Structural Use of Full Culm Bamboo: 
The Path to Standardization

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Abstract: Standardization of material test methods for bamboo is critical if the material is to gain greater engineering acceptance. Methods that capture fundamental material properties permit comparison of the behavior and performance of different bamboo species, geometry, weathering and treatment methods. Appropriate standardized test methods able to reliably provide fundamental material properties permit the calibration of material resistance factors and the extension of design guidance to different species. Standardized test methods used in well-defined experimental studies also permit the isolation of factors that affect material performance and behavior. This process represents the path to rational and universal design methods for bamboo. This paper provides an overview of existing standard test methods, their use and practical utility in a field environment. Focus is placed on the authors’ efforts to develop standard test methods suitable for characterizing the longitudinal splitting behavior of full-culm bamboo.

Keywords: Bamboo, material properties, shear, splitting, standard tests, tension

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1 MOTIVATION AND CONTEXT

A 2006 Rand Corporation report (Silberglitt et al. 2006) anticipates an increasing socio-technical-economic gap developing between scientifically “advanced” countries (e.g., United States and Western Europe) and those that are “proficient” (e.g., the so-called BRIC countries: Brazil, Russia, India and China), “developing” (e.g., Mexico and Turkey) and “lagging” (e.g., Egypt and Nepal). Additionally, particularly within scientifically proficient countries expected to experience great growth, a similar widening gap between urban and rural populations is anticipated. Sixteen so-called “new technologies” are predicted to proliferate by 2020; most involve aspects of civil infrastructure. Indeed, the Rand report cites the lack of stable infrastructure (including electricity, potable water, roads, schools and transportation systems) as the primary barrier to the adoption of technology. The report further cites the increased emphasis by advanced countries on “sustainable practices” as being largely unattainable (by 2020) for proficient, developing or lagging regions. Two key new technologies cited in the Rand report are the focus of the present work: inexpensive, autonomous housing and “green” manufacturing and construction.

A critical aspect of sustainable infrastructure is its ability to perform under both service conditions and extreme events. Safety in the built environment is a fundamental right (United Nations 1948; United Nations 1994). Recent “great” natural catastrophes have resulted in unacceptably high casualty tolls. The 2001 earthquake in Bhuj (India) left over 19,700 dead; the 2003 Bam (Iran) earthquake: over 26,000 dead; the 2004 Aceh earthquake and subsequent tsunami: over 275,000 dead; the 2005 Kashmir earthquake: over 80,000 dead; the 2008 Sichuan earthquake: over 70,000 dead; and the 2010 Haiti earthquake: over 170,000 dead. The injured are many times these numbers and the displaced are often an order of magnitude or two greater. In reviewing this litany of statistics, one must acknowledge the clear disparity between developed and less developed regions. The 2010 Chilean earthquake, the largest event of those listed and the fifth largest recorded since 1900, resulted in less than 521 casualties primarily due to the adoption of advanced building codes and earthquake-hazard mitigating technology.

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It is within this international context that we begin considering bamboo as a viable, sustainable and engineered alternative to present practices in many areas of the world. Specifically, bamboo’s light weight and relative flexibility make it a particularly attractive alternative for residential construction in seismic regions. Recognition of bamboo as a sustainable construction material is growing, with research and construction not limited to developing countries but being initiated worldwide. Structural applications of bamboo are diverse and include flooring, “oriented strand board”, glue-laminated members (“glubam”), reinforcement (culms and partial culms for concrete and masonry and fibers for mortars and polymers), and framing. Nonetheless, the majority of knowledge of bamboo construction is based on cultural tradition. To develop bamboo as a sustainable construction material, in both engineering and cultural senses, one must evaluate traditional non- or marginally-engineered building techniques in terms of engineering standards and develop equivalent methods of design and performance assessment.

2 STANDARDIZATION

In the context of civil infrastructure, conventional construction materials such as steel and reinforced concrete were once unconventional and unproven materials. Acceptance was achieved through decades of testing, analysis, and experience which evolved into standardized practices. Even today, the standardization of these materials continues to be refined through the work of universities, laboratories and professional organizations. More recently, fiber reinforced polymer composites, which were initially developed for aerospace applications, are being standardized for use in civil infrastructure and their use is burgeoning. Increasing focus is now being placed on the standardization of sustainable building alternatives such as natural fiber composites like bamboo.

