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## Original Article

# Weibull analysis of the tensile strength dependence with fiber diameter of giant bamboo<sup>☆</sup>



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## ABSTRACT

The fibers extracted from the stem of the giant bamboo plant have been investigated as possible composite reinforcement due to their relatively high tensile strength. A dimensional characterization of the distribution and the effect of diameter on the mechanical resistance of bamboo fiber of the species *Dendrocalmus giganteus* has not yet been performed. The present work characterized the distribution of a bundle of this bamboo fiber. Based on this characterization, diameter intervals were set and the dependence of the tensile strength of these fibers with a corresponding diameter was analyzed by the Weibull method. The results indicated an inverse dependence, in which the highest tensile strength was obtained for the thinnest fibers. Moreover, a mathematical hyperbolic relationship was found to adjust well this inverse correlation. An investigation of the microstructure by means of scanning electron microscopy revealed a potential mechanism for this correlation.

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## 1. Introduction

Bamboo is a well known grass-type plant with a hard and stiff stem or culm that can reach, in some species, more than 10 cm in cross section diameter and stand several meters height. Owing to its low density, approximately  $0.9\text{g/cm}^3$ , bamboo culms have been used in house construction from

scaffoldings to panels. As an abundant natural resource in tropical and temperate regions, especially in Asia and South America, bamboo is also a substitute for wood and plastics in furniture and even lightweight parts of automobile [1,2]. The cylindrical shape of the culm is, however, a limitation for its direct use in engineering systems. Consequently, research works have been conducted on bamboo fibers stripped off from the culm as reinforcement of polymer composites [1–13].

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**Fig. 1 – Bamboo trees (a), dried bamboo culm (b) and its fibers longitudinally stripped with different diameters (c).**

According to Shin et al. [3] bamboo fiber-epoxy laminates can be made into specific sizes and shapes, preserving the natural microstructural properties. These fiber composites overcome the limitation of the culm's cylindrical macrostructure. As a further advantage, Shin et al. [3] indicated that cracking and bioerosion caused by insect pests is prevented.

Works on the mechanical properties of polymer composites reinforced with culm-stripped bamboo fibers [3–5,12,13] reported mechanical strength and modulus that could vary significantly with the amount of incorporated fiber, the type of polymeric matrix, the fiber disposition (short-cut, continuous, aligned, mat-arranged) and the fiber diameter. In particular, the diameter dependence of the common bamboo fiber (*Bambusa vulgaris*) was found to vary inversely with the tensile strength [13]. Tensile strength from 100 to 200 MPa were obtained for average fiber diameters of 0.85–0.35 mm, respectively. Owing to the oriented lignocellulosic structure, as recently reviewed for other natural fibers [14–17], it is relevant to investigate how the mechanical behavior of the stronger species of giant bamboo fibers is affected by its cross section diameter.

Depending on the ability and cutting technique, the manual culm stripping off process produces bamboo fibers with different diameters. Therefore, the objective of this work was to investigate the giant bamboo fiber tensile strength dependence on its diameter using a Weibull statistic analysis, which has been applied in several lignocellulosic fibers, including those from other bamboo species [13,18,19].

