Interlaminar tensile strength of the composite of African palm oil bunches rachis fibers and epoxy matrix

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Abstract. The organic composite materials are very competitive due to their low density and good flexibility by design, suitable for certain working conditions such as installations where high mechanical strength at a low weight is required. Additionally, they contribute to the environment by taking advantage of organic components that are currently waste. The composite proposed in this work consists of an epoxy matrix reinforced with African palm rachis fibers. The specimens were manufactured under the manual rolling process due to the nature of the reinforcement. Moreover, the variation of the interlaminar tensile strength was investigated, using a four-point flexion testing and varying the thickness of the specimen in order to evaluate the feasibility of the organic reinforcement. The experimental analysis was performed with a curved beam geometry and low flexion.

1. Introduction
Composite materials have been designed to take advantage of the properties of their constitutive materials for the construction of elements subjected to stress and strain in different areas of engineering, such as civil, aeronautical, and mechanical engineering due to their high strength/weight ratio [1–3]. The characterization of composite materials can be performed both physical and virtual [4]. Composite materials can fail due to different causes, and interlaminar failure can be a predominant damage mechanism [5], with the delamination of the layers specifically as a primary failure mode [6].

On the other hand, the rachis is a residue of the African palm, which is extensively farmed in Colombia, and has a high participation of sowing especially in the Meta region [7]. This waste is used in the sludge to make vermiculture [8], it is also used to avoid the fly of the stables, for paper production [9], and also as a reinforcement on the cardboard with the intention of improving its mechanical properties [10]. The African palm, or oil palm, waste known as rachis or bunch is a lignocellulosic material with 60% to 65% moisture and 1% to 2.5% vegetable oil, and it is the product of the separation between the fruits and their support from the plant [11]. Regarding the composite proposed in this study, the density of the rachis is approximately 417 kg/m³ [12] and for the epoxy, it oscillates between 1.11 g/cm³ to 1.4 g/cm³.

Reinforcements of composite materials are used with the intention of improving the properties of the matrix material. First, we must characterize both the matrix and the reinforcement and, then, look at the behavior of the structure as a whole [13]. Currently, there are residues generated by agriculture which
are not optimally used and therefore are thrown away or underutilized as fertilizer [14], this yields an opportunity in the research of new materials for engineering applications, where proper material characterization is required [15,16].

For the determination of interlaminar tensile stresses (ILTS), it is commonly used the ASTM D6415-99 [17] standard, which is not very accurate due to the manufacture of the specimen and on the other hand, there is a high dispersion in the data of the strength [18]. However, it is a good reference to determine the stresses of interlaminar tension, in addition, to varying the thickness of the sample in the test shows the incidence of this variable with respect to the ILTS [19]. Moreover, the topic has been investigated using polyurethane matrix and African palm rachis fiber, obtaining good results and an economic comparison to obtain a balance between the two materials used in the composite [20].

The main objective of this work is to determine the resistance to the interlaminar stress for the composite of the polymeric matrix of epoxy and rachis fiber of the African palm, seeking for alternatives to materials such as steel, and other non-sustainable materials with limited natural resources, giving also the opportunity to reduce waste from companies producing African palm oil. We compare the interlaminar tensile strength and their variability with respect to the change in the thickness of the specimen, due to this relation is non-linear.

2. Materials and test configuration

2.1. Materials
A composite material is always composed of matrix material and a reinforcement, in this case respectively a polymer and organic fiber. The polymeric material used in this research as a matrix was the epoxy resin R744, with its proper catalyst for its preparation. The mixing ratio for obtaining the hard resin was 4: 1 [21] to avoid non-uniform solidification and the generation of bubbles. The modulus of elasticity for the epoxy is 2.0 GPa [22]. The reinforcement material used in this work was the fibers of African palm rachis which is of organic origin, with a modulus of elasticity of 960 MPa [23]. There was a process of collection of several bunches in the palm oil extraction plant, these were later opened in the laboratory to be able to extract the fibers manually. Fibers with a minimum length of 12 cm were selected to meet the required geometry, long fibers were cut to size to meet the indications of the standard, the average diameter of the measured fiber was 0.5 mm, obtained with the caliper. This value was used to calculate the volume fraction.

2.2. Specimen design
For the design of the experiment, two groups of five composite samples (fiber and epoxy) were made for different thicknesses "t", these thicknesses were 3 mm and 6 mm with a roundness of 6.4 mm in the curvature of 90° as shown in Figure 1. The 3 mm specimens had a reinforcement layer and the 6 mm specimens had two reinforcing layers. In addition, only resin samples were made for the same thicknesses, in order to analyze the behavior variation for only the resin works and when it is reinforced with fibers.

