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BAMBOO: FUNCTIONALLY GRADED COMPOSITE MATERIAL

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ABSTRACT

The bamboo structure can be generally viewed as a Functionally Graded composite material constituted by long and aligned cellulose fibres embedded in a lignin matrix. Analysing the transversal section of a bamboo culm, one can observe that the fibre distribution is variable through its thickness. The non-uniform distribution of fibres prevents the direct application of equations used to model the behaviour of composite materials, as the rule of mixtures equations for strength and modulus of elasticity. These equations assume, besides the perfect bonding between fibre and matrix, uniform distribution of the fibres in the matrix. In bamboo, the fibre distribution follows an organized pattern with a higher concentration of fibres on the outer surface of the culm. Establishing how this variation occurs, the basic equations from the composite materials approach can be modified in order to model the mechanical behaviour of bamboo.

This paper presents the meso-structure analyses of bamboo culms through Digital Image Analysis. The variation of the volume fraction of the cellulose fibres across the transversal section of the bamboo is established. The developed methodology is successfully applied to study the volume fraction variation of fibres in two different samples of bamboo species Phyllostachys heterocycla pubenscens, commonly know as “Moso”.

Keywords: bambo, composite materials, MOSO, digital image analysis.

1. INTRODUCTION

The shortage of housing in developing countries motivates the search for low cost materials that can be applied in the construction of affordable houses, especially in earthquake regions of the world. In this context many researchers have been studying the application of the locally abundant natural materials as building materials such as mud blocks, natural fibres reinforcing soil or cement matrixes and bamboo culms. These materials and the traditional building

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techniques, which almost have vanished after the wide implementation of the building industry, are the main focus of the researchers on non-conventional materials and techniques at the present time of environmental crisis, which our globe is facing.

The understanding of the mechanical behaviour of bamboo has caught the attention of engineers, architects, biologists and material researchers due to bamboo's great potential to be used as a construction material. Bamboo presents advantages in relation to other construction materials for its lightness, high bending capacity and low cost, besides the fact that it requires simple and low cost processing techniques. It is the fastest growing plant on earth in addition to being a renewable natural resource (Ghavami and Hombeeck [1981]; Liese 1986; Ghavami and Zielinski 1988; Ghavami and Culzoni 1987; Ghavami 1988; 1995a; Ghavami and Solorzano 1995; Amada 1996, Ghavami and Rodrigues 2000)

Observing the transversal section of a bamboo culm, one can note that this material is roughly constituted by two distinct phases, which are the cellulose fibres and the lignin matrix as is shown in Figure 1. Therefore bamboo can be considered as a composite material and the well-established approach to these materials, such as the rule of mixtures, can be applied and adjusted for the variability of its fibres.

Through the images obtained by (Liese 1986) in his analysis of the micro-structure of bamboo, it was observed that what is considered as fibres are, in fact, vascular bundles composed of veins to transport the sap and cellulose micro-fibres. These vascular bundles are briefly discussed according to the analysis of (Dunkelberg 1985) as shown in Figure 2.

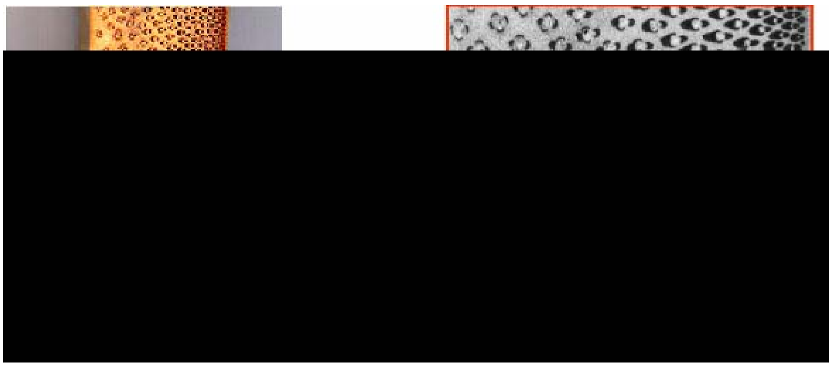

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Figure 1 Fibre packing in the composite bamboo: functionally graded

