Correlation between cross sectional area and torsion degree of fique yarns by image analysis system

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Abstract. The improvement of the natural fibers which are used in composite materials engineering applications depends on the reliable estimation of their mechanical properties, whose calculation is directly associated with the determination of their physical characteristics, such as cross-sectional area and diameter. The cross-sectional area of fique yarns, a natural fiber obtained from “furcraea andina” plant, consists in the sum of several singular fiber areas packaged thanks to the torsion effect of the spinning process. In this study, cross-sectional areas of fique yarns were obtained by optical micrographs, afterwards, the images were processed by two different approaches: the first one using Fiji, a specialized software for image processing; and the second one, through an own Matlab programming. The results obtained by both methods were compared and the respective diameter values for each fiber were extracted, assuming a circular shape of fique fibers cross-section. To perform the microscopic shots, fique yarns (0.877 and 0.714 tex) with torsion degrees of 1.5, 2.0 and 2.5 turns/inch were selected. The results indicated that even though linear density remain constant, the cross-sectional area varies with torsion degree. Additionally, the image analysis method allowed to improve the accuracy of calculations. It is expected that the measurement method proposed contributes to improving mechanical analysis of these type of materials in future studies.

1. Introduction
Over the past 20 years, the use of natural fibers as reinforcement of polymer composites has gained acceptance in several industries like automotive and construction, mainly due to its low environmental impact and advantageous mechanical properties [1–4]. Other reasons that have recently motivated the use of natural fibers are related to socio-economic and sustainability features [5]. One of the aspects that represents a disadvantage for the effective use of natural fibers compared with synthetic ones, as reinforcement for structural purposes, is the high dispersion of the values found in their mechanical properties, which do not allow an adequate projection of its mechanical performance. The great variability in physical properties of natural fibers is a natural characteristic associated with the irregular morphology both longitudinally and transversally and is reflected in the maximum resistance, the modulus of elasticity and
percentage of elongation \[6–10\], as well as other characteristics like the diameter too \[11–15\]. The reasons for this high variability in the values reported may be related to growing conditions, the specific region where plantations are located, and other factors referred to the nature of the fibers \[16\]. Other variables that can influence the variability of the results founded could be related with the methods used to carry out physical and mechanical characterization, the quantity of material studied and the statistical approach to analyze the data obtained \[11,17,18\].

Fique fibers obtained from “furcraea andina” leaves plants are characterized by their length (between 80 and 120 cm) and their stiffness. These make them ideal for different products made with yarns and textiles like ropes, sacks, handcrafts and recently, for reinforcement products. The mechanical properties of fique fibers had been analyzed in the last two decades, in which the differences between the values founded are broad, for instance, the maximum tensile resistance of fique fibers had been reported between 31 MPa and 625 MPa, likewise, the fique fiber equivalent diameter had been founded between 50 and 400 microns \[6,11,12,15,19–23\]. These results can be explained from the fiber’s morphology point of view. Fique fibers are characterized by having a great morphological variability, which makes it difficult to establish a representative geometric shape of its cross section, this is how, in the same section of a fique yarn it is possible to find semi-circular, oval and other shapes (see Figure 1).

The procedures to determine natural fibers cross-sectional areas can be divided into direct and indirect methods: firstly, the direct methods start from taking microscopic images (optical or electronical) of fibers cross section, followed by a digital treatment of the images taken which has the purpose of improving the definition and contrast between the areas with fiber content of the rest. Then, from the images taken and processed the pixels are scaled to the real size to calculate the areas. This method was used for D’Almeida et al., Thomason et al. and Munawar et al. in flax, sisal and other natural fibers \[24–26\]. In this process, to define image thresholding is an initial step in the most of algorithms for digital image processing. There are several thresholding methods proposed in the bibliography but the researchers, whose are focus on this topic, agree that Otsu method image thresholding gets good results in this kind of work \[27,28\]. Otsu method finds the threshold that make minimal the intra class variance; secondly, indirect methods determine the fibers cross-sectional area by observing the profile of the respective fiber.
from which the its thickness measurement is taken. Most of these procedures assumed a circular geometry for cross-section shape, then this thickness is assumed as a diameter of these circular sections, from which the area is calculated. This procedure had been used by Basu et al. [29], Khan et al. [30] and placet et al. [31] among others in different types of natural fibers.

