MECHANICAL BEHAVIOUR ANALYSIS OF FIBRE/MATRIX INTERFACE IN HEMP/EPOXY COMPOSITES BY DIGITAL IMAGE CORRELATION

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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 resins 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 for enough precision, and a numerical model was also 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 behaviours of the different constituents of the specimens can be approached by these analyses. These results constitute a complete data base on hemp/epoxy interface mechanical behaviour.

1. Introduction

Plant fibres are good candidates for glass fibre replacement, but the incompatibility of hydrophilic fibres and hydrophobic matrices induces a decrease in interfacial characteristics compared to glass/polymer composites [1]. Thus a fine characterisation of the interface between plant fibre and polymer matrix is required. In order to improve the understanding of the deformation mechanisms involved at the interface, the whole strain fields 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. This technique has been successfully used at the ply scale to measure local strain fields in composites made with epoxy matrix reinforced with woven synthetic [2–4] or natural fibres [5]. 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 work. Their mechanical properties are studied and longitudinal, transverse and shear strain fields are measured by digital image correlation under optical microscope. 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, one being partially bio-based, are compared.

A finite element model is also developed, with the aim of better understanding the local behaviour of the different composite components.

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2. Materials and methods

2.1. Materials

The studied composite materials were made of a single hemp yarn embedded in an epoxy matrix. Besides the irregular cross-section, the hemp yarns, which were no treated, had an apparent diameter of about 300 µm [6]. Two epoxy resins were used: a fully synthetic epoxy resin, Epolam 2020, with a density of 1.10 g/cm^3 after curing [7], and a partially bio-based resin, Greenpoxy 56, with a density of 1.18 g/cm^3. Composite plates were manufactured at Pprime Institute by contact moulding in a specific mould. Dumbbell samples 53 mm long were cut in these 2 mm thick plates in two different directions, in a way that the yarn was oriented at 90° or 45° in regard to the tensile direction.

2.2. Digital Image Correlation

Plane strain fields on each specimen surface were obtained by digital image correlation. The principle consists in seeking, for each sub-window of a reference image, the most similar one in a deformed image (in terms of spatial distribution of grey levels), using a correlation function. This was performed thanks to the correlation software OpenDIC [8]. In order to match sub-windows uniquely and accurately, the object surface must have random speckle pattern which deforms together with the object. In this study, specimen were prepared by laying a mixture of paint and particles of 200 nm diameter. This made possible to obtain a fine random pattern on the material surface.

With the aim of performing measurements with high spatial resolution, tests were done with a tensile testing micromachine placed under an optical microscope (Fig. 1a). Pictures taken with a 5 Megapixel camera covered a surface of 846 × 709 µm². In this experimental configuration, 1 pixel was equal to 0.345 µm. The sub-windows used for correlation had a linear size of 21 µm, 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 Figure 1b.

On the face or edge which was not involved in the DIC measurement, macroscopic strain was measured by a video extensometer. In that purpose, dumbbell samples were marked with two dots made with a marker pen, spaced approximately 10 mm apart. Only measurement on the edge of 90° oriented yarn are presented here, but other results can be found in [9].

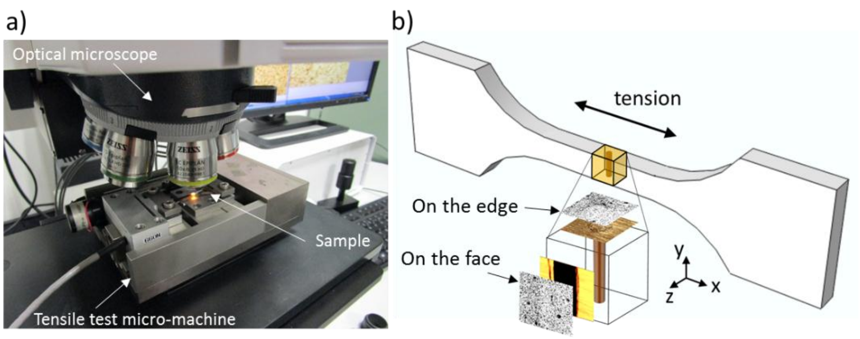

Figure 1. a) Experimental setup, b) DIC measurement locations on the edge or on the face of a specimen.

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. 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

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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 [10], and the Poisson's ratio from an analytical model of a hemp yarn [6]. An 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.