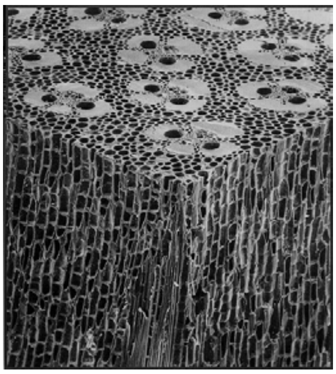

Figure 2 Details of the microstructure of the bamboo

The region with high density in the vascular bundle is called sclerenchyma and is composed of cellulose micro-fibres. These groups of fibres are responsible for the bamboo strength. The veins are responsible for the transport of sap from the soil to all parts of the plant. The cellulose micro-fibres around the veins keep them straight along the whole culm. The lignin that surrounds the vascular bundles is called parenchyma, which acts as matrix and represents the weak part of the bamboo composite.

A preliminary assessment of the mechanical behaviour of composite materials in the elastic range can be achieved using the rule of mixtures, which is a group of equations that gives the values of mechanical properties of composites based on the mechanical properties and the volume fraction of their constituents, fibres and matrix. As an example, equation 1 shows how to establish the Young modulus for a composite knowing the values of the Young modulus of the fibres and matrix and their volume fractions.

$$E_c = E_f V_f + E_m V_m = E_f V_f + E_m (1 - V_f) \tag{1}$$

The hypothesis in the development of the equations of the rule of mixtures assumes long and aligned fibres, with a perfect bonding between fibres and matrix and uniformly arranged fibres inside the matrix. However, it is observed in Figure 1 that both the area and the distribution of fibres are not uniform, varying through the thickness of the bamboo culms. They follow a regular pattern, with the volume fraction increasing from the interior to the outer surface of the bamboo culm. Due to this fact the meso-structure feature of bamboo has been called a functionally graded material, as it was designated by (Ghavami and Solorzano 1995, Amada 1996). More fibres are found on the outer surface of bamboo, where higher strength is required, in order to withstand wind loads, the most frequent loading of bamboo in nature. This inherent property of bamboo makes it an ideal material to be used in the earthquake regions of the globe.

To make it possible to apply the equations of the rule of mix to analyse bamboo, it is necessary to modify these equations in order to consider the volume fraction variation of the fibres along its thickness. Admitting an “x” axis in the transversal radial direction of the bamboo culm with its origin on the internal surface of the culm and its maximum limit at the external surface, the equations of the rule of the mixtures can be used in the form of equation 2. The variation of the volume fraction along the “x” axis is assessed through digital image analysis (IA), techniques.

$$E_c = f(x) = E_f V_f(x) + E_m (1 - V_f(x)) \tag{2}$$

2. THE IA PROCEDURE

The method used to establish the volume fraction variation of the fibres was the sectioning of the image obtained from a sample of the cross-section of the bamboo in slices normal to the radial direction. The volume fraction of fibres is calculated for each slice and is plotted against the position along the thickness, showing the variation of fibres in the whole sample. Through this figure a fitting curve representing the volume fraction variation of fibres along the thickness is established. This equation for this curve can be applied in equation 2.

The IA procedure follows a general sequence, depicted in the Figure 3. The application of this procedure in the study of the bamboo meso-structure is explained in this paper.

Image Acquisition ⇒ **Digitization** ⇒ **Pre-Processing** ⇒ **Segmentation** ⇒
⇒ **Post-Processing** ⇒ **Feature Extraction**

Figure 3 Common sequence for IA applications

The bamboo samples extracted from the cross-section of the culm were polished up to the surface smoothness of 3 μm in order to observe and photograph them in an optical microscope. The black and white negatives obtained were digitized with a slide scanner, resulting in images such as in Figures 1 and 4.

