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DURABILITY EVALUATION OF MADAKE BAMBOO BY FE ANALYSIS OF FRACTURE WITH CONSIDERATION OF FIBRE DIRECTION

RAVIDUTH RAMFUL [*], ATSUSHI SAKUMA [†] AND HAJIME KIMURA [*]

[*]Graduate School, Kyoto Institute of Technology (KIT)
Matsugasaki, Sakyo-ku, Kyoto, 606-8585, Japan
e-mail: r.ramful@uom.ac.mu

[†] Division of Textile Science, Kyoto Institute of Technology (KIT)
Matsugasaki, Sakyo-ku, Kyoto, 606-8585, Japan
e-mail: sakuma@kit.ac.jp, web page: http://www.fibro.kit.ac.jp/

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Abstract. *The flexural stiffness of bamboo is inherently influenced by heterogeneous material characteristic owing to its unique hierarchical structure. In addition, low interfacial strength and unequal distribution of fibres lead to a complex fracture behavior in the material. This research study aims to probe into the limited durability of MADAKE bamboo (Phyllostachys bambusoides) by investigating its fracture mechanism through numerical simulation. The influence of functionally graded material (FGM) on the fracture behavior of bamboo culm was evaluated. A half-solid cylindrical model consisting of a rigid section and a 4-layered wall section was simulated in pure bending mode on LS-DYNA. The effects of material homogeneity and inhomogeneity were replicated by inputting elastic and orthotropic-elastic material data comprising of longitudinal to flexural stiffness ratio. These ratios were derived from experimental results of three-point flexural test. Analysis of results, based on maximum principal strain, showed that the homogeneous model displayed fracture characteristics similar to conventional elastic material. In contrast, the inhomogeneous model displayed maximum principal strain on the lateral surface corresponding to fracture mode of bamboo culms observed in nature. Numerical study of material heterogeneity is a step further in understanding the fracture mechanics of functionally graded materials.*

1 INTRODUCTION

As an indispensable construction material to human life, bamboo has been widely used in buildings, bridges and other infrastructures involving structures. In modern times, despite being in an era of highly advanced materials, the growing trend towards sustainable development is reigniting the interest on greener materials. Bamboo has full potential as a sustainable material and could be considered as an alternative to conventional materials used in construction such as steel and concrete. Two factors; (1) a high-strength to weight ratio, and (2) an unrivalled growth rate of up to 100 cm per day, completely outclass other materials of its category [1,2].

The distinct morphology of bamboo culms is composed of cylindrical sections (internodes) reinforced with nodes. Being an organic material with a composite structure, it has been classified as a functionally graded material (FGM). This given structure is the result of millions of years of natural evolution in the natural environment. The inherence of FGM provides excellent material attributes, namely high strength, good stiffness and wear resistance, suitable for structural design. The longitudinally aligned cellulose fibres, which are immersed in a matrix of lignin, forms vascular bundles. These are non-uniformly distributed throughout the thickness resulting in a graded pattern [1].

The vascular bundles, which are smaller and concentrated towards the outermost culm wall and larger and fewer towards the innermost section, account for the increase in effective section moment of inertia. In addition, the volume fraction of vascular bundles increases with height. This large volume fraction compensates for the inferior bending strength inherited by the top most culm section due to a reduction in diameter and wall thickness. This smart structure enables bamboo to withstand extreme flexural loading caused by wind and snow [1,3,4].

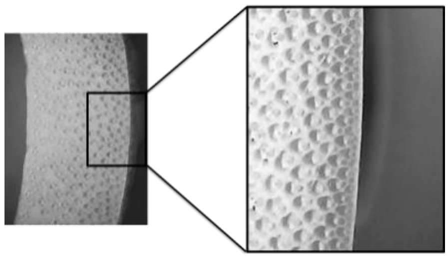


Figure 1: Functionally graded material (FGM)

Mechanical characterization has shown an asymmetric flexural behaviour in bamboo. Unlike fibers strand, parenchyma cells, which displays greater elasticity, can accommodate larger deformation, hence accounting for the substantial flexibility in the culm structure [5,6]. In 4-point bending tests of *Phyllostachys pubescens*, maximum flexural rigidity was noted when the hardest outer part and softest inner part were strained and compressed respectively. Parenchyma cells were found to absorb large compressive deformation and was described as a highly compressible foam-like structure [7]. Recently, engineered bamboo with improved mechanical properties and homogeneity have been produced through advanced techniques [8].

