Construction and Building Materials 165 (2018) 241–246

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Technical note

Relationship of structure and stiffness in laminated bamboo composites

Matthew Penellum [a], Bhavna Sharma [b], Darshil U. Shah [c], Robert M. Foster [c,1], Michael H. Ramage [c,*]

[a] Department of Engineering, University of Cambridge, United Kingdom
[b] Department of Architecture and Civil Engineering, University of Bath, United Kingdom
[c] Department of Architecture, University of Cambridge, United Kingdom

ARTICLE INFO

Article history:
Received 22 August 2017
Received in revised form 22 November 2017
Accepted 23 December 2017

Keywords:
Microstructure
Mechanical properties
Analytical modelling
Bamboo

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

* Corresponding author.
E-mail address: mhr29@cam.ac.uk (M.H. Ramage).
[1] Present address: School of Civil Engineering, University of Queensland, Australia.

https://doi.org/10.1016/j.conbuildmat.2017.12.166
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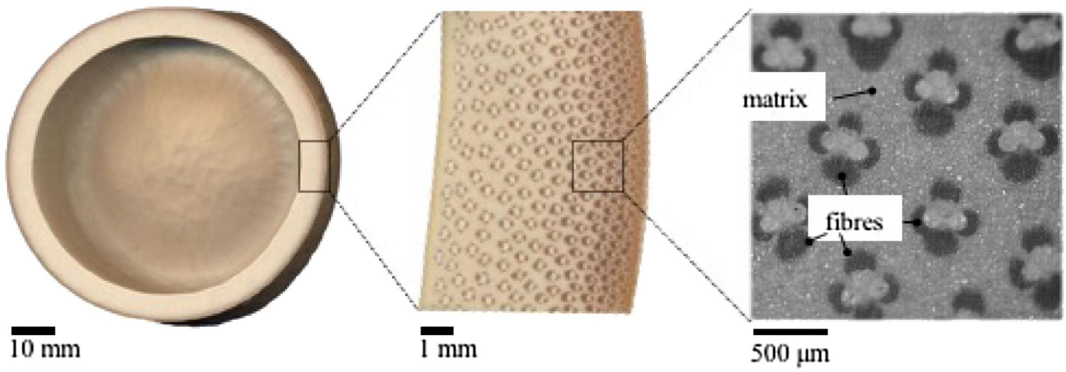

Fig. 1. Bamboo culm showing microstructural detail.

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.

Table 1
Details of beam cross-sections used in fibre volume fraction analysis.

Specimen	Manufacturer	Preservation Method	Strip Orientation	Strip Size	No. of samples
PCE	Plyboo	Caramelised	Edgewise	Small	10
PCF			Flatwise		10
PBE		Bleached	Edgewise	Large	10
PBF			Flatwise		10
MCE	Moso International BV	Caramelised	Edgewise	Large	20
MCF			Flatwise		20

An example of a scanned image under ImageJ thresholding analysis is shown in Fig. 4.

For high reliability and accuracy of fibre detection, the analysis was conducted as follows: (1) all cross-sections were sanded with grade P80 sandpaper and polished with grade P220; (2) scanned with a resolution of 1200DPI; and (3) the minimum and maximum fibre size thresholds were set in the ImageJ analysis, where areas smaller than 3 pixels or larger than 10,000 pixels were neglected from the volume fraction calculation to remove detection errors. The experimental method is reliable for making meaningful comparisons of the fibre volume fraction in different beam types, as demonstrated by the low coefficient of variation (<5%). The analysis was optimised to capture the majority of fibres, however the dark colouration of certain strips resulted in rejection in areas of the beam where the 10,000 pixel threshold setting was exceeded (see Fig. 4). ImageJ [11] can also output the location (in x and y coordinates) and area of each of the red sections it has detected, i.e. each fibre. This feature was used when considering strip orientation effects to assess the distribution of fibres in the cross-section.