Image processing and analysis was developed under the software KS400. The pre-processing step started with the sectioning of the image, treating each slice separately until the feature extraction step. An image with its sectioning in four slices is shown in Figure 4.

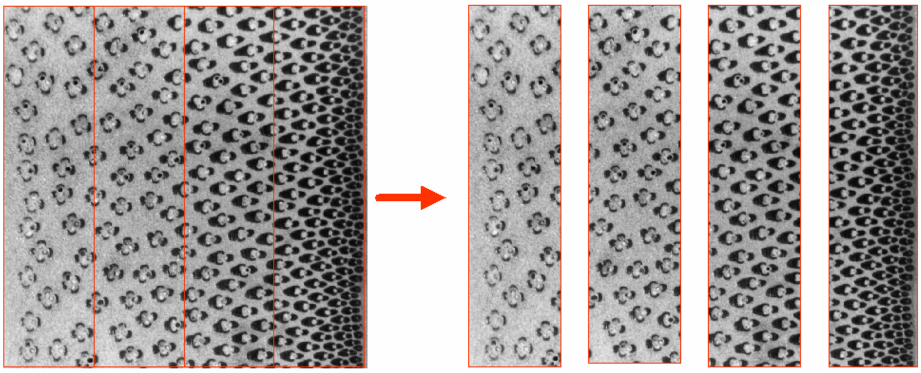

Figure 4 Sectioning of the original image in four slices

Figure 4 also shows variations in contrast appearing as a darker region across the central part of the images. These variations can be caused by specimen preparation or image acquisition in the optical microscope. This problem prevents automatic fibre segmentation and must be dealt with in the pre-processing step.

The solution was to employ a background correction method in which each image is strongly blurred with a low-pass filter to produce an image that represents only the non-uniform background, see Figure 5. This image is then subtracted from the original leading to a corrected image, also shown in Figure 5.

The corrected images were then automatically segmented to detect the fibres as show in Figure 6. This pure black and white image, called a binary image, is used for the measurements of interest. The post -processing was constituted only by the elimination of the very small regions that were initially considered as regions of interest by the segmentation process. The volume fraction of fibres in each slice of the original image then was the only attribute extracted from the process.

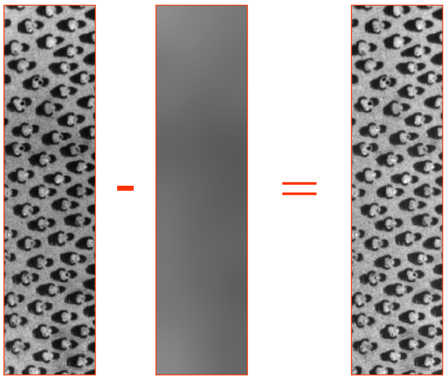

Figure 5 Correction of the non uniform brightness

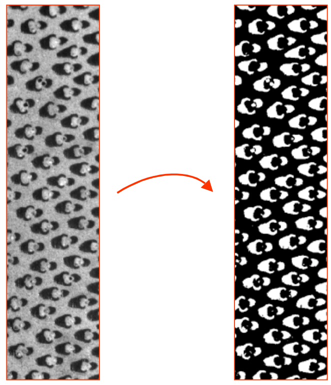

Figure 6 Automatic segmentation

3. APPLICATIONS

The developed procedure was applied in establishing the different problems studied. In this paper two different bamboo species, *Phyllostachys heterocycla pubenscens* commonly know as “Moso” and *Dendrocalamus giganteus* are presented. In each of these examples the volume fraction variation of the fibres was established. The first study on bamboo Phyllostachys heterocycla pubenscens was carried out in order to show the exactness of the method.

