Numerical and experimental study of flexural behaviour in polymer composite materials reinforced with natural fique textiles

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Abstract. This work presents the experimental testing and numerical modelling for the flexural behaviour of polymer composites reinforced with fique fibre (furcraea andina) textiles. We considered two different textile configurations embedded in an epoxy matrix to perform the experimental tests and used finite element analysis (FEA) for the numerical approximation. Bending tests are performed according to ASTM D7264. We determined the equivalent elastic properties for the woven composites, according to the properties of raw materials and the fibre-matrix interface. Next, we applied flexural loads to the numerical models to analyse their mechanical behaviour and compared the numerical results with the experimental data previously obtained. This research aims to contribute to establish a baseline to develop new mechanisms to forecast the mechanical behaviour of composites reinforced with natural textiles, and, in this way, propose applications for structural engineering.

1. Introduction
In the past twenty years, the increasing need for sustainable materials has driven the development of new alternatives for natural fibres as reinforcements for polymer composites. Such is the case of several natural fibres like jute, sisal and henequen [1,2]. One of the most widely used polymer composites are the laminated ones, their main properties are sustainability, economic production and commercial costs, and extensive possibilities of applications [3,4].

A strategy to promote the use of natural reinforcements is to improve their mechanical performance. For this purpose, several ideas have been developed, among them: modifying chemically the properties of natural fibres reinforcement [5,6], designing yarn and knitting spatial configurations [7,8], developing numerical models of their mechanical behaviour to improve mechanical response [9–11].

The use of woven textiles as reinforcement agents for polymer composites present advantages compared with non-woven textiles. Numerical models, e.g., finite element analysis (FEA), have been extensively used to evaluate the mechanical response of structures, both for homogeneous and composite materials [12,13]. For composites, research has been performed for the development of numerical models at different scales, to reproduce their configurations, and evaluate their properties.
Mechanical performance of composites reinforced with knitted textiles can be homogenised [15,17–19], analysing the stress and strain fields limited to a representative unit cell [20,21].

This work deals with the study of the mechanical performance of polymer composites reinforced with natural fique textiles under flexural loads. We performed ASTM D7264 tests to characterise the composite material. Then, a numerical model is proposed to reproduce the characteristics of the knitted configuration and study the stress and strain fields in the fibre and matrix. With the model, it is possible to estimate the properties of different composite configurations.

2. Methods and materials

2.1. Materials
The natural fibre used in this research was fique, which is extracted from furcraea andina plant. The raw material was supplied by Coohilados del Fonce Ltd., in the region of Santander (Colombia). According to previous studies, the fique fibres have 625MPa tensile maximum resistance, 25.5GPa modulus of elasticity and 5.7% percentage of elongation [2], and a density between 0.72 and 0.87gr/cm3 [22]. The configuration selected for the reinforcement fabrication was: yarns with 1400 meters/kilogram (0.714Tex) and 2 turns per inch. With a statistical approach, it was determined that the yarn is used is made up of 29 singular fibres average, each one of them with 0.016mm diameter and 1.44mm yarn diameter average. The knitted textiles used were selected in two different configurations: 20D×26 (double warp) and 24×24 yarns per decimeter, the numbers describe the density of yarns in warp and weft framework. On the other hand, the polymeric matrix selected was a thermoset epoxy resin R744.

2.2. Flexural test setup
Three-point bending tests were performed following the ASTM D-790 “Standard Test Methods for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials” [23]. The equipment used was an MTS BIONIX multitest system, with a 25kN load cell, and 5mm/min speed of testing. The maximum stress \( \sigma_{\text{max}} \), modulus of elasticity \( E \), and strain percentage \( \varepsilon_{\text{max}} \) were obtained from experimental data. For each type of specimens, five samples were tested. Test specimens were fabricated with 120mm length, 8mm thick and 9mm width average, the textile reinforcement used was a single textile layer arranged at half the height.

2.3. Scanning electronic microscopy (SEM)
A quanta FEG 650 electronic microscope, equipped with a backscattered electron detector (BSED) solid state type, was used to observe the material failure mode and assess the quality of adherence between matrix and reinforcement.

2.4. Finite element model
We consider the linear elasticity problem of the composite test specimen defined in ASTM D-790, and use a Galerkin formulation to solve for the displacement field \( u^h \) in a space of finite dimension \( V^h \): Find \( u^h \in V^h \) such that \( \forall v \in V^h \):

\[
\int_{\Omega} \varepsilon(v)^T D \varepsilon(u^h) \, d\Omega = \int_{\Omega} v^T b \, d\Omega + \int_{\Gamma_N} v^T t \, d\Gamma,
\]

where \( \varepsilon \) denotes de strains, \( D \) is the elasticity matrix of the material, \( b \) are the body loads, \( t \) are the Neumann tractions on \( \Gamma_N \). For the segmentation of the composite material, we use TexGen to generate a structured mesh of voxel linear elements. Validation of the material model for tensile loads was presented in [24], obtaining an acceptable error of 6.67% w.r.t. experimental values. The Neumann and Dirichlet boundary conditions are defined according to the ASTM D-790 test and fixed from the load values obtained in the experimental tests.
3. Results