4. Results and discussion

The results from the ImageJ analysis are presented in comparison to the previous work conducted in Sharma et al. [8–10]. Both the bleached (PB) and caramelised (PC) beams have the same cross-sectional dimensions (120×60 mm), but the comparison in Fig. 5 shows that the bending stiffness of the caramelised beams, which are made with smaller constituent strips, is consistently higher than that of the bleached beams (i.e. PCE is stiffer than PBE and PCF is stiffer than PBF). This stiffness difference has previously been attributed to the difference in treatment method used [9], with the assumption that constituent strip size does not affect laminated bamboo properties. Here the effect of strip size on the fibre volume fraction of the beam was assessed to determine whether this may be the reason for the stiffness difference.

Each laminated bamboo beam is assumed to behave as a fibre reinforced composite whose elastic modulus in bending, E_b, can be treated as having a uniform value across the section [6,7]. The presented work showed the influence of the individual strip size on the elastic modulus, rather than the section size or the ultimate base material of *P. pubescens*. As a result of being a natural functionally-graded composite [7], there is a variation in the elastic modulus of the individual strips when they are cut from the culm wall. We show how this affects beam design and manufacturing. Beams made of small strips have a mean bending modulus of 11.9 GPa, whereas those made of large strips have a bending modulus of 10.4 GPa, 14% less [8,9]. The fibre volume fraction comparison between beams made with small versus large strips is presented in Table 2.

Manufacturing laminated bamboo beams out of smaller constituent strips appears to significantly increase the fibre volume fraction in the beams, and this increase in fibre volume fraction closely correlates with the observed stiffness difference in testing, suggesting that there is a strong link between fibre volume fraction and the elastic modulus in bamboo. Modelled as a fibre reinforced composite, the bending stiffness of the laminated beams should obey the simple composite rule of mixtures [13]:

$$E_{bc} = V_f E_f + (1 - V_f) E_m \quad (1)$$

where E_{bc} is the elastic modulus of the composite material in bending, E_f is the elastic modulus of the fibres, E_m is the elastic modulus of the matrix material, and V_f is the fibre volume fraction in the section.

Previous studies into the stiffness of bamboo suggest approximate elastic modulus values of 40 GPa for bamboo fibres (E_f) and 2 GPa for the 'parenchyma' matrix (E_m) [7,14]. Using these values for elastic moduli and the fibre volume fraction (Table 3) the composite rule of mixtures predicts an elastic modulus of 11.3 GPa for beams with small strips and an elastic modulus of 9.9 GPa for beams with large strips.

Table 3 shows that the elastic modulus values predicted when the beams are modelled as a fibre reinforced composite material are very close to those observed in the testing [8–10], and also that the predicted change in stiffness due to a change in the fibre volume fraction closely matches the observed behaviour. These results suggest that modelling the elastic bending stiffness of laminated bamboo beams as fibre reinforced composites is a valid design approach, with a difference between measurement and prediction of only 5%, which is within the variance of a typical engineering design.

The results also show that using smaller constituent strips to build up a section leads to an increase in the fibre volume fraction of the resulting section. This implies that the increased fibre volume fraction is likely to be the cause of the increased bending stiffness of the caramelised beams, rather than the preservative treatment method used on the beam. The method of laminated bamboo analysis developed in this project has therefore been shown to provide clearer and more substantial explanation for the observed behaviour than any previous theory.

The cause of the higher fibre volume fraction of smaller constituent strips is attributed to the variation of fibre distribution within culm wall from which the strips are cut. As a functionally graded material, the fibre density increases radially from the centre outwards, with a high concentration of fibres at the outer edge and relatively dispersed fibres near the inside wall of the culm. The large strips include a greater proportion of the inner culm area, which contains fewer fibres. Therefore, beams built up from larger strips will have a lower overall fibre volume fraction (Fig. 6).

Regardless of size, the overall fibre distribution in an individual strip is consistent. In addition to the effect of strip size on stiffness, we observe an additional smaller variation in stiffness due to strip orientation (Fig. 7).