Standardization of construction materials and practices serves both technical and social purposes. The objective of a standard material test procedure, for instance, is to accurately determine a design value of the material (e.g., strength and stiffness) as well as to provide a common frame of reference for the user community. Data from such comparable tests can be compiled to obtain a more reliable understanding of a material’s properties based on a statistical analysis which can lead to the refinement of and confidence in design values, leading to broader acceptance of the material in the design community. Such acceptance, coupled with advocacy, can lead to broader social acceptance of previously marginalized vernacular construction methods.

2.1 Existing Test Methods for Bamboo

In 2004, the International Organization for Standardization (ISO), in cooperation with the International Network for Bamboo and Rattan (INBAR), developed model standards for the structural design of bamboo (ISO 2004a) and for determining the mechanical properties of bamboo (ISO 2004c; ISO 2004b). If the use of bamboo is limited to rural areas, ISO (2004a) recognizes established “experience from previous generations” as being an adequate basis for design (ISO 2004a). However, if bamboo is to realize its full potential as a sustainably obtained and utilized building material on an international scale, issues of the basis for design, prefabrication, industrialization, finance and insurance of building projects, and export and import of materials all require some degree of standardization (Janssen 2005).

The intent of the ISO (2004a) standard is to establish a modern limit states design approach while recognizing traditional design and practices. Precisely because of this dichotomy, however, the standard is simultaneously inadequate on both counts in the context of application in developing regions. A limit states approach requires specialized knowledge and engineering which may not be readily available. The traditional approach, while often adequate for service conditions, is unable to address ultimate limit states, particularly those associated with extreme events such as earthquakes.

The ISO standard includes four tests (1 to 4 in Table 1) for determining (1) full-culm compressive strength; (2) longitudinal tensile strength using a “dogbone” specimen taken from the culm wall; (3) longitudinal shear using the “bowtie test” (Janssen 1981); and (4) flexural capacity based on a three-point bend test of a long length of culm. The latter test is typically governed by longitudinal shear behavior (i.e., $V_{Ay}/It$) and is therefore not a true modulus of rupture test. The standard also provides guidelines for determining moisture content, mass, and shrinkage of bamboo. Other tests focused on the longitudinal shear capacity of bamboo include a typical “S-type” shear coupon (INBAR 1999; see test 6 in Table 1) and a two-plane test arrangement (Cruz 2002; see test 7 in Table 1). Each test method is summarized in Table 1, including the fundamental material property obtained from the tests.

2.2 Standardized Methods for Field Implementation

These established tests provide a promising starting point for standardization. However, they neglect important limit states such as longitudinal shear and connection-induced splitting and many cannot be practically implemented in the field. In the further development of standard test methods, the approach outlined here involves: (1) determining appropriate limit states of behavior; (2) characterizing the limit states through formal laboratory tests; (3) developing field-appropriate tests; and (4) correlating theory with complex and simpler test methods.
Material Property Obtained | Description of Test
--- | ---
1. **Compression parallel to culm (ISO 2004b); see Figure 1b**
\[ \sigma_c = \frac{F_c}{A_{culm}} \]

where

\[ A_{culm} = \frac{\pi}{4} [D^2 - (D - 2t)^2] \]

The ultimate compressive stress of the full culm (\(\sigma_c\)) is found from a compressive test of a length of culm (\(L\)) no longer than twice its outside diameter (\(D, L \leq 2D\)). The net area of the culm (\(A_{culm}\)) is used in this calculation. Separate tests are required for specimens that include nodes and those that do not since their capacities will differ. The compressive modulus of elasticity (\(E_c\)) can be obtained using electrical resistance strain gages placed at mid-height at either side of the culm. The strain is averaged and the compressive modulus is calculated between 20-80% of the resulting stress-strain curve. Care must be taken to minimize friction between the loading head and culm which affects results. Steel shims or sulphur capping compound have been shown to be adequate to minimize friction. Rigid loading blocks are required to ensure that \(F_c\) is distributed uniformly to the culm section.

2. **Tension parallel to culm (ISO 2004b); see Figure 1c**
\[ \sigma_t = \frac{F_t}{A_t} \]

A “dogbone” style tension test is used to determine the tension capacity parallel to the fibers (\(\sigma_t\)). The coupon thickness (\(t\)) corresponds to the culm wall thickness (\(t\)) and the coupon breadth (\(b\)) is a circumferential chord of the culm. The reduced area gage length is typically 50 to 100 mm in length. Additional specimen length is provided for wider clamping tabs. The tensile stress is calculated over the reduced gage length area (\(A_t = b_t\)). The tensile modulus of elasticity (\(E_t\)) can also be calculated using clip gages or strain gages. Care must be taken so that gripping stresses do not cause local damage to the specimen affecting results.