To maximise the integration of bamboo in further engineering application and structures, it is essential to consider certain steps to improve its durability. The average natural durability of raw bamboo culms is about 2 years and up to 7 years if protected from exterior exposure. A noticeable increase in the mechanical strength has been observed in bamboo specimens constituting a lower moisture content than the fiber saturation point (FSP) [9]. By attaining a new state of equilibrium through a series of shrinking and swelling processes, internal stresses are often induced within the material, leading to crack formation and premature split of bamboo culms [1].

Carbonized bamboo has been used over the centuries in building construction owing to its excellent long term durability and preservation of its mechanical properties. In Kyoto, Japan, a traditional craftsmanship technique of wood preservation, known as Shou Sugi Ban, is applied to bamboo to carbonize the outermost layers. In the final product, termed as Yakisugi, moisture is drawn out of the material by thin carbon film, created during a light surface burn process. In the process of drying, whereby fibers gain strength but lose their toughness, bamboo becomes brittle and prone to premature failure by longitudinal split along culm length [1,10].

1.1 Fracture

The flexural stiffness of bamboo is inherently influenced by heterogeneous material characteristic owing to its unique hierarchical structure. Most tissues in this highly anisotropic biomaterial are arranged longitudinally and bound by non-cellulose component. This particular structure, which results in an inferior interfacial strength, surprisingly contributes to the high transverse toughness, making bamboo culms resistant to flexural loads. However, low interfacial strength and unequal distribution of fibres also lead to a complex fracture behavior in the material [5,7,11].

Few research on the fracture toughness has been conducted to elucidate the crack propagation in bamboo. In Moso bamboo, Askarinejad *et al.* found cracks to propagate parallel to the longitudinal direction of fibers irrespective of notch direction and crack bridging was more pronounced in inner fibers [12]. Low fracture toughness parameter in Mode I interlaminar fracture investigation, showed that crack followed an easy path parallel to grain. The resistance against crack propagation, governed by interfacial strength was lower in the outer layer [11]. In Mode II numerical analysis, the interlaminar fracture toughness was found to be unrelated to length of original crack [13].

Typical fracture in bamboo occurs by splitting of culms under the action of stresses, namely impact loads, fatigue loads, creep, internal stresses and external factors [14]. Fracture of bamboo culm by cracking through time-dependent deformation results in creep. Mechano-sorptive is a recurrent creep phenomenon experienced by natural composites as a consequence of cyclic moisture variation on loaded specimens. Creep behaviour of bamboo under various desorption conditions is influenced by; distribution of vascular bundles, density and material anisotropy [15-17].

The inherent FGM structure of bamboo is well adapted to preserve its natural durability against external factors such as wind loadings. When the maximum bending moment threshold is exceeded, failure of culm structure occurs as displayed in Figure 2. Crack is observed to propagate longitudinally along culm length. Several studies have been conducted on the effect of bending moment on cross-sectional deformation of culm structure and onset of fracture [18-20]. During bending of tubular section, cross-sectional inward forces, induced by longitudinal tensile and compressive stresses on the convex and concave sections respectively, have a tendency to ovalize the cross-section [21,20]. This ovalization is amplified by an increase in curvature as a maximum value of bending moment is reached [18].

Figure 2: Natural fracture of bamboo – side culm failure

This deformation by cross-sectional flattening, which was first reported by Brazier on the bending of thin-walled cylinders, leads to a decrease in the second moment of area and stiffness due to instability in the structure [21]. Huang *et al.* identified four modes of failure mechanism of hollow trunks caused by bending. These are Brazier buckling, cracks in the tangent direction/longitudinal split, typical bending failure and shear failure. Key research findings revealed that tangential cracking, followed by longitudinal splitting, is likely to happen as a result of cross-sectional flattening and are initiated at 4 vertices of the ovalized section [19].