Phyllostachys heterocycla pubenscens

This species has a cylindrical culm, as almost all bamboo species. However, due to a physical restriction imposed by a wooden mould during the bamboo growth, the *Phyllostachys* studied here has its culm grown with a square transversal section. From a piece of the culm showing the whole square-shaped section, two samples were extracted, one from a straight part and the other from a curved section, as shown in Figure 7. The objective in applying the IA procedures developed is to determine how the volume fraction variation of the fibres occurs in these two samples and if the imposed restriction changes the distribution of the fibres in the composite constitution. This study also tests the precision of the used process.

First, the influence of different number of image slices in establishing the final result of the fibre distribution was studied. The analysed results from the division of the original image in 4 and 16 slices for both straight and curved samples are shown in Figures 8 and 9 respectively. The position of each image slice is normalized in relation to the thickness of the bamboo section. The comparison between the fibre distributions of the two samples from their sectioning in 16 slices is shown in Figure 10. It can be concluded that different types of sectioning do not substantially influence the final result.

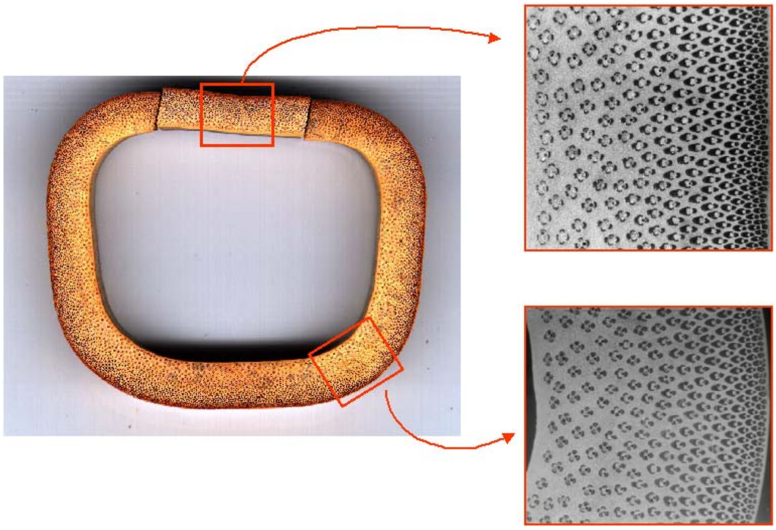

Figure 7 the “square” *Phyllostachis* and the two samples analysed

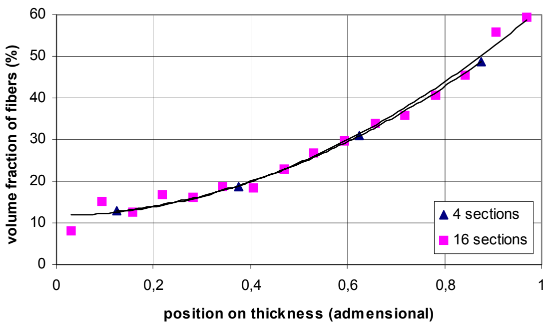

Figure 8 Fibre distribution in the straight sample, sectioned in 4 and 16 slices

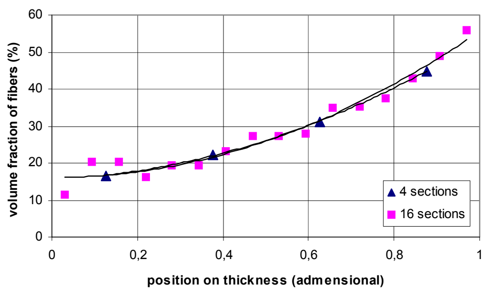

Figure 9 Fibre distribution in the curved sample, sectioned in 4 and 16 slices

Through mathematical regression analysis of the obtained data, the fitting polynomial curves to be applied to the rule of mixtures equations for bamboo as a composite material have been established and are shown in Figure 10. The fibre variation for the straight and curved samples is represented by equations 3 and 4, respectively.