3. **Shear parallel to culm (ISO 2004b); see Figure 1d**
\[ \tau_L = \frac{F_L}{4Lt} \]

To measure shear strength parallel to the fibers (\(\tau_L\)) a “butterfly” or “bowtie” shear test is used. The specimen length is equal to the outer culm diameter (\(L = D\)). The ultimate shear stress is calculated based on the applied load (\(F_L\)) distributed over the sum of the shear areas (\(Lt\)) of all four failure planes (i.e., \(4Lt\)). Separate tests are required for specimens that include nodes and those that do not since their capacities will differ. Care must be taken that the ends of the culm are smooth, parallel and at right angles to the culm longitudinal axis. Rigid loading blocks are required to ensure that load is distributed uniformly to the culm section.

4. **Bending perpendicular to fiber (ISO 2004b); see Figure 1e**
\[ f_b = \frac{F_b LD}{12b_t L^3} \]

\[ E_b \approx \frac{66b_t \Delta}{5b_t L^4} \]

where

\[ I_b = \frac{\pi}{64} [D^4 - (D - 2t)^4] \]

Flexural properties of a bamboo culm are determined from a third-point bending test as shown in Figure 1d. The specimen length is \(L \geq 30D\) to ensure a flexure-dominated behavior (minimizing the effects of perpendicular shear). The apparent modulus of rupture (\(f_b\)) is calculated from the applied moment in the constant moment span and the moment of inertia of the culm (\(I_b\)). The bending modulus of elasticity (\(E_b\)) is calculated from the measured mid-span deflection (\(\Delta\)). In this test, calculated values are “apparent” or “effective” since this test is typically governed by longitudinal shear behavior of the culm (i.e., \(\tau = VAg/I_t\) shear) and is therefore not a true modulus of rupture test. Nonetheless, the results may be used directly in design using full culm bamboo.

5. **Longitudinal shear flow from bending perpendicular to fibers (proposed by authors); see Figure 1e**
\[ \tau = \frac{F_b [D^3 - (D - 2t)^3]}{48b_t L} \]

A variation of the bending test described above proposed by the authors places a perpendicular notch, having a depth of 0.5\(D\), in the tension side of the culm at the end of the constant moment region. This notch will cause a longitudinal splitting failure of the culm initiating at its root. With the notch dimensions known, the longitudinal shear flow to cause splitting, \(\tau\), is calculated directly. This method is presently being studied by the authors.
Table 1. Summary of material properties tests available for bamboo (continued)

<table>
<thead>
<tr>
<th>Material Property Obtained</th>
<th>Description of Test</th>
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| 6. Interlaminar shear (Moreira 1991; INBAR 1999); see Figure 1f | \[
\tau_{\perp} = \frac{F_{\perp}}{A_{\perp}}
\]
Interlaminar shear (\(\tau_{\perp}\)) tests may involve coupons oriented to assess either the shear parallel or perpendicular to the through-thickness direction of the culm. An “S-type” shear specimen is used consisting of a tension coupon cut from the culm wall. This coupon is scored halfway through its depth perpendicular to the loading direction at two locations resulting in a shear plane having an area \(A_{\perp}\). The shear plane is at the middle of the specimen and therefore subject to pure shear when the specimen is loaded in tension as shown in Figure 1f. Care must be taken so that gripping stresses do not cause local damage to the specimen affecting results.

| 7. Shear perpendicular to fiber (Cruz 2002); see Figure 1g | \[
\tau_{\perp} = \frac{F_{\perp}}{A_{\perp}}
\]
Transverse shear capacity (\(\tau_{\perp}\)) of a coupon cut from a culm wall is obtained using a simple two-plane shear arrangement which restrains the flexure of the specimen. The test results in the specimen being broken into three pieces, providing the transverse shear strength of the coupon having an area \(A_{\perp}\).

