Part I: Technical Report

BAMBOO
TEST-KIT-IN-A-BACK PACK

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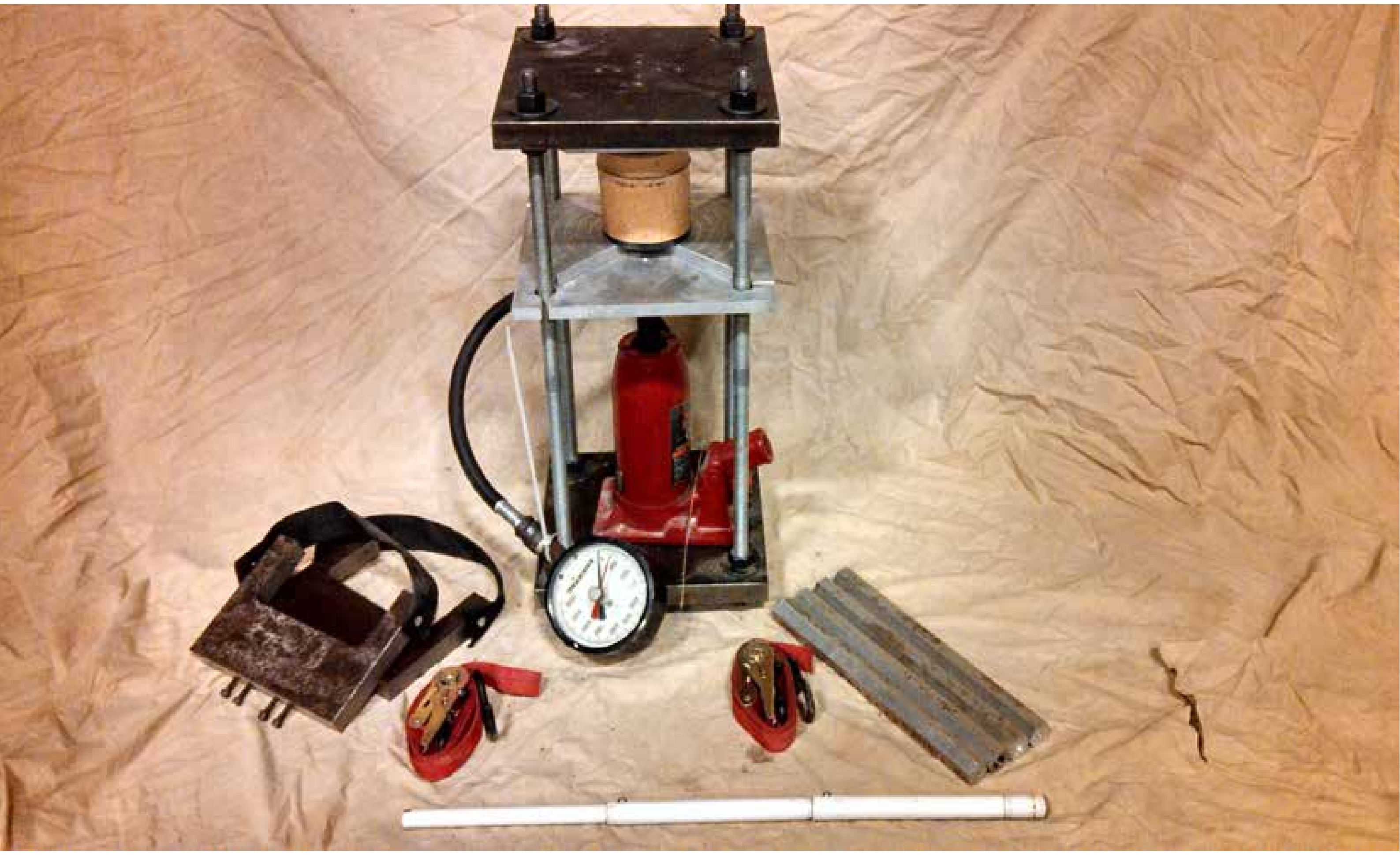

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Key words

Full-culm bamboo, material test, compression, shear, bending

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Contents

Abstract

This report documents the fabrication and use of the 'Bamboo Test-Kit-in-a-Backpack' developed by a team of undergraduate engineering students at the University of Pittsburgh. The 'kit' is intended for rapid in-the-field assessment of bamboo material properties. Presently the kit supports full-culm compression, longitudinal shear ('bowtie' test), edge bearing and culm flexural tests. Additionally, it could be further adapted for pin shear tests and a number of small clear specimen tests.

Introduction and Motivation

Standardization of construction materials and practices serves both technical and social purposes. The objective of a standard material test procedure, for instance, is to permit the accurate determination of an engineering property and/or 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 which can lead to the refinement of and confidence in design values. This leads 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.

Standard 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 22156:2004] and for determining the mechanical properties of bamboo [ISO 22157-1:2004 and ISO 22157-2:2004]. If the use of bamboo is limited to rural areas, ISO 22156 recognizes established "experience from previous generations" as being an adequate basis for design. 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 ISO standards are broadly summarised by Harries et al. [2012] and are presently (late 2014) being revised and updated by ISO TC 165.

Field Test Methods

An important consideration in the development of standard test methods for bamboo is that they can be reliably conducted in a field setting in an other-than 'scientifically advanced' nation, allowing material properties to be assessed by non-technical personnel. When developing a field test for bamboo, 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; such a test should make use of a full-culm specimen requiring only that the culm be cut to length. Second, the field test must produce a useful metric that can a) directly determine a design value; b) be correlated to values obtained in a laboratory test; or, c) be accurately used to compare different batches of material.

The advantage of 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 may violate plane stress conditions. Additionally, extracting specimens from a culm is relatively complex requiring accurate machining practice and hardened tools. At the worst, full-culm specimens only need to have their ends cut parallel for testing.

