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Technical note

Relationship of structure and stiffness in laminated bamboo composites

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ABSTRACT

Laminated bamboo in structural applications has the potential to change the way buildings are constructed. The fibrous microstructure of bamboo can be modelled as a fibre-reinforced composite. This study compares the results of a fibre volume fraction analysis with previous experimental beam bending results. The link between fibre volume fraction and bending stiffness shows that differences previously attributed to preservation treatment in fact arise due to strip thickness. Composite theory provides a basis for the development of future guidance for laminated bamboo, as validated here. Fibre volume fraction analysis is an effective method for non-destructive evaluation of bamboo beam stiffness.

1. Introduction

The use of bamboo in structural applications is a rapidly developing new field of research which has the potential to change the way that buildings and infrastructure are constructed. In recent years, as the effects of climate change have become more widely understood and documented, there has been a global effort to find new low carbon structural materials to reduce CO_2 emissions from construction. This has led to bamboo being reconsidered as an alternative structural material. Bamboo has many potential advantages as a sustainable material [1,2]. For example, bamboo grows far rapidly and can be harvested every 3–5 years, in comparison to the 20–60-year growth cycle of timber used in structural applications [3]. Studies of Chinese bamboo forests have shown that over a 60-year period, one sustainably managed hectare of *Phyllostachys pubescens* (or Moso) bamboo sequesters 220 tons of CO_2 from the atmosphere [3]. Bamboo is also widespread across the developing world in Africa, Asia and South America where the demand for new building materials is rapidly increasing. It will grow in far poorer soils than most trees, meaning that it is often found in otherwise resource-poor areas [4]. The global research effort into the structural potential of bamboo has led to the development of engineered products. The composites utilise the raw bamboo culm, processed with physical and chemical methods, to produce a building material [5]. Structural applications are currently limited by a lack of understanding of the properties. As bamboo is a type of grass, it's microstructure is significantly more heterogeneous than that of timber, consisting of small dense fibre bundles in a less dense matrix material, as shown in Fig. 1.

The objective of the presented work is to investigate if laminated bamboo can be modelled as a fibre reinforced composite. The study compares the bending stiffness of laminated bamboo beams observed under four-point bending tests with stiffness values predicted by the 'composite rule of mixtures'.

2. Theory

Composite theory has established that when loaded parallel to the fibres, fibre composites can be treated as having a single, isotropic elastic modulus, and that this modulus is simply a weighted mean of the stiffness of the fibres and the stiffness of the matrix [6]. The upper bound, or Voigt's, composite rule of mixtures is also independent of geometry and fibre fraction, and so can be applied to a wide range of composite materials [6]. The methodology has been applied to model raw, or full-culm, bamboo as a fibre reinforced composite. Dixon and Gibson [7] observed that, although the fibre volume fraction in a typical bamboo culm increases with radial distance, the basic properties of both the fibres and matrix material remain approximately constant throughout the section. The study also predicted the relative stiffness of the fibres and soft matrix material based on composite theory, which was shown to good agreement with the experimental results [7]. While the

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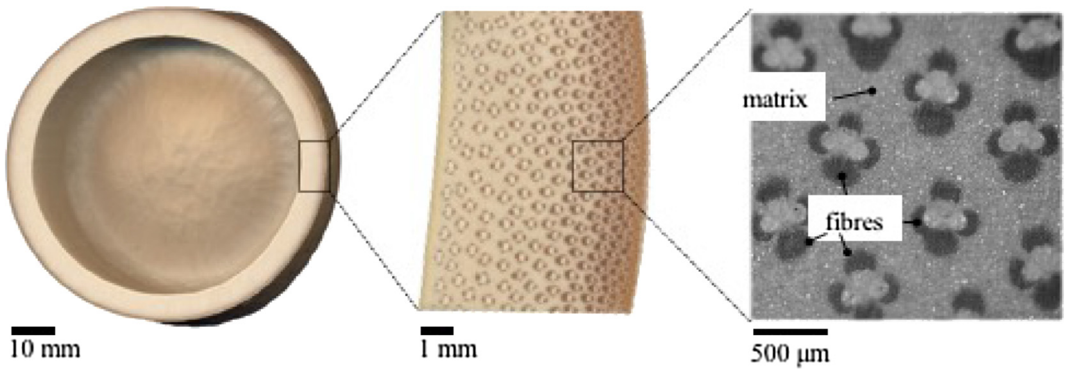

Fig. 1. Bamboo culm showing microstructural detail.

method was shown to be valid for raw or full-culm bamboo, it has yet to be explored for laminated bamboo.

