FLAT RING FLEXURE TEST FOR FULL-CULM BAMBOO

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Abstract. The development of a new simple test method suitable for assessing the tension strength perpendicular to the fibres (Mode I) of a bamboo culm – the flat ring flexure test – is presented. The proposed test places a short section of bamboo culm in through-cross section flexure, causing circumferential stresses at failure. The modulus of rupture at the failed section is a measure of the transverse tensile strength of the culm. The test is compression-based and uses a simple apparatus and specimen. The full culm specimen is symmetric and requires very little preparation. The study first investigated test parameters affecting results, thereby arriving at an appropriate and repeatable standard test method. The resulting test method is documented in a format consistent with ISO 22157 [1].

Introduction

Standardisation of construction materials and practices serves both technical and social purposes. The objectives of a standard material test procedure, for instance, are to accurately determine a characteristic or design value of the material and 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 marginalised vernacular construction methods.

Conventional construction materials such as steel and reinforced concrete were once nonconventional and unproven materials. Acceptance was achieved through decades of testing, analysis, and experience which evolved into standardised practices that continue to evolve. More recently, fibre reinforced polymer (FRP) composites, initially developed for aerospace applications, are being standardised for use in civil infrastructure and their use is burgeoning. Increasingly, focus is being placed on the standardisation of sustainable materials such as engineered natural fibre composites. Full culm bamboo, however, remains firmly in the vernacular.

Standard Test Methods for Bamboo

In 2004, the International Organisation for Standardisation (ISO) developed model standard test methods for determining the mechanical properties of bamboo [2]. If the use of bamboo is limited to rural areas, ISO recognises established "experience from previous generations" as being an adequate basis for design [3]. However, if bamboo is to achieve its full potential as a sustainably obtained and utilised building material on an international scale, issues of the basis for design, prefabrication, industrialisation, finance and insurance of building projects, and export and import of materials all require some degree of standardization [4].

The ISO test methods standard [2] includes tests for determining full-culm compressive strength, longitudinal tensile strength, longitudinal shear, and flexural capacity. These established tests provide a promising starting point for standardisation; however, they neglect important limit states such as longitudinal shear and connection-induced splitting. Splitting behaviour, in particular, has not been fully addressed and the need for additional work in this area was identified by Janssen [4, 5].

Assessing Bamboo Splitting Behaviour

A dominant failure mode of bamboo is longitudinal splitting associated with bamboo carrying flexure, compression or tension loads; splitting is exacerbated by the use of simple bolted connection details common in some bamboo construction [6]. Janssen [5] describes the bending stresses in a culm as being characterised by the longitudinal compressive stress and transverse strain in the compression zone of the culm, with failure eventually occurring due to longitudinal splitting. This is ideally a Mode II[1] longitudinal shear failure; however, in the presence of perpendicular stresses, there is some Mode I component stress which significantly reduces the Mode II capacity. The longitudinal shear test [2], shown in Figure 1a, quantifies Mode II material behaviour, however, neglects the modest Mode I contribution which is believed to drive the splitting failure.

Richard et al. [7] demonstrate the effects of such mode mixity using longitudinal shear tests (pure Mode II), split pin tests (see below; pure Mode I) and culm bending tests of different spans resulting in different degrees of mode mixing. For two different species, a thin walled *P. edulis* and thick-walled *B. stenostachya*, the split pin tests resulted in Mode I capacities equal to only 17% of the Mode II capacity determined from the longitudinal shear tests. Beam tests having mixed mode behaviour exhibited shear capacities ranging from 40-70% of the Mode II capacity. A number of test methods have been developed to better understand bamboo splitting behaviour, as summarised in the following paragraphs.

The Split Pin Test [8], shown in Figure 1b, characterises the splitting capacity of bamboo using the Mode I critical stress intensity factor which provides a measure of the material's fracture toughness. A fracture mechanics approach was selected on the premise that this will normalise the quantification of material properties thereby reducing the scatter inherent in establishing mechanical properties of bamboo.

The Bolt Shear-out Test [6] is a variation of the split pin test developed to determine the behaviour of bolt-induced forces and assess their contribution to the eventual splitting behaviour of the bolted culm. Two distinct types of failures were documented depending on loading orientation highlighting the effects of mode mixity on bamboo splitting behaviour.