In a non-technical environment, tension-based tests are difficult to conduct in a repeatable manner. Such tests require a 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 conventionally calibrated to simple-to-conduct compression-based tests. Even the so-called "direct tension test" is based on testing a concrete cylinder under a longitudinal compressive load.

Bamboo Test-Kit-in-a-Backpack

The 'kit' (Figure 1), intended for rapid in-the-field assessment of bamboo material properties, is designed to be an inexpensive, robust, portable test apparatus that may be carried, assembled, operated and maintained by a single technician. Presently the kit supports full-culm compression, longitudinal shear ('bowtie' test), edge bearing and culm flexural tests. Additionally, it could be further adapted for pin shear tests and a number of small clear specimen tests. This report documents the fabrication of the prototype built, tested and calibrated at the University of Pittsburgh. This prototype has a capacity of 72 kN (8 tons force). With the exception of the hydraulic cylinder and pressure gage, all parts are easily fabricated with access to only a rudimentary machine shop environment. The choice of simple compression cylinder (a bottle jack is used in the prototype) is robust, readily available, and easily maintained/repaired in most any environment with only rudimentary mechanical skills.

Figures 2 and 3 provide drawings documenting the fabrication of the kit prototype. Following this, guidance for scaling or assembling variations of the kit is provided.

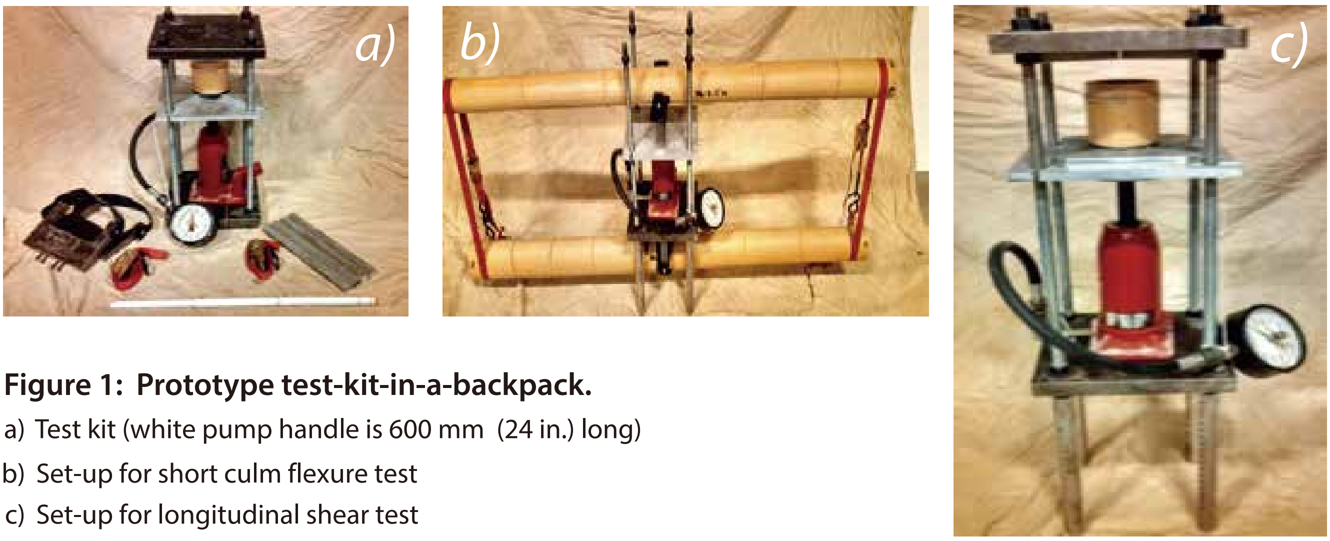


Figure 1: Prototype test-kit-in-a-backpack.

a) Test kit (white pump handle is 600 mm (24 in.) long)

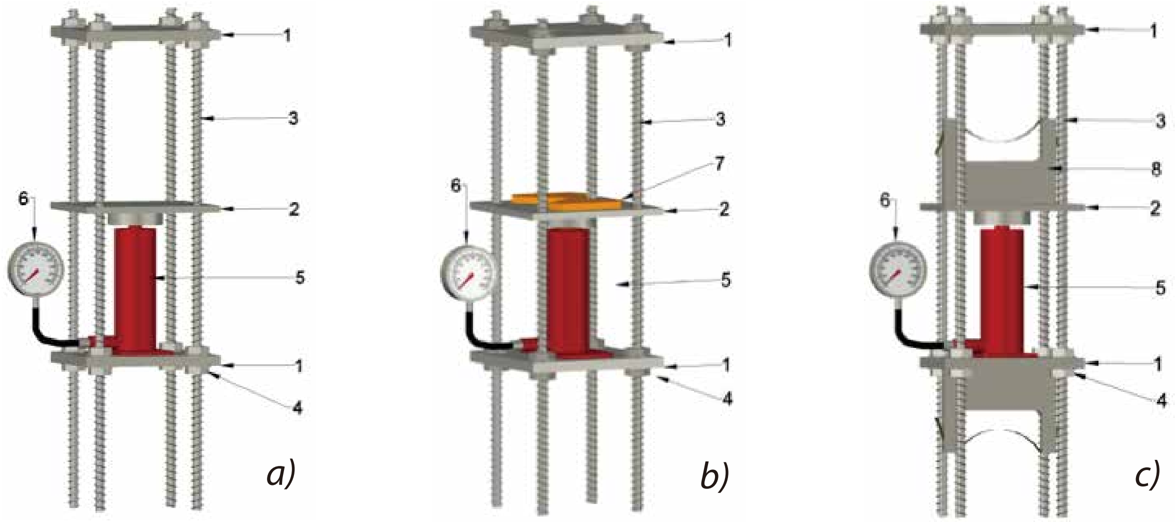
b) Set-up for short culm flexure test

c) Set-up for longitudinal shear test

Assembly

The reaction plates (part #1 in Fig. 2) are fixed in place on the threaded rods (part #3) using nuts and washers (part #4). The loading plate (part #2) moves freely; guided by the rods. The threaded base of the hydraulic cylinder (part #5) is bolted to the lower reaction plate. The 'bowtie' loading plates (part #7), flexure saddles (part #8) or any spacer plates required are provided with threaded holes and subsequently bolted to the loading plate and upper reaction plate. It is suggested that concentric circles be scribed onto the loading and reaction plates to help to centre specimens over the hydraulic cylinder.