Previously published research indicates that bending stiffness in laminated bamboo beams varies as much as 14%, where the material is the same but the manufacturing technique differs [8–10]. The presented work investigates how that difference can arise through fundamental composite design of the primary material. The approach assumes that the elastic moduli of the fibres and matrix material throughout the laminated bamboo beam section are constant. The study also explored the effect of strip size on the bending stiffness of laminated bamboo beams which is fundamental to the understanding, design, manufacturing and construction of laminated bamboo sections for structural applications.

3. Materials and methods

The study utilised samples taken from cross-sections cut from laminated bamboo beams tested in Sharma et al. [8–10]. The beams were tested in four-point bending to failure as part of prior research projects, with the methodology and results reported in Sharma et al. [8–10] (Fig. 2). Further details on the manufacturing process is available in the previous studies [8–10]. In general, the material is sourced from bamboo that is 3–7 years of age, with the bottom and middle of the culm used in the commercially produced laminated bamboo board product.

In total, 80 cross-sections were analysed, representing material obtained from two different manufacturers (Moso International BV, Amsterdam and Plyboo, USA) but the same raw bamboo species (*P. pubescens*). The samples include beams comprised of both large (19 mm × 6 mm) and small (19 mm × 4 mm) bamboo strips, oriented in both the edgewise and flatwise direction, as defined in Fig. 3.

The specimen identifier denotes the manufacturer: Moso (M) or Plyboo (P); the preservative treatment: Caramelisation (C) or Bleaching (B); and the strip orientation: Edgewise (E) or Flatwise (F). For example, the Moso caramelised edgewise beams are "MCE." The strip thickness is identified as small (4 mm) and large (6 mm). A detailed summary of the samples analysed is presented in Table 1.

Fig. 2. Four-point bending apparatus used in the testing of all beams.

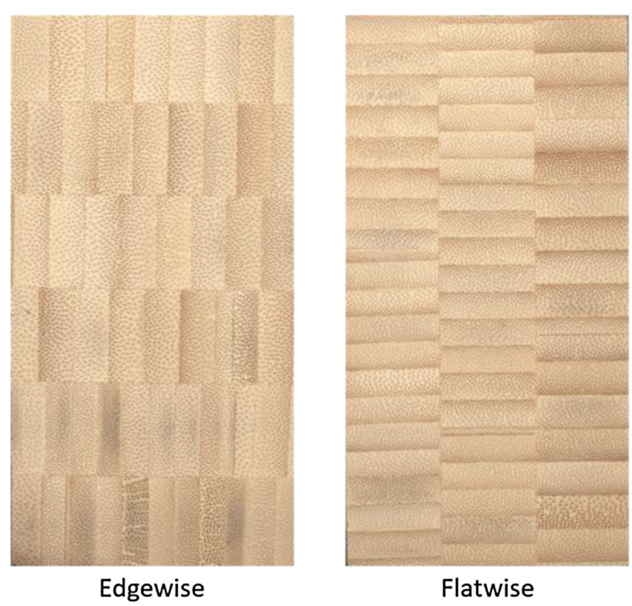

Fig. 3. Nomenclature for strip orientation.

3.1. Image processing

ImageJ [11] was used to analyse the beam cross-sections. The method utilises the contrast difference between the dark fibres and the paler matrix that surrounds them, a technique known as 'thresholding' [12]. The image is first converted to grayscale and an image intensity threshold is then applied, using a histogram shape-based method [12]. The threshold process allowed for consistent measure across all images even when light values and contrasts vary. To validate the threshold approach, visual inspection was used to ensure the software captured areas that were 'fibres.' By varying the limiting threshold value, below which the section of image should be classed as a fibrous area, the software can be programmed to detect the fibres in a beam scan. ImageJ can then output the percentage of the image area that is below the threshold, i.e. the fibre volume fraction of the cross-section.