Mechanical response to tensile stress of a composite material reinforced with sugar cane fibers

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Abstract. Composite materials reinforced with organic fibers have attracted great interest in the area of mechanical engineering in recent decades due to the wide variety of industrial applications where these materials can be used, and the low impact on the environment, compared with traditional materials. In this work, experimental and numerical tests are carried out to investigate the mechanical response to a tensile load of a composite material with an epoxy matrix, reinforced with sugar cane fibers. Mechanical tests under the ASTM standard for tensile loads were performed. Then, a numerical model to investigate the mechanical response of the composite is done by finite element analysis. Results indicate that this composite material has good performance under axial loading conditions, and can be used for structural applications.

1. Introduction

Composite materials have been the focus of attention of many researchers due to their outstanding mechanical properties, which allow them to be used in numerous aerospace, marine, automotive, and civil applications, among others [1–3]. A composite material suitable for use in engineering applications exhibits three basic aspects: (i) consists of at least two mechanically separable materials, called matrix and reinforcement, (ii) there must be a possibility for its preparation by mixing the above components, and, (iii) the final material shows superior properties to those of the individual components [4].

One of the most common configurations for composite materials is the fiber-reinforced polymer (FRP). The polymers matrices perform various functions in the composite, such as, providing the general shape of the piece or product, protecting and distributing the load in the reinforcement. The fibers are responsible for improving the strength and stiffness of the composite [5]. The polymers matrices are divided into two groups: thermosetting and thermoplastic. Thermosetting matrices include epoxies, polyesters, and polyamides. Epoxy matrices are the most commonly used for polymeric composites due to several desirable properties, such as good mechanical strength, dimensional stability, good wettability and low flammability [6,7]. The mechanical properties of the FRP, especially the tensile strength and Young’s modulus increase with the length of the fibers, therefore, to make a high-performance composite, continuous fibers should be used [8].

Due to the growing interest to protect the environment and conserve energy, many FRP studies focus on natural fibers, since they come from renewable sources and help to reduce the environmental impact generated when the material is discarded [9–11]. Fibers of sugarcane bagasse (SCB) are one of the most
attractive fibers due to their mechanical properties and great abundance. Bagasse is the waste that remains after the crushing of sugarcane for the extraction of juice. This is composed mainly of cellulose, hemicellulose, and lignin, which are connected in a network to give fiber resistance [12]. Current research indicate the possibility of reinforcing different polymer matrices with fibers of SCB, to nano, micro, or macro scale to expand the applications of polymer composites [13,14]. Saccharum officinarum, better known as sugar cane, is a tropical and subtropical crop and is the main source of sugar worldwide. The total sugar cultivation area is approximately 31.3 million hectares, of which sugarcane represents 70% [15]. The world production of SCB was registered recently at 1.6 x10^7 million tons per year [16]. Most of the sugarcane consists of a soft material called pith, while its exterior consist of a hard fibrous material called rind. The pith contains small fibers and most of the sucrose, while the rind is composed of long, hard and fine fibers. The properties of the composites reinforced with the fibers of the rind are better because it has a higher density [17].

The SCB is mainly used as a fuel to generate steam and produce electricity in sugar factories and as a raw material in paper industries. However, these are not the only applications of SCB. For example, research has demonstrated the ability of this by-product to become reinforcement of composite cement, respectful with the environment, which can be used in various internal and external building applications [18]. Some of the potential applications of natural fiber reinforced composites in the automotive industry include door and instrument panels, packaging trays, glove boxes, armrests and seat backrests [19].

In addition to experimental studies, composites can be evaluated by predictive models, usually by means of finite element analysis (FEA) models. Composite materials have been, and continue to be, one of the main research areas in computational mechanics in recent decades. The main efforts are focused on the study of laminates and composite structures [20]. Recently, an explicit unified form of boundary conditions has been developed for the analysis of a representative volume element (RVE), using the finite element method, for unidirectional laminates at different angular orientations, to predict the elastic properties of the materials. The results obtained with this method have been validated with experimental tests, presenting low percentages of error [21,22].

In this work, a composite material of epoxy matrix R744 reinforced with continuous sugar cane fibers was produced. For this, SCB was washed and the fibers were extracted, R744 epoxy resin specimens were built. The mechanical properties of the matrix and the reinforcement of the composite were obtained. Mechanical tests under the ASTM 3039 [23] standard for tensile loads were performed on the composites [24]. Finally, the mechanical behavior of the composite material subjected to tensile loads was studied numerically by means of finite element analysis.

2. Materials and method
2.1. Experimental tests
The MTS BIONIX test machine was used to perform the tensile tests on the sugarcane fibers and the R744 epoxy resin samples in accordance with ASTM 3039 standard [23]. The test machine was adjusted at a head displacement rate of 2 mm/min to produce an almost constant deformation rate on the fibers and the epoxy resin specimens. The values of the applied force and the displacement of the mobile head of the test machine were recorded automatically with a frequency of eight data per second.