The extension of the threaded rods below the lower reaction plate may be used as 'legs', raising the unit off the ground. In order to protect the threads, pipe sleeves, slightly longer than the threaded rod extensions, are slipped over the rods in this case (these are seen in Fig. 1).



a) Assembly for compression and edge bearing tests

b) Assembly for longitudinal shear test

c) Assembly for flexure test

1. 254 x 254 x19 mm fixed reaction plates (2 required; see Fig 3a)
2. 254 x 254 x 12.7 mm moving load plate (see Fig 3b)
3. 16 mm x 1000 mm long threaded rod (4 required)
4. nut and washer assemblies for rods (16 required)
5. 72 kN hydraulic cylinder (bottle jack)
6. high precision pressure gauge
7. 'bowtie' plates (two sets; see Fig 3c)
8. flexure test saddles (two required; see Fig. 3d)

Figure 2: Prototype test kit assemblies.

Considerations in Altering or Scaling the Kit

The kit may scaled up to some extent (scaling down may also be appropriate although capacity to conduct full-culm compression may be limited). Primary design considerations of the kit include:

Selection of threaded rods – together, these should have a tensile capacity exceeding twice (providing a factor safety) the hydraulic cylinder compression capacity (P_c). The net cross sectional area (A_n; accounting for threads) of each of the four rods having a yield stress of F_{ry} should exceed:

$$A_n > 0.5P_c/F_{ry} \quad (1)$$

Ideally, lower strength steel rods having larger area are preferred to smaller diameter high strength rods; the former will result in a 'stiffer' and therefore more preferable test frame response.

Plate thickness – the thickness of the loading plate (part #2) effectively spreads the applied load from the hydraulic cylinder to the bamboo specimen so that the loading on the specimen is uniform. Typiloading plate thickness (t_p) is a function of the maximum culm diameter (D) to be tested and the hydraulic cylinder diameter (d_c):

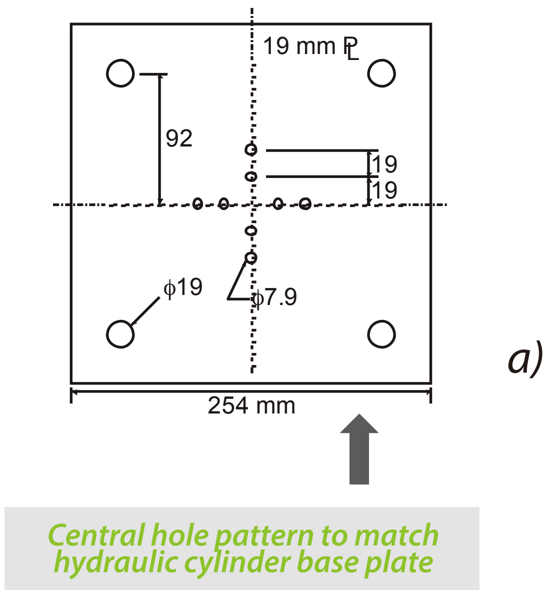
$$t_p > ¼(D-d_c) \tag{2}$$

Filler (shim) plates may be used to increase the effective plate thickness when testing large diameter culms.

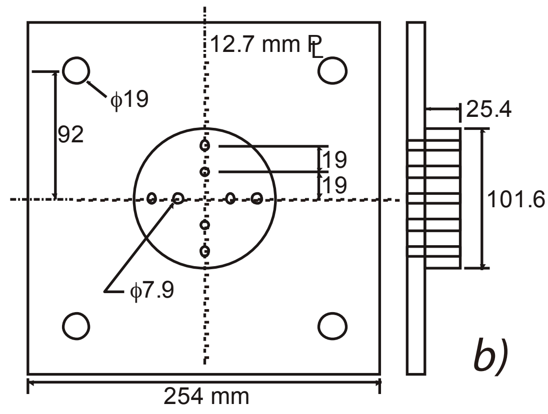
The reaction plates (part #1) must also be designed to adequately resist the load from the culm specimens to the reaction threaded rods. In this case, the minimum plate thickness (t_p) is a function of the hydraulic cylinder capacity (Pc), and the yield strength of the steel plate (F_y):

$$t_p > [P_c/(1.8F_y)]^{0.5} \tag{3}$$

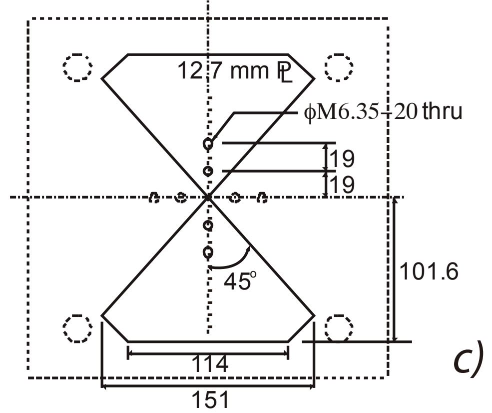
In which the factor 1.8 accounts for a strength reduction factor for the steel plate equal to 0.90. It is also suggested that concentric circles be scribed onto the loading and reaction plates to help to centre specimens over the hydraulic cylinder.