In view of further maximizing the external application of bamboo materials, it is essential to improve its durability by considering factors which contribute to its natural rate of degradation. Study of its failure mechanism and defining the fundamental mechanical behaviour is essential in the validation process of material worthiness for design construction. This paper aims to probe into the limited durability of Madake bamboo (*Phyllostachys bambusoides*) by investigating the root cause of material failure by fracture, through numerical analysis.

2 METHODOLOGY

The effects of inhomogeneous material on the failure modes of bamboo culm were investigated by numerical simulation. Figure 3 below, displays the test setup outline of section of bamboo culm model in pure bending mode. The effects of wind loadings on upper section of bamboo culm, were simulated by incorporating a rigid section to the model. The wall-end of the model was constrained in the *z*-direction only. The rigid section was assigned with elastic material data of high modulus of elasticity and constrained in the *x*-direction only.

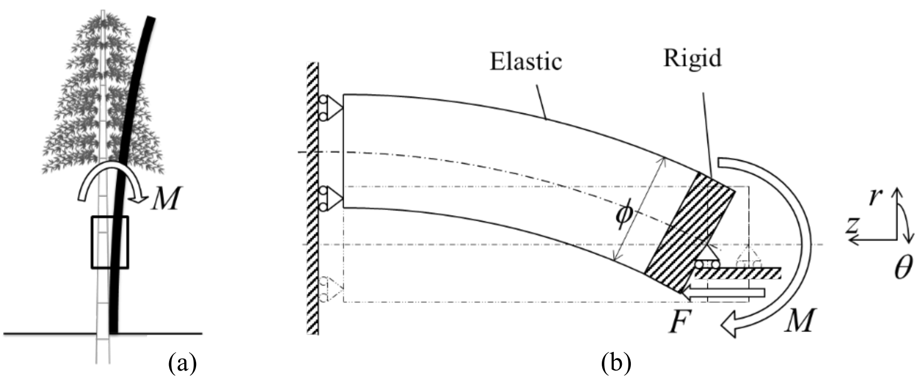
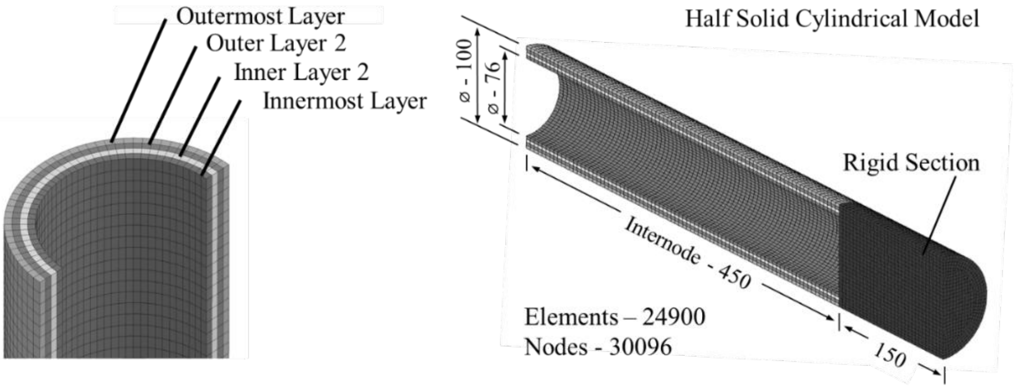


Figure 3: (a) Bending in real bamboo, (b) simulation of pure bending mode

A half-solid cylindrical model, replicating the internodal length of bamboo culm, was modelled to minimize computational time. The model, designed on FEMAP using existing literature data on Madake bamboo, consisted of a rigid solid section and a hollow cross- section composing of a 4-layered wall [1]. Detailed outline of the 3-dimensional model is shown in Figure 4. For an average internode count of 18, the internodal length, outer diameter and wall thickness was determined as 450, 100 and 12 mm respectively. HexMesh solid was used throughout and the model consisted of 24900 elements and 30096 nodes.



