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EXPERIMENTAL EVALUATION OF LONGITUDINAL SPLITTING OF BAMBOO FLEXURAL COMPONENTS

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ABSTRACT

Splitting or longitudinal shear failures in full-culm bamboo are a critical limit state when using the material for construction applications. Understanding and quantifying the behaviour must be through standardized test methods for international adoption into building practices to be successful. Current testing procedures only determine an *effective* flexural strength due to splitting failures. The present study investigates longitudinal shear failure in full-culm *Phyllostachys pubescens* (Moso) and *Bambusa stenostachya* (Tre Gai) bamboo flexural specimens through a number of standard and modified test methods. In particular, the paper proposes modifications to 'standard' culm flexural tests intended to better capture actual shear-dominated behaviour. Notched specimens are used to better establish relationships between Mode I and Mode II behaviours. Test results illustrate the significant degree of interaction between Mode I and Mode II stresses resulting from flexural tests and their associated failures, specifically the significant deterioration of Mode II capacity in the presence of even a small amount of Mode I stress. It is proposed that a uniform experimental approach using horizontally-notched flexural specimens having different shear spans and notch locations would be appropriate to establish a relationship between Mode I and II behaviour.

KEYWORDS

Bamboo, Flexure, Shear, Splitting

NOTATION

a, c	length of shear spans in four-point flexure test
A	area of partial section above the shear plane of interest
b	length of constant moment region in four-point flexure test
D	exterior diameter of the bamboo culm
h	height of rectangular specimen
I	moment of inertia of the culm section
L	length of specimen; beam clear span
m, n	empirically determined parameters in Eq. 2
M	moment in the constant moment region of four-point flexure test
t	culm wall thickness
V	shear force at the section considered
w	width of rectangular section
y	distance between the centroid of A and the neutral axis of the cross section
dv	lever arm of the internal force couple defined as the distance between the centroids of the compression and tension resisting fibres in the cross section
σ	stress
σ_I	Mode I stress
σ_{Icr}	critical Mode I stress
τ	shear stress
τ_{II}	Mode II stress
τ_{IIcr}	critical Mode II stress

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 millennia, its use remains mostly non-, or at best marginally-engineered construction. The desire to develop standardisation for bamboo as a building material – and thus achieve “engineering acceptance” is inspired by its generally excellent material characteristics. As a result of the composite-like structure of the bamboo, its mechanical properties are generally superior to those of other natural materials such as timber. As in engineered composites, bamboo fibers are much stronger than the lignin matrix, and rarely govern mechanical failure. The highly anisotropic nature of bamboo, however, makes it susceptible to orientation of loading (Janssen 1981). More specifically, the material is much weaker in its transverse direction, restricting its structural capabilities and applications to a certain degree. While there is a large body of work focusing on the anistropic and/or functionally graded natures of bamboo (e.g., Amada et al. 1997; Ghavami et al. 2003; Harries et al. 2016 provides a recent review), the present study focuses on the practical macroscopic behaviour of bamboo culms and how these may be assessed using standard test methods.

Splitting or longitudinal shear failure is the most critical failure mode associated with many bamboo structural applications and methods of culm connection (Mitch 2009; Sharma 2012). The primary contributions to splitting include the weakness of the lignin matrix and inherent flaws (i.e. cracks from drying shrinkage, harvesting damage, etc.) in the culm. Additionally, splitting is often initiated at connections, most significantly at simple through-bolted connections and at culm ends. Flexure-induced splitting poses a unique concern as it is a mixed-Mode failure exhibiting both tangential tension (Mode I) and in-plane shear (Mode II). Here, Modes I and II refer to the classic fracture mechanics modes in two dimensions (Smith et al. 2003): Mode I is related to opening or peeling-oriented separation across an interface while Mode II is shear along the same interface (Mode III is out-of-plane shear and is not considered here). Full-culm flexural behaviour, in general, is quantified by third-point flexure tests prescribed by ISO Standard 22157 (ISO 2004); typically flexural stiffness is determined and “modulus of rupture” (MoR) is calculated at the failure load. Most full-culm bamboo flexural tests tend to exhibit a longitudinal splitting type of failure associated with Mode II shear typically near the neutral axis. Thus the