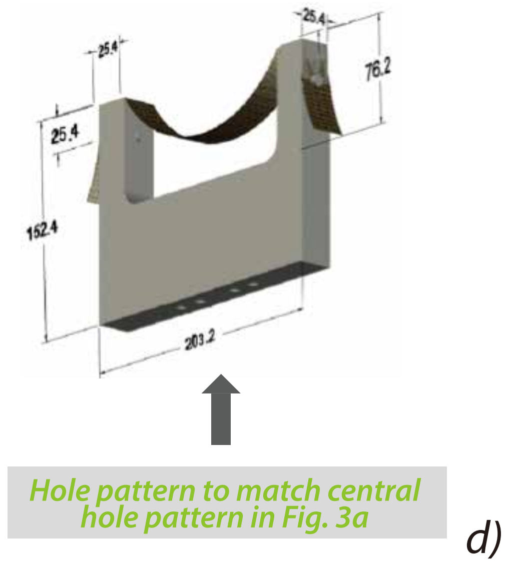
a) Fixed reaction plates (2 assemblies; part #1)



b) Moving load plate (part #2)



c) 'Bowtie' plates (2 assemblies; part #7)



d) Fiexure saddles (2 assemblies; part #8)

Figure 3: Prototype test kit plate details

Test Kit Pressure Gage and Force Conversion

The hydraulic cylinder must be fitted with a pressure transducer. In the prototype, a precision dial-type pressure gage having a peak needle is used (part #6). The force applied by the cylinder is equal to the product of the indicated pressure and the cross sectional area of the cylinder used. There may be some degree of friction loss in the cylinder associated with seal friction or binding of the cylinder; this should be minimized and can be accounted for if an alternate means of calibration is available.

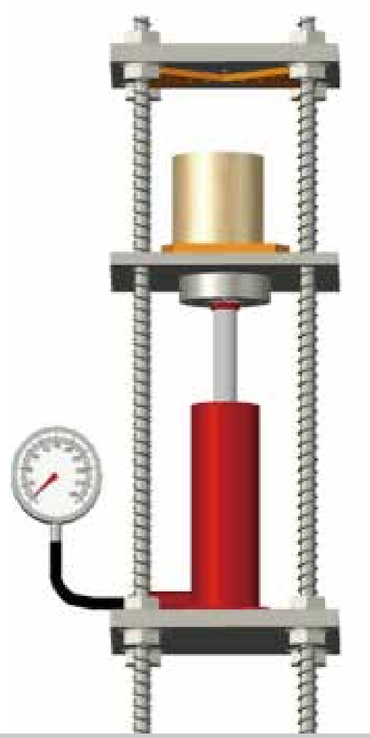
For example, for the prototype kit, the cylinder has a manufacturer-reported diameter of 38.1 mm (1.5 in.) giving an area of 1140 mm^2 (1.77 in^2). Calibration using an external load cell resulted in calibration factor of 1090 mm^2 (1.69 in^2), indicating friction losses on the order of 4.5% (a reasonable value for the bottle jack used). The applied load (*P*) for any test is therefore:

$$P(N) = 1090 \text{ x (gage pressure in MPa)} \quad (4a)$$

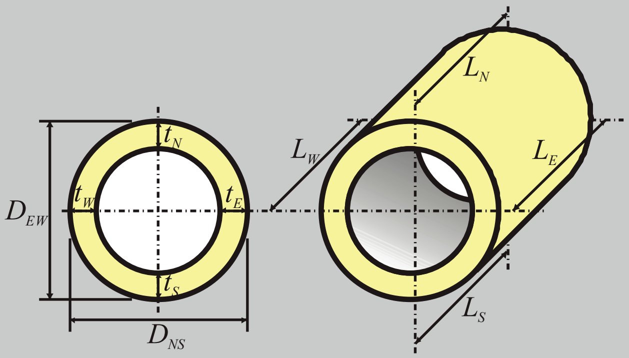
$$P(lbf) = 1.69 \text{ x (gage pressure in psi)} \quad (4b)$$

Alternatively, an electronic pressure transducer and digital output may be used. In general this will be more precise although requires a stable DC power supply for operation. Only direct measurement with an inserted load cell, however, will illuminate the need to consider friction losses.

Test Methods



Bamboo Specimen Geometry



$D = (D_{NS} + D_{EW})/2$

$t = (t_N + t_S + t_E + t_W)/4$

$L = (L_N + L_S + L_E + L_W)/4$

$$A_{culm} = (\pi/4)(D^2 - (D - 2t)^2) \quad (5)$$

$$I_{culm} = (\pi/64)(D^4 - (D - 2t)^4) \quad (6)$$

$$R = 0.5(D - t) \quad (7)$$

The following measured dimensions are obtained from the test specimens:

- D = culm outside diameter taken as average of two orthogonal measurements at any section
- t = culm wall thickness taken as average of four quadrant measurements at any section
- L = length of culm specimen taken as average of four quadrant measurements

The following geometric properties are calculated:

- A_{culm} = net cross section area of culm
- I_{culm} = moment of inertia of net culm section
- R = [characteristic] radius of culm measured to centre line of culm wall

Additionally,

- P = load applied by the test kit corresponding to specimen failure

The following sections indicate the use, calculations and limitations of each test method conducted using the kit.

Concentric Compression Test


Figure 4: Concentric compression test

This test method is reported in ISO 22157-1. The kit is assembled as shown in Figure 4 and the culm specimen is centred above the hydraulic cylinder between the loading plate and upper reaction plate. Care must be taken that the ends of the culm are smooth, parallel and at right angles to the culm longitudinal axis. Loading is applied through the hydraulic cylinder at a rate that results in failure in approximately 2 minutes. Specimens should typically not include nodes unless the inclusion of the node is a parameter of interest. Tests that include nodes will typically have lower calculated capacities.

