way that the yarn was oriented at 90° or 45° with respect to the tensile direction (Fig. 1).

2.2. Digital image correlation

Plane strain fields on each specimen surface were obtained by digital image correlation. The principle of this technique is based on a unique random pattern, recorded twice, once before loading the sample and once when the sample is deformed. The first picture taken at the initial state is the reference picture which is compared to a second one taken at a deformed state. The first picture is divided into small sub-windows, each one being a measurement point characterised by its grey level distribution. The principle consists in seeking, for each sub-window of the reference image, the most similar one in the deformed image (in terms of spatial distribution of grey levels), using a correlation function. This was performed thanks to the correlation software OpenDIC [21]. In order to match sub-windows uniquely and accurately, the object surface must have a random speckle pattern which deforms together with the object. The speckle pattern can be a natural feature of the object or an artificial feature. In this study, specimens were prepared by laying a mixture of paint and particles of 200 nm

diameter. This made it possible to obtain a fine random pattern on the material surface. The thickness of the paint layer was about $33 \mu\text{m}$.

With the aim of performing measurements with high spatial resolution, tests were done with a micro tensile tester placed under an optical microscope (Fig. 2a). Pictures taken with a 5 Megapixel camera covered an area of $846 \times 709 \mu\text{m}^2$. In this experimental configuration, 1 pixel was equal to $0.345 \mu\text{m}$. The sub-windows used for correlation had a linear size of $21 \mu\text{m}$, with the same distance between two points to avoid their overlapping. Strain fields were measured either on the specimen face (in this case, specimens were polished to reduce the thickness of the resin between the yarn and the surface), or on the edge where the yarn reaches the surface, as seen in Fig. 2b.

On the face or edge which was not involved in the DIC measurement, macroscopic strain was measured by a video extensometer. For that purpose, dumbbell samples were marked with two dots made with a marker pen, spaced approximately 10 mm apart.

2.3. Finite element modelling

In order to provide a better understanding of strain mechanisms involved in the studied single yarn composites, a numerical simulation of tensile tests was developed.

The single yarn composite specimen was modelled using the commercial finite element software Abaqus, with the yarn oriented at 90° or 45° (Fig. 3). The geometry of the model was based on the experimental specimen dimensions, and the yarn was considered as a homogeneous cylinder of constant diameter inserted in a hole of the same diameter, in the central axis of the specimen. The tensile test was reproduced by submitting one extremity of the specimen to a displacement in direction x, and by clamping the other end. The two materials, epoxy matrix and hemp yarn, were simultaneously submitted to the same displacement. To reduce the processing time, the mesh, composed of linear elements 8-node bricks C3D8, was refined only in the yarn and around it.

In this model, the yarn was considered as perfectly bonded to the resin: nodes at the interface between the matrix and the yarn were coincident. The yarn constitutive behaviour was considered as orthotropic linear elastic. The Young's modulus of the yarn was determined from tensile tests of single hemp yarns impregnated with epoxy resin [20], and the Poisson's ratio from an analytical model of a hemp yarn [7]. Elasto-plastic behaviour based on experimental results was entered point by point for the epoxy resin. The initial Young's modulus and Poisson's ratio of the resin were determined experimentally by tensile tests.

To evaluate the effect on measured strain of the speckled paint layer, a numerical calculation has been performed with an additional layer $33 \mu\text{m}$ thick at the surface of the specimen, with the same mesh size. The elastic behaviour of this layer was defined with a Young's modulus of 700 MPa and a Poisson's ratio of 0.39, which corresponds to the type of paint used. Fig. 4 shows the longitudinal strain field measured on the edge of the sample with an applied displacement of 0.53 mm for the two models (with and without speckled paint). The strain values along the horizontal dotted lines are plotted in Fig. 4c. The values calculated with the paint layer fit well those without speckled paint, except close to the yarn/matrix interface. At this location, in the model without paint, the strain values are driven by the abrupt geometrical transition between the two different materials, whereas they are smoothed in the model with the paint layer. This comparison illustrates the effect of the speckled paint; its addition can cause a smoothing of the data if the material contains abrupt transitions in the properties of its constituents, but has very small influence apart from this

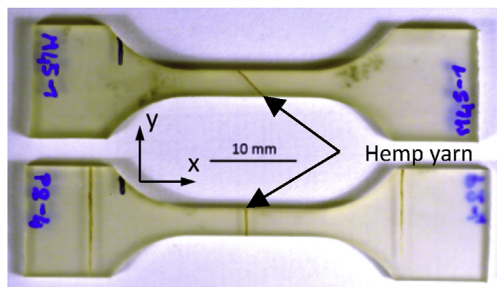


Fig. 1. Single yarn composite samples with hemp yarn oriented at 90° or 45° in regard to the tensile direction.

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