MoR calculated based on a failure load is really the flexural modulus corresponding to shear failure; this is, at best, a lower-bound estimate of the MoR. As described in the following section, this shear-dominated behaviour was viewed as undesirable when establishing a flexural test method. It is the contention of the present authors that the shear behaviour inherent in a flexural test may, indeed, provide more useful information describing the actual behaviour of bamboo culms. Addiitonally, the simple flexural test arrangement is preferable to more complex arrangements and specimen machining required for other tests intended to capture shear behaviour (such as Moreira 1991; Cruz 2002).

2. BAMBOO FLEXURAL STRENGTH

The ISO standard test for full-culm flexure (ISO 2004) prescribes a specimen loaded in third-point flexure having a length at least thirty times the culm diameter (30D). The value of 30D was proposed by Vaessen and Janssen (1997) as being critical to ensure “flexure domainate” behaviour. The value was arrived at based on the theoretical shear span at which the maximum bending stress and shear stress at the neutral axis would be reached simultaneously. and confirmed with eight third-point flexure tests of a single species (*B. bluemana*) having spans of 12D to 39D (Vaessen and Janssen 1997). Janssen (1981) defined the maximum flexural stress for bamboo as the maximum compressive stress corresponding to a controlling lateral tensile strain in the section. Vaessen and Janssen (1997) estimated the critical compression strain to be -0.0037 corresponding to an ultimate bending stress of 62 MPa for culms tested in four-point bending over a critical length selected to achieve a modulus of rupture-type failure. An ultimate shear stress of 2.2 MPa was determined from the same tests. The critical length was thereby determined to be 26.3 (rounded to 30) times the bamboo culm diameter. A specimen length of 30D, resulting in a shear span of 10D, was adopted (ISO 2004).

The authors of the present work contend that since the dominate observed behaviour of bamboo in flexure tends to be longitudinal shear splitting, a ‘flexure’ test should capture this behaviour. Therefore, considering the longitudinal shear-critical nature of full-culm bamboo observed in practice, it is proposed here that shorter shear spans may reveal more relevant material behaviours.

Bamboo Shear and Splitting Behaviour

Flexure induced splitting results from longitudinal shear, τ, in a culm section determined from:

$$\tau = \frac{VAy}{It} \quad [1]$$

Where V is internal shear force at the location considered; I is the moment of inertia of the culm section; t is the width of the cross section resisting shear; A is the area above the section of interest; and y is the distance between the centroid of A and the neutral axis of the cross section. This is shown schematically for a hollow thick-wall tube in Figure 1 and shows that τ has a component in the plane of the cross section and in the longitudinal direction. The value of τ reaches its maximum value at the neutral axis (NA), where A is equal to half of the culm cross sectional area.

The flexure induced shear stress, coupled with the bending stresses, results in a mixed Mode I and Mode II stress condition along the culm shear span. Mode I tensile opening stress perpendicular to the fibres results from the presence of a flexural gradient (along the shear span), while Mode II in-plane shear results from the flexure-induced shear (Eq. 1). Mode III, out-of-plane shear of the culm wall would result from the addition of torsional loading but is not considered in the present study.

In the presence of Mode I distortions, Mode II capacity and toughness deteriorate significantly. Thus, the Mode I component of flexure is believed to be the driving component of a splitting failure. Stated another way, splitting is more likely to occur in the high-moment region of the shear span (where there is a shear component, V) rather than in the constant moment region of a four-point bend test.