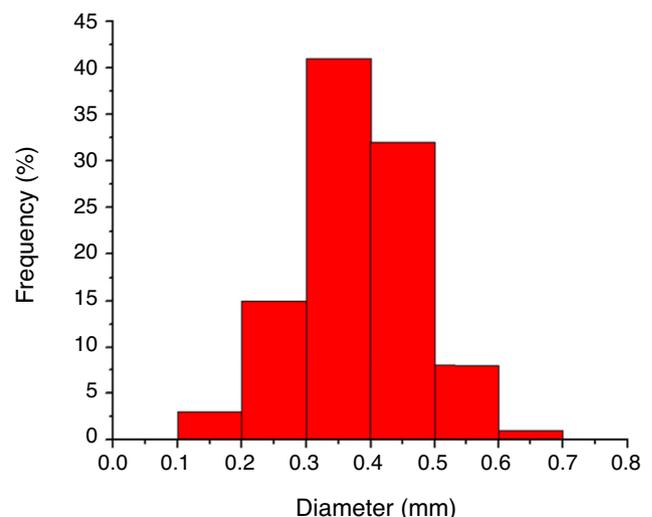
## 2. Experimental procedure

The basic material used in this work was the culm of giant bamboo (*Dendrocalmus giganteus*) supplied by a producer in the state of Rio de Janeiro, southeast of Brazil. Large bamboo bushes, Fig. 1(a), occur naturally in that region. Their culms were cut, Fig. 1(b) and dried for easy fiber extraction. Fibers were manually stripped off from dried culms, Fig. 1(c) with a sharp razor blade. The longitudinal direction of the fiber coincides with that of the culm and corresponds to the natural direction of the bamboo cellulose fibrils. Different cross section diameters were obtained, in spite of the apparently uniform manual stripping procedure. From randomly selected 100 fibers, the equivalent diameter corresponding to the average between the larger and smaller (90° rotation) cross section dimensions at five locations for each fiber, was measured in a profile projector.

The histogram in Fig. 2 shows diameter distribution of stripped giant bamboo fibers used in the present work. Based on Fig. 2, an average diameter of 0.4 mm was calculated within the range 0.1–0.7 mm. For each interval, 20 fibers were selected. All fibers were then individually tensile tested at  $25 \pm 2^\circ\text{C}$  in a model 5582 Instron machine. Special grips were used to avoid both fiber slippage and damage. The test length was 6 cm and the strain rate  $2.1 \times 10^{-4} \text{ s}^{-1}$ . It is worth mentioning that similar distributions were obtained for other bamboo species, *Bambusa vulgaris*, in the interval of fiber diameters from 0.3 to 0.9 mm [13], and *Guadua angustifolia*, from 0.08 to 0.26 mm [18].

Values obtained for the tensile strength, i.e. the ultimate stress ( $\sigma_m$ ), were statistically interpreted by means of a Weibull Analysis computer program. A minimum number of 20 fibers from each of the six diameter intervals was considered in the analysis. The program provided the corresponding characteristic stress ( $\theta$ ), the Weibull modulus ( $\beta$ ) and the precision adjustment ( $R^2$ ) parameters.

The tensile-ruptured tip of some tested fibers were attached with conducting carbon tape to a metallic support and then gold sputtered for scanning electron microscopy (SEM) observation in a model SSX-550 Shimadzu equipment operating with secondary electrons accelerated at a maximum voltage of 15 kV.



**Fig. 2 – Distribution frequency for the stripped bamboo fibers equivalent diameter.**

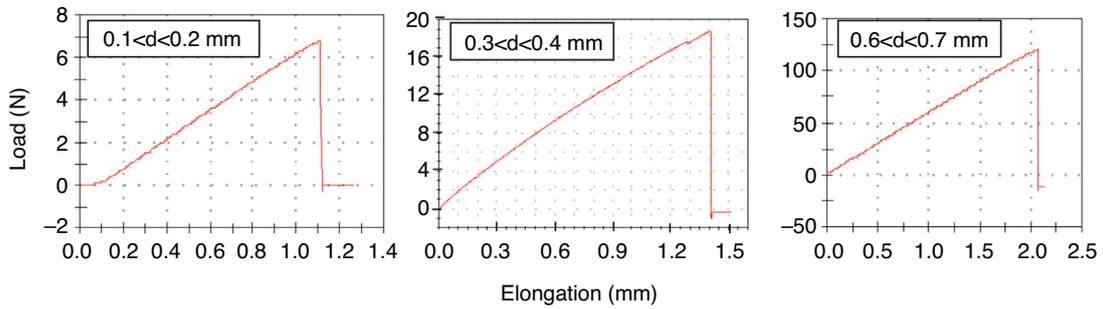


Fig. 3 – Typical tensile load vs. diameter of bamboo fibers for different diameter intervals shown in Fig. 2.

### 3. Results and discussion

Fig. 3 shows typical load vs. elongation curves that are representative of the behavior observed for fibers in all diameter intervals. These curves present an initial linear elastic behavior followed by an abrupt rupture with no apparent plastic extension. Consequently, for all diameter intervals, the culm-stripped giant bamboo fiber can be considered as a brittle material.