The ultimate compressive stress of the full culm (σ_c) is found from a compressive test of a length of culm (*L*) no longer than twice its outside diameter (*D*); that is: $L \leq 2D$:

$$\sigma_c = P/A_{culm} \quad (8)$$

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 readings are averaged (ε_{avg}) and the compressive modulus is calculated between 20-80% of the resulting stress-strain curve:

$$E_c = (\sigma_{c@80\%} - \sigma_{c@20\%})/(\varepsilon_{avg@80\%} - \varepsilon_{avg@20\%}) \quad (9)$$

ISO 22157-1 recommends that care be taken to minimize friction between the loading head and culm which affects results. If the kit is being used for the purposes of rapid screening of bamboo, it is felt that simply testing the culms against the steel plates is adequate.

Summary of Test Method

1. Assemble test kit as shown; shim plates may be used to make the loading and/or reaction plates effectively thicker (Eqs. 2 and 3).
2. Cut specimen length such that $L \leq 2D$. Specimen ends should be smooth, parallel and at right angles to culm axis.
3. Obtain dimensions *D, t* and *L* of culm specimen.
4. Centre culm specimen above hydraulic cylinder on loading plate.
5. Bring culm into contact with upper reaction plate.
6. Begin test, loading specimen at a rate that results in failure in approximately two minutes (an initial test may be required to calibrate this rate).
7. Record the ultimate load achieved *P*.
8. Calculate the ultimate compressive stress from Eq. 8.

If strain gages are used to calculate a compressive modulus steps 1 through 5 remain the same and the procedure continues as follows:

6. Begin test, load specimen in steps such that there are at least ten steps prior to failure (an initial test may be required to establish appropriate increments)
7. At each stage *i*, record the load P_i and strains ε_{1i} and ε_{2i}.
8. Record the ultimate load achieved *P*.
9. Calculate the average strain and compressive stress (Eq. 8) at each load step and plot the resulting stress-strain curve. The compressive modulus is calculated from Eq. 9.
10. Calculate the ultimate compressive stress from Eq. 8.

Longitudinal Shear ('Bowtie') Test

This test method is reported in ISO 22157-1. The kit is assembled as shown in Figure 5 using the 'bowtie' insert plates (parts #7; Fig. 3c). The culm specimen is centred above the hydraulic cylinder between the loading plate and upper reaction plate. Care must be taken that the ends of the culm are smooth, parallel and at right angles to the culm longitudinal axis. Loading is applied at a rate that results in failure in approximately 2 minutes. Specimens should typically not include nodes unless the inclusion of the node is a parameter of interest. Tests that include nodes will typically have higher calculated capacities.

The shear strength parallel to the fibers (τ_L) is determined from a specimen whose length is equal to the outer culm diameter ($L = D$). The applied load (P) is distributed over the sum of the shear areas of all four failure planes (i.e.: $4Lt$):

$$\tau_L = P/4Lt \qquad (10)$$

It is noted that failure often occurs at only one shear plane and/or the final specimen has only three failure planes. In either case, Eq. 10 is used and may be interpreted as the lower bound shear strength.

Figure 5: Longitudinal shear test

Summary of Test Method

1. Assemble test kit as shown including the bow-tie plates; ensure that the bow-tie plates are oriented in opposite directions on each plate.
2. Cut specimen length such that $L = D$. Specimen ends should be smooth, parallel and at right angles to culm axis.
3. Obtain dimensions D, t and L of culm specimen.
4. Centre culm specimen above hydraulic cylinder on bow-tie loading plate.
5. Bring culm into contact with upper bow-tie reaction plate.
6. Begin test, loading specimen at a rate that results in failure in approximately two minutes (an initial test may be required to calibrate this rate).
7. Record the ultimate load achieved P.
8. Record the number of failure planes observed n.
9. Calculate the shear stress from Eq. 10. If $n < 4$, note this indicating that the calculated shear stress is a lower-bound value for the specimen.

Edge Bearing Test

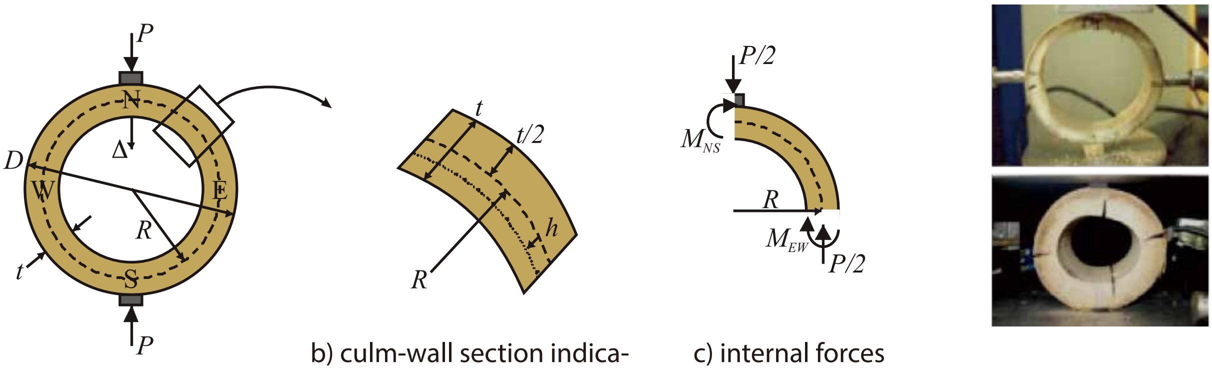
Figure 6: Edge Bearing Test

The edge bearing test described here and shown in Figure 6 has been developed and formalised by Sharma et al. [2012]; the test method has been used by a number of researchers. Edge bearing tests have been used to determine the circumferential properties along the length of the culm [Amada et al. 1996] and the "circumferential modulus of elasticity" [Torres et al. 2007] which, in fact, represents an apparent modulus of elasticity perpendicular to the longitudinal axis of the culm averaged for the tension and compression behaviours. The complex failure mechanism of an edge bearing test involves the formation of a pair of multi-pinned arches (seen in Fig. 7d) resulting from the hinges forming at the locations of maximum moment around the circumference of the culm section. From this behaviour, the culm wall bending properties may be determined. The culm wall modulus of rupture is a measure of the transverse tension capacity of the culm wall and therefore a quantification of splitting behaviour. Due to the different stress conditions under the load/reaction quadrants (designated NS) and the orthogonal (EW) quadrants, separate calculations are required for these locations.