Mode I Failure

Mode I transverse opening stress (σ_I in Figure 1), directed perpendicular to the bamboo fibres is resisted only by the relatively weak lignin matrix. Arce-Villalobos (1993) reported a tangential strain of 0.0011 at failure and no correlation between the density of bamboo and its transverse tensile strength implying a relatively universal capacity of the weak lignin matrix. Recognizing that Poisson's ratio of 0.3 is also relatively constant for bamboo (Janssen 1981); the tangential strain can be related to longitudinal strain. As reported by Shao et al. (2009), Zeng et al. (1992) found that the tensile strength perpendicular to the longitudinal fibres was only about 2% of that parallel to the fibres. Mode I fracture was further studied by Amada and Untao (2001) and Shao et al. (2009).

Mitch et al. (2010) and Sharma et al. (2012) sought to develop laboratory and field tests for tensile strength perpendicular to the longitudinal fibres. Mitch et al. developed the split-pin test (shown in Figure

2a), which determines the direct tension capacity perpendicular to the longitudinal bamboo fibres and can be used to assess the fracture toughness of the culm. Sharma et al. (2012) sought to develop a less complex test: the edge bearing test is composed of a full culm specimen loaded in compression perpendicular to the bamboo fibres. Failure is described by a pair of well-defined three-pinned arches from which the transverse modulus of rupture for the culm walls, f_r, a measure of transverse tension capacity is calculated. Both the Split-pin and edge bearing tests are being developed for inclusion in future revision of ISO (2004).

Mode II Failure

Mode II stress (τ_{II} in Figure 1) is the result of in-plane shear in the longitudinal direction of the culm. There are two standard test methods for determining bamboo shear strength parallel to longitudinal fibres: the full culm longitudinal shear or 'bowtie' test shown in Figure 2b (Janssen 1981, ISO 2004); and the 'S-type' test for inter-laminar shear (INBAR 1999, Moreira 1991). Cruz (2002) also developed a 'lap shear' test arrangement to study shear strength perpendicular to the longitudinal fibres.

Mixed Mode Failure

A significant and typically overlooked aspect in the study of longitudinal shear failure in bamboo is the relationship between the Mode I and Mode II failures; particularly in as far as mixed Mode conditions are most common in construction applications. In a general sense, failure under mixed-Mode conditions may be expressed in the form (Chai 1988):

$$\left(\frac{\tau_{II}}{\tau_{IICR}}\right)^n + \left(\frac{\sigma_I}{\sigma_{ICR}}\right)^m < 1 \qquad [2]$$

Where τ_{II} and σ_I are the Mode II and I-oriented stresses and τ_{IICR} and σ_{ICR} are the critical Mode II and I stresses. The variables n and m are material-specific parameters that may be obtained following mode partitioning. Most simply, m and n are taken as unity, defining a linear interaction between modes in which, as in most materials, the Mode II capacity is reduced in the presence of Mode I tension stresses. In longitudinally reinforced anisotropic materials, the Mode I strength and toughness may be orders of magnitude less than the Mode II values thus the Mode II capacity may decrease rapidly in the presence of even a small amount of Mode I-oriented stress. Additionally, in a flexural member, say, there is a varying Mode mixture along the shear span.

3. EXPERIMENTAL PROGRAMME

The experimental portion of this investigation was composed of three phases: a) estimation of the Mode I and Mode II capacities of the bamboo using bowtie (ISO 2004) and split-pin (Mitch et al. 2010) tests; b) small scale beam tests of rectangular specimens taken from the culm wall; and c) a series of full-culm modified flexural tests (ISO 2004) to determine longitudinal splitting strength. All tests were conducted in a laboratory environment using seasoned bamboo. The moisture content in all cases was approximately 10%.

Bamboo Species

Two species of bamboo - *Phyllostachys pubescens* (Moso) and *Bambusa stenostachya* (Tre Gai) culms were tested. These culms were obtained through an importer with the Moso culms (labelled M) sourced from China and Tre Gai culms (T) from Vietnam. Specimens for the bowtie, split-pin, and small beam tests were fabricated from the same batches of Moso and Tre Gai culms as the full-culm tests.