Based on the maximum load, Fig. 3, the tensile strength of each fiber was obtained and the values statistically analyzed by the Weibull method for each diameter interval in Fig. 2. Fig. 4 shows corresponding Weibull reliability vs. location parameter plots. It should be noted that all plots in this figure are unimodal with one straight line fitting the points in the same diameter interval. Similar plots were obtained not only for different bamboo species but also other natural lignocellulosic fibers [13,19].

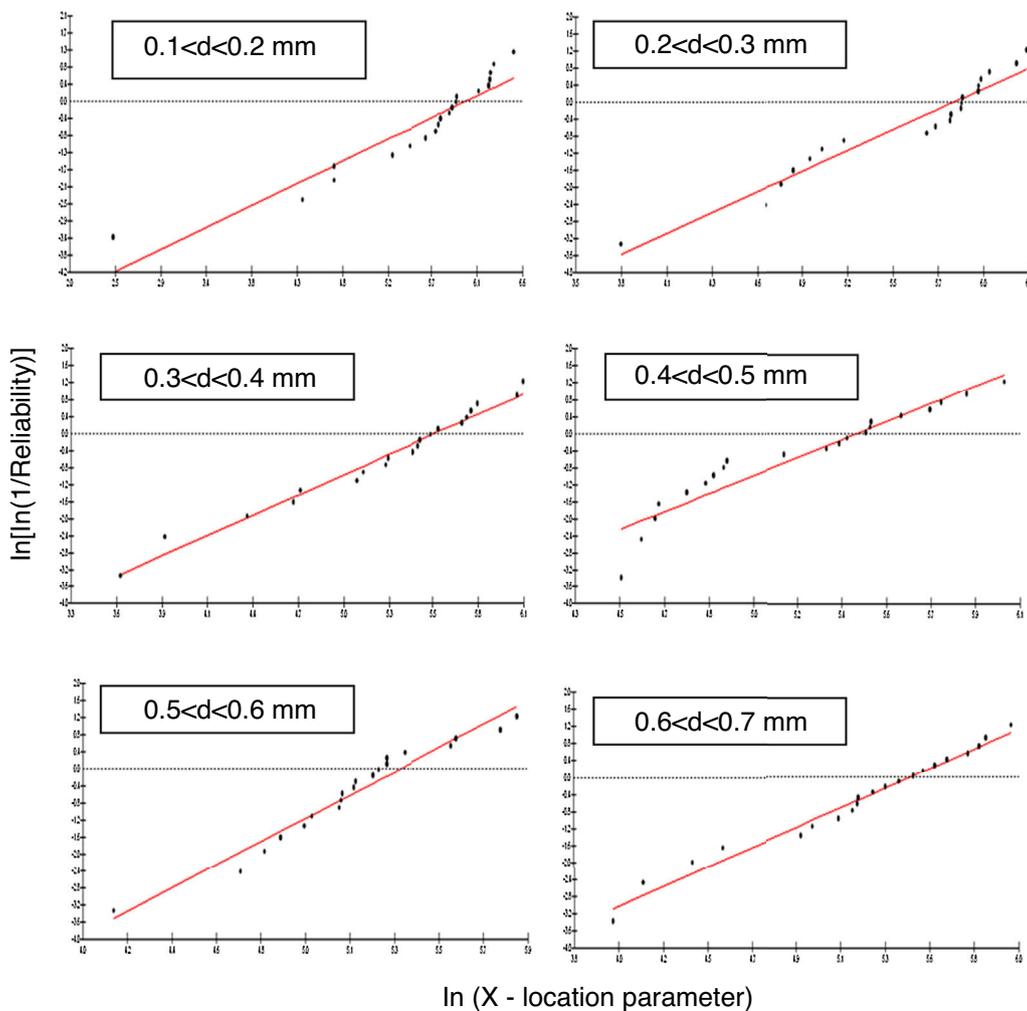
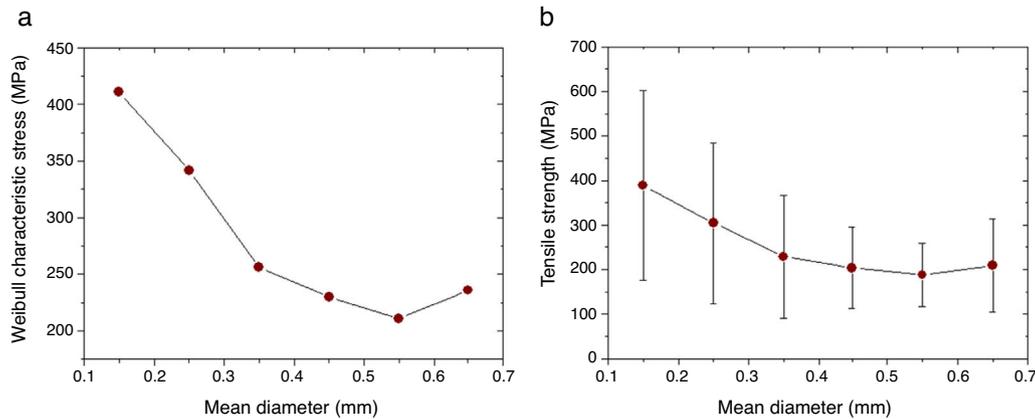