In this work two direct approaches, both based on direct methods, were used to determine the representative cross-sectional area of fique fibers, and the effect of the variation of cross-sectional area values of fique fibers was evaluated.

2. Methods and materials

2.1. Materials and experimental setup
Natural fique fibers were provided in yarns products by Coohilados del Fonce Ltda; for this study six types of yarns were used: two different linear density (1140 and 1400 m/Kg), equivalent to 0.877tex and 0.714tex respectively, and three torsion levels: 1.5, 2.0 and 2.5 turns/inch respectively as well.

Nine samples yarns of each of the six selected types, separated 2 meters each one, were encapsulated in epoxy resin, the specimens were prepared metallographically, first with sandpapers until 1200 grit, and afterwards with cloths and alumina abrasive powder 0.5 μm size, once the specimens were assembled and polished, we proceeded to take optical microscopy shots with an Olympus GX 71 microscope, the images were taken at 100 magnifications (see Figure 2)

![Figure 2: Fique yarn’s cross sectional area](image)

2.2. Cross sectional area calculations
To determine the magnitudes of cross-sectional areas in fique yarns, two direct measurement approaches were used, both based on the acquisition of yarns cross-section images, the first one based on the use of a free software and the second one trough an own programming of Matlab algorithm.

Method of areas calculation by software Fiji (image J): The measurement of fiber areas using this application begins with the acquisition of the images. In case of images that are composed by more than one shot, a fusion of the micrographs is carried out with "stitching" complement. Once the image has been merged, "binary" function is applied to transform the image into a high-contrast image of black and white, the selection of the background color (white or black) is carried out automatically by the program. Once the binary image has been transformed, the scale is established with the function "set scale" of the analyze menu, this tool set up the pixels number that contains the line of 100 μm in our case that appears in each image, for our
study, 100 μm corresponded to 147 pixels which is equivalent to 1470 pixels/mm. Afterwards, a selection of fiber areas is made manually, and finally with "measure" tool of the program shows the value of the area in mm², or any other units needed. The program stores and tabulates the studied areas and performs basic calculations of averages and standard deviations.

*Algorithm to calculate the cross sectional area:* This process begins with the electronic microscopic images from which we should measure the cross area of fique fibers. To get this data an algorithm was programed by Matlab, which makes the images processing. The first step is to convert the RGB image to binary image. In this process, the ‘global’ mode, based on Otsu’s method which establishes the image threshold, is used. A morphology operations is applied to complete de black areas by imerode Matlab function. Finally, the black area is calculated having into account the real size of each pixel.

3. Results
Cross-sectional area values were obtained using the methods previously explained; additionally, a manual counting of fibers number in each yarn section was performed; from the previous data, the single fiber average diameter of each yarn sample was calculated, assuming circular cross section shapes and constant diameter.

3.1. Results from Fiji measurement
The Table 1 shows the results of cross-sectional areas obtained by means of Fiji software. In them we observed that, on average, these values increase with the increase of yarns linear density. However, the torsion degree effect in these values differs with linear density, so that, for density yarns with 0.877 tex, the area values increase with torsion degree increase. Furthermore, for density yarns 0.714 these values decrease.

If we take into account the number of filaments or singular fibers that form each transversal sample of yarns, there is a correlation between that number of singular fibers and the total area values. So that, the greater number of fibers, the greater total area values, which assumes that linear density of the fibers is directly proportional to their concentration, regardless of their degree of torsion or its geometries.

| Yarn linear density (tex) | Twist degree (turns/inch) | Cross-sectional area mm² | Number of filaments per yarn | Fiber calculated diameter (μm) |
|--------------------------|---------------------------|--------------------------|------------------------------|-------------------------------|
| 0.877                    | 1.5                       | 0.1680 ± 0.0136          | 34.95                        | 78.2322                       |
|                          | 2.0                       | 0.2569 ± 0.0253          | 42.89                        | 87.3290                       |
|                          | 2.5                       | 0.2465 ± 0.0308          | 39.74                        | 88.8688                       |
| 0.714                    | 1.5                       | 0.2269 ± 0.0404          | 34.00                        | 92.1791                       |
|                          | 2.0                       | 0.2397 ± 0.0390          | 45.34                        | 82.0442                       |
|                          | 2.5                       | 0.1751 ± 0.0226          | 35.87                        | 78.8373                       |
3.2. Results from Matlab algorithm developed