3. Results and discussion

3.1 Comparison of experimental results and numerical model

Full-field strain measurement on the tested samples were compared with results of the finite element model. Figure 2 shows longitudinal, transverse and shear strain maps on the edge of a single yarn composite, with the yarn tilted of 90°. Because of the perfect interface definition in the model, this constitutes a qualitative comparison between the numerical and experimental results. Even if the modelled yarn is homogeneous, we can already see a good correlation between the experimental and numerical strain fields. The experimental maximum strain measured on the longitudinal strain field is 12.77%, whereas the corresponding macroscopic strain is 1.95%: at the surface of the sample, the yarn highly concentrates strains. In longitudinal and transverse strain fields, high strain levels are localised on the hemp yarn section. In the shear strain field, high strain levels are rather localised on the yarn-matrix interface. This is consistent with the fact that this interfacial area is sensitive to shear, as shown with the finite element model in the corresponding picture.

For specimens with 90° oriented yarn and Greenpoxy matrix, the measured strain fields are found similar to the ones of samples with Epolam resin.

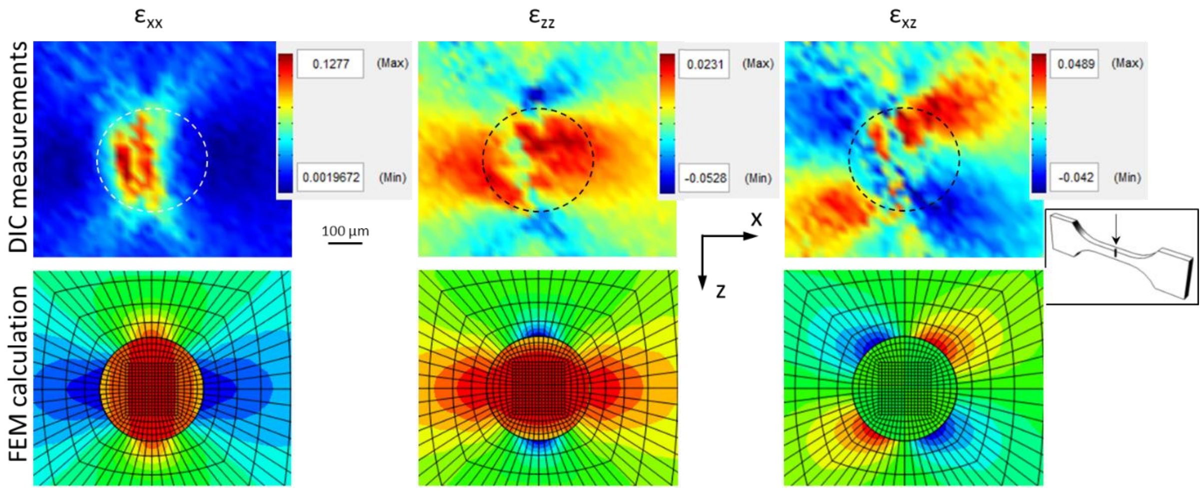

Figure 2. Qualitative comparison of strain fields (ε_{xx}, ε_{zz} and ε_{xz}) obtained by DIC at 40 MPa applied stress and FEM on the edge of a 90° oriented single hemp yarn/Epolam sample.

3.2. Experimental strain evolution along lines

The evolution of the measured strain can be more accurately described by plotting in a same graph the strain values for different stress levels of the specimen during a tensile test. Figure 3 shows

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the longitudinal strain values along a horizontal line B (see diagram on the right) for the 90° oriented yarn specimens with Epolam (Fig. 3a) or Greenpoxy (Fig. 3b) matrices, for different applied stress levels. We can see that, for both matrices, the strain increases progressively and concentrates significantly more in the vicinity of the yarn. For a given stress level, the measured strain values are lower for the hemp/Greenpoxy specimen. For example, at an applied stress value of 40 MPa for hemp/Epolam and 41 MPa for hemp/Greenpoxy, the maximum longitudinal strain values are 12.33% and 7.41%, respectively. This denotes a better strength of the interfacial zone for the hemp/Greenpoxy sample than for the sample made with hemp and fully synthetic epoxy matrix. Concerning the shape of the strains curves, one can see larger waves for the hemp/Greenpoxy specimen than for the hemp/Epolam one, certainly due to the larger section of the yarn (389 µm *versus* 332 µm along the line B, respectively).