| 8. Pin shear test (Janssen 1981; Sharma 2010); see Figure 1h | shear(\(\theta < \approx 30^\circ\)) \[
\tau_{b} = \frac{F_{b}}{bd_{t}}
\]
bearing(\(\theta > \approx 60^\circ\)) \[
\sigma_{b} = \frac{F_{b}}{2bd_{t}}
\]
The pin (or bolt) shear test is based on the configuration of a simple bolted connection of full-culm bamboo. The pin is loaded at an angle, \(\theta\), relative to the longitudinal axis of the culm. Observed behavior is complex. When the loading angle is close to being parallel to the longitudinal axis of the culm (\(\theta = 0^\circ\)) a “block shear” failure occurs provided the test set-up has a gap to permit this and the distance b is relatively short (see Figure 1i; Janssen 1981). Otherwise, a bearing failure accompanied by longitudinal splitting occurs (Sharma 2010). For angles essentially perpendicular to the longitudinal axis of the culm, a bearing failure occurs under the pin; this may be accompanied by longitudinal splitting which is a secondary failure in this case (Sharma 2010).

| 9. Split-pin transverse tension test (Mitch et al. 2010); see Figure 1i | \[
\sigma_{\perp} = \frac{P}{2t(2w - 2a)}
\]
Having its origin in fracture mechanics specimens, the split-pin test consists of a full culm intermodal bamboo specimen having a length \(2w\) with a transverse hole located at midlength. Horizontal notches are made at the edge of the holes to initiate failure in the horizontal plane. The notches and hole together represent an initial crack having length \(2a\). A split steel pin is inserted and loaded such that a transverse tension failure of the culm results. Ultimately, the test determines the direct tension capacity perpendicular to the longitudinal bamboo fibers (\(\sigma_{\perp}\)) and can be used to assess the Mode I fracture toughness of the culm perpendicular to the fibers in the form of the stress intensity factor \(K_{I}\).

| 10. Edge bearing test (Amada et al. 1996; Torres et al. 2007; Mitch et al. 2010); see Figure 1j | \[
\begin{align*}
f_{NS} &= M_{NS}(c + h)/I \\
f_{EW} &= M_{EW}(c + h) - \frac{pL}{2L} \\
M_{NS} &= \frac{pLD^3}{2c} (1 - \pi a/2w) \\
M_{EW} &= \frac{pLD^3}{2c} (1 - \pi a/2w) \\
\end{align*}
\]
where \(c = t/2, I = Lt^3/12, h = \frac{D}{2} - \frac{ln(D/2 + 1/2)}{2c}, E_{c} = \frac{pLD^3}{8I\Delta} (4 - \pi a/2w), k_{1} \approx 1 + 4.24\pi a/LtD and k_{2} = 1 - \frac{4a}{\pi a}\)
The edge bearing test is proposed as a surrogate for the more complex split-pin test. The edge bearing test is composed of a full culm specimen loaded in compression along the longitudinal axis of the culm (for the sake of calculation, the applied load (\(p\)) is given as force per unit length). The test is used to determine the transverse (or through-wall) modulus of rupture (\(f_{r}\)) for the culm walls - a measure of transverse tension or splitting capacity. Based on fundamental mechanics, the apparent transverse modulus of elasticity (\(E_{c}\)) can be determined from the vertical deflection (\(\Delta\)) of the compressed culm. This value has no practical value for design but is believed to be an excellent measure for comparison between materials, treatments, environmental conditioning and other factors. This simpler test requires minimal specimen preparation and only a method of applying compressive forces; thus it is proposed as an appropriate field test for determining difficult-to-obtain transverse material properties. Study is ongoing to correlate data obtained from each method.
An important consideration in the development of standard test methods is that they can be reliably conducted in a field setting. This allows material properties to be assessed by non-technical personnel. One simple example from the conventional construction industry is the concrete “slump test” which is correlated to water-cement ratio in order to assess concrete quality. When developing a field test such as this, two major points should be considered. First, a simplified test method that requires little equipment or specialized machining will be easily implemented and executed in the field. In the case of bamboo, for instance, a field test should make use of a full-culm specimen that only requires cutting the culm to length. Second, as with all test methods, the field test must produce a useful material metric that can (1) directly determine a design value; (2) be correlated to values obtained in a laboratory test; or (3) be accurately used to compare different batches of material.