4.1. Effect of fibre distribution

In order to assess the effect that the distribution of fibres in laminated bamboo beams has on beam's bending stiffness, the assumptions made so far about how laminated bamboo behaves

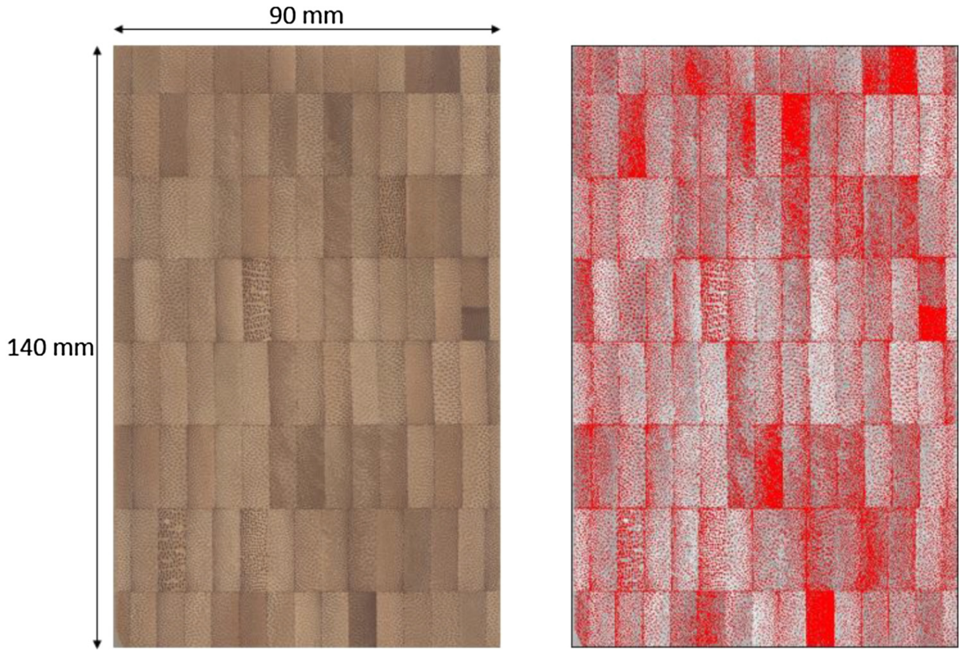

Fig. 4. Cross-section MCE1; scan (left) and ImageJ analysis (right). Red areas showed detected fibres.(For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