3.1. Experimental results
Figure 1 shows the stress vs. strain curves for five different types of specimens: epoxy resin R744, unidirectional (UD) fibres with one yarn, UD with two yarns, textile 1 20D×26, and textile 2 24×24. The bending test revealed that mechanical response of the composites varies according to the type of reinforcement, in the composites reinforced with yarns, the modulus of elasticity increases with the number of yarns, see Figure 1. The same behaviour occurred in the composites reinforced with knitted textiles. Table 1 shows the maximum stress $\sigma_x^{\text{max}}$, max. strain $\varepsilon_x^{\text{max}}$, and modulus of elasticity $E$. The strain decrease, due to the stiffening produced by the amount of reinforced textile. Comparing these results with [24], we notice a better response of the composites for the case of tensile loads than flexural moments. This behaviour is associated with the distribution of the fibres within the cross section.

![Figure 1. Composites stress-strain curves obtained by bending tests.](image)

| Type            | $\sigma_x^{\text{max}}$ (MPa) | $\varepsilon_x^{\text{max}}$ (%) | $E$ (GPa) |
|-----------------|-------------------------------|----------------------------------|-----------|
| Epoxy           | 64.2 ±1.4                     | 5.1±0.7                          | 2±0.08    |
| UD 1 yarn       | 59.3±6.4                      | 3.71±0.7                         | 2±0.01    |
| UD 2 yarns      | 56.6±13.5                     | 3.7±1.3                          | 2±0.04    |
| Textile 1 - 20D×26 | 58.3±5.5                    | 4.0±0.7                          | 2±0.09    |
| Textile 2 - 24×24 | 58±3                          | 3.6±0.2                          | 2±1.2     |

3.2. Fractographic analysis
An FEI Quanta FEG 650 (ESEM) electronic microscope was used for taking micrographs for fractographic analysis. In Figure 2 we can see (a) delamination phenomena, (b) matrix-fibre separation, (c) fibre pull-out, and (d) the effect of the load in the y-axis. Figure 2 revealed matrix-fibre delamination, which is a typical failure mode where bending loads are applied in a composite material, however, the direction of the pull-out fibres, and the scarce fibres-matrix separation indicates good adherence between phases, which may explain the improvement in the composite mechanical
properties, proposed product of the proper compounding process [25]. The matrix extraction process of fibres could have been generated since the fibres were not subjected to any cleaning or preparation treatment, however, the observed failure was homogeneous, indicating a uniform failure process as reported in bibliography [26,27].

The bending tests failure zone made evident separations between fibres and matrix, which shows its detachment; furthermore, the load direction was aligned with the delamination direction and the delamination distance increase with the proximity to the load application point, which showed a stress distribution typical of bending loads, this behaviour showed besides, that the delamination occurred in a progressive manner, as well as fibres breakage was homogeneous and the composite failed uniformly.

3.3. Numerical results

We obtain values for the flexural stresses under a load of 183N, which corresponds to the applied force obtained in the experimental tests. Table 2 shows the results for the maximum, $\sigma_{x}^{\text{max}}$, and minimum, $\sigma_{x}^{\text{min}}$, normal stresses in the axial direction, and the von Mises stress, $\sigma_{vm}^{\text{max}}$, for the two
composite specimens with textile reinforcement. Notice that the magnitude of the minimum value of the normal stress (at compression) is close to the nominal values obtained for the textiles in the tests. This agrees with the stress values projected for the epoxy. As expected, the local $\sigma_{\text{max}}^x$ values are located in the area reinforced with fibres, which provide stiffness, thus, higher values of stress are obtained. Moreover, due to their higher stiffness, the maximum normal and von Mises stress values are obtained in the fibres, with 297MPa for the specimen with 24×24 yarns-per decimeter textile. This same textile fails first in Figure 1.

Table 2. Flexural test results for the numerical models.

| Type   | $\sigma_{\text{min}}^x$ (MPa) | $\sigma_{\text{max}}^x$ (MPa) | $\sigma_{\text{vm}}^x$ (MPa) |
|--------|-------------------------------|-------------------------------|-------------------------------|
| Textile 1 | -55.04                        | 183.16                        | 188                          |
| Textile 2 | -52.06                        | 297.51                        | 287                          |

4. Conclusions
A polymer composite reinforced with natural fique yarns and textiles was fabricated. The bending mechanical properties were obtained according to ASTM D790, and the stress-strain curves were obtained, as well as, the maximum strength, the flexural modulus of elasticity, and the strain at the breakpoint. The data obtained revealed that, for the reinforcement configurations under consideration, the influence of the fibres in the performance of the composite is not as high as for the case of tensile loads [24], which showed an increase of the modulus of elasticity up to 66.8%.

The numerical model was formulated using a voxel FE mesh, to approximate the mechanical behaviour of the composite proposed. The numerical model allows analysing the behaviour of both components, matrix and reinforcement, separately. The experimental results showed differences about 7% compared with the model proposed for tensile conditions, thus, indicating the reliability of the material model. The use of numerical models represents an alternative to studying more complex composite configurations.

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