Longitudinal Shear 'Bowtie' Tests

Longitudinal shear or 'bowtie' tests (Figure 2b) were conducted in accordance with ISO standard 22157-1:2004(E) (ISO 2004) on six Moso and five Tre Gai specimens to estimate the Mode II in-plane shear strength (τ_{II}) of each species. Specimens were taken from undamaged regions of full-culm beam specimens after flexural testing. Tests were conducted in a servo-hydraulic universal testing machine with 'bowtie' compression loading plates at the ISO-prescribed loading rate of 0.01 mm/sec. The maximum load and location(s) of failure were noted for each specimen and testing stopped automatically when the load fell to 50% of the peak. Moso specimens had average ultimate shear strength τ_{II} = 14.23 MPa (coefficient of variation (COV) = 0.104), while Tre Gai specimens displayed average ultimate shear strength τ_{II} = 8.65 MPa (COV = 0.075).

Split Pin Tests

Split-pin tests were conducted on four Moso and three Tre Gai specimens to determine the Mode I tensile strength perpendicular to fibres (σ_I). Similar to the bowtie tests, specimens were taken from full culm flexural tests after testing. Each specimen was approximately 67 mm long ($L \approx D$) and had a 25.4 mm diameter hole drilled through opposing sides. Crack initiators 3 mm in length were cut parallel to the length of the culm on either side of the drilled holes with a fine toothed hacksaw blade resulting in a dimension $2a$ = 31.4 mm (see Fig. 2b). The specimens were loaded at a rate of 0.005 mm/sec in a servo-hydraulic controlled universal testing machine and the ultimate load was recorded for each test. An average ultimate tensile strength of σ_I = 2.40 MPa (COV = 0.244) was calculated for the Moso specimens while Tre Gai specimens had an average ultimate tensile strength of σ_I = 1.52 MPa (COV = 0.162). As expected, the Mode II strength is significantly greater than the Mode I: τ_{II}/σ_I = 5.9 and 5.7 for Moso and Tre Gai, respectively.

Small Clear Specimen Flexural Tests

Small 'clear specimen' beam tests were conducted to determine the longitudinal shear strength of bamboo within the culm wall. Specimens of Moso and Tre Gai were cut from culm wall internodes using a milling machine. Specimens were oriented in such a way that the width, b was measured in the radial direction of the culm and the height, h was oriented in the tangential direction as shown in Figure 3a. The resulting Moso specimens had $b \approx 5.9$ mm and $h \approx 12.5$ mm and were tested over a simple span of L = 152 mm while the thicker-walled Tre Gai had $b \approx 11.1$ mm and $h \approx 18.6$ mm and was tested over a span of L = 229 mm.

As shown in Figure 3, the specimens were tested in third-point bending with a 0.5h deep laser-cut notch in the tension face under one load point. Unnotched specimens were also tested. The notches provide a stress raising effect which drives the desired failure mode at a specific location. The notched four-point bend test configuration (Charalambides et al. 1989) results in peeling (Mode I) stresses at the notch root. As a result, one would anticipate the shear stress, τ, determined from such a test to be significantly affected as indicated by Eq. 2.

Shear stress calculated based on Eq. 1 resulted in the average shear stress in the notched specimens, τ = 1.82 MPa (COV = 0.31) and τ = 0.79 MPa (COV = 0.26) for the Moso and Tre Gai, respectively. Unnotched specimens exhibited shear capacities of τ = 7.0 MPa and τ = 5.9 MPa for Moso and Tre Gai, respectively. The unnotched capacities are less than τ_{II} since this test configuration introduces a component of Mode I stress. When notched, the Mode I component is more significant, further impacting the results obtained. The significant difference in the effect of the notch from species to species requires further study.