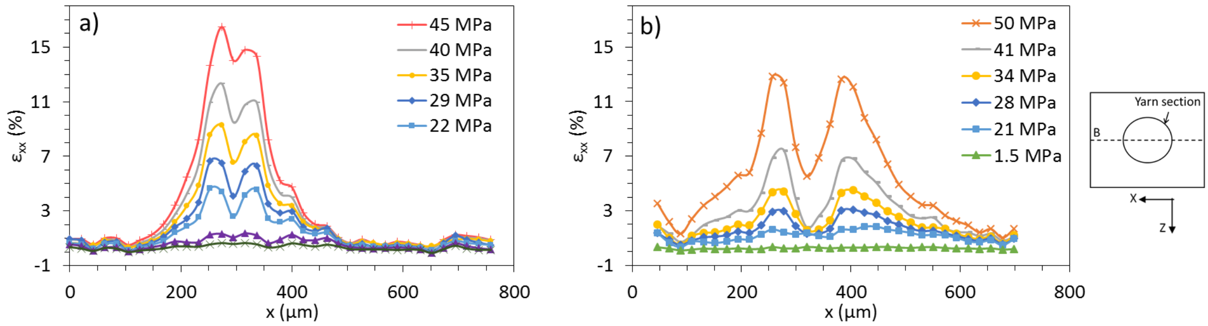

Figure 3. Longitudinal strain values along line B (see diagram) measured by DIC at different applied stress levels on the edge of 90° oriented yarn specimens a) a single hemp yarn/Epolam sample, b) a single hemp yarn/Greenpoxy sample.

3.3. Towards the interface local behavior

The objective of using the DIC full-field technique is the determination of the local mechanical behaviour. It enables us to characterise the local behaviour of each constituent of the composite (resin and yarn) and of the yarn/resin interface. For example, local stress-strain curves for some points at specific locations (in the yarn section, at the yarn/matrix interface and in the matrix away from the yarn) are plotted in figure 4. Stress values correspond to the applied stress levels, and strain ones correspond to the longitudinal strain values measured by DIC. This type of curves allows us to follow local strain evolution anywhere in the studied area and gives an approach to the local constitutive behaviour at the chosen points. Thus, figure 4 shows that strain values are higher in the yarn than in the resin, as observed on the strain fields. It appears that the higher the applied stress, the higher the gap between the maximum and minimum strain values, which illustrates again the heterogeneity in material deformations. At the interface, the studied points have intermediate behaviours, strain values are 47% and 45% below the ones measured in the middle of the yarn cross section for the hemp/Epolam and the hemp/Greenpoxy specimen, respectively. The macroscopic strain, measured by video extensometer, takes into account every components of the composites. As yarn and interface exhibit lower apparent stiffness than the resin one, the apparent stiffness of the whole composite is a bit lower than for bulk resin. Indeed, we can see that the apparent stiffnesses of each component are very different. In the resin, it is higher than in the yarn and in the interfacial zone. The apparent stiffness in the yarn, which represents its transverse apparent stiffness, is found between 825 MPa (with Epolam matrix) and 1574 MPa (with Greenpoxy matrix). This is not so far from the data previously determined for the impregnated yarn: 1264 MPa [9]. At the points of the interface, the estimated apparent stiffnesses have intermediate values with 1171 MPa for the hemp/Epolam sample and 1869 MPa for the hemp/Greenpoxy one. With no specific treatment applied to the hemp yarn for

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the manufactured composites with the two polymer matrices, these results show that the interface adhesion quality is better with the partially bio-based Greenpoxy resin than with the fully synthetic Epolam one.

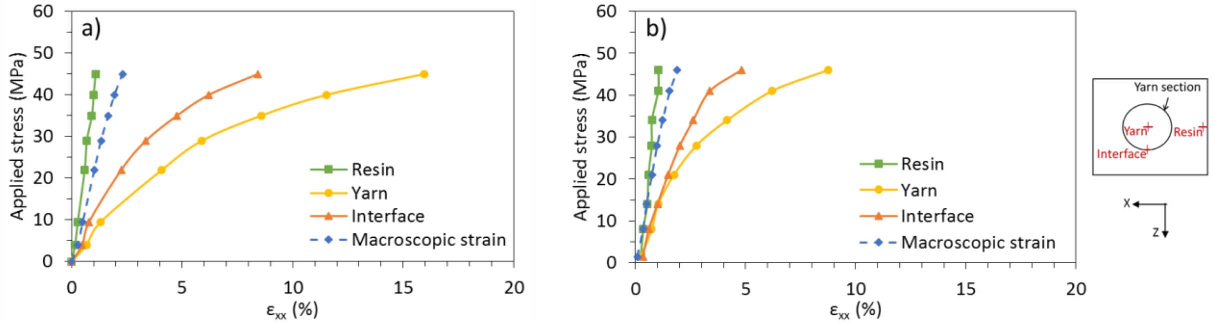

Figure 4. Stress-strain curves obtained by DIC at different locations on the edge of 90° oriented yarn sample a) a single hemp yarn/Epolam specimen and b) a single hemp yarn/Greenpoxy specimen.