The Edge Bearing Test [9], shown in Figure 1c, was developed as a field-appropriate alternative to the more complex split-pin test. The failure mechanism of an edge bearing test specimen involves the formation of a pair of multi-pinned arches resulting from 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 [6, 10]. Specifically, the culm wall modulus of rupture is a measure of the transverse tension capacity of the culm wall and therefore the splitting behaviour.

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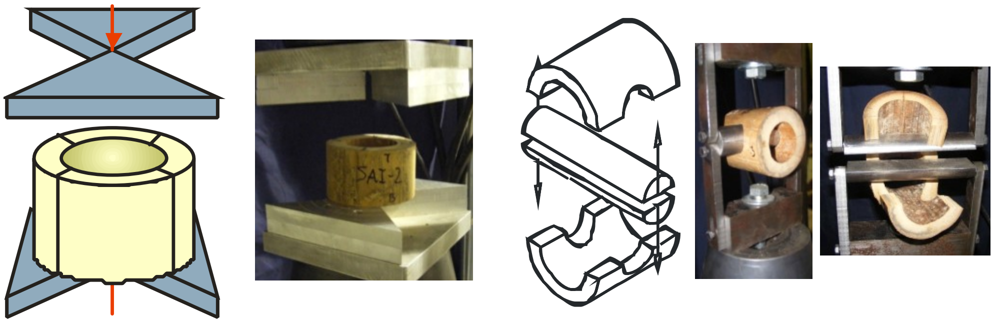
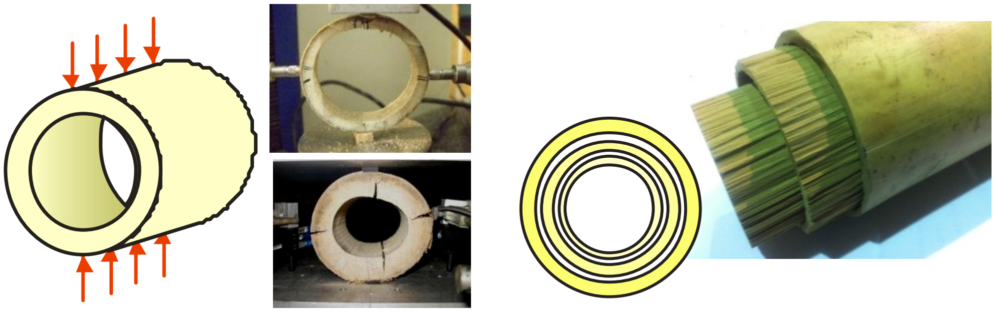
[1] Reference to Modes II and I are in relation to classical fracture mechanics in which Mode II refers to forces resulting in 'in-plane shear' and Mode I refers to perpendicular in-plane 'peeling' forces.

The Concentric Annular Edge Bearing Test [11], shown in Figure 1d, was used to obtain greater resolution of through-culm-wall properties and to isolate the effect of the material property gradient. In this test, the culm was cut, using a water jet, into two or three concentric annular sections. 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 although the test method was impractical for all but thick-walled species and was cumbersome even then.



a) longitudinal shear test [2]

b) split pin test [8]



c) edge bearing test [9]

d) concentric annular edge bearing test specimens [11]

Figure 1. Bamboo Test Methods to Assess Longitudinal Behaviour.

The split pin and edge bearing tests have been successfully adopted into the forthcoming revised ISO 22157 Standard [1]. The longitudinal shear test will also remain in this revised document. Nevertheless, these methods have their drawbacks. The longitudinal shear test captures only Mode II behaviour and therefore significantly over estimates splitting capacity. While the split pin test captures Mode I behaviour, it is a tension-based test requiring specialised apparatus and test specimen fabrication making it ill-suited as a field test. The edge bearing test, while simple to conduct, does not accurately reflect the nature of splitting failures. Additionally, test results are derived from simplified analysis and the test is not appropriate for thick-walled bamboo species.

Research Significance

The present study reports the development of the flat ring flexure test, which is a simple test method suitable for assessing Mode I behaviour of a bamboo culm. The test is compression-based (indeed, in the field it can be run using free weights rather than a test machine) and uses a simple apparatus and specimen. This developmental study investigates test parameters affecting results, thereby arriving at an appropriate and repeatable standard test method. The resulting test method is documented in a format consistent with ISO 22157 [1].

