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Bending strength and nondestructive evaluation of structural bamboo

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HIGHLIGHTS

- Density, stiffness, bending strength properties and nondestructive evaluation of bamboo.
- Bamboo culms used on the construction of a prototype ecological and sustainable village.
- Bamboo culm density and dynamic modulus of elasticity can be used to determine its strength and stiffness.
- SWT can be used for nondestructive evaluation of bamboo culms strength and stiffness.

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ABSTRACT

Optimization on the use of bamboo requires comprehensive understandings of the physical, mechanical, and chemical properties. When using bamboo as a building material, one needs to know its specific gravity, stiffness and bending strength properties. This work investigated density, stiffness, bending strength properties and nondestructive evaluation of four-year old *Bambusa vulgaris* 'Vittata', very common in Manaus, used on the construction of an ecological and sustainable village for Amazonia. Flexural bending strength samples were cut from eight culms in three 3-m segments (base, middle, and top). The 3-m long culms were first tested nondestructively through axial sonic vibration of a Stress Wave Timer (SWT), then in thirdpoint loading static bending with a clear span of 2.71 m. The average moisture content and density of the bamboo culms tested were 12.95% and 646 kg m^{-3}, respectively. The average dynamic modulus of elasticity was 17.3 GPa. The average ultimate load, modulus of rupture and modulus of elasticity were 7.9 kN, 88 MPa and 9.6 GPa, respectively. Analysis of the results showed that bamboo culm density and dynamic modulus of elasticity can be used to determine its strength and stiffness. Also, SWT can be used for nondestructive evaluation of bamboo culms strength and stiffness.

1. Introduction

1.1. Bamboo as a green structural material

Building with bamboo is a long tradition in the world's tropical (with Brazil being an exception) and sub-tropical regions, as cited by Sá Ribeiro et al. [1]. Bamboo is largely utilized as a construction material, mainly in rural housing. Bamboo constructions are easy to build, resilient to wind and even earthquake forces when given the correct detailing. Construction process applications involve bamboo based panels [2,3] and bamboo reinforced concrete [4], among others.

The density of bamboo is found to vary from 500 to 800 kg m^{-3}, depending on the anatomical structure such as the quantity and distribution of fibers around the vascular bundles [5]. Density increases from the center to the periphery of the culm [6,7] and also from the base to the top of the culm [8]. The maximum density is attained in about three-year-old culms [9–12].

Bamboo is a renewable resource with low weight and high strength properties, especially tensile strength. Most of the properties depend on the species and the climatic conditions under which they grow [13,14]. Strength varies along the culm height [4]. Compressive strength increases with height, while bending strength decreases with height [6,9–11,15–17]. An increase in strength is reported to occur at 3–4 years, and thereafter it decreases [9–12]. Therefore, the maturity period of bamboo may be considered as 3–4 years with respect to density and strength. Maturity of culm is a prerequisite for the optimum utilization of bamboo in construction and other structural uses.

Bamboo culms critical load is hard to determine due to the variation along the culm axis of the modulus of elasticity (MOE), wall thickness and diameter, and by the presence of nodes and the

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variations of the said factors around the nodes. Culm characteristic crookedness induces early load-displacement effects. The random nature of this load-displacement effect is mobilized by the lateral displacementss of the structure under lateral loads and governed by the culm initial deformations [18].

Test results of clear specimens are not directly transferred as those of full culms, because the culm tends to fail in the weakest link (the nodal regions), and to develop high tensile parallel stresses. Both factors are very much random in nature. The culms initial deformations would also lead to low rigidity at the start of the load-displacement path [18].

Bambusa vulgaris is the most common cultivated bamboo species in Manaus (03°06′07″ S, 60°01′30″ W, 93-m). In spite of its plentiful, the properties of *B. vulgaris* grown in this region are yet to be researched in detail. Vetter et al. [8] investigated the seasoning, density and shrinkage characteristics of *Bambusa vulgaris 'Vittata'* grown in Manaus. *B. vulgaris* was used for the construction of a sustainable ecological village in the Amazon in 2007 [2]. The present work aimed to attain data on density, stiffness, bending strength properties and nondestructive evaluation (NDE) of full culm *B. vulgaris 'Vittata'* and how these properties are related.