**Full-Culm versus Specimen Machined from Culm**

The preference for full-culm test specimens stems from the variation of bamboo material properties, particularly through the culm-wall thickness and the geometry of the culm itself. Only a full-culm specimen “balances” material variability and therefore results in “average” or “representative” material properties appropriate for use in design. For example, due to the significant gradation in material stiffness through the culm-wall, “dogbone” tension coupons used in test method 2 (see Table 1) may violate plane stress conditions necessary for such a test. Similarly, tension specimen orientation relative to the original culm wall will also affect results. Similar arguments may be made for test methods 6 and 7. For example, Amada and Untao (2001) and Low et al. (2006) report ostensibly the same material property derived from similar test geometries that differ by an order of magnitude. Mitch (2009) concluded that this difference resulted from the use of specimens having a different orientation relative to the culms they were machined from. Finally, extracting these specimens from a culm is relatively complex requiring accurate machining practice. At the worst, full-culm specimens only need to have their ends made parallel for testing.

**Compression versus Tension and Ease of Testing**

In a non-technical environment, tension-based tests are difficult to conduct in a repeatable manner. Such tests require some kind of gripping apparatus and often additional machined test parts. Gripping a bamboo specimen, or any material having significantly heterogeneous material properties, requires special care and occasionally complex methods in order to ensure representative and reliable specimen failures. Compression-based tests, on the other hand, are relatively simple to conduct and typically require simpler fixtures. Additionally, in a non-technical environment, compression-based tests are simpler to calibrate, ensuring greater repeatability and reliability. An analogy for the preference for compression testing, particularly for heterogeneous materials, may be found in concrete. Tensile and shear properties of concrete are all conventionally calibrated to simple-to-conduct compression-based tests. Even the so-called “direct tension test” (ASTM 2011) is based on testing a concrete cylinder under a longitudinal compressive load.

2.3 Assessing Bamboo Splitting Behavior

The following discussion briefly describes the progression of the authors’ development of new test methods developed to assess the longitudinal splitting behavior of bamboo. The development is guided not only by technical necessity but by the practical considerations described in the previous section.

A dominant failure mode of bamboo is longitudinal splitting. Such failures are associated with bamboo carrying flexure, compression or tension loads and are exacerbated by the use of simple bolted connection details common in some bamboo construction (Sharma 2010). Splitting behavior has not been fully addressed and the need for additional work in this area was identified by Janssen (1981), in which he notes the compressive modulus perpendicular to the fiber as being very low and unknown. Splitting failure also occurs in bending tests; Janssen describes the bending stresses in a culm as the maximum compressive stress and lateral strain in the compression zone of the culm, with failure occurring due to longitudinal splitting. This is ideally a Mode II longitudinal shear failure characterized by the VQ/I shear flow equation; however, in the presence of perpendicular shear (as in a beam), there is some Mode I component stress which significantly reduces the apparent pure Mode II capacity. Janssen (1981) developed and standardized the “bowtie” test (see test 3 in Table 1) in an attempt to quantify this material behavior. This test, however, neglects the modest Mode I contribution which is believed to drive the splitting failure.

**Split Pin Test**

Mitch et al. (2010) explored various test methods to characterize the splitting capacity of bamboo basing his analysis on the Mode I stress intensity factor, $K_1$, which provides a measure of the material’s “fracture toughness”. A fracture mechanics approach was selected on the premise that this will “normalize” the quantification of material properties thereby reducing the significant scatter inherent in establishing mechanical properties of bamboo. A fracture mechanics approach should, it was hypothesized, result in more comparable measures of behavior allowing, for instance, more rational interspecies comparison. Mitch et al. explored multiple test configurations and selected the configuration believed to introduce the least unnece-
necessary variation: a full culm split pin test (see test 9 in Table 1). Mitch et al. also conducted compression and “bowtie” shear tests (see test 3 in Table 1) to compare and assess the variation in test results. The proposed split pin test showed the least variation in results. The average $K_1$ value obtained for $B. stenostachya$ treated with a borate solution was 0.174 MPa·m$^{1/2}$ (COV = 0.22). Additional tests conducted to determine the influence of the split pin diameter showed little influence on the average $K_1$ value as should be expected for a fracture mechanics test. The split pin test also permits the direct tension capacity perpendicular to the fibers to be determined. For the same $B. stenostachya$, the average tensile rupture stress perpendicular to the fibers was found to be 1.06 MPa (COV = 0.22). Mitch et al. conclude that the split-pin test captures the splitting behavior of bamboo with improved repeatability (lower variation) than other test methods. Additionally, the full-culm specimen geometry eliminates the complexities and eccentricity of partial culm tests.