Proposed Test Method

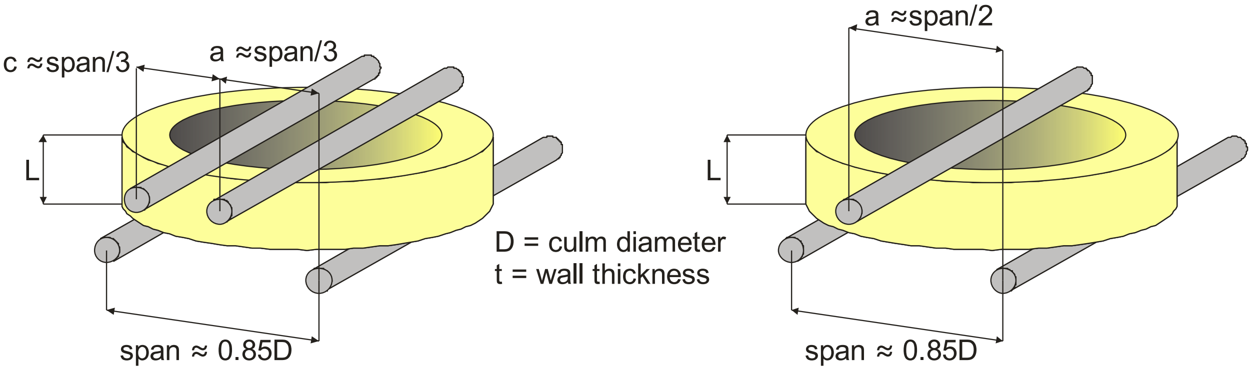
The proposed flat ring flexure test places a short section of bamboo culm in through-cross section flexure. The modulus of rupture at the failed section is a measure of the transverse tensile strength of the culm. The test method utilises a full culm section requiring very little specimen preparation (cutting and sanding ends parallel only) and results in a symmetric specimen in which only circumferential stresses are present.

A schematic view of the test arrangement is shown in Figure 2. In order to ensure alignment, a serrated-plate test arrangement with alignment pins was used as shown in Figure 3. The serrations provide accurate positions for the load and reaction rollers; span lengths and constant moment lengths may be selected in 10 mm increments (for the apparatus shown). This design ensures repeatability of tests and eliminates the need for fine measurements of each test set up.

The modulus of rupture, f_r, is calculated as:

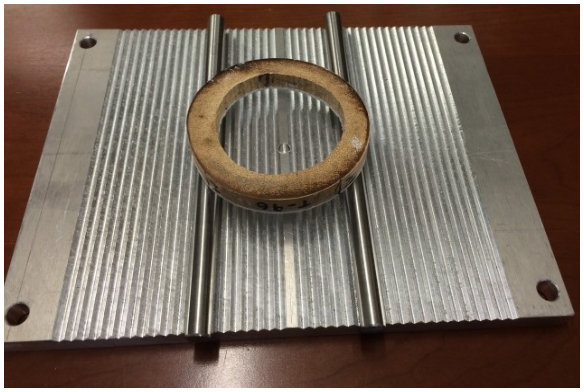
$$f_r = 3Pa/(t_N + t_S)L^2 \tag{1}$$

where P = total load applied to specimen
a = shear span
t_N and t_S = culm wall thicknesses at failure locations on either side of the culm
L = length of culm section tested (flexural depth of specimen)

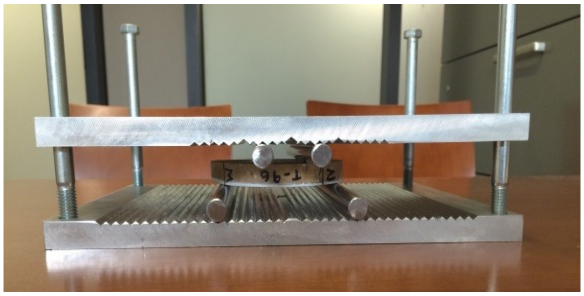


a) four-point flexure b) three-point flexure

Figure 2. Flat Ring Flexure Test Geometry.



a) serrated base plate with 100 mm diameter specimen



b) complete test frame with alignment pins in place

c) test being conducted in universal test machine
(shown 100 mm diameter specimen tested over 80 mm span with 25 mm shear span)

Figure 3. Flat Ring Flexure Test Set-Up.