Full-Culm Flexural Tests

Sixteen Moso and 11 Tre Gai full culm flexural tests, summarized in Table 1, were conducted. The full culm tests had different length and notch details in order to investigate the effects of specimen geometry on derived shear capacities and to attempt to develop a flexure-base mixed Mode test for assessing shear capacity. The following test geometries were used:

Full-culm flexure tests (test type A), shown in Figures 4a and b, are based on those prescribed in the current ISO (2004) standard. Culms are tested in third-point flexure (i.e. a = b = c = L/3 as shown in Table 1) over a simple span exceeding 30D (30 culm diameters). As described above, this length was proposed to be sufficient to achieve a modulus-of-rupture-type failure, rather than a shear dominated failure. Regardless of the failure Mode, the maximum shear at the failure load may be calculated using Eq. 1.

Short full-culm flexure tests (test type B) are identical to test type A except that the culm span is less than 30D. In this test program, spans between 16D and 24D were tested. With a shorter span, shear becomes more dominant in the response. Therefore, it is proposed that shorter span flexure tests may better capture the anticipated shear behaviour of the culm.

Test type C uses the same test geometry as Type A (i.e. ISO 2004) but introduces a vertical notch through the lower half of the culm beneath one of the load points. Type Ci introduces this notch at a distance D into the shear span from the load point. Notch geometry and location are shown in Figure 4c and d. The notched four-point bend test configuration (Charalambides et al. 1989) results in a near perfect Mode I stress field at the root of the notch. Vertical notches were saw-cut to provide a flat root and have a kerf of about 2 mm.

Following investigation of the vertical notch (Type C), 60 mm long horizontal notches (Figures 4e and f) were introduced through both culm walls. In this case, rather than developing a peeling stress, these notches provide a stress raiser at which a shear failure may initiate (allowing instrumentation to be focused at an *a priori* known failure location as seen in Figure 4e). Type D notched flexure tests had the notch located at midspan in the constant moment region (i.e. region c in Table 1). This arrangement captures the culm's ability to resist the internal force couple required to resist bending in the constant moment region.

Type E specimens used a shorter shear span, a ≈ 5D (while b = c ≈ 10D) and located the notch a distance approximately midway between the support and point of applied load. Horizontal notches (Figure 4e) were created by first drilling a 9.5 mm hole straight through the culm in order to ensure that the notch was located at the same location on both sides of the culm. A rotary tool with a stone grinding wheel was then used to produce a notch 25.4mm to each side of the hole. The total length of the notch was therefore 60 mm. The notch was approximately 3 mm wide and passed fully through the thickness of each culm wall. The shear at the notch for test type E is determined from Eq. 1.

All full-culm flexure tests were conducted in a hydraulic universal test machine. Load and support saddles were fabricated from web sling material and providing both full support of the culm and permitting significant rotation of load and support points (Figure 4b). In some notched culms, following failure at the notch under load point P1 (Figure 4a) in an initial test, the culm was 'repaired' with steel pipe clamps, a second notch was introduced at the other, undamaged support region, P2, and a second test conducted. These are designated A and B in Table 1.

4. FULL-CULM FLEXURE TEST RESULTS

Test results are summarized in Table 1 the reported value of shear, V, is one half the applied ultimate load. In some test arrangements an incremental failure (or residual capacity) is observed, in these cases, V was determined at the initial observed failure. Shear stress is determined from Eq. 1. Table 2 summarizes the results of each of the test arrangements, A through E, conducted.

As expected, the strength of the un-notched specimens was significantly higher than the strength of notched specimens. Nonetheless, despite the relatively long test length (>30D) of the ISO-compliant flexure tests type A, longitudinal cracking was observed in some un-notched specimens (M9, M4, and T7). The observed longitudinal cracking was often associated with existing surface cracking resulting from drying shrinkage. Such longitudinal cracking drove the failures of all shorter test type B specimens. The observed capacity of the shorter type B specimens was at least 1.5 times that of the type A. This reflects the greater shear to moment ratio resulting in a lower Mode I component of stress at the eventual splitting plane in the shorter specimens. It is for this reason that the authors argue that a shorter standard flexural test may better capture the shear-dominant behaviour of full-culm bamboo.