Fig. 4 – Tensile strength Weibull plots for the different diameter intervals of giant bamboo fibers shown in Fig. 2.

**Table 1 – Weibull parameters for the tensile strength of giant bamboo fibers associated with different diameters.**

Diameter interval (mm)	Weibull Modulus, $\beta$	Characteristic stress, $\theta$ (MPa)	Precision adjustment, $R^2$	Tensile strength (MPa)	Statistical deviation (MPa)
0.1–0.2	1.174	411.1	0.8856	389	212.4
0.2–0.3	1.737	341.8	0.9415	304.5	180.8
0.3–0.4	1.708	256.1	0.9776	228.4	137.7
0.4–0.5	2.358	229.8	0.9066	203.7	91.83
0.5–0.6	2.892	210.8	0.9567	187.9	70.59
0.6–0.7	2.107	235.8	0.9783	208.8	104.2

**Fig. 5 – Variation of the (a) characteristic stress and (b) tensile strength with the diameter for each interval in Fig. 2.**

The values of the Weibull parameters ( $\beta$ ,  $\theta$  and  $R^2$ ), as well as the average mechanical strength and associated statistical deviations, are presented in Table 1.

Based on the  $R^2$  parameter, it can be concluded that the data follows a Weibull statistical distribution with good precision. The variation of the characteristic stress ( $\theta$ ) and the tensile strength ( $\bar{\sigma}_m$ ) with the average fiber diameter for each one of its intervals are presented in Fig. 5.

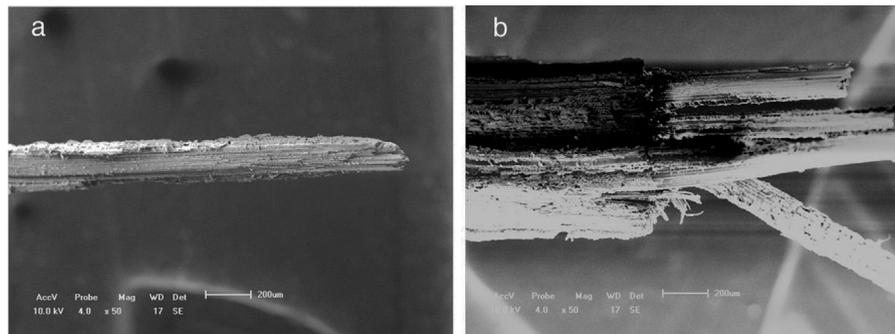
In Fig. 5(a), there is a tendency for the  $\theta$  parameter to vary inversely with the average giant bamboo fiber diameter. This tendency is similar to that found for the common bamboo (*Bambusa vulgaris*) [13] but with improved parameter. Indeed, the giant bamboo fiber tensile strength varied from 210 to 411 MPa with corresponding average diameter respectively from 0.15 to 0.65 mm of average diameter. By means of a

mathematic correlation, a hyperbolic equation was proposed to fit the data in Fig. 5.

$$\theta(\text{MPa}) = \frac{40}{d} + 154.5 \quad (1)$$

In order to analyze the physical meaning of Eq. (1), the average tensile strength,  $\bar{\sigma}_m$ , evaluated in this work for the culm-stripped giant bamboo fibers was plotted as a function of the diameter in Fig. 5(b). In this figure an apparent hyperbolic inverse correlation also exists between  $\bar{\sigma}_m$  and  $d$  within the error bars (statistical deviations) and investigated limits.