Pilot Test Programme

The objective of this pilot study was to establish standard test parameters for the proposed method. Specifically, appropriate test values for the specimen depth to diameter ratio, *L/D* and shear span to depth ratio, *a/L*. Other practical test parameters will also be discussed. The pilot programme used *P. edulis* culms having a diameter (*D*) ranging between approximately 50 and 115 mm. Specimen depth was selected to be nominally $L = 0.1D$, $0.2D$ or $0.3D$. The test spans were varied to some extent, targeting a span of approximately $0.85D$. Tests were conducted in four-point flexure with a constant moment region (*c*) and both shear spans (*a*) equal to approximately one third the span (Figure 2a). A limited number of smaller diameter culms were tested in three-point flexure (Figure 2b) for which the shear span (*a*) is one half the span. It is not practical to test smaller culm diameters using four-point flexure, especially considering the limitation of 10 mm increments for loading locations. The culm diameter *D* is taken as the diameter oriented parallel to the flexural test span. In some instances, the culms were slightly oval; these were tested such that *D* was the longer principal axis. Due to the symmetry of the test arrangement, this is not believed to effect results. All specimens were cut from Borax-treated *P. edulis* culms having a moisture content of 10.5 ± 1%. Table 1 summarises test arrangement and specimen geometries tested.

Table 1 - Summary of Pilot Test Program: *P. Edulis* Specimen Dimensions and Results

test	nominal *L/D*		*D* [mm]	*D/t*	*L/D*	*a/L*	failure locations		f_r (Eq. 1) [MPa]	
4 pt	0.1	avg.	117.2	9.2	0.100	2.66	n	19	avg.	12.30
		COV	0.034	0.046	0.074	0.105	CMR	15	COV	0.160
		max	124.2	10.6	0.118	3.28	*a*	1	max	15.79
		min	108.8	8.8	0.091	2.05	support	3	min	9.81
4 pt	0.2	avg.	99.5	10.5	0.204	1.28	n	21	avg.	14.01
		COV	0.070	0.127	0.056	0.088	CMR	15 + 2 outliers	COV	0.124
		max	114.7	12.4	0.222	1.45	*a*	2	max	16.86
		min	92.2	8.7	0.182	1.12	support	2	min	11.45
4 pt	0.3	avg.	102.6	10.8	0.305	1.04	n	20	avg.	15.63
		COV	0.065	0.142	0.028	0.093	CMR	8 + 1 outlier	COV	0.087
		max	114.6	12.4	0.315	1.21	*a*	0	max	18.25
		min	95.7	8.2	0.283	0.88	support	11	min	14.22
4 pt	0.2	avg.	49.9	7.45	0.215	0.933	n	12	avg.	18.24
		COV	0.015	0.086	0.021	0.027	CMR	12	COV	0.137
		max	51.2	8.11	0.222	0.977	*a*	0	max	21.77
		min	49.0	6.07	0.206	0.886	support	0	min	14.50
3 pt	0.2	avg.	49.1	7.52	0.220	1.86	n	9	avg.	18.87
		COV	0.036	0.087	0.046	0.022	midspan	9	COV	0.102
		max	50.5	8.11	0.241	1.90	*a*	0	max	22.30
		min	44.7	6.36	0.209	1.78	support	0	min	15.62

n = number of specimens
CMR = failing in constant moment region
a = failing in shear span
f_r is calculated based ONLY on specimens failing in CMR or at midspan; shaded failure modes are excluded
outliers noted are defined by ASTM E178 [12] (Grubbs method) at 99% significance level

Four-Point Flat Ring Flexure Tests

72 four-point flexure specimens (Table 1, Figures 2a and 3) were tested in an initial evaluation of observed behaviour. Failures were classified as falling in i) the constant moment region (CMR), ii) the shear span (*a*), or iii) in the immediate vicinity of the support. A failure in the constant moment region is desired – additionally, this is the only failure mode for which the modulus of rupture may be calculated using Eq. 1 and without accounting for the in-plane curvature of the specimen. Distribution of failure types by specimen depth is shown in Table 1. Only specimens exhibiting a failure in the constant moment region were considered in subsequent analysis. For those specimens failing in the CMR, outliers were determined using Grubb's Method at a 99% significance level [12]; these were also excluded from subsequent analyses.