The edge bearing test is composed of a full culm specimen loaded in compression along the longitudinal axis of the culm (Figs 6, 7a and 7d). The culm specimen is centred above the hydraulic cylinder between the loading plate and upper reaction plate such that the applied load (*P*) is distributed uniformly along the length (*L*) of the specimen. Typically small flat and thin softwood (popsicle sticks or medical tongue depressors work well) or neoprene shims are used at the loading and reaction points (N and S in Fig. 7a). Specimens having a variation in diameter exceeding *0.05D* over their length (*L*) should not be used. Loading is applied at a rate that results in failure in approximately 2 minutes.

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. It is suggested that the specimen *L/D* ratio be approximately 1; larger values may result in greater variation in results. Nodes should be excluded from specimens.

	sections along NS axis	sections along EW axis	
transverse (or through-wall) modulus of rupture	$f_{rNS} = M_{NS}\dfrac{12\left(t/2+h\right)}{Lt^3}$	$f_{rEW} = M_{EW}\dfrac{12\left(t/2+h\right)}{Lt^3} - \dfrac{P}{2Lt}$	(11)
Where:			
longitudinal moment at quadrant; see Fig 7c	$M_{NS} = \left(\dfrac{PR}{\pi}\right)\left(1-\dfrac{t^2}{12R^2}\right)$	$M_{EW} = \left(\dfrac{PR}{\pi}\right)\left(1-\dfrac{t^2}{12R^2}\right) - \dfrac{PR}{2}$	(12)



a) edge bearing specimen geometry

b) culm-wall section indicating shift in neutral axis (*h*) associated with flexure of curved element

c) internal forces acting on free-body diagram of one quadrant

d) example failures of thin and thick-walled culms

Figure 7: Edge bearing test specimen geometry and internal reactions.

estimate of neutral axis location for a curved rectangular beam [Young 1989]; see Fig. 7b

$$h = R - t \Big/ \ln\left(\frac{2R}{t} + 1 \Big/ \frac{2R}{t} - 1\right) \tag{13}$$

characteristic radius of centreline of culm wall; see Fig. 7a

$$R = 0.5\,(D - t) \tag{7}$$

Based on fundamental mechanics, the apparent transverse tangent modulus of elasticity (E_φ) can be estimated from the relative vertical deflection between the loaded points (N and S) of the compressed culm (Δ). The value Δ is shown in Figure 7a assuming point S to be fixed. The value E_φ has no practical meaning for design but is believed to be an excellent metric for comparison between materials, treatments, environmental conditioning and other factors [Sharma et al. 2012].

$$E_\varphi \approx \frac{3PD^3}{2Lt^3\Delta}\left(\frac{\pi k_1}{4} - \frac{2k_2^2}{\pi}\right) \tag{14}$$

In which: $k_1 \approx 1 + \frac{7.6\,t^2}{D^2}$ and $k_2 \approx 1 - \frac{t^2}{D^2}$ (15)

The apparent tangent modulus may be calculated at any coincident load (P_i) and displacement (Δ_i) pair.

It is important that the measurement of Δ not include kit compliance or include the compression of the shims. Measuring the actual vertical displacement between N and S points is most appropriate but can be impractical for small culm diameters. Determining the difference between independent measurements of the loading and reaction against a fixed datum can recover a reasonably accurate value of Δ.

Summary of Test Method

1. Assemble test kit as shown.
2. Cut specimen length such that $L \approx D$.
3. Obtain dimensions D, t and L of culm specimen.
4. Place small flat and thin softwood or neoprene loading shim in loading plate centred over hydraulic cylinder.
5. Centre culm specimen above hydraulic cylinder such that the culm longitudinal axis is aligned along the shim.
6. Place second shim along top of specimen parallel to lower shim (aligned along the culm longitudinal axis).
7. Bring culm-shim assembly into contact with upper reaction plate.
8. Begin test, loading specimen at a rate that results in failure in approximately two minutes (an initial test may be required to calibrate this rate).
9. Record the ultimate load achieved P.
10. Calculate the transverse through-wall modulus of rupture from Eq. 11.
11. If vertical deflection (Δ) was measured, the apparent transverse tangent modulus of elasticity (E_φ) is calculated from Eq. 14.

If culm vertical deflection (Δ) is to be measured at different stages during the test, steps 1 through 7 remain the same and the procedure continues as follows:

8. Begin test, load specimen in steps such that there are at least ten steps prior to failure (an initial test may be required to establish appropriate increments)
9. At each stage i, record the load, Pi and deflection Δ_i.
10. Record the ultimate load achieved P.
11. Calculate the transverse through-wall modulus of rupture at each load step from Eq. 11.
12. The apparent transverse tangent modulus of elasticity (E_φ) at any step, i, is calculated from Eq. 14 using Pi and Δ_i.

Full-culm Flexural Test

This test is modified from the flexure test reported in ISO 22157-1 and is based on work completed by Richard [2013]. Significant differences from the ISO test include:

• The kit utilises a midpoint flexural arrangement rather than the third point arrangement promulgated by ISO 22157-1.

• The culm length-to-diameter (*L/D*) need not be specified provided it is reported and comparisons are only made between culms having comparable *L/D* ratios

• The kit utilises 'soft' reactions (straps) and a two-culm self-reacting system. For this reason, great care must be taken if displacements are measured since these may include the compliance of both the reaction straps and two-culm system. A method for measuring the true displacement of either culm is shown in Figure 9.