![Figure 1. Model of specimen in 3D.](image)

2.3. Manufacturing
In this procedure, to be able to make the specimens, we used a steel mold made by the process of rolling and bending to guarantee an angle of 90° with a radius of curvature of 6.4 mm, as indicated by the standard, and 30 cm long to generate several test tubes simultaneously, see Figure 2(a). First, this mold
was covered with plastic cover paper to decrease the adhesion between the mold and the specimen, then clay paths were made to generate the cavity where the specimen was formed. The mold surface was covered with a petroleum jelly-based product to make easy the extraction of the specimen. Additionally, a long fiber is traversed in the curve of the mold to keep the fibers suspended when they are assembled in the mold. The fibers are pre-grouped as indicated in Figure 2(b), using clay at the end to assemble them in the mold as shown in Figure 2(c). Next, the upper part of the test pieces is covered with cardboard protected by plastic cover paper and petroleum jelly-based product to avoid adhesions, this cover has a hole in the curved part of the specimen to introduce the resin, as shown in Figure 2(d). All the side holes are sealed with clay to prevent resin leaks. Later, the resin/catalyst mixture was prepared and poured into the mold. Finally, after 24 hours of the previous process, the dismantling of the specimens is shown in Figure 3(a) for the specimen with reinforcement, and in Figure 3(b) for the specimen of epoxy only.

![Fabrication process](image1)

**Figure 2.** Fabrication process: (a) steel mold, (b) grouping of the fibers using clay, (c) preparation of the fibers in the steel mold, (d) preparation of the mold with cardboard and petroleum jelly-based product.

![Specimens](image2)

**Figure 3.** Types of specimens: (a) with reinforcement, (b) epoxy only.

Table 1 shows the values corresponding to the thickness, number of samples, volume of the sample, considering a mass of rachis and epoxy per each sample for a concentration of 6.5% load in the volume of fiber with respect to the total volume of the test piece. The data show the intrinsic characteristics of the samples used for each thickness and concentration configuration for subsequent validation.
| Number | Thickness (mm) | Number of specimens | Volume (cm³) | Mass of rachis (gr) | Mass of epoxy (g) |
|--------|----------------|---------------------|--------------|---------------------|-------------------|
| 1      | 3.00           | 5.00                | 8.43         | 0.23                | 9.85              |
| 2      | 3.00           | 5.00                | 8.43         | 0.00                | 10.54             |
| 3      | 6.00           | 5.00                | 17.21        | 0.46                | 16.11             |
| 4      | 6.00           | 5.00                | 17.21        | 0.00                | 21.51             |

2.4. Testing

The universal testing machine MTS BIONIX was used for a four-point bending test. The geometrical dimensions of the assembly for the test were: support cylinder with diameter D = 10 mm, distance between lower supports $l_b = 75$ mm, distance between upper supports $l_t = 48$ mm, the other measurements are calculated in the following section, see Figure 4.

![Figure 4. Dimensions of the assembly.](image)

After the assembly is completed, the test is continued by programming the machine using the software "Multipurpose Elite" with a speed of 1 cm/min, satisfying the standard requirements, which recommends a test duration between 1 and 10 minutes. Below, in Figure 5, is shown the process from the beginning of the test to the moment of failure.

![Figure 5. Test stages (a) start test, (b) during test, (c) final test, and (d) failure.](image)
3. Experimental results

The epoxy resin samples offer high resistance, but also a behavior of a fragile material. Figure 6 shows the applied load (P) vs vertical deformation (Δ).

![Figure 6](image1)

Figure 6. Load vs displacement for specimens with only epoxy: (a) 3 mm thickness, (b) 6 thickness.

From the above figures, it is possible to determine the maximum load before failure and the deformation as longitudinal displacement. For the case of the 3 mm thick specimen, the maximum load was 40.6 N and the deformation was 14.24 mm. For the 6 mm specimen, the maximum load was 400.42 N and the deformation was 19.37 mm.

Similarly, Figure 7 shows that the maximum load supported by the 3 mm reinforced specimen was 32.65 N, with a displacement of 19.24 mm, and the specimen of 6 mm had a maximum load of 314.63 N and a displacement of 13.45 mm.

![Figure 7](image2)

Figure 7. Load vs displacement for specimens with fiber: (a) 3 mm thickness, (b) 6 thickness.

Using the equations from the standard [17] and the equations of composites to calculate the curved beam strength (CBS) and interlaminar strength (σr), the latter being the objective of this work. Table 2 shows the calculated values for each type of specimen, as listed in Table 1.

| Table 2. Test results. |
|------------------------|
| Number | Thickness (mm) | Composition | P (N) | Δ (mm) | CBS (N) | σr (MPa) |
|--------|----------------|-------------|-------|--------|---------|----------|
| 1      | 3              | Compound   | 32.650| 19.240| 23.110  | 2.253    |
| 2      | 3              | Epoxy      | 40.600| 14.240| 28.730  | 2.801    |
| 3      | 6              | Compound   | 314.630| 13.450| 249.40  | 10.261   |
| 4      | 6              | Epoxy      | 400.420| 19.370| 317.40  | 12.754   |
4. Conclusions
The interlaminar resistance of the composite was determined for the thicknesses of 3 mm and 6 mm with a concentration of 6.5% reinforcement in volume. The increase in interlaminar resistance when doubling the thickness was approximately 5 times. The reinforcement with fibers decreases the maximum load supported before failure for the first time with respect to the epoxy only specimens, but one advantage is the preventive detection of the total failure of the composite due to the delamination that occurs, in this way, each layer is acting and they are broken until the final failure of the material, otherwise the epoxy only fails once as a fragile material. The concern for further research is the variation of the interlaminar resistance when varying the concentration of African palm fiber for an epoxy matrix.

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