It is seen in Table 1, that the deeper specimens ($L/D = 0.3$) exhibited fewer desirable failures in their constant moment regions (only 9 of 20 specimens). For specimens having a nominal depth to diameter ratio of $L/D = 0.3$ (actual values, $0.28 < L/D < 0.32$), the corresponding nominal shear span-to-depth ratio is $a/L = 0.94$ ($1.21 > a/L > 0.88$). It is hypothesised that such a short shear span led to arching action, rather than flexural behaviour and resulted in a disproportional number of failures in the support region (11 of 20 specimens) and an increase in observed capacity for those specimens that did fail as desired in the CMR. For this reason, it was concluded that these deeper specimens, being less reliable, should be excluded and that $L/D \leq 0.20$.

Modulus of rupture results are shown in Table 1 and plotted in Figure 4. Each grouping in Figure 4 can be shown (Table 2) to be statistically distinct from one another with confidence exceeding 97% (using double sided t-test). Thus, there is an increase in measured modulus of rupture with increasing L/D or decreasing a/L ratios. Once again, this is believed to be partially attributed to arching action in the deeper spans. Additionally, as is often observed, the smaller specimens (nominal diameter $D = 50$ mm) exhibited higher moduli of rupture than those having a larger diameter (nominal diameter $D = 100$ mm).

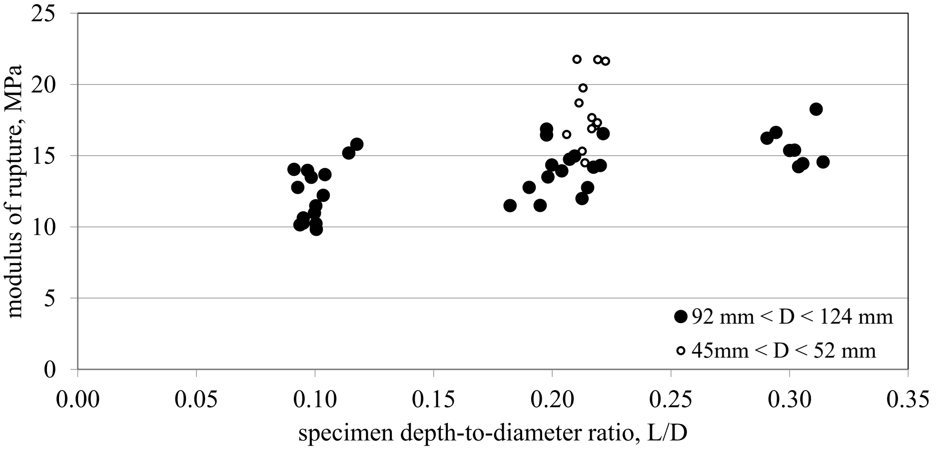


Figure 4. Modulus of Rupture Versus L/D for Specimens Tested in Four-Point Flexure.

Table 2. t-Test Significance.

test			4 pt	4 pt	4 pt	4 pt
	D		100	100	100	50
		L/D	0.1	0.2	0.3	0.2
4 pt	100	0.2	0.018			
4 pt	100	0.3	0.000	0.025		
4 pt	50	0.2	0.000	0.000	0.008	
3 pt	50	0.2	na	na	na	0.537

Selection of L/D for Testing. Based on the observations of the pilot programme, it is desirable to reduce L/D to the lowest value practical. Certainly, for L/D greater than 0.2, a disproportionate number of tests do not fail in the constant moment region. The proportion of unacceptable failures (i.e., "bad tests") for $L/D \leq 0.2$ is similar at about 20% of specimens.

In order to mitigate arching action, it is desirable to maximise a/L (thus minimising L/D), however this must be balanced with rational specimen dimensions. Particularly for smaller diameter culms, $L/D = 0.2$ is about as small a specimen as may be practically prepared. Thus the following recommendations are made: 1) $L/D \leq 0.20$; and 2) results from specimens having different L/D ratios should not be compared. As this test method is standardised, in order to mitigate the need for the second recommendation, the authors propose that $0.18 < L/D < 0.22$.

