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Methods of determining transverse mechanical properties of full-culm bamboo

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HIGHLIGHTS

- ▶ Edge bearing test to obtain transverse material properties of bamboo is proposed.
- ▶ Effect of through-culm-wall fiber gradation on edge bearing strength is explored.
- ▶ Strain profile shift of the neutral axis is less pronounced in thin wall sections.
- ▶ Observations will lead to more reliable through-wall properties being established.
- ▶ Properties may be used to refine modeling of full-culm bamboo materials.

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ABSTRACT

The potential for adopting the relatively simple-to-conduct edge bearing test as a surrogate for direct determination of the critical transverse material properties is investigated. The research explores the effect of through-culm-wall fiber gradation on the edge bearing, or 'diametric compression', strength of full-culm bamboo. The test method also utilizes a full culm section cut into two or three concentric annular sections. Tests results for each 'ring' provide a measure of through thickness transverse properties. The objective of this work is the development of practical test methods for field assessment of bamboo material properties.

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1. Introduction

Conventionally reported material properties of bamboo typically focus on the strength parallel to the fibers; these include tension, compression and flexural (modulus of rupture) capacities [1]. Transverse material properties such as longitudinal shear [1] and tension perpendicular to the fibers [2], while arguably more relevant to the behavior of assembled bamboo structures, are reported less often. The present understanding of the material properties of bamboo, as expressed in the ISO Design Standard [3] and the Indian National Building Code [4], for instance, stem largely from the work done by Janssen [5] and Arce-Villalobos [6]. While these standards are a start, there are many areas that require further exploration. Janssen quotes several researchers who claimed that "the collapse of the bamboo was always sudden and the material was split into pieces parallel to the longitudinal axis." Arce-Villalobos concludes "Bamboo culms do not fail in compression, in bending or shear, but do fail when a maximum tangential tensile stress is reached." Despite these acknowledgements, the splitting behavior of bamboo has not been adequately addressed in the literature or in present standards.

The present work explores the so-called "diametric compression strength", technically the edge bearing strength, of the bamboo culm. The aim of this work is to investigate the potential for adopting the relatively simple-to-conduct edge bearing test as a surrogate for direct determination of the critical transverse material properties. The objective of the study is to use the edge bearing test to determine specifically the transverse modulus of elasticity, ultimate diametric compressive stress and culm wall modulus of rupture. The study is carried out using specimens of *Phyllostachys aurea* and *Bambusa stenostachya* bamboo.

1.1. Standard test methods for bamboo

Material properties of bamboo are typically obtained based on the ISO 22517-1 *Bamboo – Determination of physical and mechanical properties* guidelines [1]. This document provides general guidance on specimen preparation and testing. Information is also given on

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(a) bolt induced splitting (b) column splitting

Fig. 1. Bamboo splitting failure observed at Cambury, Sao Paulo, Brazil.

determination of moisture content, mass, and shrinkage. Sharma [7] summarized the ISO tests for mechanical properties, as well as two non-ISO tests that have been adopted for bamboo materials. Specimens are typically taken from the top, bottom and middle regions of the culm to establish an average value over the height of the culm. The authors contend that tests using full culm specimens are preferable since they eliminate any bias associated with sampling sections from various culm locations. Factors that may affect tested properties include the curvature of the culm cross section and the through-thickness gradient of material properties of the culm wall.

The splitting behavior of bamboo (Fig. 1) has not been adequately addressed in present standards. Arce-Villalobos [6] conducted tests on two species of bamboo with different origins and unspecified age. The author concluded based on the results that there is no correlation between the density of bamboo and its transverse tensile strength. This is important because the dominant limit state of bamboo is splitting, and the resistance to splitting is based on the transverse tensile strength. With wood, for instance, there is a strong correlation between strength and density. The fact that this relationship is unclear in bamboo makes strength determination much less intuitive.

Mitch [2,8] explored various test methods to characterize the splitting capacity of bamboo basing his analysis on the transversely oriented Mode *I* stress intensity factor, K_I, which provides a measure of the material's "fracture toughness". A fracture mechanics approach was selected on the premise that this might 'normalize' the quantification of material properties thereby reducing the significant scatter inherent in establishing mechanical properties of bamboo. A fracture mechanics approach should, it was hypothesized, result in more comparable measures of behavior allowing, for instance, more rational interspecies comparison. Mitch explored multiple test configurations and selected the configuration thought to introduce the least unnecessary variation: a full culm split pin test. The test configuration selected and developed by Mitch, shown in Fig. 2, includes a split steel pin to which a tensile load is applied inducing a splitting failure in the test specimen. Specimens have a notch located at the edges of the hole drilled through the culm, perpendicular to the load direction (Fig. 2b) in order to initiate the failure – allowing for the most reliable calculation of K_I. Mitch also conducted compression and "bowtie" shear tests [1] to compare and assess the variation in test results. The proposed split pin test showed the least variation in results. The average K_I value obtained for *B. stenostachya* treated with a borate solution was 0.174 MPa m$^{1/2}$ (COV = 0.22). Additional tests were conducted to determine the influence of the pin diameter, which was shown to have little influence on the average K_I value as should be expected for a fracture mechanics test.

The split pin test also permits the direct tension capacity perpendicular to the fibers to be determined. For the *B. stenostachya* tested by Mitch [2], the average tensile rupture stress perpendicular to the fibers was found to be 1.06 MPa (COV = 0.22). The split pin test is adopted in the present work and calculations associated with its use are presented.

Amada and Untao [9] investigated the fracture properties of Moso (*Phyllostachys edulis Riv*.) bamboo. The experiment was carried out through a series of notched longitudinal tension tests from different sections of the bamboo culm. The results indicated that the fracture toughness (K_I) of Moso bamboo, averaged across the radius, was 56.8 MPa m$^{1/2}$. Low et al. [10] in contrast, used flexural tests to calculate K_I values for young (1 year) and old (5 year) *Sinocalamus affinis* bamboo; the values obtained were 8.0 and 5.5 MPa m$^{1/2}$, respectively. Additional data was obtained from Guatibonza [11], where longitudinal tension tests were used to obtain K_I values for *Dendrocalamus giganteus*. The average value obtained in this case was 53 MPa m$^{1/2}$. The variation in reported values of 'fracture toughness' results from each study using a different test arrangement and therefore calculating a different parameter, although all defined this parameter as K_I based on their selected test orientation. Amada and Untao [9] and Guatibonza [11] report the behavior of longitudinal tension tests; Low et al. [10] reports what amounts to a modulus of rupture test; while Mitch [2] addresses tension perpendicular to the fiber. The results reflect the hierarchy of bamboo material properties: it is very strong and tough in tension parallel to the fiber direction; approximately an order of magnitude weaker in longitudinal flexure; and another order of magnitude less robust in tension applied perpendicular to the fiber direction. It is this last property that most influences

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