1.2. Axial sonic vibration (longitudinal stress waves)

Stress wave emission or acoustic emission represents the transient elastic wave generation caused from an impact on a solid material. Proper detection and analysis of stress wave emission signals can permit remote identification of wave properties and the associated structural alteration of solid materials. Hence, this can increase understanding of material behavior, can be used as a quality control method for processing and fabrication of materials, and can serve as a NDE technique for assessing the structural integrity of materials under service conditions. Several researchers used NDE techniques to assess structural wood properties [19–22].

The determination of the dynamic modulus of elasticity (E_d) by a longitudinal stress wave propagation technique involves the impacting of the specimen by a hammer and measuring the time it takes the stress wave to travel a predetermined distance, as described by Sá Ribeiro and Sá Ribeiro [19]. From the measured time and length, the velocity (v) of the stress wave can be calculated. The velocity of the longitudinal stress wave is proportional to the square root of E_d and the mass density (ρ) of material [23]. Therefore, the dynamic modulus of elasticity can be expressed as

$$E_d = \rho v^2 \tag{1}$$

Chen et al. [24] applied NDE techniques by means of a Stress Wave Timer (SWT) to determine the moisture content (MC) at fiber saturation point (FSP) for three bamboo species: *Dendrocalamus giganteus* Munro, *Dendrocalamus latiflorus* Munro, and *Bambusa stenostachya* Hackel. More recently, Lin et al. [25] used NDE techniques to determine E_d of *Phyllostachys edulis* lamina.

2. Materials and methods

2.1. Sampling and conditioning

Eight culms from two clumps were collected from a plantation at the Brazilian National Institute for Amazonian Research (INPA) in Manaus (latitude −3°06′07″, longitude −60°01′30″, altitude 93 m), Amazonas. The culms were approximately four years old with 87-mm average diameter.

Each culm was cut into three segments (base, middle, and top) of 3-m long, labeled, measured, and conditioned according to the standard ISO 22157-2 [26]. These culms were conditioned for nondestructive testing (NDT) and for the flexural bending test. Some specimens were discarded due to cracks along the length of the culm, and were not substituted due to time constrains. Samples for MC determination and density were taken from each culm immediately after the completion of the bending test.

2.2. Nondestructive testing of the culms

Determination of moisture content, density (mass by volume) and bending strength properties of the bamboo culms were done according to the standard ISO 22157-2 [26]. The 3-m long culms were first tested nondestructively through axial sonic vibration of a Metriguard 239A Stress Wave Timer, as illustrated in Fig. 1. The testing procedure was the following:

1. Attach the bamboo culm ends to the stop and start clamps of the SWT. Measure the distance between the start and stop accelerometers.
2. Impact the start-end of the specimen with the pendulum ball-hammer device. Read the time (in microseconds) it takes for the stress wave to travel the predetermined distance and record it.

2.3. Flexural bending test

Flexural bending test of full bamboo culms was done using a Universal Testing Machine with a 500-kN load cell capacity at a speed of 30 mm min^{-1} up to rupture. Test specimens were loaded with a third point loading and simply supported over a 2.71-m clear span, as illustrated in Fig. 2. Deflections were measured at mid-span using a potentiometer. The potentiometer was Celesco position transducer with a measuring range of 254 mm and a position sensitivity of 94 mV V^{-1} $inch^{-1}$.

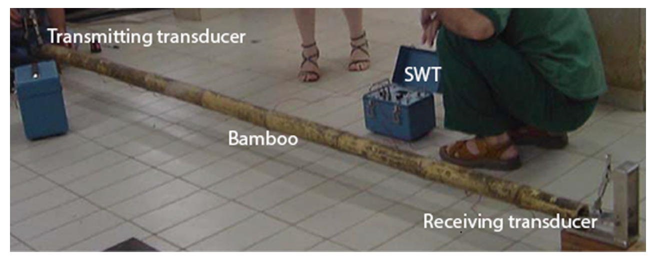

Fig. 1. NDT of a bamboo culm using the Metriguard SWT.

Fig. 2. Third-point loading bending strength test for bamboo culm.