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Creep behaviour of bamboo

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HIGHLIGHTS

- Creep behaviour of small clear through-culm-wall bamboo specimens is presented.
- Greater modulus of rupture but lower apparent modulus when outer culm-wall in tension.
- Greater post-creep residual capacity when outer culm-wall in compression.
- Creep conditioning had strengthening effect when outer culm-wall in compression.
- Tre Gai bamboo is seemingly better able to withstand sustained loads than timber.

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ABSTRACT

The phenomenon of creep, particularly in anisotropic and fibre-reinforced materials, is critical to structural design. The objective of this study is to study the creep behaviour of bamboo in particular considering the effect of specimen orientation. The experiment is motivated by the restriction of sustained load on various materials, particularly fibre reinforced materials, due to creep. In this study, half of the radially-cut *Bambusa stenostachya* (Tre Gai) specimens subjected to a sustained load were oriented so that the fibre-rich outer culm wall is in tension; the other half were loaded so that the outer culm wall is in compression. All tests were conducted in accordance with, and assessed based on, established creep test standards for wood. The orientation of the specimen was found to have significant effect on both the creep behaviour and residual strength of creep-conditioned specimens. The results showed that the bamboo loaded with the outer culm-wall in tension (OT) exhibited (a) a larger modulus of rupture; (b) a lower apparent modulus of elasticity; and (c) a lower residual strength when compared to specimens with their outer culm-wall in compression (OC). In terms of post-creep residual strength, creep conditioning appeared to have a strengthening effect on OC specimens and a detrimental on OT specimens. Results were assessed against common design values for timber and it concluded that the Tre Gai bamboo is seemingly better able to withstand higher sustained loads than timber.

1. Introduction

The exploration of the structural material properties of bamboo is motivated by its potential to serve as an alternative sustainable building material. Although bamboo has been used as a building material for thousands of years, the majority of applications do not abide by any standard design criteria. In this context, bamboo construction is considered to be non-, or at best marginally-engineered construction. The desire to develop standardization for bamboo as a building material is inspired by its generally excellent material characteristics. As a result of the fibre composite-like structure of the bamboo, its mechanical properties are generally superior to those of other natural materials such as timber.

For most woody species, the structure of bamboo is composed of culms with solid transverse diaphragms or ‘nodes’ separating hollow inter-nodal regions along its height (Fig. 1a). The circular cross section is composed of unidirectional cellulosic fibres oriented parallel to the culm’s longitudinal axis embedded in a lignin matrix (Fig. 1c). The fibres, which provide the culm’s strength, are grouped around vessels for water and sap transport in vascular bundles (Fig. 1d). Bamboo is a functionally graded material that has evolved to resist its primary loading in nature: its own self-weight and the lateral loading effects of wind [20,11]. The density of fibres increases from about 10% to 15% at the culm’s inner wall to about 60% at the outer wall. The variation in density through the

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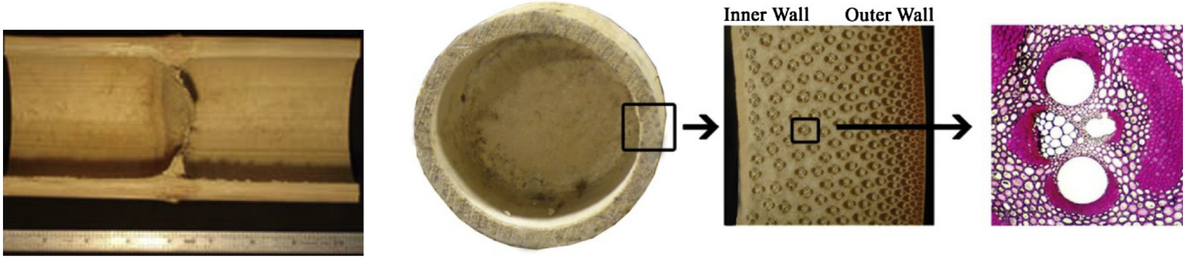

(a) longitudinal section of bamboo culm showing portions of internodes to either side of node

(b) cross section of culm

(c) section through culm wall

(d) vascular bundle

Fig. 1. Anatomy of bamboo culm.

culm wall is often assumed (for convenience) to be linear [10,13,25] although this is not the case. The variation has been reported to be exponential [20], quadratic [11], and is known to be species-dependent [3,4]. Regardless, due to the complex variation of the fibres and vascular bundles, the variation of mechanical properties through the culm-wall thickness has been shown to be highly nonlinear [22]. Janssen [14] states that the longitudinal modulus of elasticity is correlated to the areal density of vascular bundles and that the functional gradation of fibres in the cross section increases gross culm stiffness by 10% as compared to a uniform distribution having the same fibre volume.

In some species, the wall thickness will be largest at the base of the culm and decrease with height up the culm. Along its height, nodes provide buckling restraint to the thin walled internode regions and serves to arrest cracks propagating in the internodes. The fibre volume increases with culm height compensating for loss in strength and stiffness due to reductions in diameter and wall thickness near the top of the culm. This results in relatively uniform engineering properties along the entire culm height [3].