Table 2: Cross-sectional area measured in fique yarns by Matlab algorithm

| Characteristics | Image processing |
|-----------------|------------------|
| 1140 linear density (Kg/m), 0.714 tex, 1.5 torsion level (turns/inch) | ![Image](image1.png) |
| 1140 linear density (Kg/m), 0.714 tex, 2.0 torsion level (turns/inch) | ![Image](image2.png) |
| 1140 linear density (Kg/m), 0.714 tex, 2.5 torsion level (turns/inch) | ![Image](image3.png) |

The Table 2 and Table 3 show the image processing results by Matlab algorithm developed. The grayscale images, binary images and eroded images are presented. These results are listed having into account the linear density of each fique yarn and the torsional level applied to each one. The fique yarns used have 1140 tex and 1400 tex of linear density, and torsion applied at three levels: 1.5, 2.0 and 2.5 turns/inch.
Table 3: Cross-sectional area measured in fique yarns by Matlab algorithm

| Characteristics | Image processing |
|-----------------|------------------|
| 1400 linear density (Kg/m), 0.714 tex, 1.5 torsion level (turns/inch) |
| ![Image](gray_scale_image) | ![Image](binary_image) | ![Image](eroded_image) |
| 1400 linear density (Kg/m), 0.714 tex, 2.0 torsion level (turns/inch) |
| ![Image](gray_scale_image) | ![Image](binary_image) | ![Image](eroded_image) |
| 1400 linear density (Kg/m), 0.714 tex, 2.5 torsion level (turns/inch) |
| ![Image](gray_scale_image) | ![Image](binary_image) | ![Image](eroded_image) |

The Table 4 shows consolidated results of the cross sectional area calculations by Matlab algorithm developed. The areas and equivalent diameter are listed in this table.

Table 4: Cross-sectional area measured in fique yarns by Matlab algorithm

| Yarn linear density (tex) | Twist degree (turns/inch) | Cross-sectional area ($mm^2$) | Number of filaments per yarn | Fiber calculated diameter ($\mu m$) |
|--------------------------|---------------------------|-------------------------------|-----------------------------|----------------------------------|
| 0.877                    | 1.5                       | 0.2009 ± 0.0195               | 39.45                       | 85.5573                          |
|                          | 2.0                       | 0.3294 ± 0.0044               | 42.89                       | 97.5265                          |
|                          | 2.5                       | 0.2902 ± 0.0160               | 39.74                       | 96.4249                          |
| 0.714                    | 1.5                       | 0.2253 ± 0.0214               | 34.00                       | 91.8535                          |
|                          | 2.0                       | 0.3167 ± 0.0771               | 45.34                       | 94.2982                          |
|                          | 2.5                       | 0.1896 ± 0.0127               | 35.87                       | 82.0295                          |

The variation in the results obtained and the atypical behavior in some values of area found,
for example, yarn 0.877 tex (1.5 turns/inch) and yarn 0.714 tex (2.5 turns/inch), can be attributed to variations inherent to the industrial spinning process.

The results found in cross sectional area values and the estimated diameter of the singular fibers were similar and consistent in both methods used, which allows them to be used as a test and corroboration method in an indistinct manner, although the precision in the results depend on the quality in the preparation of the specimens, thus, for yarns with linear density 0.877 tex, the area of fibers was between 0.223 mm$^2$ and 0.276 mm$^2$ on average, which represents a 23% variation of value, which is acceptable taking into account the variations that can be added to the data found as a result of the differences in the digital image treatment, similarly, in 0.714 tex yarns this variation in the average results was 13%.

4. Conclusions
The main purpose of this study was to contribute to the understanding of the relationship between the physical and mechanical properties of fique fibers, in order to improve the estimation accuracy of their mechanical performance as composite reinforcements.

The average diameter of the fibers, determined from the count of cross-sectional areas divided in the average number of fibers per yarn was 80 ± 6 μm, to determine this value it was assumed that the areas are homogeneous and have a circular section shape; As previously stated in this study, these assumptions are not precise respect to fiber morphology presented, but they may serve to contribute to the state of knowledge in this matter.

Both methods, Fiji application and Matlab algorithm, demonstrated their effectiveness in carrying out the cross-sectional area calculation of fibers and can be used in a complementary manner or to corroborate results. In cases where the use of Fiji does not yield reliable results, or the use of tools becomes difficult, Matlab algorithm may allow additional control over the image processing variables, for instance, the threshold.

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