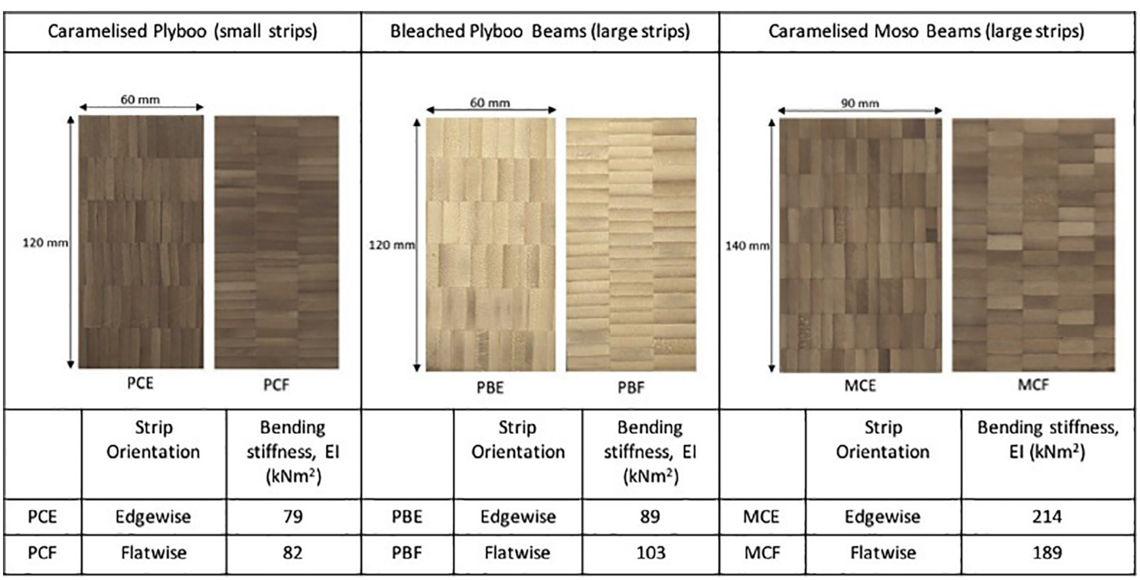

Fig. 5. Mean bending stiffness of the two types of caramelised (PC) beams tested [9].

Table 2
Comparison of fibre volume fraction for beams made with different sized strips.

	Fibre volume fraction % (COV)	Stiffness (kNm^2)
Small Strips		
PCE	24.3 (0.06)	79
PCF	24.1 (0.05)	82
	Large Strips	
PBE	20.6 (0.03)	89
PBF	21.1 (0.04)	103
MCE	21.7 (0.04)	214
MCF	20.1 (0.05)	189
Small strips	24.4 (0.05)	–
Large strips	20.9 (0.05)	–
Difference (%)	17	–

Table 3
Comparison of elastic modulus predicted by the fibre reinforced composite model to measured mean values.

	Predicted E_{bc} (GPa)	Measured E_{bc} (GPa)	Difference
Small strips	11.3	11.9	5.3%
Large strips	9.9	10.4	5.1%

must be changed. The previously presented analysis assumed that laminated bamboo behaves as a fibre reinforced composite, and therefore can be treated as having a uniform elastic modulus. This modelling assumption has been shown to produce stiffness predictions that closely match with the observed bending stiffness of laminated bamboo beams, and so to be a very powerful tool in bamboo behavioural analysis. However, the model disregards the

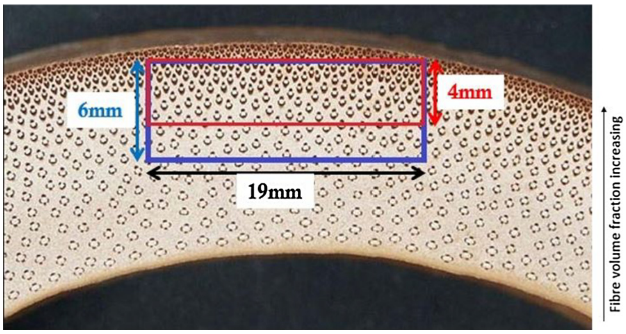

Fig. 6. Small strip (red) and large strip (blue) cross-sections imposed over a typical culm cross section. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

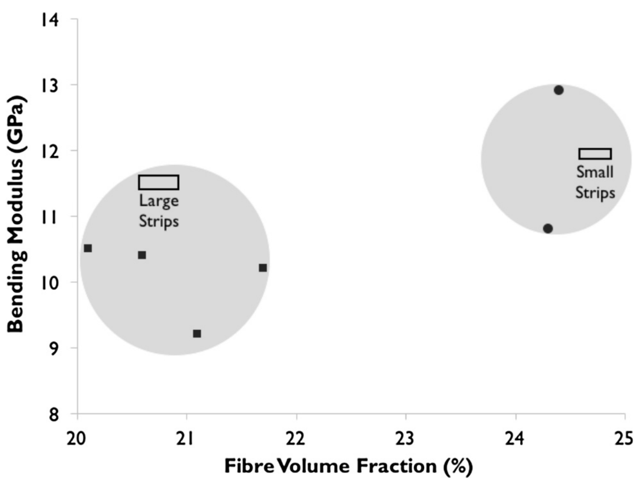

Fig. 7. Difference in fibre volume fraction and bending modulus in small and large strips. Shading represents grouping of strip size.

size and position of fibres within the beam; only the overall fibre fraction has been considered.