$$V_f(x) = 49.456X^2 + 0.66X + 11.72 \quad (3)$$

$$V_f(x) = 40.12X^2 - 0.55X + 16.12 \quad (4)$$

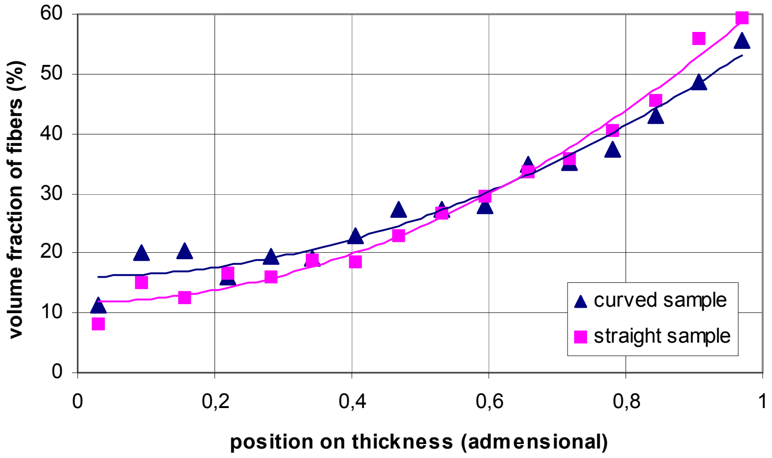

Figure 10 the “square” *Moso* and the two samples analysed

From equations 3 and 4 it can be noted that the curved sample presents a fibre distribution slightly more uniform than that presented by the straight sample. The curved sample has more fibres in the internal region and less fibres near its outer surface when compared with the straight sample. This finding is compatible with the real physical behaviour of the cross-section of bamboo as the total number of fibres along the thickness of the section of these two samples is the same. The fibre distribution obtained using this procedure for the bamboo *Phyllostachys* is similar to the fibre distribution presented by (Amada 1996) for the same bamboo species.

Dendrocalamus giganteus

To establish the composite behaviour of the whole bamboo culm for species, which are used in most of the structural elements, developed at PUC-Rio the IA process was used. For this purpose the fibre distribution is studied in samples extracted from different parts along the culm length. Samples from the base, middle and top of bamboo *Dendrocalamus giganteus* were analyzed, as shown in Figure 11.

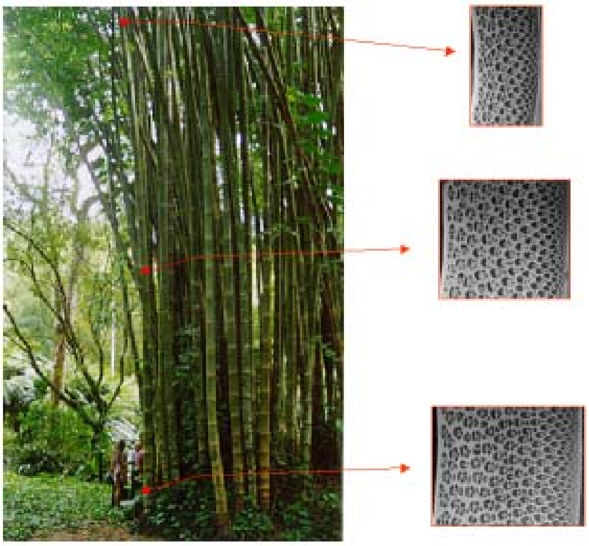

Figure 11 The *Dendrocalamus giganteus* and the locations of the three samples

The variation of the fibres distribution in different parts of the culm is compared in Figure 12. Based on the obtained data three equations for the fibres variation along the bamboo culm were established. Equations 5, 6 and 7 are related to base, middle and top samples, respectively.