Using the flexure saddles (Fig. 3d; part #8) and two sets of reaction straps (ratchet-type tie down straps work well), two similar culms are placed into the kit as shown in Figure 8. Alternatively, one culm may be replaced with a steel pipe (or similar) to provide the required reaction, minimise compliance and provide a means of calculating deflection of part of the self-reacting system (Fig. 9b).

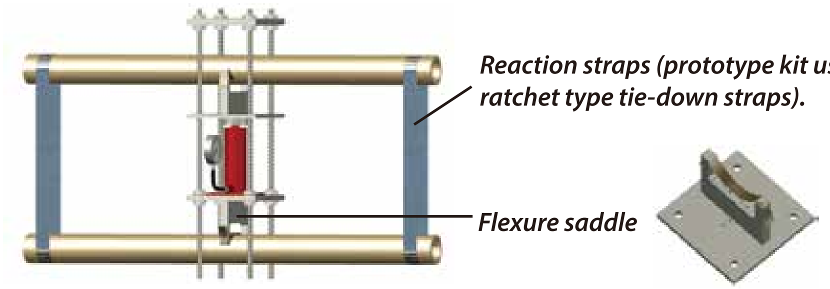


Figure 8: Full-culm flexure test

Only data associated with the first culm to fail is used. The ultimate flexural stress of the full culm (σ_f) is calculated as:

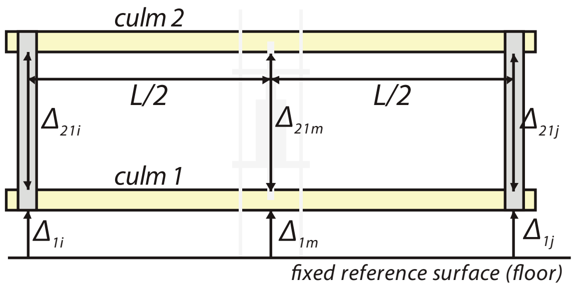
$$\sigma_f = PLD/8I_{culm} \tag{17}$$

It is important to recognize that σf is an 'apparent' modulus of rupture. Typically, failure will be governed by a longitudinal splitting failure of the culm rather than tension rupture or crushing of the extreme section fibres. Richard [2013] proposes providing initial notches in the culm to establish controlled splitting failures from which longitudinal shear capacity may be calculated using the flexural test arrangement. These notched test approaches are still being developed by the authors.

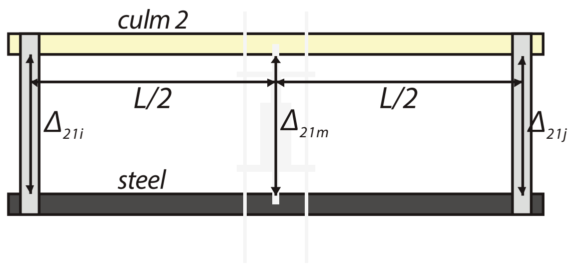
If the net deflection at the midspan (i.e.: at *L/2*) of the first culm to fail (Δ) is determined, an apparent tangent modulus of elasticity (E_a) of the full culm may be calculated as follows; this value is interpreted as an average value calculated across the culm cross section.

$$E_a = PL^3/48\Delta I_{culm} \tag{18}$$

The apparent tangent modulus may be calculated at any coincident load (P_i) and displacement (Δ_i) pair.



a) two self-reacting bamboo culms



b) use of known reaction member (steel or other)

midspan displacement of culm 1:

$$\Delta_1 = 0.5\,(\Delta_{1i} + \Delta_{1j}) - \Delta$$

midspan displacement of culm 2:

$$\Delta_2 = \Delta_{21m} - 0.5\,(\Delta_{21i} + \Delta_{21j})$$

midspan displacement of steel:

$$\Delta_1 = PL^3 / 48\,E_{steel}\,I_{steel}$$

midspan displacement of culm 2:

$$\Delta_2 = \Delta_{21m} - 0.5\,(\Delta_{21i} + \Delta_{21j})$$

Figure 9: Methods for calculating individual culm displacements

Summary of Test Method

1. Assemble test kit as shown with the flexure saddles on the loading plate and base reaction plate.
2. Cut specimen length to the desired length *L*. To be consistent with ISO 22157, *L > 20D* (i.e.: shear span length exceeds *10D*) although this is not a requirement provided test results are only compared with other results sing the same *L/D* ratio.
3. Obtain dimensions *D* and t of culm specimen.
4. Centre the culms on the flexure saddles and place the straps around the ends of the culms at equal distances from the saddle (i.e: the saddle is located at the mid length of the culms).
5. Extend the hydraulic piston until the culms are snug against the straps and the culms are parallel; adjust the strap lengths until the culms are parallel keeping the straps equidistant from the saddle.
6. Measure the tested length of the culm *L*, as the distance between the centrelines of each strap; verify that the flexure test saddle is located at *L/2*.
7. Begin test, loading specimen at a rate that results in failure in approximately two minutes (an initial test may be required to calibrate this rate).
8. Record the ultimate load achieved *P*.
9. Calculate the ultimate flexural stress from Eq. 17.
10. If net culm deflection at midspan (Δ) was measured, the apparent transverse tangent modulus of elasticity (E_a) is calculated from Eq. 18.

If net culm deflection at midspan (Δ) is to be measured at different stages during the test, steps 1 through 6 remain the same and the procedure continues as follows:

7. Begin test, load specimen in steps such that there are at least ten steps prior to failure (an initial test may be required to establish appropriate increments)
8. At each stage *i*, record the load P_i and deflection Δ_i.
9. Record the ultimate load achieved *P*.
10. Calculate the flexural stress at each load step from Eq. 17.
11. If net culm deflection at midspan (Δ) was measured, the apparent transverse tangent modulus of elasticity (E_a) at each load step is calculated from Eq. 18.