In order to find how the fibres are distributed in a beam, and how this may affect the bending stiffness of the beam, the beams are analysed using an elastic transformed section approach. The transformed section method is commonly used to analyse the elastic bending stiffness of reinforced concrete beams, but it has seen limited use in the analysis of natural fibre-based materials such as bamboo. In fibre composite materials, it is generally assumed that the fibres are evenly distributed throughout the section, however, this may not always be a valid assumption, as the gradient of fibre volume fraction across individual strips may lead to an overall non-uniformity in fibre distribution across the section. The basic principles of the elastic transformed section method, as it will be applied here, are shown in Fig. 8.

When analysing laminated bamboo using the elastic transformed section method, it is assumed that variations in the bending stiffness, EI, are entirely due to variations in the second moment of area of the transformed section. This transformed section is treated as having a uniform elastic modulus equal to the modulus of the matrix material (E_m).

ImageJ is used to obtain the second moment of area of the fibres. Using the method developed to detect the fibres in a cross-section, ImageJ can be made to output the x-y coordinates and area of each of the fibres it has detected (the software typically detects around 25,000 fibres per beam, so this is a significant quantity of data to be manipulated). Once the location and size each fibre is known, the major axis second moment of area of the fibres can be calculated. In this calculation, the second moment of area of each individual fibre about its own neutral axis is neglected (as the fibres are very small). The elastic neutral axis of the overall section is assumed to be in the centre of the beam (to simplify the calculation of the overall transformed second moment of area of the beam).

The variation of second moment of area of the fibres due to strip orientation in the different beams therefore correlates with the variation in bending stiffness observed when the beams were tested. The PB and PC beams have a higher fibre second moment of area when the strips are in the flatwise orientation, and the MC beams have higher fibre second moment of area when the strips are in the edgewise orientation.

In order to assess whether this variation in fibre second moment of area can account fully for the observed bending stiffness differences, the second moment of area of the fibres must be combined with the second moment of area of the matrix, using the transformed section method. The full second moment of area of the laminated section is given in Eq. (2):

$$I_{xx,T} = I_{xx,m} + (m-1)I_{xx,f} \quad (2)$$

where

- $I_{xx,T}$ = the total transformed second moment of area of the beam
- $I_{xx,m}$ = the second moment of area of the matrix material
- $I_{xx,f}$ = the (untransformed) second moment of area of the fibres

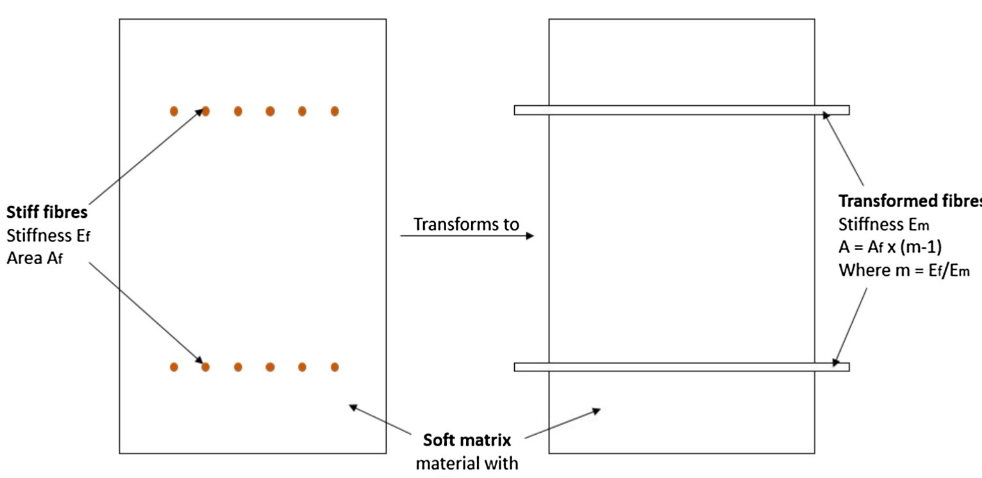

Fig. 8. Diagram illustrating the elastic transformed section approach used to analyse the effect of fibre distribution. Adapted from [15].