4. Conclusions

This study deals with full-field measurements on single hemp yarn composites. Two types of epoxy resin have been used: a fully synthetic one (Epolam 2020) and a partially bio-based one (Greenpoxy 56). Tensile tests coupled with the digital image correlation method have been performed under optical microscope. In-plane longitudinal, transverse and shear strain fields have been obtained at the scale of the yarn. For a better understanding of strain mechanisms involved in such composites, a numerical model has been developed, considering, in a first step, a perfect adhesion between the yarn and the matrix.

The experimental DIC results show a strong heterogeneity in strain fields which develops with the applied stress. A comparison with the underlying microstructure and with the numerical model has been realised. It made possible the analysis of the influence of the yarn presence on the longitudinal, transverse and shear mechanical behaviours. This analysis enabled us to approach the local behaviour at specific locations on the edge of the samples. Local strain values in each component of the composites, *i.e.* in the yarn, at the yarn/matrix interface and in the matrix, have been plotted versus the applied stress, giving a first step towards the determination of local behaviours.

These results constitute a complete data base on hemp/epoxy interface mechanical behaviour. It is essential for determining the local constitutive behaviour of the interface, which is needed for precise finite element calculations. In a next step, the influence of water ageing on the strain measured on specimens with such natural reinforcement will be studied.

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References

[1] T.-T.-L. Doan, H. Brodowsky, E. Mäder. Jute fibre/epoxy composites: Surface properties and interfacial adhesion. *Compos. Sci. Technol.* 72:1160–1166, 2012.

[2] P. Lecomte-Grosbras, B. Paluch, M. Brieu, G.D. Saxcé, L. Sabatier. Interlaminar shear strain measurement on angle-ply laminate free edge using digital image correlation. *Compos. Part Appl. Sci. Manuf.* 40:1911–1920, 2009.

[3] G. Nicoletto, G. Anzelotti, E. Riva. Mesoscopic strain fields in woven composites: Experiments vs. finite element modeling. *Opt. Lasers Eng.* 47:352–359, 2009.
[4] D.S. Ivanov, S.V. Lomov, A.E. Bogdanovich, M. Karahan, I. Verpoest. A comparative study of tensile properties of non-crimp 3D orthogonal weave and multi-layer plain weave E-glass composites. Part 2: Comprehensive experimental results. *Compos. Part Appl. Sci. Manuf.* 40:1144–1157, 2009.
[5] A. Perrier, D.S. de Vasconcellos, F. Touchard, L. Chocinski-Arnault, D. Mellier. Full-field measurement at the weave scale in hemp/epoxy composite using digital image correlation. *Polym. Polym. Compos.* 23:589–600, 2015.
[6] C. Guillebaud-Bonnafous, D. Vasconcellos, F. Touchard, L. Chocinski-Arnault. Experimental and numerical investigation of the interface between epoxy matrix and hemp yarn. *Compos. Part Appl. Sci. Manuf.* 43:2046–2058, 2012.
[7] D.S. de Vasconcellos, F. Touchard, L. Chocinski-Arnault. Tension–tension fatigue behaviour of woven hemp fibre reinforced epoxy composite: A multi-instrumented damage analysis. *Int. J. Fatigue.* 59:159–169, 2014.
[8] N. Vanderesse, M. Lagacé, F. Bridier, P. Bocher. An Open Source Software for the Measurement of Deformation Fields by Means of Digital Image Correlation. *Microsc. Microanal.* 19:820–821, 2013.
[9] A. Perrier, F. Touchard, L. Chocinski-Arnault, D. Mellier. Mechanical behaviour analysis of the interface in single hemp yarn composites: DIC measurements and FEM calculations. *Polym. Test.* 52:1–8, 2016.
[10] A. Perrier, R. Ecault, F. Touchard, M. Vidal Urriza, J. Baillargeat, L. Chocinski-Arnault, et al. Towards the development of laser shock test for mechanical characterisation of fibre/matrix interface in eco-composites. *Polym. Test.* 44:125–134, 2015.

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