Comparison with Laboratory-Generated Data

In order to verify the precision and repeatability of results obtained using the kit, a direct comparison was made with results obtained using a customised mechanical test frame (MTF). The 44 kN (5 ton) capacity test frame, shown in Figure 10, is equipped with a calibrated and certified 44 kN load cell and utilizes a precision gear-drive system such that load application rates as low as 0.0006 mm/min may be reliably applied. Due to the precision gearing, simply knowing the time to failure allows the gross platen displacement to be calculated.

Figure 10: Mechanical test frame set up for edge bearing test

Ten sets of four adjacent specimens, all having $L = D$, were obtained from Moso culms. In each set, two specimens were subject to the Longitudinal Shear Test – one in the kit and one in the MTF – and two specimens were subject to the Edge Bearing Test – also one using the kit and one the MTF. In this manner, each series of tests using each machine should have the same natural variation of properties. The p-values exceeding 0.80 reported in Table 1 indicate that the culm D and t dimensions were statistically the same. Using the MTF, the loading rate for the longitudinal shear and edge bearing tests was 0.51 mm/min and 1.14 mm/min, respectively. Results are presented in Table 1.

	Kit			MTF			p-value
	n	mean	COV	n	mean	COV	
Longitudinal Shear Test							
D	9	83.03 mm	0.12	9	83.93 mm	0.13	0.85
t	9	7.76 mm	0.13	10	7.66 mm	0.19	0.86
τ_L	9	11.46 mm	0.12	10	12.69 mm	0.13	0.10
Edge Bearing Test							
D	10	84.46 mm	0.12	10	85.23 mm	0.13	0.88
t	10	7.84 mm	0.20	10	7.99 mm	0.21	0.84
f_{rEW}	7	13.40 mm	0.35	9	12.50 mm	0.22	0.37
f_{rNS}	2	20.20 mm	0.08	1	24.30 mm	-	-
E_φ	9	1785 mm	0.23	10	1833 mm	0.15	0.80

Table 1: Comparison of Kit and MTF-generated data

The results from the kit and those from the MTF are shown to be statistically similar (p-value in Table 1) and to yield similar coefficients of variation (COV in Table 1) indicating that the kit has essentially the same performance as the MTF having high precision displacement control and a calibrated load cell.

References

Amada, S., Munekata, T., Nagase, Y., Ichikawa, Y., Kirigai, A. and Zhifei, Y. (1996) The mechanical structures of bamboos in viewpoint of functionally gradient and composite materials. Journal of Composite Materials, 30, 800-819.

Harries, K.A., Sharma, B. and Richard, M.J. (2012) Structural Use of Full Culm Bamboo: The Path to Standardisation, International Journal of Architecture, Engineering and Construction, 1(2), 66-75.

International Organization for Standardization (ISO) (2004a) ISO 22156:2004(E), Bamboo – Structural Design. Geneva.

International Organization for Standardization (ISO) (2004b) ISO 22157-1:2004(E), Bamboo – Determination of Physical and Mechanical Properties – Part I: Requirements. Geneva.

International Organization for Standardization (ISO) (2004c) ISO 22157- 2:2004(E), Bamboo – Determination of Physical and Mechanical Properties – Part II: Laboratory Manual. Geneva.

Janssen, J.A. (2005) International Standards for Bamboo as a Structural Material. Structural Engineering International, 15, 48-49.

Richard, M. (2013) Assessing the Performance of Bamboo Structural Components Doctoral Dissertation, University of Pittsburgh.

Sharma, B., Harries, K.A. and Ghavami, K. (2012) Methods of Determining Transverse Mechanical Properties of Full-Culm Bamboo, Journal of Construction and Building Materials, 38, 627-637.

Torres, L.A., Ghavami, K. and Garcia, J.J. (2007) A Transversely Isotropic Law for the Determination of the Circumferential Young's Modulus of Bamboo with Diametric Compression Tests. Latin American Applied Research, 37, 255-260.

Young WC. (1989) Roark's formulas for Stress and Strain. 6th ed. New York: McGraw-Hill.

INBAR
INTERNATIONAL NETWORK
FOR BAMBOO & RATTAN

INBAR is an intergovernmental organization established in 1997 by Treaty deposited with the United Nations and hosted in Bejing, China. It is the only Intergovernmental Organization headquartered in China. INBAR currently has 41 Member States, comprising most of the bamboo and rattan resource countries from the Global South. Since its creation two decades ago, INBAR has run projects and programmes in over 20 countries, and provided capacity building and awareness raising on the productive use of bamboo and rattan in over 80 countries. Today, INBAR's global programme is coordinated from its secretariat in Beijing, and put into action through country and regional offices in China, Ecuador, Ethiopia, India and Ghana. INBAR fields an international team of professionals, expert in bamboo and rattan, forestry and natural resource management, ecosystem services, socio-economics, capacity building and knowledge sharing.

The University of Pittsburgh (Pitt) is a Carnegie Research I institution located in Western Pennsylvania. Founded in 1787, Pitt is home to 35,000 students and over 5000 faculty. The Swanson School of Engineering is also a partner, with Sichuan University in Chengdu China, in the Sichuan University - Pittsburgh Institute, an innovative education and research partnership. The bamboo materials research program at the Watkins Haggart Structural Engineering Laboratory was initiated in 2005 and is the preeminent facility for such research in North America. The primary objective of the bamboo research programme at Pitt is to establish the framework and tools required to evaluate the material and mechanical properties of full-culm bamboo. This seminal research objective is aimed at establishing the standardization of the material – placing it on the same footing as timber as a conventional building material. The bamboo research programme has established collaborations in the UK, Brazil, China, Colombia, India and Indonesia.

Producer & Designer: Liu Kewei