SCB was obtained after the extraction of the juice contained in the stalks of the sugarcane. This process is carried out by means of a mill. In order to improve the adherence between the fibers and the epoxy resin, the bagasse was immersed in boiling water for 30 minutes to remove the pasty tissues and residues adhered to the surfaces of the fibers. After this, it was put to dry for 72 hours under ambient conditions. The fibers were manually subtracted from the bagasse rind, where the longest and most resistant fibers are found, this was performed with the help of a scalpel. The bundles of fibers were cut with a length of 100 mm, having an approximate diameter of 0.5 mm, Figure 1(a). To find the mechanical properties of the fiber, ten bundles of fibers were subjected to tensile tests according to the ASTM standard.
Epoxy resin R744 was mixed with a catalyst agent to harden it, the volume ratio of resin and hardener used for the mixture was 4:1, as recommended by the manufacturer. The manufacturing of the epoxy resin specimens was carried out by hand lay-up technique, which consists of preparing the mixture of resin and hardener in a container and, then, depositing it in a mold. The mold was manufactured in balsa wood, this was coated with polyvinyl alcohol, which acted as a mold release agent, before pouring the mixture. The components of the epoxy resin specimen were mixed slowly for five minutes, to avoid creating air bubbles that could become stress concentrators in the specimen. Once the mixture was in the mold, it was dried under ambient conditions for 24 h. Five specimens with dimensions of 100×20×5 mm were manufactured following the recommendations of the ASTM standard, Figure 1(b).

![Image](image1.png)

**Figure 1.** (a) Sugar cane fibers, (b) test specimens.

The test machine transferred the tensile force to the epoxy resin specimens and to the fibers by means of two correctly aligned and hydraulically controlled jaws, see Figure 2. For each test, approximately 220 data were recorded. Once the test was completed, the location and failure mode of each test piece was inspected to verify that the fractures occurred as expected. The properties of sugarcane fibers and R744 epoxy resin obtained through the mechanical tests can be seen in Table 1.

![Image](image2.png)

**Figure 2.** Tensile test set-up under ASTM 3039 standard [23].

|                  | $\sigma_u$ (MPa) | $E_1$ (GPa) | $\varepsilon_{\text{máx}}$ (%) |
|------------------|------------------|-------------|-----------------------------|
| Sugar cane fiber | 264.333          | 12.936      | 2.3                         |
| Epoxy resin R744 | 25.237           | 0.951       | 7.4                         |

*Table 1. Mechanical properties of the composite components obtained experimentally.*
2.2. Numerical model
Geometrical and mechanical properties of sugar cane fibers and epoxy resin, indicated above, were established in the model. Figure 3 shows the model of composite material. For this arrangement, the fiber volume fraction is 10%.

Figure 4 shows the meshes for the fibers and the epoxy resin. SOLID187 elements were used. In the reinforcement-matrix interface of the model bonded contact conditions were established. The convergence of the numerical results was evaluated in terms of the stresses, assuming 5% of the allowable difference for the asymptotic range [25]. Table 2 shows the mesh convergence values, for a final mesh with 91195 elements.

![Figure 3. Composite model.](image)

![Figure 4. Composite mesh: (a) fiber, (b) matrix.](image)

| Table 2. Mesh convergence value. |
|----------------------------------|
| Nodes | Elements | \( \sigma_{\text{max}} \) (MPa) | Variation (%) |
|-------|----------|-----------------|---------------|
| Model 1 | 358453 | 71346 | 286.59 | - |
| Model 2 | 457059 | 91195 | 295.76 | 3.2 |

The model was analyzed as a linear elastic problem. Figure 5 shows the boundary conditions applied to the model. The displacements on the right plane are restricted in all degrees of freedom and a force aligned with the longitudinal direction of the fibers was applied on the left plane of the specimen.
3. Results

A load of 2600 N is applied to obtain the stress distribution on the composite. Figure 6 shows the von Mises stress distribution, showing the sugar cane fibers that act as reinforcement for the composite material and the epoxy resin that acts as its matrix. As expected, the sugarcane fibers bear most of the load of the composite, since they support stresses near to 230.2 MPa, while the epoxy resin supports an average stress of 9.5 MPa. The stresses are concentrated in the reinforcement-matrix interface, close to the end of the model, where the load is applied, thus, it could be expected that the material fails close to these zones.

Considering the load and the cross-sectional area of the model of 100 mm$^2$, the nominal stress that the composite supports is 26 MPa. Figure 7 shows the principal stress in the longitudinal direction, the normal stress that the matrix supports is 11.3 MPa, that is, 0.45 times the nominal stress. At the ends of the model, where the stress of the matrix is concentrated, the stresses reach values of 29 MPa, 1.12 times the nominal stress. On the other hand, the maximum stress of the model is on the fibers, which bear a stress of 367 MPa, exceeding its maximum strength.

Figure 6. Von Mises stress distribution of the composite material.
4. Conclusions
According to the analysis of the convergence of the models, it is feasible to estimate the behavior of composite materials reinforced with organic fibers. The results obtained by the finite element analysis suggest that the failure mechanism may be associated with the zones where the admissible stresses in the matrix are exceeded. It must be taken into account that in the model the condition of complete adhesion between the fibers and the epoxy resin was used, which restricts the displacements in the reinforcement - matrix interface. This adhesion does not completely occur in the manufacture of composite materials, therefore, in experimental tests, the behavior of the composite in these zones may be different. Stress analyses indicate that sugarcane fibers absorb 38% of the load in the composite, indicating that the sugar cane fibers have a good performance under this type of loads. Thus, this composite has the potential to be used in structural applications under tensile loads.

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