The vertically notched specimens (Type C) exhibited very low capacities related to the fact that the initiation of splitting in these specimens is a Mode I peeling Mode. While initially promising, the peeling stress-raising effect of the notch is likely too pronounced to yield useful design values. The initiation of failure is governed by the very high Mode I stress raiser at the root of the notch, the properties of which will not be easily determined for full culm bamboo and may vary considerably even within a single internode. Provided representative samples can be obtained, the notched small clear flexure test may be preferred.

Horizontally notched type D and E specimens, on the other hand, appear to be very promising. By locating the shear failure initiator along the span, the shear-to-moment ratio, and therefore a measure of the Mode I-to-Mode II stress ratio may be determined *a priori*. As seen in Figure 4f the nature of the shear failure is evident in these specimens. The effect of locating the horizontal notch in a short shear span in type E specimens is that there is reduced Mode I contribution to stress and therefore a greater shear capacity obtained.

5. DISCUSSION

The full-culm flexural tests exhibited lower strength values than the comparable bowtie, split-pin, and smaller clear bamboo flexural specimens. Table 2 summaries the results for all tests conducted. The deterioration of the Mode II capacity in bending due to the existence of the Mode I component is illustrated in the values normalized to the bowtie test results which capture only Mode II behaviour: the value $1 - 1/\tau_{II}$ is the proportion of capacity exhausted by Mode I stresses. The Mode I capacity is considerably lower (by a factor of about 5) than the Mode II. This result is typical of many brittle materials especially unidirectional fibre-reinforced materials.

The geometry of splitting failures in full culms also confirms the mixed Mode nature of the failure. Figure 5 shows images of a vertically notched flexure test (type C). The image is taken with a handheld high magnification camera and shows the horizontal splitting failure in a culm of *Dendrocalamus giganteus* also tested by the author (Richard 2013). Images were taken on the same face of the culm to either side of the vertical notch following testing. The images show crack-bridging occurring as the crack propagates towards away from the notch; this is an indication of a mixed-Mode failure; the opposite orientation of shear to either side of the notch is also evident.

In practice, it would be rare to have a scenario in which Mode II stresses occur without Mode I stress present. Additionally splitting is the dominant observed failure in full-culm bamboo structures and connections. The ratios of $1/\tau_{II}$ in Table 2, clearly indicate the dominance of even small degrees of Mode I stress being present. Thus, the authors propose that flexure based tests – particularly those utilizing a horizontal notch to initiate a shear failure at a specific location (and therefore known shear-to-moment ratio) be adopted. While the 'bowtie' test yields consistent results, these are clearly very much greater than may be practically achieved in flexural loading scenarios. Limited work on bolted culm connections (Sharma 2010 and Janssen 1981) also suggests that the bowtie test over estimates achievable shear capacity. Further study is necessary particularly to identify practical and useful parameters for standardising horizontally-notched flexural specimens. Variation of shear span length and notch location will affect different moment-to-shear ratios, while different notch lengths (and perhaps kerfs) may affect observed capacities.

6. CONCLUSIONS

A number of standard and modified tests for assessing longitudinal shear behaviour of full-culm bamboo are presented. Test results illustrate the significant degree of interaction between Mode I and Mode II stresses, specifically the significant deterioration of Mode II capacity in the presence of even a small amount of Mode I stress. In terms of establishing parameters for Eq. 2 there is insufficient data at this time, however, it is proposed that the exponent will likely be less than unity. It is proposed that a uniform experimental approach using horizontally-notched flexural specimens having different shear spans and notch locations would be adequate to determine exponents n and m for Eq. 2. Based on the two species considered in this study, it is suggested that these values will also likely be species-specific.

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Figure 1: Shear in thick-walled cylinder due to flexure

Figure 2: Small full-culm shear tests.

Figure 3: Small Beam Flexural Specimen Configuration

Figure 4: Flexure test geometries

Figure 5: Crack bridging on either side of notch in vertically-notched specimen (Richard 2013)

Table 1: Summary of flexure specimen geometry and test results.

Table 2: Comparison of results obtained from different test arrangement