(a) (b)

Figure 4: (a) Cross-section of layered model, (b) dimensions outline of culm model

The final model was exported to LS-DYNA and implicit analysis was performed by using appropriate simulation parameters. The effects of material homogeneity and inhomogeneity were replicated by inputting elastic and orthotropic-elastic material data respectively through FE analysis in LS-DYNA. The maximum strength in fibre direction was obtained experimentally through 3-point bending tests and an average value of 15 GPa was taken. Other engineering constants, namely Poisson's ratios and shear moduli were determined by using equations (1) and (2) respectively with respect to their orthogonal directions [22].

$$\frac{v_{ij}}{E_i} = \frac{v_{ji}}{E_j} \qquad i, j = 1, 2, 3 \quad i \neq j \tag{1}$$

$$G_{ij} = \frac{E_i E_j}{E_i + E_j + 2E_j v_{ij}} \qquad i, j = 1, 2, 3 \quad i \neq j \tag{2}$$

The material models were reproduced by assuming a longitudinal to transverse flexural stiffness ratio in the fibre and radial direction respectively. Two material models were investigated in pure bending mode. A homogeneous material model, consisting of uniform isotropic properties in the radial direction, was devised with a uniform modulus of elasticity of 15 GPa throughout as shown in Table 1. A second material model of inhomogeneous nature, consisting of axial reinforced transversely isotropic material, was devised with a longitudinal to transverse stiffness ratio of 100:1 as shown in Table 2.

Table 1: Engineering constants for perfectly isotropic material

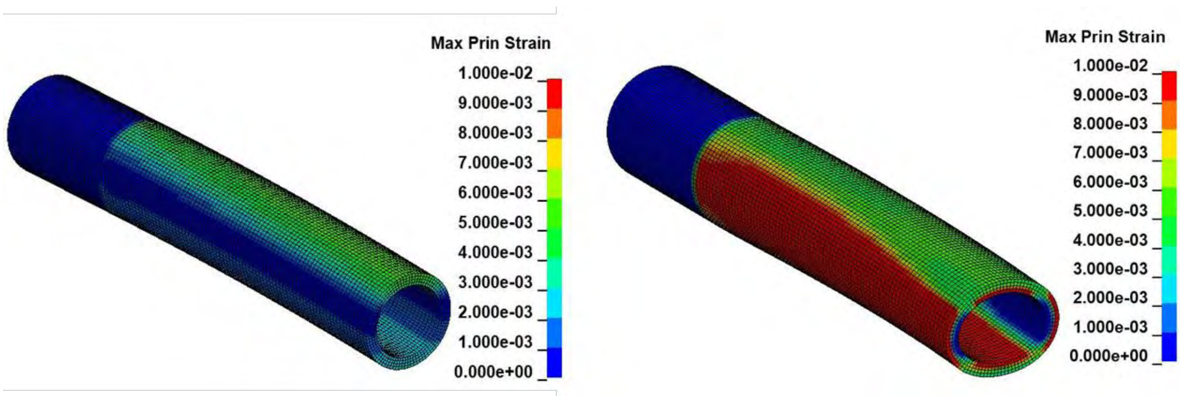
LS-DYNA Material Parameter - MAT_001 Elastic		
Parameter	Elastic Section	Rigid Section
Young's Modulus	E = 15 GPa	$E = 15 \times 10^6$ GPa
Poisson's ratio	ν = 0.3	ν = 0.3

Table 2: Calculator of engineering constants for axial reinforced transversely isotropic material

LS-DYNA Material Parameter - MAT_002 Orthotropic _Elastic					
Defined material data for flexural stiffness ratio longitudinal/transverse - 100:1					
Young's Modulus	Fiber Direction	E_z = 15,000 MPa	Poisson's ratio	Out-Plane	ν_{zr}, $\nu_{z\theta}$ = 0.3
	Radial and Circumferential Direction	E_r, E_θ = 150 MPa		Out-Plane	ν_{rz}, $\nu_{\theta z}$ = 0.003
Shear Modulus		G_{zr}, $G_{\theta z}$ = 148 MPa		In-Plane	$\nu_{r\theta}$, $\nu_{\theta r}$ = 0.003
		$G_{r\theta}$ = 75 MPa			

3 ANALYSIS OF RESULTS

The flexural behavior of 2 material models was investigated by considering the maximum principal strain criterion. The fringe components of selected range of maximum principal strain distribution of both models are displayed in Figure 5. The strain distribution from Figure 5(a), which represents the perfectly isotropic homogeneous model, is found to be greatest at the outermost section of the convex side of the culm. On the other hand, the strain distribution of the axial reinforced transversely isotropic model differed throughout the outer surface of the cross-section. The area of maximum principal strain is located midway on the outer surface and on the inner surface of both convex and concave sides of the culm. From Figure 5(b), ovalization of the cross-section is found to increase with increasing bending moment. Buckling of culm is likely to occur as this cross-sectional flattening weakens the structure [20].