Table 4
Comparison of full second moment of area, observed bending stiffness values with those predicted by the transformed section model. The percentage difference in parentheses are negative values.

	$I_{XX,T}$ 10^6 mm^4	Difference %	Observed			
			EI_{XX} kNm^2	Difference %	$E_mI_{XX,T}$ kNm^2	Difference %
PCE	35.2	10%	79	4%	70	10%
PCF	38.9		82		78	
PBE	34.7	10%	89	16%	69	10%
PBF	38.1		103		76	
MCE	91.9	(3%)	214	(12%)	184	(3%)
MCF	88.8		189		178	

The value m is the ratio of the stiffness of the fibres (E_f = 40 GPa) to the matrix material (E_m = 2 GPa) and is assumed to be 20. The total second moment of areas of the different beam types (calculated using the equation above) and the percentage variations due to strip orientation, are shown in Table 4.

The variation in total second moment of area caused by the change in strip orientation appears to be significant. These $I_{xx,T}$ values can be used to calculate the expected bending stiffness of the beams, using the assumption that the elastic modulus of the transformed section is uniform and equal to the elastic modulus of the matrix material ($E = E_m \approx 2$ GPa). These values can then be compared to the bending stiffness observed during testing to assess whether the transformed section method is producing valid predictions of beam behaviour, and whether the I_{xx} variations can explain the difference in bending behaviour of the beams (Table 4).

The error between the observed values and model predictions is attributed to compounded error from the ImageJ threshold analysis (see Section 3.1). The bending stiffness values predicted by the elastic transformed section method are consistently lower than the observed bending stiffness, particularly in the edgewise beams. Also, the variations due to change in strip orientation predicted by the model do not match the observed stiffness differences. Therefore, the use of the transformed section method to model the section requires further refinement to draw meaningful conclusions on the effect of strip orientation.

5. Conclusions

The work presented focused on modelling of laminated bamboo using two common methods, the fibre reinforced composite model and the elastic transformed section model. The effect of strip size indicated that smaller strips leads to a significant increase in the fibre volume fraction of the resulting section. This increased fibre volume fraction correlates closely with the higher bending stiffness observed in beams made with smaller strips. These results show that laminated bamboo can be modelled as a fibre reinforced composite. Modelling laminated bamboo as a fibre reinforced composite material is a method that has not been previously used to analyse laminated bamboo. The presented work has validated this modelling technique and produced predictions that closely agree with observed testing. The work has also shown that the bending stiffness variations previously attributed to solely the preservative treatment method are caused by a difference in the size of the constituent strips. Use of smaller constituent strips leads to a higher overall fibre volume fraction, with thinner strips obtained from the outer culm, which has a high concentration of fibres. Large strips, therefore include more of the inner culm, which has a relatively low fibre concentration. In the assessment of this strip orientation effect, the results suggest that changing the orientation of the constituent strips does not significantly affect the overall microstructure of the beam, but the transformed section model used requires further refinement. This study has shown that laminated bamboo can be modelled accurately as a fibre reinforced composite, and has also developed a methodology for calculating the stiffness of laminated bamboo beams without the need for specialised equipment. ImageJ image processing software provides a low-cost and effective method of analysing its makeup and thus calculating its expected bending stiffness. With further research, these methods could form the foundation for development of design standards and codes for laminated bamboo, which is an essential step if the material is to become widely adopted.

Acknowledgements

This work was conducted as part of a MEng thesis project in the Department of Engineering at the University of Cambridge. The work was also supported by a Leverhulme Trust Programme Grant and the Engineering and Physical Sciences Research Council (EPSRC Grant EP/K023403/1). Additional data related to this publication is available at the University of Cambridge's Institutional Data Repository (https://doi.org/10.17863/CAM.17204).

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