**Bolt Shear Test**

Since splitting is also often associated with bolted connections. The split pin test is analogous to a bolt shear test if the small crack initiators (see Figure 1i) are not...
included. To address the effect of the angle of bolt loading (which varies in a real structure), an adaptation of the split pin test was developed (Sharma 2010) to determine the behavior of bolt-induced forces and assess their contribution to the splitting behavior of the bolted culm (see test 8 in Table 1). Two distinct types of failures were documented: For specimens having a load orientation of 0° and 30°, the behavior was brittle: loading increased to a point where the bamboo split at which point bearing capacity was lost. For the specimens having loading oriented more transversely to the fibers (60° and 90°), a bilinear behavior was observed. This behavior is explained by the fact that splitting does not result in catastrophic failure at these “flatter” orientations and some reserve capacity associated with bearing remains. Observed bolt-bearing capacities for the same *B. stenostachya* as tested by Mitch (2009) ranged from 30 to 40 MPa while the COV varied from 0.15 to 0.30. Although splitting was observed, this test does not quantify this behavior.

**Edge Bearing Test**

Neither the split-pin or bolt bearing tests satisfy the ‘simplicity’ criteria described previously. Sharma et al. (2010) investigated the application of an edge bearing test geometry (see test 10 in Table 1) as an alternative for the more complex split-pin test for assessing splitting behavior. The edge bearing strength (sometimes referred to as diametrical compression) of a bamboo culm, is often not included in studies due to the low strength of the material and the difficulty of interpreting the test results. Trujillo (2007), for example, excluded edge bearing due to the nature of the failures that result from the test method. Amada et al. (1996) noted the use of edge bearing tests to determine the circumferential properties along the length of the culm for *Phyllostachys edulis* Riv. Torres et al. (2007) conducted edge bearing tests on *Guadua angustifolia* and *Phyllostachys pubescens* specimens, to determine the “circumferential modulus of elasticity, *E*<sub>c</sub>.” Torres considered the difference in this modulus at various locations along the culm as well as the variation of the modulus of test specimens having different lengths. Torres’s “circumferential modulus”, in fact, represents an apparent modulus of elasticity in the direction perpendicular to the longitudinal axis of the culm averaged for the tension and compression behaviors. The complex failure mechanism of an edge bearing test involves the forma-
tion of a pair of multi-pinned arches (see Figure 1j) resulting from the hinges forming at the locations of maximum moment around the circumference of the culm section. From this behavior, the culm wall bending properties may be determined. The culm wall modulus of rupture, \( f_r \), is a measure of the transverse tension capacity of the culm wall and therefore the splitting behavior. Sharma et al. (2010) presented a complete derivation of the equations used in conjunction with edge bearing test results to determine both the circumferential modulus of elasticity, \( E_{\phi} \), and the apparent modulus of rupture of the culm wall, \( f_r \) (see test 10 in Table 1).

Two series of edge bearing tests were conducted on thin-walled \( P. \) aurea specimens and thick-walled \( B. \) stenostachya specimens (Sharma et al. 2010, see Figure 1j). The tests were carried out in two different laboratories with slightly different test protocols. The results showed that the variation for the apparent modulus of rupture (\( f_r \)) for \( P. \) aurea edge bearing tests as 0.41 while that for \( B. \) stenostachya was lower, COV = 0.27. The improved repeatability of the thicker-walled specimens was hypothesized to result from the reduced gradient of through-wall properties in the thick walled specimens. A similar “size effect” is seen in testing other brittle materials such as concrete. Electrical resistance strain gages installed on both the inner and outer edges of the culm wall confirmed the effect of the through-wall gradient of material properties and a shift in the neutral axis of the wall subject to flexure. The observed neutral axis was shifted toward the outside of the culm wall section falling between 0.65t and 0.80t as measured from the inside of the culm as shown in Figure 2(a). Additionally, the high compressive strain at the inner face of the culm wall indicates the significant compressibility of the interior surface, which is attributed to the compressibility of the interior wall parenchyma cells (Obataya et al. 2007). To further explore the influence of the fiber gradient on the apparent modulus of rupture, the concentric annular edge bearing test was developed.