Three-point Flat Ring Flexure Results

Testing small diameter culms becomes impractical using four-point flexure tests and, even with *L/D* = 0.20, may result in relatively deep shear spans if the proposed test apparatus is used (requiring spans at multiples of 10 mm). Thus, a second series of specimens having a nominal culm diameter, *D* = 50 mm and *L/D* = 0.2 were conducted. Half of these tests were conducted in the four-point flexure condition as previously described (Figure 2a) and half in three-point flexure (Figure 2b). The shear span-to-depth ratio, *a/L*, can be made greater for the three-point test (almost doubled for the small culms tested here), thus the effects of arching action can be minimised. For a three point flexure test, a desirable failure falls within the distance *L* centred on the midspan load point. As is seen in Table 1, all smaller culms exhibited desirable failures and no outliers were identified. Furthermore, as indicated in Table 2, the modulus of rupture results are statistically indistinguishable from each other regardless of test set-up (t-test $p = 0.54$). Results from these tests are shown in Figure 5. Thus three-point flexure is equivalent to four-point flexure tests provided (in both cases) the rupture occurs in the desired region: within the CMR for four-point flexure and within the distance *L* centred on the load point for three-point flexure. Nonetheless, the authors feel that four-point flexure, when it is practical, is preferred since the failure in the CMR will not be directly affected by the bearing of the load points. As this test method is standardised, the authors propose that four-point flexure be required for $D > 75$ mm but that three-point flexure be permitted for $D < 75$ mm. Appendix A provides a proposed flat ring flexure test method written to be consistent with the current ISO 22157 test methods document [1].

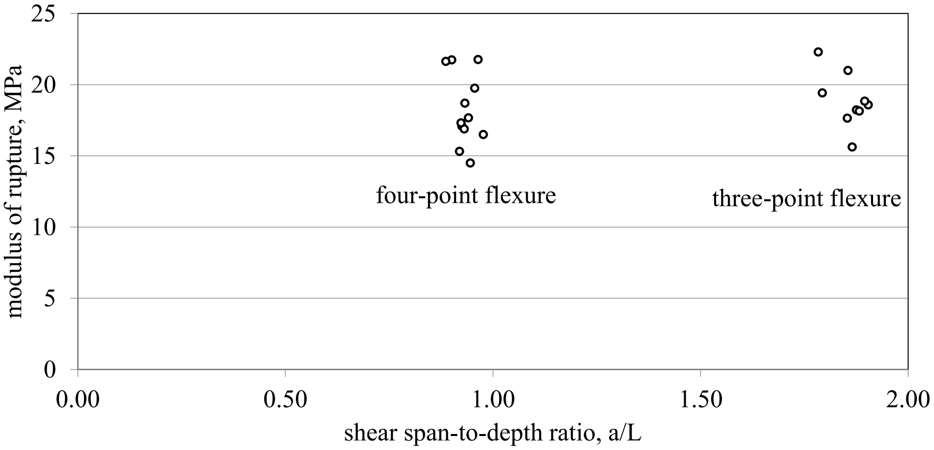


Figure 5. Modulus of Rupture of Nominal *D* = 50 mm Specimens Having *L/D* = 0.2 Subject to Four- and Three-Point Flexure.

Conclusions

The flat ring flexure test for assessing tension strength perpendicular to the fibres of full-culm bamboo specimens is proposed. Through a parametric study, and considering practical use of the test, specimen and loading parameters are determined for standardising this test method. A proposed standard test – compatible with ISO 22157 [1] is presented in Appendix A.

The research team is presently establishing a database of flat ring flexure test results including data from at least four laboratories, covering (to date) ten species of bamboo. This data will be used to establish precision guidelines for the flat ring flexure test.

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APPENDIX A

The following is a proposed test method written to be consistent with ISO 22157 [1]. This method is not presently included in, nor has it been considered for inclusion in ISO 22157 at the time of this writing.