$$\bar{\sigma}_m = \frac{40}{d} + 127 \quad (2)$$

**Fig. 6 – SEM fractographs with same magnification of tensile-ruptured bamboo fibers: (a) thinner,  $d = 0.1255$  mm and (b) thicker,  $d = 0.6946$  mm.**

Here it is important to mention that the large dispersion (error bars) in the values of the tensile strength in Fig. 5(b) is due to the heterogeneous and random characteristics of the biological process of formation of any lignocellulosic fiber [20], such as the giant bamboo in this work. As a consequence, one could also consider a horizontal line passing within the error bars as a possible correlation between  $\bar{\sigma}_m$  and  $d$ . In this case, the tensile strength would not vary with the diameter. However, the variation of  $\theta$  with  $d$  in Fig. 5(a) suggests that an inverse correlation adjusts better the experimental results for the giant bamboo fibers. It is also possible to consider that the values of  $\bar{\sigma}_m$  in Fig. 5(b) and  $\theta$  in Fig. 5(a) are approximately constant, around 200 MPa, for fibers thicker than 0.4 mm. Under this consideration, only the thinner giant bamboo fibers,  $d \leq 0.4$  mm, present the inverse correlation, but not necessarily hyperbolic. This should be further investigated. Based on Eqs. (1) and (2) it is suggested that, as in other lignocellulosic fibers [13], a hyperbolic type of mathematical equation is the best statistical correlation between the tensile strength and the diameter of culm-stripped giant bamboo fibers. A simple inverse tensile strength vs. diameter correlation was also found in Chinese Moso bamboo fibers (*Phyllostachys edulis*) [19]. However, for a *Guandua angustifolia* bamboo species fiber, Trujillo et al. [18] reported only dispersed values of fiber strength within a limited diameter interval from 0.1 to 0.22 mm.

A SEM observation of the tip of representative tensile-ruptured fibers, shown in Fig. 6, provided further evidence of a fracture mechanism that could justify the hyperbolic correlation in Eq. (2). With the same magnification, the thinner fiber, Fig. 6(a), shows a more uniform fracture associated with lesser fibrils. By contrast, a fiber with larger diameters, Fig. 6(b), displays a relatively non-uniform fracture with participation of more fibrils. Statistically, there is always a chance that one of the many fibrils of the thicker giant bamboo fiber in Fig. 6(b), would prematurely break and then act as a flaw to cause the fiber rupture at a lower stress as compared to the thinner fiber, Fig. 6(a). In other words, the larger distribution of fibrils strength of the thicker fiber allows one of them breaking shortly than any of the fewer fibrils of a thinner fiber. Wang and Shao [19] also attributed the reduction in mechanical properties of bamboo fibers to accumulation of defects within fiber diameter variations.

As a final remark, it should be mentioned that an inverse correlation such as that in Eq. (2), could allow, in practice, a selection of stronger culm-stripped thinner giant bamboo fibers to effectively reinforced polymer composites with improved mechanical properties. The tensile strength of these stronger thinner fibers, Table 1 and Fig. 5, indicates an advantage over other natural fibers [13–17] as feasible reinforcement of polymer composites.

#### 4. Conclusions

- A Weibull statistical analysis of tensile-tested manually culm-stripped giant bamboo fibers revealed an inverse correlation between the tensile strength and the fiber diameter.
- This correlation is similar to that found for the much weaker common bamboo fibers and indicates a possible

hyperbolic mathematical equation to hold, at least, for diameters below 0.4 mm.

- SEM observations provided evidences that a thicker giant bamboo fiber, with more fibrils than a thinner one, could undergo rupture at a comparatively lower stress. Statistically, the larger distribution of mechanical resistances of fibrils in the thicker fiber allows the weakest fibril to break shortly than any of the fewer fibrils of the thinner fiber.
- The tensile strength above 300 MPa obtained for thinner fibers of giant bamboo is a desirable condition for their application as reinforcement of polymer composites.

#### Conflicts of interest

The authors declare no conflicts of interest.

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