2. Material creep behaviour

The phenomenon of creep, particularly in anisotropic and fibre-reinforced materials, is critical to structural design. Creep is the permanent inelastic deformation of a material due to changes in the material caused by the prolonged application of stress. Creep effects, at a minimum, have the potential to affect the serviceability of structure. A more severe issue related to creep is its ability to alter material characteristics and subsequent mechanical properties of a structural element or system. Eventually, excessive creep may result in the failure of a structure.

Although the creep of bamboo has been considered briefly in previous research [15,13], it often exists only as a supplemental experiment to some primary study. Creep has rarely been the focus of a study, and therefore the available information on the creep of bamboo lacks detail. By studying the phenomenon of creep on relatable materials, wood and fibre composites, a fundamental understanding may be developed and hypotheses developed. The following sections develop these analogies.

2.1. Creep behaviour of wood

The natural growth of bamboo results in material properties and behaviour similar to those of wood. The strengths of wood and bamboo are affected by similar variables including: (a) species; (b) direction of loading in relation to the fibre or grain orientation; (c) growth characteristics (i.e. knots, growth cycles, specific gravity, etc.); (d) environmental conditions (i.e. moisture content, relative humidity, wet-dry cycles, temperature, etc.); and (e) duration of load. Because of these similarities, creep tests of bamboo may be expected to reflect the tendencies and performance of timber under sustained loads. In timber design [8], where significant data is available, the effect of sustained load is considered by expressing wood strength in terms of its ten year strength. A permanent load, for example, may be designed for 90% of the ten year strength whereas a rare impact load may consider 200% of the ten year strength. The usable strength of structural wood decreases as the duration of the load increases.

2.2. Creep behaviour of fibre composite materials

As described above, bamboo may be categorised as a naturally-occurring functionally-graded fibre-reinforced composite. Therefore, understanding the effect of creep on unidirectional fibre composites is beneficial in the investigation of bamboo under a sustained load. Studies of creep effects in composites often focus on the difference in material properties of the fibre and the matrix and the structure of the fibres within the matrix [17]. Regardless of the specific materials that make up the matrix and reinforcement phases, concerns involving the effect of sustained loads remain unchanged. Creep of a composite material relies on the materials' individual properties as well as the properties of the composite as a whole. Each of the materials involved in the composite may creep individually, influencing the overall creep of the specimen. In most cases (at least those considering loads below the elastic limit of the material), it is assumed that the creep of the fibre is equal to the creep of the matrix and therefore, is equal the creep of the composite as a whole. This assumption is valid in composites that have continuous unidirectional fibres over the length of the composite member [2]. This simplifying assumption is believed appropriate in the present work in which bamboo specimens are cut from an internode; these are expected to have continuous fibres through their length which would not be the case for a culm containing multiple nodes. In composites composed of short and rigid fibres, the structure must be considered at both micro- and macro-scales. The interaction of the materials may have positive or negative effects on creep behaviour in this case [16]. The different bases for creep behaviour based on fibre architecture does raise the question: *will bamboo creep behaviour differ when determined for small clear specimens than when determined for full-culm specimens?* The scope of the present work only considers small clear internode specimens subject to creep.

2.3. Creep behaviour of bamboo

The performance of bamboo as a structural material relies heavily on moisture content [26] and creep. Although creep behaviour of bamboo may be susceptible to loading parallel to the fibres, loads perpendicular to the fibres which induce longitudinal splitting behaviour are commonly reported as the dominant mode of failure in bamboo members [23,18].

Bamboo and wood have similar composition in terms of cellulose (~55%) and lignin (~25%) content [13] and crystallinity (~58%); the latter refers to the weight fraction of crystalline cellulose, which affects the mechanical properties of cellulose fibres [5]. This similar composition leads to similar creep mechanisms and the description of bamboo creep by a Burgers-model [13].

Motivated by the use of bamboo trusses in practical construction, Janssen [13] reports the testing of "truss 5", a simple truss 8 m long having a roof slope of 1:2. The truss was tested under repeated midspan loading on its lower chord to approximately 80% of its ultimate capacity (as determined from previous tests) to investigate creep and creep recovery. Midspan deflection was increased and released in five cycles over 380 days. Janssen [13] reports creep deformation as a result of compression, bending and shear and concluded that the deformation may be categorised into three ranges. The permanent deformation takes place in the viscous range and accounts for 49% of the total deformation. The immediate deformation occurs in the elastic range and accounts for 39% of the total deformation. Finally, creep takes place during the retarded elastic state and accounts for 12% of the total deformation. The creep recovery plot for this experiment resembles a Burgers-model. Janssen [13] reported the permanent plastic deformation caused by creep in bamboo to be only 3–5% of the immediate deformation, concluding that creep in full-culm bamboo is negligible.

On a smaller scale, creep deformation may be related to the structure of the bamboo. The creep behaviour of the bamboo depends on the composition and fibre angle of the samples [13,15].