Concentric Annular Edge Bearing Test

In order to obtain greater resolution of through-culm wall properties and to reduce the effect of material property gradient, an annular ring specimen was developed for the edge bearing test and a series of pilot tests conducted (Sharma and Harries 2011). In this test, the full culm was cut into two or three concentric annular sections, as shown in Figure 3. Edge bearing test results for each “ring” provide an improved measure of through-thickness transverse properties than may be obtained from a single full-culm section. Annular ring specimens were prepared using a water jet cutting tool to cut a single culm into two or three rings (depending on the original wall thickness). The water jet utilizes a mixture of water and sand under high pressure to cut lengthwise through the culm specimen and results in the loss of material (the “kerf” of the cut; see Figure 3) between adjacent rings. The annular sections were tested using the edge bearing testing method. Results were found to be more uniform, since the material gradient in each ring is less than the whole culm. As seen in Figure 2(b), the flexural behavior of concentric rings (only two are shown in Figure 2(b)) is more uniform with the neutral axis falling closer to the middle of each ring (approximately 0.40t). From these tests, the additional effect of fiber density (greater toward the outside of the culm) was also seen in the increased variability of test results for the outer rings (COV = 0.57) compared to the middle (COV = 0.36) and inner rings (COV = 0.27). Increased fiber density toward the outside of the culm was also seen to reduce the deformability of this material, indicating a more brittle behavior than the matrix-dominated inner material.

The annular ring edge bearing test, while impractical for field application, is able to provide significant insight into through-wall culm properties affecting splitting behavior. Data from such tests will inform and improve analytical modeling of bamboo sections. Ultimately, this approach will improve the utility and correlation of simple field tests with the more complex assessment of splitting behavior required for design.

3 DISCUSSION

The progression of the development of test methods 8-10 (see Table 1 and above) illustrate the necessary synergy of developing a sound understanding of the underlying mechanics and material behavior and the need to develop practical and field-appropriate test methods. The test methods address the important (and arguably overlooked) limit state of longitudinal splitting. The methods evolve from those that establish fundamental properties yet are complex and only appropriate for a laboratory environment to those that capture in situ behavior and are simpler and thus appropriate for field use. In this case, the splitting limit state provides continuity in this evolution and informs the eventual correlation of results from different methods.

Standardization of bamboo test methods is critical if the material is to gain greater engineering acceptance. Methods that capture fundamental material properties permit comparison of the behavior and performance of different bamboo species, geometry, weathering and treatment methods. Appropriate standardized test methods able to reliably provide fundamental material properties permit (1) the calibration of material resistance factors, and (2) the extension of design guidance to different species. Standardized test methods used in well-defined experimental studies also permit the isolation of factors that affect material performance and behavior. This process represents the path to rational and universal design methods for bamboo.
While we are certainly not there yet, the approach presented may eventually lead to simple design equations for fundamental properties such as compression, tension, shear and splitting capacities which can be used to design complex structures having uniform confidence of performance. Such a design approach is consistent with those used for all other engineering materials (concrete, steel, timber, masonry, etc.) and takes the general form of:

\[
Q_d = \varphi_i \cdot F_i \cdot [C_1 \times C_2 \times ... \times C_k]
\]

where \(Q_d\) is the demand determined from structural loading; \(F_i\) is the material property engaged to resist \(Q_d\) (compression, tension, shear, splitting, etc.); and \(\varphi_i\) is the material resistance factor corresponding to the property \(F_i\). \(\varphi_i\) is statistically derived from standard material test results and reflects the variation in properties and the degree of confidence required in the design approach. The factors \(C_1\) to \(C_k\) account for factors that may affect \(F_i\). These may be determined from well-designed experimental studies and may include effects associated with (1) culm species; (2) culm geometry and size; (3) environmental exposure (hydrothermal effects); (4) harvest, preparation and treatment of the culms; (5) connection geometry (bolts, incisions, etc.); and (6) others.

4 CONCLUSIONS

Through standardization of non-conventional materials like bamboo, the triple bottom line of sustainable development is realized, most notably in regard to equity. Standard field tests for non-conventional materials provide rural communities greater equity in terms of safe, adequate, and reliable housing and sustainable development using local resources resulting in an improved standard of living. Standardization of non-conventional building materials serves both a technical and social purpose and can promote sustainable practices in developing regions. The test method development reported here provides a model approach for developing standardized test methods for non-conventional materials with an emphasis on tests suitable for the field.

REFERENCES