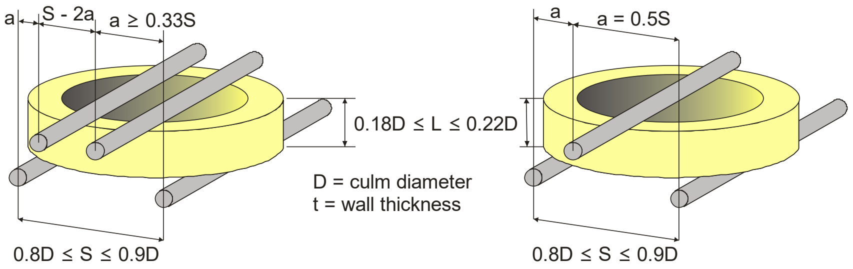
A. Tension strength perpendicular to the fibres by flat ring flexure

This clause specifies a method for determining the tension strength perpendicular to the fibres on specimens from bamboo culms.

A.1 Apparatus

Test machine. Tests shall be carried out on a suitable testing machine capable of measuring compression load with a precision of at least 1%.

Flat ring flexure apparatus capable of applying four-point and/or third point bending loads to a flat ring bamboo specimen.



a) four-point flexure

b) three-point flexure alternative for $D \leq 75$ mm

Figure A-1. Schematic View of Flat Ring Flexure Loading Setup and Specimen.

Figure A-2. View of Example Flat Ring Flexure Apparatus in Test Machine

Rollers providing support and used to apply load shall have a minimum diameter of 10 mm and shall be continuously supported in the test machine. Rollers shall be aligned such that they are parallel and that their spacing remains constant during a test.

A.1.1 Test span, S

The flexural test span shall be between 0.80 and 0.90 times the specimen diameter; that is, $0.8D \leq S \leq 0.9D$.

A.1.2 Four point loading shear span, a, and constant moment regions

The loading rollers shall be arranged to provide a central ‘constant moment region’ and two equal shear spans. Each shear span shall be at least one third the flexural test span; that is, $a \geq 0.33S$.

A.1.3 Three point loading

For specimens having $D \leq 75$ mm, it is permissible to provide a single roller in the middle of the flexural test span, resulting in two equal shear spans of length $a = 0.5S$

A.2 Preparation to test specimens

Test culms shall be selected according to [ISO 22157 Clause] **6**.

Flat ring flexure tests shall be made on specimens without a node. The length of the specimen shall be between 0.18 and 0.22 times the diameter; that is, $0.18D \leq L \leq 0.22D$. The specimen ends shall be parallel.

A.3 Procedure

Measure the diameter of the specimen and select the axis for testing [typically this will be the larger of the two principle diameters of an oval specimen]. This axis will be assumed to intersect 0º and 180º around the culm circumference and be labelled N-S.

Measure the length, L, and wall thickness, t, at both the 90º (E) and 270º (W) locations.

The specimen shall be placed in the test apparatus so that its primary N-S axis is the flexural test span; that is, the N-S axis is perpendicular to the roller orientations.

A small load, not exceeding 1% of the expected failure load is initially applied to ‘seat’ the specimen in the apparatus.

Application of load shall comply with [ISO 22157 Clause] **5.2**.

> *The following is ISO 22157 Clause 5.2; it is included here is in the interest of clarity.*
>
> **5.2 Rate of load application**
>
> The rate of load application of the testing machine shall be selected such that failure is reached within (300 ± 120)s. Tests that fail in less than 30 seconds shall be removed from analysis. The load shall be applied continuously without interruption at the required rate throughout the test. For tests run in displacement control, the rate of traverse of the movable head of the testing machine shall be the free running or no-load speed of the head for mechanical drive type machines, and the loaded head speed for hydraulic or servo-hydraulic driven testing machines. The time to failure for each individual specimen shall be recorded in the test report.

The reading of the maximum load, F_{ult}, at which the specimen fails shall be recorded.

Following each test, obtain specimens for the determination of moisture content in accordance with [ISO 22157 Clause] **7**.

A.4 Calculation and expression of results

The tension strength perpendicular to the fibre, f_r, shall be calculated from

$$f_r = 3F_{ult}a/(t_N + t_S)L^2 \qquad \text{Eq. A-1}$$

where F_{ult} = total load applied to specimen

a = shear span

t_N and t_S = culm wall thicknesses at failure locations on either side of the culm

L = length of culm section tested

A.5 Test report

The test report shall be in accordance with [ISO 22157 Clause] **5.4**.