(a) (b)

Figure 5: Comparison of fringe component of selected range of max-principal strain in; (a) perfectly isotropic material, (b) axial reinforced transversely isotropic material

A relative comparison of the maximum principal strain distribution of both material models was derived from Figure 5 and summarized in Figure 6. A local coordinate θ relative to the radial axis (Figure 3(b)) was used to describe the strain distribution across the cylinder cross-section. The areas more susceptible to failure by fracture in the perfectly isotropic model is located at 0° on the outer surface of the cross-section. This mode of failure is comparable to the strain distribution exhibited by isotropic materials in pure bending mode. In contrast, the distribution of maximum principal strain on the inner and outer circumference of the transversely isotropic model was found to be greatest at 0° and 180° followed by 90° with strain values of 0.032, 0.037 and 0.028 respectively.

Failure by fracture based on maximum principal strain criterion is bound to initiate from the inside sections followed by lateral sides of the culm. As reported in literature, cracks are expected to be initiated at four vertices of the circumference corresponding to the maximum principal strain shown in Figure 5(b) [18-20]. As bending load increases, it is assumed that these cracks will propagate longitudinally along culm length. This anticipated mode of failure corresponds to the fracture behavior of bamboo in nature as described in Figure 2.

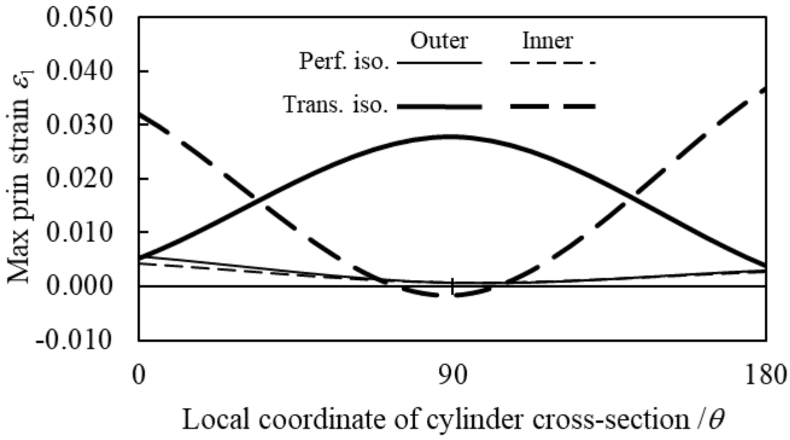


Figure 6: Comparison of maximum principal strain distribution

Modification of the inner culm section at 0° and 180° is a possible consideration to delay the onset of crack initiation by altering the maximum principal strain. This is a potential measure to address fracture from the inside of bamboo culms without requiring modification of its outermost surface. Even though this analysis has been conducted on intermodal length, it is worth mentioning about the contribution of nodes to resist bending. By having small intermodal length at the base of the culm, nodes provides additional reinforcement to the culm structure to resist maximum bending loads. However, as the intermodal length reaches a maximum value in the central part of the culm, this region becomes vulnerable to cross-sectional flattening and buckling [1,18].

4 CONCLUSION

This numerical study highlights the influence of inhomogeneous material on the fracture behavior of culm structure. Fracture behavior of homogeneous material model was found to be analogous to conventional fracture of isotropic material. Significant change in the circumferential distribution of maximum principal strain was observed in simulation of inhomogeneous model as material composition changed from elastic to orthotropic-elastic which comprised of axial reinforced fibres.

Results of this study correlates with natural failure observed in bamboo culms. Based on the criterion of maximum principal strain, cracks, which are likely to be initiated at four vertices of the circumference, are expected to propagate longitudinally.

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