$$V_f(x) = -8.57X^2 + 32.94X + 28.93 \tag{5}$$

$$V_f(x) = 6.66X^2 + 29.11X + 26.14 \tag{6}$$

$$V_f(x) = -12.47X^2 + 50.78X + 21.33 \tag{7}$$

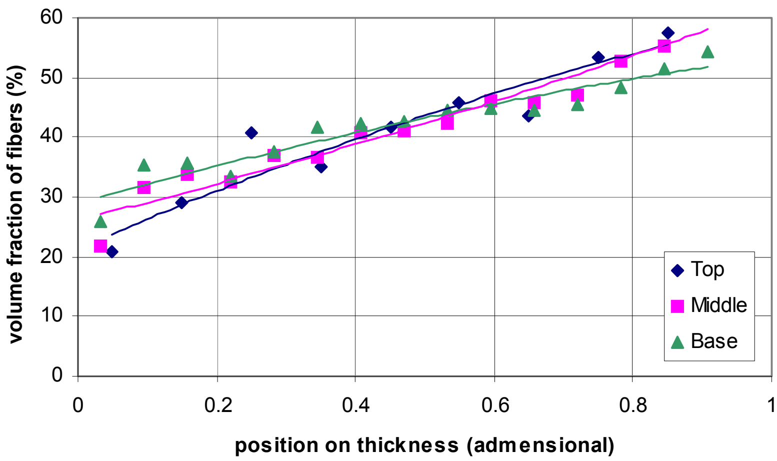

Figure 12 Fibres distribution at the base, middle and top of the Dendrocalamus culm

The plotted fitted curves in Figure 13 show that at the base, the fibres distribution is more uniform than at the top of the culm. This can be explained by considering that at the base, besides the wind force, the bamboo must support its own weight. Therefore, the section is subjected to a combination of compression and bending stresses.

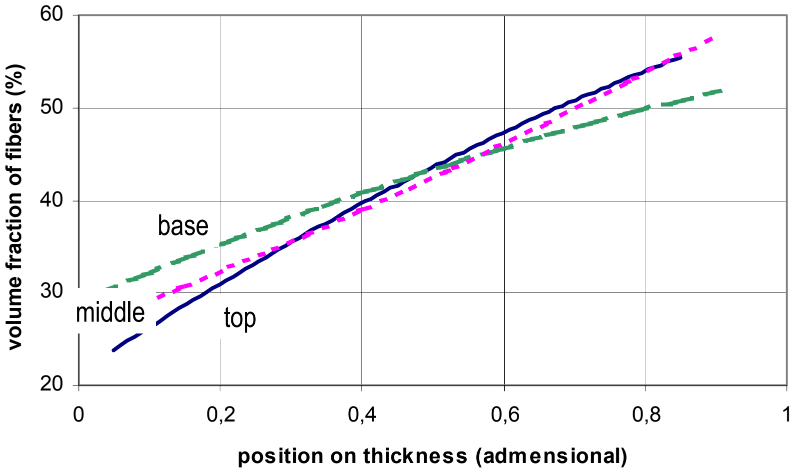

Figure 13 Details of the fibres distribution along the *Dendrocalamus* culm

4. CONCLUSIONS

Increasing the application of bamboo as structural elements requires profound scientific knowledge about its behaviour in nature, considering its macro, meso and microstructures. From the structural mechanics point of view, bamboo acquired several natural geometries mainly in order to counteract wind load and the own weight. These characteristics turn it into one of the best materials/structures for the requirements of compression-deflection. A conical form along the culm, an approximately circular transversal section, a hollow form in most species, which reduces its weight, a functionally gradient rigidity of its cross-section to deflection in the radial direction among others.

Through the application of the Digital Image Analysis (IA) method the properties of two species of bamboo, *Phyllostachys heterocycla pubenscens* and *Dentrocalamus giganteus*, were established. Appropriate equations were developed to present the fibre distribution across the thickness of the cross-section. These equations allow the designer to calculate the modulus of elasticity of bamboo with some degree of precision. In this paper it has been shown that IA provides a reliable method for establishing the meso-structure of bamboo. Studies are underway to establish the form of the vascular bundles of different types of bamboo through which the species of bamboo can be recognised.

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